Calculated Levels from Broadband Over Power Line Systems and their Impact on Amateur Radio Communications Circuits

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1 **Abstract:** This paper summarizes the results of several different methods of calculating the emissions levels from Broadband Over Power Line systems. The resultant data are then used to determine the calculated level of degradation in the ambient noise level of several types of HF and VHF amateur installations.

2 Calculations Based on the Part 15 Radiated Emissions Limits

2.1 BPL is a carrier-current system and is required to meet the radiated emissions limits for intentional emitters. These limits are:

> *Section 15.209 Radiated emission limits, general requirements.*
>
> *(a) Except as provided elsewhere in this Subpart, the emissions from an intentional radiator shall not exceed the field strength levels specified in the following table:*

Frequency (MHz)	Field Strength (microvolts/meter)	Measurement Distance (meters)
0.009 - 0.490	2400/F (kHz)	300
0.490 - 1.705	24000/F (kHz)	30
1.705 - 30.0	30	30
30 – 88	100	3
88 – 216	150	3
216 – 960	200	3
Above 960	500	3

2.2 These limits are high enough that signals from unlicensed emitters operating at these limits will be picked up by nearby antennas. The strength and effect of these signals is related to the following factors:

- Strength of the emission
- Frequency of the emission (path loss varies as 20 log[frequency])
- Distance between the source and receiving antennas[2]
- Gain of the receive antenna
- Noise figure (sensitivity) of the receiver
- Ambient noise level from other sources
- Frequency distribution and nature of the emitted signal
- Receiver bandwidth

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[2] In the far field region, the strength of the electric and magnetic fields varies as $20\log_{10}$(distance). This is only approximately true in the near-field regions.

2.3 FCC Part 15 rules do not define any specific requirements for the way that BPL signals must be generated, so the encoding and modulation methods can vary significantly. On HF, the quasi-peak-detected radiated emissions from these systems are measured in a 9-kHz bandwidth; on VHF a 100-kHz bandwidth is used. The peak-to-average power ratio of an emission could range from 0 dB for a carrier to tens of dB for some modulation types and systems. Most BPL systems in present use are OFDM (orthogonal frequency-division multiplexing – essentially a multi-carrier system) or DSSS (direct-sequence spread spectrum). The peak-to-average ratio of these systems can vary, depending on how many carriers are present in a given measurement channel. In this paper, it will be conservatively assumed that all BPL systems have a peak-to-average ratio of 10 dB, close to the ratio of gaussian noise.

3. Amateur Stations

3.1 Receive systems used in the Amateur Radio Service have a wide range of function and capabilities. ARRL has selected a few categories within this range and developed hypothetical reference circuits to describe these stations. The reference circuits are included as an appendix to this report. The following are the station configurations that have been selected for this report. This list is by no means complete. A complete copy of ARRL's hypothetical reference-circuit data for the amateur bands between 1.8 and 54 MHz has been provided to the FCC in a separate report.

Table 1:

Station configuration	EIRP	Emission designator[3]	Receiver noise floor	Ambient noise floor[4]
3.5 MHz SSB high-end	43.5 dBW	2K50J3E	-157 dBW	-135 dBW
3.5 MHz SSB typical	38.5 dBW	2K50J3E	-157 dBW	-135 dBW
14 MHz SSB high-end	48.3 dBW	2K50J3E	-157 dBW	-149 dBW
14 MHz SSB typical	43.1 dBW	2K50J3E	-157 dBW	-145 dBW
50 MHz SSB typical	44.4 dBW	2K50J3E	-168 dBW	-160 dBW
50 MHz FM base	21 dBW	15K0F3E	-160 dBW	-152 dBW

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[3] Receiver bandwidth is the same as the transmit bandwidth defined by the emissions designator.

[4] This includes the effects of typical man-made and atmospheric noise.

4. Received Signal Levels

4.1 This analysis assumes that the radiated emissions from most BPL systems will be at or near the permitted FCC limits. The amount of signal an antenna will pick up if it is placed in a specific radiated field would be defined by the following formulas[5] in the far-field region of the two antennas involved:

$$\mathbf{RSL_{dBW} = -107.2 + dBuV/m - 20log_{10}(F_{MHz}) + RcvAntGain_{dBi} - dB_{losses}}^{6} \qquad \textbf{Eq. 1a}$$

$$\mathbf{RSL_{dBm} = -77.2 + dBuV/m - 20log_{10}(F_{MHz}) + RcvAntGain_{dBi} - dB_{losses}} \qquad \textbf{Eq. 1b}$$

4.2 This formula assumes that the RSL is in the same bandwidth as the measurement bandwidth to determine the level in dBuV/m. If the bandwidths are different, then for uncorrelated signals (ie, noiselike) the following correction must be made to the RSL:

$$\mathbf{RSL_{actual} = RSL_{measurement} - 10log\ (measurement\ bandwidth / receiver\ bandwidth)} \qquad \textbf{Eq. 2}$$

4.3 In-situ, radiated fields include the effects of earth ground and other scattering conductors, so to be conservative, ARRL will use the free-space gain of typical amateur receive antennas for its calculations.[7] Using the formulas above, assuming $dB_{losses} = 0$ dB, the following data are calculated:

Table 2:

Frequency	Amateur antenna type	Amateura antenna gain	Receive system bandwidth	BPL signal RSL at 30 meters[8]	BPL signal RSL at 10 meters[9]
3.5 MHz[10]	Half-wave dipole	2.14 dBi	2500 Hz	-92 dBW	-82.5 dBW
3.5 MHz	Array	8.0 dBi	2500 Hz	-86.1 dBW	-76.6 dBW
14 MHz	3-element Yagi	8.0 dBi	2500 Hz	-98.1 dBW	-88.6 dBW
14 MHz	Stacked array	13 dBi	2500 Hz	-93.1 dBW	-83.6 dBW
50 MHz[11]	5-element Yagi	9.5 dBi	2500 Hz	-127.7 dBW	-118.2 dBW
50 MHz	¼-wave ground plane	1.6 dBi	15000 Hz	-127.8 dBW	-118.3 dBW

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[5] These formulas use the free-space gain of the receive antenna. For low-gain antennas, this will result in a conservative estimate. The field strength at any individual point is determined by the direct signal from the radiator and any scatterers, such as earth ground or other nearby conductors. If the pattern of the antenna has little directivity, it will capture energy from the direct radiation and the scatterers approximately equally, so free-space gain appropriately captures the radiated emissions. For higher-gain antennas with directivity, free-space gain may underestimate the field strength by up to 6 dB.

[6] Losses include the receive antenna feed line, connectors, etc.

[7] This is conservative because antennas located close to ground will lose some of their gain due to impedance mismatch and mutual coupling with the lossy earth.

[8] All RSLs in this table have been corrected for receiver bandwidth relative to the measurement bandwidth in the rules.

[9] The RSL has been corrected to 10 meters distance by using a 20dB/distance decade ratio. This gives a conservative estimate compared to the 40 dB/decade ratio permitted by Part 15 rules.

[10] On 3.5 and 14 MHz, the RSLs are calculated based on a field strength of 30 uV/m at 30 meters distance.

[11] On 50 MHz, the RSLs are calculated based on a field strength of 100 uV/m at 3 meters distance.

4.4 These RSLs relate to the reference circuits for the amateur stations being analyzed in the following way:

Table 3:

Frequency	Antenna type	Receive system ambient[12]	BPL RSL dB level relative to ambient, 30 meters distance	BPL RSL dB level relative to ambient, 10 meters distance
3.5 MHz	Half-wave dipole	-135 dBW	43 dB	52.5 dB
3.5 MHz	Array	-135 dBW	48.9 dB	58.4 dB
14 MHz	3-element Yagi	-145 dBW	46.9 dB	56.4 dB
14 MHz	Stacked array	-149 dBW	55.9 dB	65.4 dB
50 MHz	5-element Yagi	-160 dBW	32.3 dB	41.8 dB
50 MHz	¼-wave ground plane	-152 dBW	24.2 dB	33.7 dB

4.5 To amateur radio communications, the received BPL signals are noise. The increase in noise level calculated is a conservative calculation of the RSLs that will occur from fields that are at the FCC Part 15 limits for intentional emitters. ARRL has included another paper in its filing, outlining the complex ways that radiated emissions can vary around a large radiating conductor. Near-field effects may also affect the amount of signal picked up on the antenna, in a similar way to how those effects will affect measurements made in the near-field region of the power-line radiator. These effects can be calculated more accurately with antenna-modeling techniques and software.

5. Antenna Modeled Calculations

5.1 These formula-based calculations assume that the coupling between the radiating element and the receive antenna is ideal and that the antenna would be placed at the point of maximum field strength, presumed to be at the FCC Part 15 limit. This normally would be in the main beam of the antenna pattern. This figure, reproduced from another paper ARRL has presented in this filing, “Power Lines as Antennas From 0.1 to 30 MHz ,” shows the type of radiated pattern that may be typical of medium-voltage (MV)[13] power-distribution lines as radiators.

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[12] These levels conservatively represent typical residential environs, as described in CCIR Report 322, June 1995, http://www.nosc.mil/sti/publications/pubs/td/2813/. Quiet rural areas ambient levels are 10 to 20 dB lower during the winter months.

[13] The FCC NOI refers to the power-line distribution lines as “medium-voltage” lines. The electric-utility industry usually categorizes lines as distribution equal to or less than 13 kV, sub-transmission less than 69 kV and transmission equal to or greater than 69 kV. In this paper, the term medium-voltage refers to lines that are typically 13 kV or less.

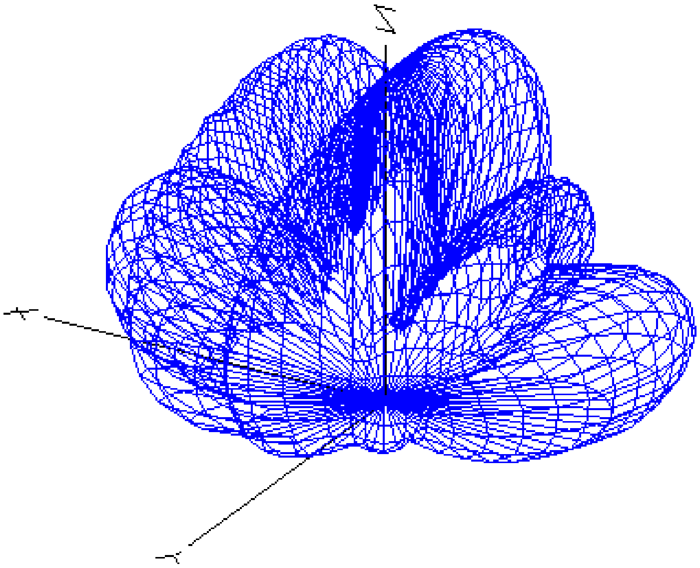

Figure 2: This complex pattern results when a 3.5 MHz signal is applied to the power-line model. On 14 MHz, the same model showed a pattern that was much more complex. (file: DIP3R5.EZ)

5.2 ARRL used the EZNEC[14] model described in a separate paper submitted with this filing, "Electric and Magnetic Fields Near Physically Large Radiators" to establish the correlation between some of the above calculated data and modeled coupling between the power line radiator and nearby half-wave dipole antennas. As in earlier models, the power line was 200 meters long, consisting of two phases, separated by 1 meter. One of the phases was connected to earth ground, using a small radial system, simulating a relatively poor ground. One phase was fed, 25% of the distance from one end. A 50-ohm load was placed at each end of this transmission line model, to simulate the losses and power absorbed by the BPL modems that would be part of this system. A half-wave dipole was placed at various positions in the model and EZNEC was used to determine the amount of received RF energy in a 50-ohm load placed in the center of the dipole. This dipole was always parallel to the power lines and at a distance of 30 meters radially from the line.

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[14] EZNEC software is available from Roy Lewellan, P.E., PO Box 6658, Beaverton, OR 97007, Tel: 503-646-2885, Email: w7el@eznec.com, Web: http://www.eznec.com. This software was being used with the NEC-4.1 calculation engine, a program distributed by the Lawrence Livermore National Laboratories, http://www.llnl.gov.

5.3 The dipole was modeled at 3 places near the line:

- With its center at the point 30 meters from the line that EZNEC modeled would have the maximum electric field
- With its center opposite the point where one phase was fed, at the height of the modeled power line (10 meters height)
- With its center 30 meters from the center of the power line, at the height of the line (10 meters)

5.4 ARRL obtained the following results:

Table 4:

Frequency	Half-wave dipole center location	30-meter path loss	Loss to modeled half-wave Dipole	EZNEC file
3.5 MHz	At point of maximum electric field above power line X = 85 meters, Y = 0.5 meters, Z = 40 meters	12.9 dB	14.0 dB*	Dip3-1.ez
3.5 MHz	Opposite feed point X = 50 meters, Y = -30 meters, Z = 10 meters	12.9 dB	32.9 dB**	Dip3-2.ez
3.5 MHz	Opposite power-line center X = 0 meters, Y = -30 meters, Z = 10 meters	12.9 dB	30.8 dB	Dip3-3.ez
3.5 MHz	At end nearest feed X = 80 meters, Y = -30 meters, Z = 10 meters	12.9 dB	18.8 dB	Dip3-4.ez
3.5 MHz	At end away from feed X = -80 meters, Y = -30 meters, Z = 10 meters	12.9 dB	27.3 dB	Dip3-5.ez
3.5 MHz	At end away from feed X = -80 meters, Y = -22.4 meters, Z = 30 meters	12.9 dB	16.4 dB	Dip3-6.ez
14 MHz	At point of maximum electric field above power line X = -35 meters, Y = 0.5 meters, Z = 40 meters	24.9 dB	35.7 dB	Dip14-1.ez
14 MHz	Opposite feed point X = 50 meters, Y = -30 meters, Z = 10 meters	24.9 dB	32.61 dB*	Dip14-2.ez
14 MHz	Opposite power-line center X = 0 meters, Y = -30 meters, Z = 10 meters	24.9 dB	44.7 dB**	Dip14-3.ez
14 MHz	At end nearest feed X = 95 meters, Y = -30 meters, Z = 10 meters	24.9 dB	34.5 dB	Dip14-4.ez
14 MHz	At end away from feed X = -95 meters, Y = -30 meters, Z = 10 meters	24.9 dB	35.1 dB	Dip14-5.ez
14 MHz	At end away from feed X = -95 meters, Y = -22.4 meters, Z = 30 meters	24.9 dB	36.7 dB	Dip14-6.ez

* = Worst case of locations modeled per band
** = Best case of locations modeled per band

5.5 ARRL did not perform exhaustive calculations to determine the point of absolute-best coupling between the transmission-line and nearby-amateur-antenna models. The several points ARRL selected on both frequencies modeled indicate that the coupling can and does approach the theoretical coupling derived from the path-loss formula. The path-loss approach to estimate received signal levels is, therefore, a useful tool.

6. Correlation with BPL Power Levels, modeled antenna gain and measured field strength

6.1 ARRL has little data on the characteristics of the present BPL systems. Manufacturers have not published much technical data and the information in the required semiannual reports on the FCC experimental licenses has either not yet been filed, has been filed under a confidentiality request or does not contain much specific information about BPL-system power levels, power-spectral density or losses through the couplers used to connect BPL systems to MV lines.

6.2 As a reasonable starting point, ARRL has presumed that BPL systems that are in current use or development have a device quasi-peak power-spectral density of –80 dBW/Hz. When modulated with high-speed BPL signals, the resultant spectrum can be conservatively considered to be poorly correlated, so the quasi-peak PSD can be presumed reasonably to vary as $10\log_{10}(\text{MeasurementBandwidth}_{\text{Hz}})$. In a 9 kHz bandwidth, this is a quasi-peak signal level of –40.5 dBW. ARRL estimates that the couplers used to connect this signal to the medium-voltage power-distribution lines have a loss of 10 dB. In-building BPL systems typically use a PSD of –86 dBm/Hz[15], with no coupling losses. ARRL has chosen a quasi-peak PSD of –50 dBW / 9 kHz for the following calculations.

6.3 In the far-field region of a radiator, there is a precise relationship between radiated power and field strength. This relationship holds reasonably well for the strongest fields found in the radiating near field of the same radiator.

$$\textbf{Field strength (dBuV/m)} = \textbf{EIRP (dBW)} + 115.7 - 20\log_{10}(\text{distance}_{\text{meters}}) \quad \textbf{Eq. 1}$$

6.4 To obtain a field strength of 29.5 dBuV/m at 30 meters, the emitter would have to have an EIRP of -76.7 dBW. If the BPL-system 9-kHz bandwidth power were –50 dBW, as ARRL has estimated, then the power-line radiator would have to have a gain of –26.7 dBi for the system to meet the FCC Part 15 regulations. ARRL has provided the FCC with a NEC antenna model for a simple power line. This model shows the gains listed in Table 5.

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[15] This is the level in the HomePlug specification. This is the most prevalent in-building BPL at this time.

Table 5:

Frequency	Gain (dBi)	File
1.8 MHz	-3.4 dBi	DIP1R8. EZ
3.5 MHz	1.6 dBi	DIP3R5.EZ
5.3 MHz	1.2 dBi	DIP5R3.EZ
7.0 MHz	6.5 dBi	DIP7.EZ
10.1 MHz	7.4 dBi	DIP10R1.EZ
14.0 MHz	7.7 dBi	DIP14.EZ
18.1 MHz	7.6 dBi	DIP18R1.EZ
21.0 MHz	7.8 dBi	DIP21.EZ
24.9 MHz	10.6 dBi	DIP24R9.EZ
28.0 MHz	7.9 dBi	DIP28.EZ
50.0 MHz	9.2 dBi	DIP50.EZ

6.5 In no case was ARRL able to model any load or reasonable change to its model that resulted in a decrease in gain approaching –26.7 dBi. On 14 MHz, varying the value of the loads intended to simulate losses and the attached BPL modems from 10 to 1000 ohms produced changes in gain no more than +- 1 dB from the nominal 7.7 dBi. Once RF is applied to a conductor, its potential as an antenna is determined primarily by its geometry. For physically large wires, loading or losses at the end of that wiring are not a major determining factor in the overall gain of the conductor as an antenna.

6.6 It is difficult to impossible to technically justify that a BPL-systems of –50 dBW / 9 kHz will result in a radiated field strength of +29.5 dBuV/m at 30 meters distance, based on modeling alone. However, in it technical paper, “Electric and Magnetic Fields Near Physically Large Radiators,” several additional factors were discussed that could easily explain the differences:

- In real-world BPL installations, it is difficult to obtain access to enough measurement points to ensure that the maximum radiated emission has actually been measured. In all of the peaks, valleys and reflections present near a power-line installation, it is not likely that a few measurements at practical locations will actually find the maximum field.
- On HF, the modeled distribution line had a radiation pattern that resulted in the point of maximum radiation, and the resultant electric and magnetic fields, being at high elevation angles. It is not at all likely that measurements were made at points higher than the overhead distribution lines.
- Making measurements at distances closer than 30 meters and extrapolating at 40 dB/decade can easily result in an underestimation of the actual maximum field at 30 meters distance, by over 20 dB in some cases.
- These factors, taken in combination, easily explain the difference between modeled results and measurements taken in-situ near BPL systems.