Broadband Over Power Lines Analysis

By James K. Boomer, April 14, 2005

Foreword

The author has previously submitted documents to the FCC regarding BPL that show the major issues, and that recommend actions by the FCC. This submittal presents more detail, and also uses the ITU 1993 ambient noise data in the calculations. It is hoped that this paper will be of use to the FCC in re-evaluating its BPL Report and Order. In fact, as shown herein, the FCC must abandon the current approach to BPL. Indeed, it must re-evaluate the whole BPL proposition, and develop new regulations based on sound engineering principles, if it intends to go forward with BPL.

Summary

Successful Broadband Over Power Lines (BPL) implementation demands exhaustive engineering, and regulatory analyses, to arrive at a sound go/no-go decision. If the conclusion is "go," the FCC must develop new regulations that include licensing, and attendant specifications for maximum output power, bandwidth, spurious emissions limits, and frequency allocations. This will assure electromagnetic compatibility with licensed radio stations operating in the 1.705- to 28 MHz frequency range, and in other frequency ranges for that matter. BPL transmitters connected to power lines are intentional emitters connected to radiating antennas, not unintentional emitters. Therefore FCC Part 15 field strength regulations are not applicable to BPL.

Technical Issues

BPL is an unacceptable source of interference to licensed radio stations. In its Report and Order (R&O), released on October 28, 2004, the FCC acknowledges BPL electromagnetic compatibility (EMC) problems by specifying frequency bands and zones where BPL operations are forbidden (because of interference concerns).

Indeed, these forbidden bands and zones are an admission that BPL causes interference with licensed radio services.

Power lines are electromagnetic radiators when BPL radio frequency energy is applied to them. And, this radiated energy interferes with radio receivers operating in its frequency range of 1.705 MHz to 80 MHz, and probably others. However, this paper addresses Access BPL and the amateur radio 1.8-28 MHz frequency bands falling in the 1.705- to 80 MHz frequency range.

The combinations and permutations of BPL systems, power line configurations, and licensed radio station configurations, make it impossible to predict the compatibility of BPL with licensed radio stations whose frequencies it uses. Indeed, *every configuration* would have to be certified, and re-certified again, if changed after initial certification.

As we will show below, it is impossible to guarantee BPL electromagnetic compatibility with licensed radio stations using Part 15 field strength measurements.

The only way BPL can be successfully implemented is for the FCC to issue licenses, specify power levels, spurious emission limits, and frequency allocations based on objective detailed engineering analyses and measurements, which, as yet, have not been done.

Regulatory and Legal Issues

The FCC has taken a fatal shortcut in issuing the BPL R&O, which permits BPL providers and power companies to furnish unlicensed systems that operate on licensed radio stations' frequencies.

Indeed, the R&O ignores the preponderance of BPL interference evidence already encountered in trial systems in communities such as Cedar Rapids, Iowa, and Briarcliff Manor, New York, and the lack of timely FCC attention to these individual instances of interference. Additionally, the American Radio Relay League has documented many measurements and complaints. Fundamentally, the FCC BPL R&O ignores the basic laws of radio physics.

Unfortunately, FCC Chairman Powell is on record, stating that BPL will affect spectrum users. Additionally, according to the American Radio Relay League, he has implied that the FCC must "balance the benefits of BPL against the relative value of other licensed services." Essentially, the FCC is saying, "BPL is so important that we are willing to abandon our role of sound frequency spectrum management, and let it interfere with some licensed radio services, instead of doing our engineering and regulatory homework to assure EMC with licensed services."

The FCC's BPL approach throws the inherent problems over the transom to BPL providers, users, and licensed stations, with the exception of "forbidden zones and frequencies," which is an overt admission that BPL interferes with licensed radio services.

Instead of doing its technical and regulatory homework, the FCC naively seeks parties' "good faith" in identifying and resolving any instances of BPL interference, and describes questionable methods wherein the providers will solve interference problems.

The problem here is timely verification and elimination of interference. The FCC, supported by some prospective providers, naively tries to show how EMC problems can be identified and fixed almost instantaneously by such techniques as notching frequencies, power control, and shut down. The FCC understandably fails to show how these measures would be implemented, because their real time implementation to solve EMC problems in a timely manner is impossible. Verification of EMC problems requires measurements, and elimination requires detailed analysis, system changes, and further measurements, all of which consume financial, and personnel resources, and all of which deepen the intrinsic resentment on the part of providers and people who are experiencing interference. This is the regulatory Achilles' heel of BPL.

Clearly, massive legal battles over "who shot John" are built into the FCC R&O for BPL. Users of BPL systems will be complaining about interference from licensed transmitters operating within FCC regulations, and licensed radio station operators will be complaining about BPL interference. Indeed, the FCC R&O is a windfall for attorneys.

Business Case Issues

While this paper concentrates on the BPL technical and regulatory issues, the BPL business case is clearly open to question because the wideband market is already exploding in response to increasing consumer demand via the proven cable, satellite, and wireless systems.

So, in the face of this rapidly expanding market, objective people must question the economic viability of BPL. Indeed, by the time all of the BPL technical and regulatory issues are identified and resolved, and the attendant monetary and personnel resources are expended, how much market share will remain for BPL? Additionally, if the FCC proceeds as currently described in its R&O, the massive built-in litigation will further impact, delay, and increase the cost of being in the BPL business. This, in turn, will be reflected in the service prices and shrinking market share.

Currently, prospective BPL providers are trumpeting the FCC's technical naiveté and falsely or naively claiming that BPL implementation will go smoothly with very few if any problems. This is the formula for business failure because the BPL environment is full of technical, regulatory, and legal "landmines" that must be objectively addressed.

Recommendation

The FCC must rescind its BPL R&O, which is the epitome of technical and regulatory naiveté. If the FCC intends to pursue BPL, it must undertake much more objective, unbiased technical and regulatory analyses to arrive at a sound go/no-go decision, and a feasible implementation approach if the decision is "go."

Technical Analysis

The following technical analysis shows the extent of the BPL EMC problem, and how the current FCC approach guarantees failure to achieve EMC with licensed radio services. Indeed, it clearly shows that a successful implementation is possible only with specific regulations that contain frequency allocations, power levels, and spectral requirements, based on sound engineering principles.

Radio Receiver Considerations

A radio receiver's noise factor is defined as,

$F = (C_i/N_i)/(C_o/N_o)$ Equation 1

Where,

F= Noise factor (power ratio)

C_i= Input radio frequency carrier level (Watts)

N_i= Input noise level (Watts)

C_o= Output carrier level to the receiver's demodulator (Watts)

N_o= Output noise level (Watts)

Solving Equation 1 for (C_o/N_o), we have,

$(C_o/N_o) = (C_i/N_i)/F$ (power ratio) Equation 2

But,

$C_o = C_iG_r$ Watts

Where,

G_r=Receiver gain from its antenna terminals to the demodulator input (power ratio)

Substituting this in Equation 2, and solving for N_o, we have,

$N_o=G_rN_iF$ Watts

The input noise is,

$N_i=kT_oB$ Watts Equation 3

Where,

k= Boltzmann's Constant = 1.38×10^{-23} Joule per degree Kelvin

T_o= Standard temperature = 270 degrees Kelvin

B= System noise bandwidth (Hertz)

Thus, from Equation 3, the receiver output noise (also called the noise floor) is:

$N_o = G_r N_i F = kT_o B G_r F$ Watts Equation 4

We are interested in determining how much the receiver's noise floor will increase when external noise is applied to its antenna input terminals. That is, if external noise raises the receiver noise floor 1dB, the output carrier-to-noise ratio will be degraded by that amount, assuming a constant input signal level.

Assume the added noise power applied to the receiver's antenna input is mkT_oB, where,

m= The multiplier with respect to $kT_o B$, the receiver's noise input level.

Then, the resulting receiver output noise power with the added input noise power is:

$N_o' = kT_oBG_rF + m\,kT_o\,BG_r$ Watts Equation 5

The ratio of the receiver noise floor with external noise to its noise output level without external noise is:

$N_o'/N_o = (kT_oBG_rF + m\,kT_o\,BG_r)/(kT_oBG_rF) = 1 + m/F$ (power ratio) Equation 6

For example, if m=F, then, from Equation 6, $N_o'/N_o = 2$, which means the receiver's output noise floor power is doubled with this added input noise power. This is, in fact, one procedure for measuring a receiver's noise factor—we add input noise until the output noise power is doubled. Then the added input noise equals the receiver's internally generated noise.

Noise figure, which is expressed in decibels, is equal to ten times the logarithm, to the base ten, of the noise factor. Thus, if a receiver's noise factor is 2, its noise figure is $10\log_{10}2 = 3.01$ dB.

With the above information, we are now in a position to evaluate the maximum allowable interference from a BPL system.

Maximum Allowable Interference

General

Some BPL systems use spread spectrum modulation, which is essentially band-limited random noise for interference analysis purposes. In this case, we can assume that BPL interference to a receiver is essentially random noise.

In cases where BPL modulation consists of discrete signals, we have to calculate the interference to a receiver by considering its cross modulation and intermodulation characteristics.

For this analysis, we will assume that a BPL system is using spread spectrum modulation. And, we will be examining the interference problem in the popular amateur radio high frequency (HF) bands in the 1.8- to 28 MHz frequency range.

Ambient Radio Noise in The 1.8- to 28 MHz Frequency Range

The ambient noise sources in the 1.8- to 28 MHz frequency range are atmospheric noise, man-made noise, and galactic noise. Their levels vary with time, season, and world location. Ambient noise levels are characterized from "quiet" to "noisy." Sparsely populated areas have the lowest man-made noise. And atmospheric noise increases in the summertime when thunderstorms are most prevalent. Galactic noise originates outside the earth and its atmosphere.

At a given frequency, location, season, and time, the external noise power induced at a radio receiver's antenna terminals depends upon the type of antenna connected to it.

In 1993, the International Telecommunications Union (ITU-R) published Recommendation P.372-8, which characterizes ambient noise. Table 1 summarizes the total noise in a quiet winter Alaskan environment. These data are chosen, because there must be BPL-licensed station EMC in a quiet environment. The table shows the noise level, in one Hertz of bandwidth, in dB with respect to one Watt (dBW/Hz), and with respect to thermal noise (kT_o) in one Hertz of bandwidth.

Freq. (MHz)	Ambient Noise Level (dBW/Hz)	Ambient Noise Level (dB-kT_o/Hz)
1.8	-153	51
3.5	-159	45
7	-166	38
10	-173	31
14	-178	26
18	-181	23
21	-183	21
24	-184	20
28	-186	18

Table-1 Ambient Noise Level-Quiet Environment (Data Source: ITU-R)

Clearly, an antenna other than the short vertical over perfectly conducting ground, as assumed for Table 1, will result in a different value of ambient noise applied to a receiver's antenna input terminals. In addition, some antennas reject noise better than others. But for this analysis, we will use the data in Table 1, which gives us a good starting point.

Effect of Ambient Noise Upon Receiver Carrier-to-Noise Ratio

Now, let us show an example of how to calculate the effect of the external ambient noise on a receiver's noise floor and output carrier-to-noise ratio at 28 MHz.

First we calculate m. Table 1 shows that at 28 MHz the ambient noise level is 18dB above kT_o, which is a power ratio of 63.10—thus m=63.10, that is:

Power Ratio=$10^{(dB/10)}$ =$10^{1.8}$=63.096=63.10 (rounded to two decimal places) for the above example.

Typical modern HF receivers have noise figures of 6 dB or less at 28 MHz. Then, the noise factor is:

Noise Factor=$10^{[F(dB)/10]}$ Equation 7

Then for the above example with a receiver whose noise figure is 6dB,

Noise Factor=F=$10^{[6/10]}$=3.98

We use Equation 6 to calculate the noise floor increase with the ambient noise applied to the receiver's antenna terminals:

$N_o'/N_o=1+m/F=1+(63.10/3.98)=16.85$ (power ratio)

Thus, we see that ambient noise input increases the receiver output noise floor by 16.85 times. We convert power ratios to dB using the equation:

$(N_o'/N_o)_{dB} = 10\log_{10}(1+m/F)=10\log_{10}(1+63.10/3.98)=12.27\text{dB}$

So, in summary, in the above example, the external ambient noise, 18 dB above thermal, increases the receiver noise floor by 12.27dB.

From the above analysis, we see that if we increase the receiver's noise floor by 12.27dB, we have to increase the input carrier power by 12.27dB to maintain the same output carrier-to-noise ratio (C/N) to the receiver's demodulator.

Now, assume that we are communicating using binary phase shift keying (BPSK). Figure 1 shows the required receiver C/N output to its demodulator, for a given bit error rate (BER) in a modern system, including the implementation loss. Both uncoded and coded (using rate-1/2 convolutional coding with constraint length 7) data are shown.

A BER of less than 10^{-5} is required for essentially error-free communications, and a BER of 10^{-3} is the maximum allowable for minimum communications reliability. As shown in Figure 1, a C/N of 6.5dB into the demodulator is required for a coded system BER of 10^{-5}. Notice that a C/N decrease of 1.5dB increases the BER from 10^{-5} to 10^{-3}.

One popular mode communicates at 50 bits per second. Thus with a half-rate code, the required detection bandwidth is 100Hz (some systems use different coding and consume less bandwidth). But for our example, we will assume the receiver bandwidth is, B=100Hz.

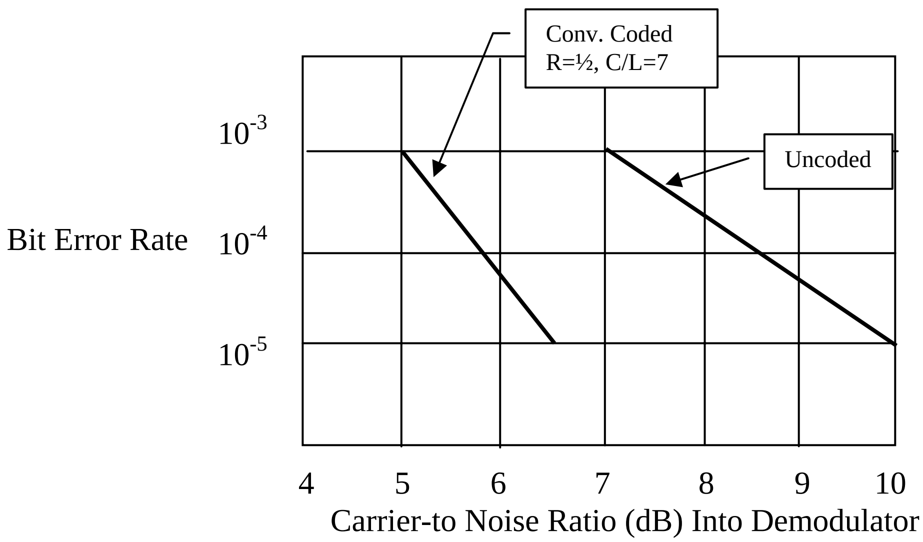

Figure-1 Binary Phase Shift Keying (BPSK) Bit Error Rate vs. C/N Ratio

We determine the required carrier input level for a given system without added external noise as follows:

From Equation 1 and Equation 3,

$F = (C_i/N_i)/(C_o/N_o)$

Solving for (C_i/N_i), we have,

$(C_i/N_i)= (C_o/N_o)F$, from which,

$C_i= N_iF\ (C_o/N_o)=kT_oBF(C_o/N_o)$ Watts Equation 8

We find it convenient to express Equation 8 in terms of dB for the carrier-to-noise ratio and dBW for carrier levels. Thus,

$$C_i(dBW)=10\log_{10}(1.38x10^{-23}x290)+10\log_{10}B+F_{dB} + (C_o/N_o)_{dB} \qquad \text{Equation 9}$$

Then for the above example, for an output C/N of 6.5dB, the required carrier input with no additional input noise is:

$$C_i(dBW)= 10\log_{10}(1.38x10^{-23}x290)+10\log_{10}100+6+6.5= -171.48dBW$$

Now, we have shown that when connected to the antenna, the external ambient noise causes the receiver's noise floor to increase by 12.27dB. Thus, in order for us to maintain an output C/N of 6.5dB, we must increase the carrier input by 12.27dB. Thus the carrier input must be increased to –159.21dBW (–171.48+12.27= -159.21). For the time being, we will assume that the receiver's antenna has unity gain with respect to an isotropic radiator. Later, we will discuss the effects of antenna directivity gain.

Effect of External Ambient Noise Plus Additional External Noise Upon Receiver Carrier-to-Noise Ratio

We can calculate the effect of other external input noise, in addition to the external ambient noise, upon a receiver's output C/N as follows.

Consider the above 28 MHz receiver example. We determined that with an ambient noise level 18dB above thermal, we need a –159.21dBW carrier input in a 100Hz bandwidth for a 6.5dB output C/N into the receiver's demodulator. In addition, we showed that this ambient noise 18 dB above thermal increased the receiver noise floor by 12.27dB**.**

From Figure 1, we see that a 1dB decrease in C/N to the receiver's demodulator increases the system BER from 10^{-5} to between 10^{-3} and 10^{-4}, which is the maximum degradation for reliable throughput. Thus, let us determine how much external interfering noise can be added to the external ambient noise to reduce the output C/N into the receiver's demodulator from 6.5- to 5.5dB. In other words we need to know how much additional external input noise is required to raise the receiver's noise floor by an additional1dB over its value with just external ambient noise added.

We have determined that when m=63.10, the receiver's output noise floor increases by a factor of 16.85 (12.27dB). So, now we need to calculate the value of m for an output noise floor increase of 1dB to 13.27dB. The power ratio corresponding to 13.27dB is 21.23.

We will now proceed to derive a convenient equation we can use to calculate the maximum allowable additional external input noise for a given maximum allowable increase in the receiver's noise floor, which corresponds to a given maximum allowable decrease in C/N output to the receiver's demodulator.

From Equation 6, we have:

$N_o'/ N_o=1+m/F$

Solving for m:

$m= F[(N_o'/ N_o)-1]$ Equation 10

The additional noise applied to a receiver's antenna terminals is just:

$N_{ia}=mkT_oB= F[(N_o'/ N_o)-1]kT_oB$ Watts

Where,

(N_o'/ N_o)=Ratio of receiver output noise floor with additional input noise to its value with no additional input noise.

Let us designate the external ambient noise power as:

$N_{ia}=m_akT_oB = F[(N_o'/ N_o)-1] kT_oB$ Watts

Where,

m_a= The external ambient noise multiplier with respect to $kT_o B$ (thermal noise)

F=Receiver noise factor

(N_o'/ N_o)=Ratio of receiver noise floor with external ambient noise input, to the noise floor without external ambient noise input

Noise power density (Watts/Hz, or dBW/Hz) is a convenient way to represent noise. However, we will also show how to calculate actual power in given bandwidths.

From the earlier analysis, the external ambient noise input to the receiver is:

$N_{ia}= m_akT_oB$ Watt, and the noise power density (noise power in one Hertz of bandwidth) input is just $N_{ia}= m_akT_o$ Watts/Hz—i.e. B=1.

Let us also designate the parameter, m, associated with external ambient noise plus additional external noise, as m_T. Finally, let us designate the additional noise floor increase power ratio, due to the additional noise above external ambient, as r_a.

Then,

$m_T= F[(N_o'/ N_o)r_a-1]$

The total noise input power density to the receiver's antenna terminals is:

$N_{iT}= m_TkT_oB$ Watts= m_TkT_o Watts/Hz

The additional noise power, N_{iI}, above ambient noise power is:

$N_{iI}=N_{iT} - N_{ia}= m_T kT_oB- m_a kT_oB=kT_oB(m_T - m_a)$ Watts= $kT_o(m_T - m_a)$ Watts/Hz

After substitution and combining, we have:

$N_{iI},= kT_oF(N_o'/ N_o)(r_a-1)B$ Watts

$= kT_oF(N_o'/ N_o)(r_a-1)$ Watts/Hz Equation 11

Reviewing the terms in Equation 11,

N_{iI}=Additional noise power density input to the receiver's antenna terminals in addition to the external ambient noise.

k=Boltzmann's Constant=$1.38x10^{-23}$ Joule per degree Kelvin

T_o=Standard temperature=290 degrees Kelvin

F=Noise factor (power ratio)

(N_o'/ N_o)=Increase in receiver's noise floor with external ambient noise input to its antenna terminals.

r_a=Increase in receiver's noise floor above (N_o'/ N_o) (power ratio)

It is convenient to express Equation 11 in terms of dBW, and dB, as follows:

N_{iI} (dBW/Hz)= $10\log_{10}kT_o + F_{dB} + (N_o'/ N_o)_{dB} + 10\log_{10} (r_a-1)$ Equation 12

Earlier, in the 28 MHz example we showed that external ambient noise 18dB above thermal, applied to the receiver's antenna terminals, increases the its noise floor by 12.27dB.

We want to know how much additional external noise input it takes to decrease the receiver's C/N output to its demodulator by 1dB from what it is with just external ambient noise applied. Thus, r_a in Equation 12 is 1.2589, the power ratio corresponding to 1dB.

Thus, we calculate the maximum allowable additional external noise, N_{iI}, from Equation 12, as:

N_{iI} (dBW/Hz)=$10\log_{10}(1.38x10^{-23}x290)+6+12.27+10\log_{10} (1.2589-1)$
= -191.58 dBW/Hz

We have used this same approach to calculate the maximum allowable external noise input to the receiver, in addition to the external ambient noise, for the popular radio amateur bands (See Table 2). Note that Table 2 shows a 10dB noise figure for the1.8 MHz receiver, and a 6dB noise figure for the rest of the frequencies.

Freq. (MHz)	Receiver Noise Figure (dB)	Ext. Ambient Noise (dB-KT_o)	Noise Floor Increase Due to Ambient Noise (dB)	Max. Allow. BPL Intf. for 1dB C/N Degrad. (dBW/Hz)
1.8	10	51	41.00	-158.85
3.5	6	45	39.00	-164.85
7	6	38	32.00	-171.84
10	6	31	25.01	-178.83
14	6	26	20.04	-183.80
18	6	23	17.09	-186.76
21	6	21	15.14	-188.71
24	6	20	14.17	-189.68
28	6	18	12.27	-191.58

Table 2-Maximum Allowable BPL Interference to Licensed Station BPSK Receiver
(See Text)

Notice in the above analysis, we have assumed that the receiver's antenna has unity gain. In the further analysis to follow, we will deal with antennas with other than unity gain.

Typical BPL Configuration Analysis

By law, a licensed radio station is entitled to operate interference-free, from unlicensed sources, or from malicious interference sources, in low or high ambient noise conditions.

So the notion that we can stand a1dB degradation in output C/N to a licensed station receiver's demodulator is generous.

With the above technical background, let us examine the BPL-licensed station EMC issue.

We can use EZNEC antenna modeling software to determine the maximum allowable BPL power output to the electrical transmission lines in order to have EMC. Furthermore, we can use the same modeling technique to determine the level of interference the BPL system will encounter in the presence of a licensed station transmitted signal.

The antenna model we have chosen (Figure 2), emulates one system described in NTIA Report 04-413, namely, three 10 mm diameter power lines, 340 meters long, spaced 60 cm. apart, and 8.5 meters above the ground. Each line is terminated in 50 Ohms at each end, and one outside line is center fed by the BPL transmitter. In addition, we collocated a half-wave dipole 30 meters from the three-wire electrical power transmission system, and at a height of 8.5 meters above the ground. We choose a 30-meter separation because the American Radio Relay League (ARRL) has determined that a significant number of radio amateurs' antennas are collocated at this distance, and the FCC targets EMC at this distance from the power lines.

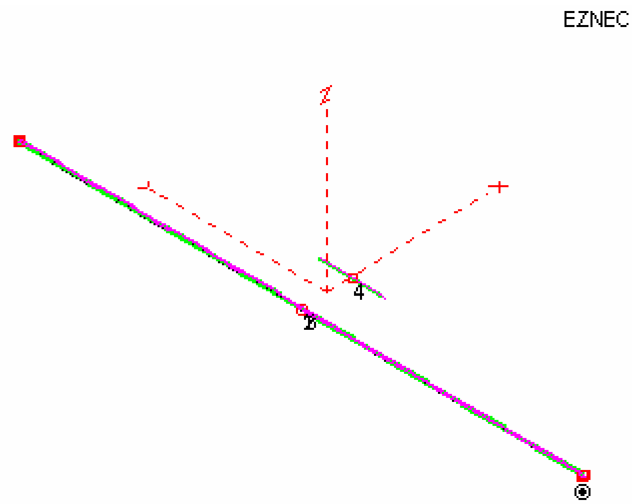

Figure 2-BPL-Licensed Station Antenna Modeling Geometry

In Figure 2, the three power lines look like one conductor, but this is just because of the scale of the figure. There are, in fact, three power line conductors, and a collocated half-wave dipole.

BPL Transmit-Licensed Station Receive Analysis (3.5 MHz)

The licensed station dipole center is lined up with the center of the power line system because the maximum directivity gain is near right angles to the power lines' orientation, as shown in Figure 3. That is, if the power lines are oriented north to south, the maximum gain of the power line array is near east to west. Note in Figure 3 that the power line array has a maximum directivity gain of 11.19dB relative to an isotropic radiator (11.19dBi) at a 30-degree elevation angle, and at 85 degrees azimuth with respect to the power lines' direction.

With the geometry of Figure 2, at 3.5 MHz, a BPL power output of $3.4x10^{-15}$ Watt/Hz (-144.69dBW/Hz, or –114.69 dBm/Hz) to the power line system results in an interference power of –164.85dBW/Hz to a licensed station receiver connected to a half-wave dipole antenna collocated 30 meters from the power lines. This is the maximum interference level permitted in accordance with Table 2. If the BPL system bandwidth is, say, 10 MHz, and its signal structure is essentially band-limited pseudo-random noise—i.e. spread spectrum, its maximum allowable output to the power line system is –144.69+10 log 10^7= -74.69 dBW, or –44.69dBm ($3.40x10^{-8}$ Watt) in a 10 MHz bandwidth.

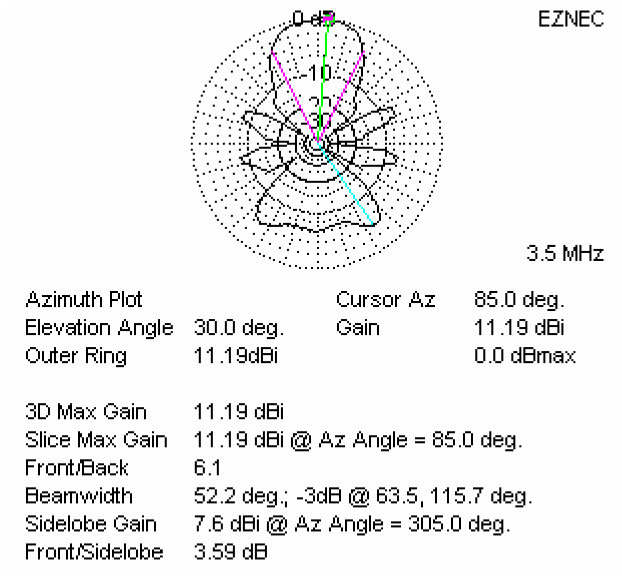

Figure 3-Power Lines' Far Field Directivity Pattern With Licensed Station Half-wave Dipole Collocated 30 meters Away (See Text)

<u>Licensed Station Transmit-BPL Receive Analysis</u>

With the basic geometry of Figure 2, we excite the half-wave dipole with 1500 Watts of power, and determine how much power is received by the BPL system coupled to the center of one of the three power lines.

Figure 4 shows the directivity pattern of the half-wave dipole when it is spaced 30 meters from the power line system.

With the geometry of Figure 2, at 3.5 MHz, 1,500Watts output to a half wave dipole collocated 30 meters from the power line system, results in a received power by the BPL system of 0.26 Watt (-5.85 dBW, or +24.15 dBm). Its interference from, say, a single sideband (SSB) voice transmitter with a bandwidth of 2.8 kHz will be –5.84 dBW peak envelope power in this bandwidth at 3.5 MHz. So, in this 2.8 kHz bandwidth, the BPL system will be operating with a signal-to-interference (S/I) ratio of: –74.69-(-5.85)= -68.84 dB. The performance of BPL with this coherent interference will depend upon its signal and coding architecture, and its dynamic range—i.e. this narrowband signal may desensitize the BPL system.

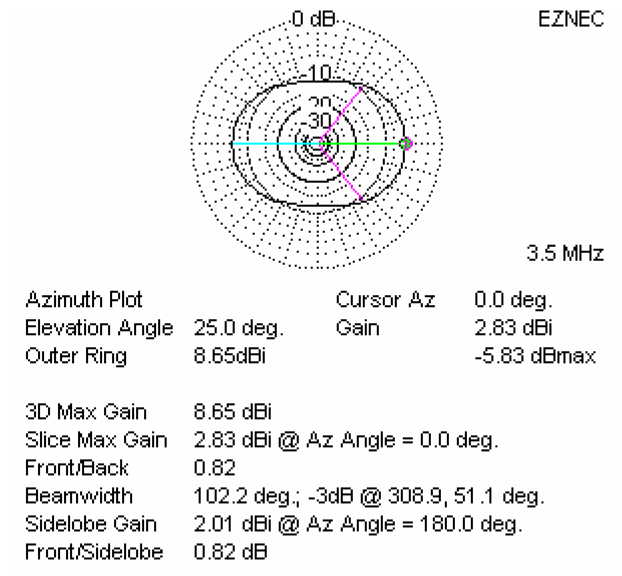

Figure 4- 3.5 MHz Half-wave Dipole Azimuth Pattern When 30 Meters From Power Lines (See Text)

The directivity gain of the half-wave dipole is greater at higher angles than shown in Figure 4.

The BPL interference induced to a licensed station receiver's antenna terminals will be altered by its antenna gain. If an antenna has 8dB gain over a half-wave dipole (8dBd), the interfering noise from BPL will be 8dB greater at the azimuth where this gain is realized. Likewise, with this antenna gain, the interference to the BPL system from the licensed station's transmitter will be 8dB greater than it would be with the half-wave dipole shown in Figure 2. Unlike the BPL interference, the external ambient noise may or may not be amplified by the licensed station's antenna, since it emanates from many directions. Thus the EMC problem could be greater than noted above.

Antenna Modeling Summary

Clearly, the directivity gain of the power line system will be different at different frequencies and with different geometries than shown in Figure 2. Additionally, many licensed stations use antenna systems with substantially higher directivity gain arrays at 3.5 MHz and at other frequencies. Thus, the maximum allowable BPL output power for EMC with 30 meters separation, or any separation for that matter, will vary with frequency and antenna directivity gain.

In fact, from the above single example:

We see that we can be assured of EMC only if we evaluate every combination of power outputs, modulations, and radiating system directivity gains for both the BPL and licensed station systems. This is a massive task to say the least, and clearly points to the need to treat BPL as a radio transmitting and receiving system.

We have not addressed in-house systems where the BPL signals are conducted and radiated by house wiring. Clearly, this is another set of complex issues that must be addressed.

Field Strength Considerations

In considering field strength we have to specify whether the antennas are in each other's near field or far field. In the above 3.5 MHz case (Figure 2), medium voltage power lines carrying BPL energy, and a collocated half-wave dipole separated 30 meters from them, are in each other's near field, since 30 meters is less than a half-wavelength at 3.5 MHz. Mutual impedance between the radiators affects each antenna's radiation pattern.

An antenna's far field is considered to be five wavelengths or more removed from it. At this distance, mutual impedance effects are negligible. So, at 3.5 MHz, the BPL-licensed station antenna separation must be greater than 429 meters (85.7x5=428.57 meters)—i.e. more than approximately 0.27 mile, in order for the system to behave in accordance with far-field radio antenna physics. Field strength measurements made with the intent to extrapolate them to a specific neighboring antenna can be misleading if, in the actual application, the neighboring antenna and the BPL power lines are in each other's near field.

However, it is informative to consider field strength, since the current BPL system's emission limit is 30 microvolts per meter in a 9kHz bandwidth at 30 meters from the BPL medium voltage power lines.

Table 2 shows that the maximum allowable interfering broadband energy at the antenna terminals of a 3.5 MHz licensed station's receiver of 6dB noise figure, is -164.85dBW/Hz.

With the received power known, the field strength is given by:

$$E_f=(0.2294 x f_{(MHz)}) \text{ x } (P_r/G_r)^{1/2} \text{ Volts/meter} \qquad \text{Equation 13}$$

Where,

E_f= Field strength, Volts per meter

$f_{(MHz)}$=Frequency, Megahertz

P_r=Received power, Watts

G_r=Receiver antenna gain, referenced to an isotropic radiator (power ratio)

FCC Part 15 specifies a field strength measurement bandwidth of 9kHz. So, the maximum allowable interfering power, in this bandwidth, to a licensed receiver at 3.5MHz is:

P_r= -164.85+10$\log_{10}$9000= -125.31 dbW = 2.94 x10^{-13} Watt in a 9 kHz bandwidth

Assume a half-wave dipole antenna, which has a directivity gain of 1.64 (power ratio) relative to an isotropic radiator. Note that this is a directivity gain of 2.15dB (1.64 power ratio converted to dB—i.e. 10$\log_{10}$1.64=2.15dB).

Then, from Equation 13, we have

$E_f=(0.2294xf_{(MHz)})$ x $(P_r/G_r)^{½}$ =0.2294x3.5x(2.94x10^{-13}/1.64)$^{1/2}$= 3.4x10^{-7} Volt/meter in a 9kHz bandwidth=0.34 microvolt/meter.

Notice that this is 38.91dB below the FCC proposed 30 microvolts/meter limit, that is, 20log10(0.34/30)= -38.91dB. In other words the FCC specification of 30 microvolts/meter is 38.91 dB too high for EMC with the above licensed station operating at 3.5 MHz.

Table 3 lists the maximum permissible BPL interference in dB with respect to one microvolt per meter per Hertz of bandwidth (dB-µV/m/Hz), and the maximum allowable BPL field strength in microvolts per meter in a 9 kHz bandwidth, assuming a half-wave dipole antenna. Notice that this is just Table 2 with two additional columns.

Equation 13 can be expressed in terms of dBW/Hz, dB, and dB-µV/m as follows:

$$E_f \text{ (dB-µV/m)} = 20\log_{10}0.2294+20\log_{10} f_{(MHz)})+10 \log_{10} P_r - 10 \log_{10} G_r +20\log_{10}10^6$$

$$=107.21+20\log_{10} f_{(MHz)})+ P_r(dBW)-G_r(dBi) \quad \text{Equation 14}$$

Freq. (MHz)	Receiver Noise Figure (dB)	Ext. Ambient Noise (dB-KT_o)	Noise Floor Increase Due to Ambient Noise (dB)	Max. Allow. BPL Intf. for 1dB C/N Degradation, BPSK System (dBW/Hz)	Max. Allow. Field Strength from BPL system (dB-microvolts/meter/Hz)	Max. Allow. Field Strength from BPL system (microvolts/meter)-9kHz BW
1.8	10	51	41.00	-158.85	-48.68	0.35
3.5	6	45	39.00	-164.85	-48.90	0.34
7	6	38	32.00	-171.84	-49.88	0.30
10	6	31	25.01	-178.83	-53.77	0.19
14	6	26	20.04	-183.80	-55.82	0.15
18	6	23	17.09	-186.76	-56.59	0.14
21	6	21	15.14	-188.71	-57.20	0.13
24	6	20	14.17	-189.68	-57.01	0.13
28	6	18	12.27	-191.58	-57.57	0.13

Table 3-Maximum Allowable BPL Interfering Field Strength to BPSK Receiver in 9 kHz Bandwidth (See Text)

Notice from Table 3 that the maximum allowable field strength for a 1 dB degradation in C/N to a 6dB noise figure BPSK receiver's antenna terminals, in a quiet external ambient noise environment, is 0.13 microvolt per meter, measured in a 9 kHz bandwidth, at 28 MHz. This is 47.26dB below the FCC Part 15 limits of 30 microvolts per meter—i.e. $20\log_{10}(30/0.13)=47.26$dB. In other words, the FCC field strength limits are about 47dB too high for EMC at 28 MHz with the licensed station's receiver connected to a half-wave dipole antenna.

Thus, the FCC must lower the allowable BPL field strength limit from 30 microvolts per meter to about 0.1 microvolt per meter in order for the BPL system to have EMC with modern licensed stations with half-wave dipole antennas.

If a licensed station uses an antenna with 10dB directivity gain, referenced to a half-wave dipole antenna (10dBd, which is 12.15dBi), at 28 MHz, for example, which is a realistic array, the maximum allowable BPL field strength at the licensed station's antenna is 0.04 microvolt per meter—10dB lower than with a half-wave dipole antenna, as expected, from Equations 13 and 14. Thus an Access BPL radiated field strength of, say, 0.04 microvolt per meter, measured in a 9kHz bandwidth, at 30 meters distance from the power lines (57.5dB less than the current limit), would provide a reasonable assurance of EMC with modern licensed HF radio stations using 10dBd antennas at 28 MHz.

Note that some amateur stations have antennas with more than 15dBd gain in the 1.8- to 28 MHz frequency range. Thus, the BPL interfering field strength should be at least 5dB below the above-mentioned value of 0.04 microvolt/meter, or approximately 0.02 microvolt/meter, as measured in a 9kHz bandwidth.

In summary, the current FCC Part 15 field strength limit of 30 microvolts per meter at 30 meters distance from the Access BPL power lines is at least 64dB too high—it should be no more than 0.02 microvolt per meter in a 9 kHz bandwidth at 30 meters distance from the power lines.

Field Strength Measurement and Specification Issues

FCC Part 15 was written for so-called point sources, not radiating antenna arrays. But Access BPL power lines are radiating antenna arrays at radio frequencies. Thus, attempting to specify field strength, as a BPL electromagnetic compatibility control, opens a completely new set of issues.

Point sources include devices such as TV sets, radio receivers, VCRs, and computers, which emit radio frequency energy that may interfere with licensed radio services or other appliances. These devices are called unintentional radiators because their emissions are unintentional. Indeed, manufacturers would be delighted if these devices emitted no radio frequency energy at all—take it from one who has developed and certified equipment to Part 15. Measurement of these unintentional radiated emissions (and conducted emissions) is straightforward and predictable from unit to unit.

BPL transmitters are intentional radiators, because BPL implementation requires that BPL transmitter energy be coupled to power lines for transmission to a receiver at the other end of the circuit. In fact, the BPL system consists of transmitters and receivers connected to antennas, since the power lines are, in fact, radiating antenna arrays.

Although one can measure energy radiated from the power lines in a particular system, the emissions are not predictable from system to system. Indeed, maximum allowable radiated field strength from a BPL system is a random variable because of the variation in power line run lengths, height above the earth, earth conductivity, layout direction, directivity gain magnitude versus frequency, power lines proximity to licensed radio station antennas, and BPL's susceptibility to interference from licensed radio stations. Some power line runs are long, some are short, some have bends that follow streets or rivers, some are near the ground, and some are substantially above the ground.

Clearly, it is impossible to establish practical BPL field strength limits, because the directivity gain of the power line antenna system varies from system to system. Also, the proximity of licensed radio stations can be near or far from the BPL power line radiators—i.e. in the near field or the far field. Furthermore, every system will have different radiation patterns, mandating that field strength be measured over 360 degrees of azimuth, and, say, ±45 degrees axially, for the total power line run, and fully characterized.

Finally, new measurements would be required every time the system is changed, particularly, if the power line configuration is changed.

Obviously, treating BPL as an unintentional radiator, and trying to establish EMC by specifying field strength is impossible. Indeed, this system must be licensed, just like any other radio communications system with power, spectral and spurious output limits, and frequency allocations.

Conclusion

Successful Broadband Over Power Lines (BPL) implementation demands exhaustive engineering, and regulatory analyses, to arrive at a sound go/no-go decision. If the conclusion is "go," the FCC must develop new regulations that include licensing, and attendant specifications for maximum output power, bandwidth, spurious emissions limits, and frequency allocations. This will assure electromagnetic compatibility with licensed radio stations operating in the 1.705- to 28 MHz frequency range, and in other frequency ranges for that matter. BPL transmitters connected to power lines are intentional emitters connected to radiating antennas, not unintentional emitters. Therefore FCC Part 15 field strength regulations are not applicable to BPL.

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- Electronics Engineer, BSEE (Major in Communications Electronics), 1954 from the University of Nebraska
- Radio Design Engineer, Collins Radio Company, Cedar Rapids, Iowa, 1954
- Jet Fighter Pilot, Instructor Pilot, and Communications Officer, U.S. Air Force, 1954-1957 (leave of absence from Collins Radio Company for military service)
- Radio and Communication Systems Design Engineer, Staff Engineer and Project Engineer, Collins Radio Company, Cedar Rapids, Iowa, 1957-1964
- Communication Systems Design Engineer and Project Engineer for National Cash Register Company, Dayton, Ohio, 1964 to 1966
- Communication Systems Staff Engineer, Design Engineer, Project Engineer, and Engineering Section Manager at Magnavox Company (now Raytheon), 1966-1974
- Communication Systems Senior Marketing Product Manager at Magnavox Company (now Raytheon), 1974-2000—Retired in 2000.