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INTERNATIONAL ELECTROTECHNICAL COMMISSION

INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE (CISPR)

SUBCOMMITTEE I: ELECTROMAGNETIC COMPATIBILITY OF INFORMATION TECHNOLOGY EQUIPMENT, MULTIMEDIA EQUIPMENT AND RECEIVERS

WG3: EMISSIONS FROM INFORMATION TECHNOLOGY EQUIPMENT

TASK FORCE ON ISN

Subject: **Initial results of FCC tests related to in-house Power Line Communications (PLC)**

1. Introduction

The FCC has begun testing emissions from mains wiring of houses while injecting radio-frequency (RF) signals into power outlets of the houses. The purpose of the tests is to allow the FCC to develop or assess conducted alternatives to the radiated emissions testing presently required for in-home Power Line Communications (PLC) devices operating under Part 15. Though only one house has been tested at this time, the initial results may be useful in evaluating CISPR/I/44/CD. Additional results are expected over the coming months.

Under Part 15 of its rules, the FCC requires that PLC devices operating below 30 MHz comply with a quasi-peak radiated emission limit of 30 uV/m at a distance of 30 meters over the frequency range from 1.705 to 30 MHz. (When necessary, field strength measurements can be made at a closer distance and extrapolated to 30 m at 40 dB/decade of range, but “an attempt should be made to avoid making measurements in the near field.”) Other conducted and radiated limits apply below 1.705 MHz. Compliance is based on testing at three “representative” installations. Emissions must be below the limit on each of a series of radials around each of the three installations. Because such testing is costly to the manufacturers and yields results that are not easily repeatable due to variations between installation sites, the FCC is interested in developing a laboratory-based alternative to this testing. A conducted test is being considered for frequencies below 30 MHz because of the difficulty of building a representative test fixture for radiated testing when wavelengths may be 10’s or even 100’s of meters. The conducted test method and limits described in CISPR/I/44/CD comprise one possible candidate for adoption by the FCC; however, a careful assessment of this method and the present radiated limits must be performed.

2. Background

The test method proposed in CISPR/I/44/CD is an adaptation of that used in CISPR 22 for telecommunications ports. It is based on the fact that symmetric (differential mode) current in telecommunications cables produces very little radiation because the fields produced by the currents in the two, closely-spaced conductors tend to cancel. The primary source of radiation is then the asymmetric (common mode) current caused by imbalances in either the equipment under test (EUT) or the telecommunications network. CISPR/I/44/CD proposes the use of a T-ISN with an intentional imbalance that is representative of mains wiring. The asymmetric voltage (or current) resulting from the imbalance of the T-ISN and from any imbalance in the EUT is measured and is required to be below the limits specified in CISPR 22.

CISPR/I/44/CD proposes to establish the imbalance to be implemented in the T-ISN based on measurements of longitudinal conversion loss (LCL) of mains networks. The initial value proposed was 36 dB +/-3 dB. A task force selected to establish a final value for LCL selected 30 dB +/-6 dB.

The validity of a conducted limit based on LCL of mains wiring has been questioned because mains wiring does not consist of well-balanced, conductor pairs that remain closely spaced throughout the home. In particular, the connection of the neutral conductor to earth may affect the balance, and the presence of switched lamp circuits and switched outlets can result in a single conductor carrying radio frequency (RF) currents from a PLC device without an adjacent conductor carrying an oppositely-phased current to cancel the radiation, as illustrated in Figure 1.

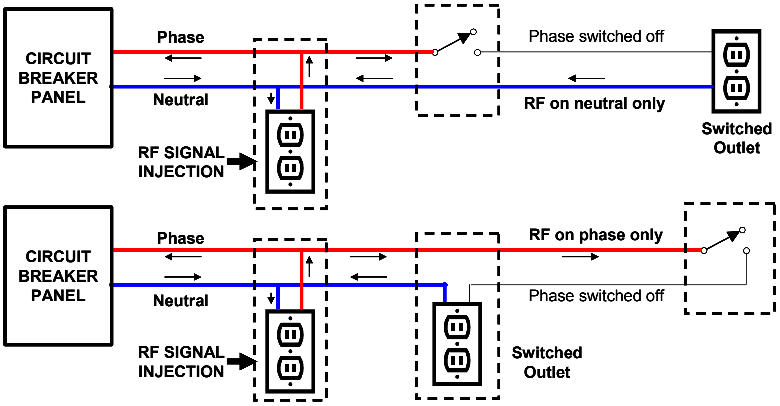


Figure 1. Unbalanced RF Currents in Mains for Two Common Methods of Wiring Switched Outlet Circuits

3. Test Description

The primary purpose of the FCC tests is to determine **radiated** emissions resulting from injecting signals into mains wiring of houses. Because symmetric injection of signals was expected to produce lower radiated emission levels than asymmetric injection, the test program includes both types of signal injection. In addition, measurements of conducted voltages and currents at the injection point are included. These measurements allow LCL and transverse conversion loss (TCL) to be computed.

The test has been performed on only one house so far. The methods used are described below. Some modifications to the test methods will be made in future tests as a result of learning from this first test.

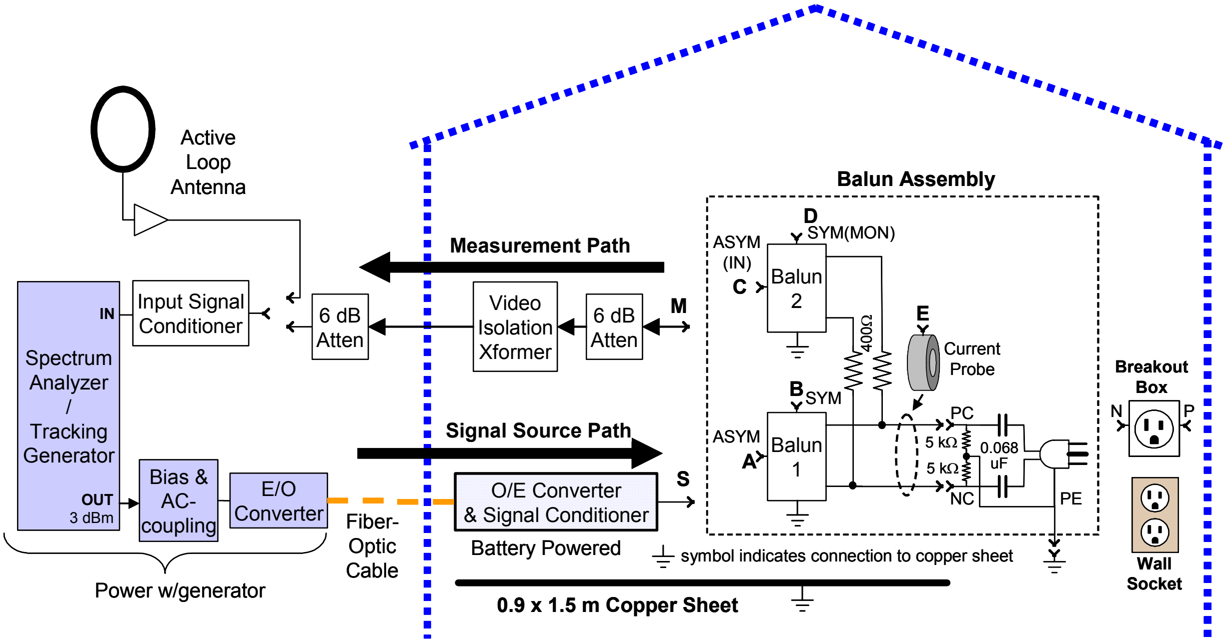
Field strengths were measured at eight locations outside the house at a distance of 10 meters from the exterior walls of the house and a height of 1 meter above the ground. The measurements were made with a magnetic loop antenna, but were converted into electric field strength units based on the impedance of free space. (Though this conversion is not strictly valid in the near field, it is commonly used in emissions testing.) Two orthogonal antenna orientations were used at each antenna location—both with the axis of the loop antenna oriented in a horizontal plane.

Figures 2 through 4 show the test setup used for the tests. A tracking generator provided a swept RF signal through a fiber optic cable (by means of electrical-to-optical and optical-to-electrical converters). The optical connection ensured that no fields or common mode currents are produced in the signal path. Balun 1 was used to convert the signal to either a symmetric (differential mode) or an asymmetric (common mode) signal for injection (through coupling capacitors) into an electrical outlet. Balun 2--connected through series resistors--was included to allow measurement of the actual injected voltage levels (both symmetric and asymmetric), since the RF impedance of the power line was variable. Current probes were used to measure symmetric and asymmetric currents.

The signal injection balun (Balun 1) provided a symmetric source impedance of 100 ohms. The measurement balun (Balun 2)—together with its series resistors—reduced the symmetric source impedance to 90 ohms. To simulate the high asymmetric impedance of a PLC device, the asymmetric inputs of the baluns (ports A and C in Figure 2) were left open when symmetric signal injection was used; this condition was maintained at all times except when measuring the asymmetric voltage. When the signal was injected asymmetrically or when asymmetric voltage was measured, termination of the asymmetric inputs on the baluns resulted in an asymmetric source impedance of 42 ohms (the combined effect of the 50-ohm asymmetric impedance of the baluns and the resistors in series with the measurement balun).

All equipment was powered by batteries or a gasoline-powered generator to provide isolation from the power network. In addition, a video isolation transformer was used in the measurement path for all conducted measurements. A fixed low-pass filter and a set of three tunable trap notch filters (Figure 3) were used to reduce the levels received from television stations and AM radio stations, respectively, so that these unwanted signals would not affect the dynamic range of the measurements. An indicator on the active loop antenna was monitored to confirm that the ambient levels were below the 1-dB compression point of the antenna amplifier.

A copper sheet (0.9 by 1.5 meters) provided a local RF ground at the signal injection point. The copper sheet was connected to the balun housings through approximately 33 cm of braided mesh cable which then connected to protective earth ground through the ground prong of the electrical outlet into which the signal was injected. (This connection could be removed if desired.)



Notes:

- *Baluns: North Hills Signal Processing 0322BF (100-ohms symmetric impedance)*
- *Connect S to A for asymmetric (common mode) injection or to B for symmetric (differential mode) injection.*
- *Connect M to A, B, C, D, E, P, & N for conducted measurements. Disconnect for radiated measurements.*
- *Terminate measurement points B, D, P, & N in 50 ohms except those connected S or M. A & C are open when not connected to S or M.*
- *When measuring current, both conductors pass through current probe—as shown for asymmetric current, but with one conductor reversed for symmetric current. Remove current probe when not in use.*

Figure 2. Measurement Setup

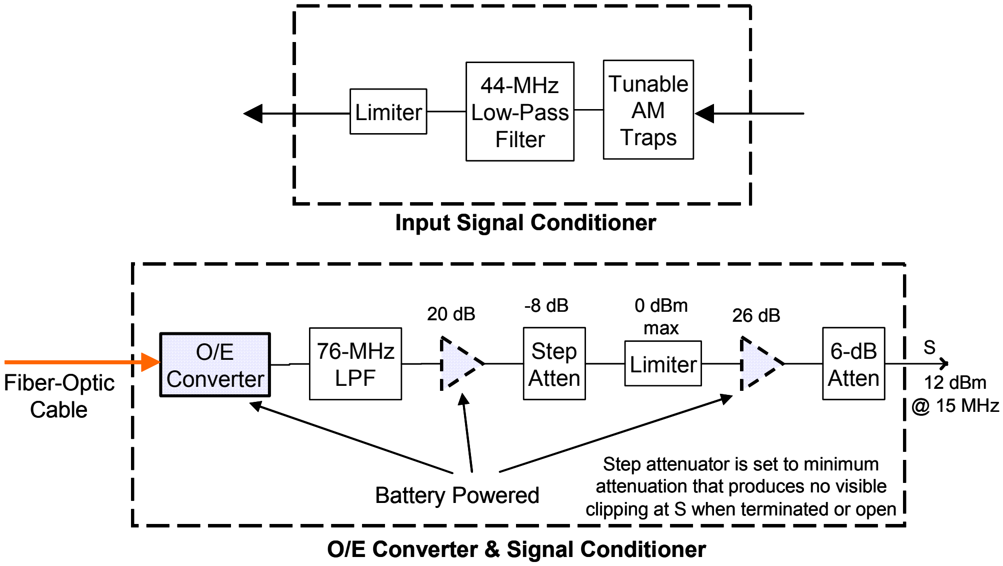


Figure 3. Signal Conditioner Details

Figure 4. Photographs of Indoor Test Fixtures

To minimize cable length effects, the balun assembly was plugged directly into the wall socket, and all connections within the balun assembly had lengths less than 5 cm, except for the connection from Balun 1 to PC/NC (see Figure 2). That connection was approximately 65 cm in length (0.06 wavelength at 30 MHz) when measuring symmetric current and 25 cm in length at all other times. (These cable lengths were subsequently reduced to 47 and 7 cm, respectively, as explained below.)

A frequency-dependent calibration of all measurement points was performed by plugging the balun assembly into a breakout box that provided a 50-ohm termination from each side of the power line plug (phase and neutral) to the ground prong of the plug—resulting in 100 ohms symmetric and 25 ohms asymmetric impedance. A signal was injected symmetrically or asymmetrically, and voltages were measured at each measurement point, including the phase and neutral (P and N) breakout points, as functions of frequency. The voltages measured at P and N breakout points matched each other within 0.1 dB across the entire frequency band. Asymmetric voltage during this measurement was assumed to be equal to the voltage at P or N; symmetric voltage was assumed to be 6 dB above the voltage at P or N. These symmetric and asymmetric voltages were then adjusted by -0.4 dB and +2.5 dB, respectively, to obtain the "applied" symmetric and asymmetric voltages—i.e., the voltages that would have been measured if the load impedance matched the balun source impedance (90 ohms symmetric and 42 ohms asymmetric). The resulting measurements were used to establish a frequency-dependent relationship between voltage at each measurement point and the "applied" symmetric or asymmetric voltage. All measurements were then calibrated using this relationship and were expressed relative to the "applied" symmetric or asymmetric voltages.

Balance of the test fixture was measured using the terminated breakout box described above. Both the TCL and the LCL exceeded 56 dB throughout the frequency range from 100 kHz to 30 MHz.

The calibration measurements (performed after testing at the first house) showed one anomaly. During asymmetric signal injection with the breakout box connected (50-ohm terminations to ground), the voltages at P and N decreased by 4 dB and the asymmetric voltage as measured by the baluns increased by 5 dB as the injected frequency was increased to 30 MHz. No significant frequency dependence was observed during symmetric signal injection. This result could be explained by the presence of an asymmetric mode (common mode) inductance of about 0.38 uH between the baluns and the breakout box. This connection consists of a 25 cm twisted cable pair between Balun 1 and points PC and NC in Figure 2—together with the connections through the coupling capacitors, breakout box, and asymmetric mode return path (an additional 25 cm). Theoretical calculations indicated that the twisted cable pair would have an asymmetric mode inductance of 0.25 uH. (The theoretical symmetric-mode inductance was lower—0.19 uH—and had negligible effect because it operated into the 100-ohm symmetric impedance of the calibration load rather than into the 25-ohm asymmetric impedance.)

After testing at the first house, the length of the twisted pair cable was reduced to 7 cm in order to reduce the asymmetric-mode inductance; this change reduced—but not eliminate—the observed frequency dependence. The asymmetric-mode return path length was then reduced to 3 cm (requiring the elimination of the outlet box containing the coupling capacitors) to achieve a calibration with minimal asymmetric-mode inductance.

Although the asymmetric-mode inductance was reduced to negligible levels for the calibration measurements, it should be noted that the inductance (estimated to be 0.38 uH) was present during the conducted measurements on the mains. In particular, the conducted asymmetric voltage measurements contained in this report are actually the voltage developed across the series combination of this inductance and the mains.

4. Initial Results

Only one mains outlet in one house has been tested. More tests are planned.

Figure 5 shows the tested house and the location of the indoor electrical outlet into which the signals were injected.

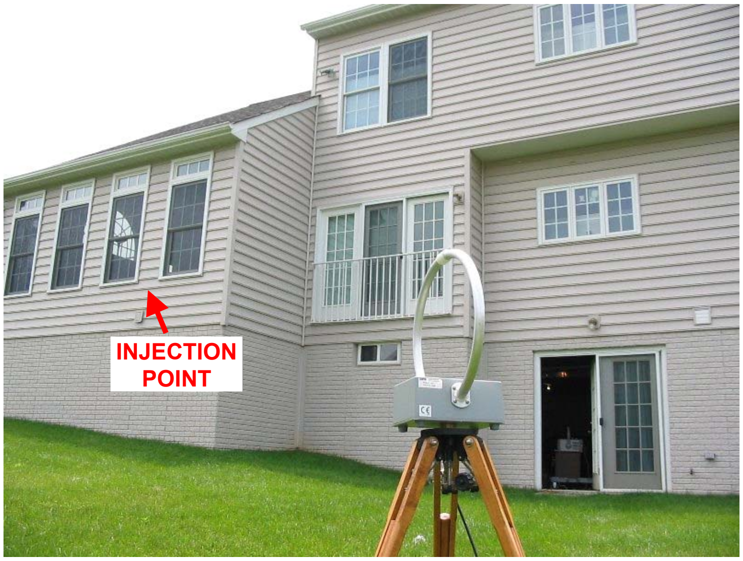
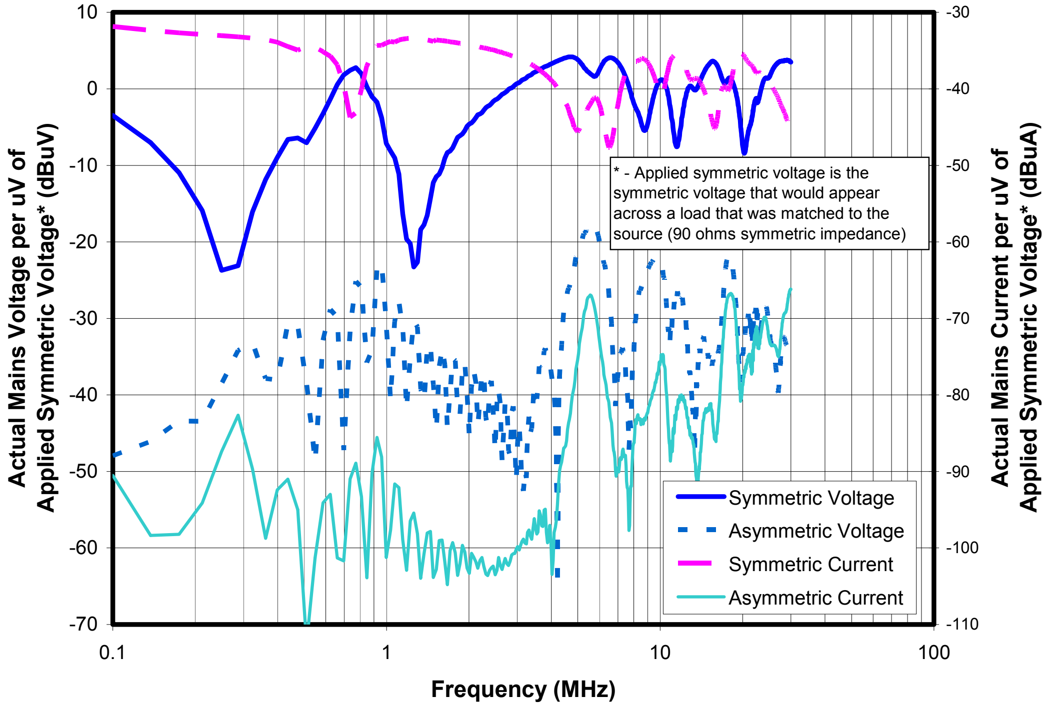


Figure 5. Tested House and One of 16 Antenna Positions and Orientations Used in the Tests

Conducted Measurements

Figure 6 shows the results of conducted measurements when a symmetric voltage was applied to the mains. In the plot, voltage data is read on the left-hand scale and current data is read on the right-hand scale. The values plotted are relative to the "applied symmetric voltage", which we define as the voltage that would appear across a load that was matched to the source. Because the mains symmetric impedance differs from the 90-ohm symmetric impedance of the source and is a function of frequency, the ratio of actual symmetric voltage to applied symmetric voltage is not 0 dB, but rather varies from -24 to +4 dB.



* - Applied symmetric voltage is the symmetric voltage that would appear across a load that was matched to the source (90 ohms symmetric impedance)

Figure 6. Conducted Measurements with Symmetric Signal Injection

Figure 7 shows the conducted measurements when an asymmetric voltage was applied to the mains. The values plotted are relative to the "applied asymmetric voltage", which we define as the asymmetric voltage that would appear across a load that was matched to the source. Because the mains asymmetric impedance differs from the 42-ohm asymmetric impedance of the source and is a function of frequency, the ratio of actual asymmetric voltage to applied asymmetric voltage is not 0 dB, but rather varies from -22 to +5 dB. Note that a mains resonance at 900 kHz causes the actual mains asymmetric voltage to drop below the symmetric voltage produced by imbalance in the mains.

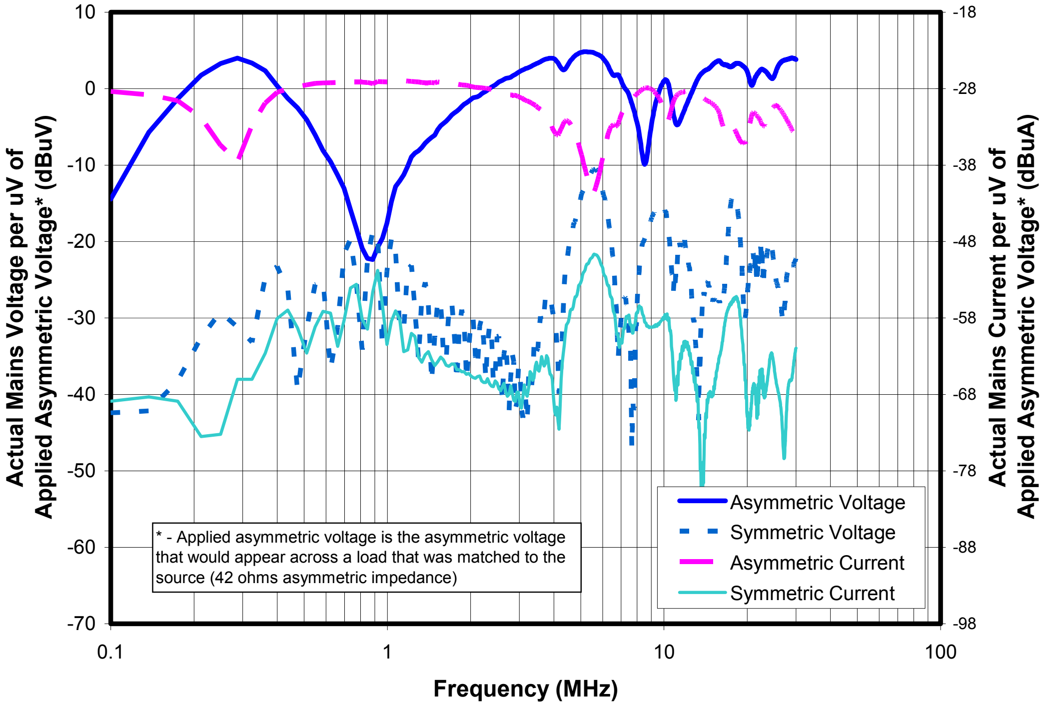


Figure 7. Conducted Measurements with Asymmetric Signal Injection

Figure 8 shows the magnitudes of the symmetric and asymmetric impedances computed from the voltage and current measurements of the previous two graphs. Symmetric impedance ranges from 3 to 380 ohms, with a median value of 100 ohms. The asymmetric impedance ranges from 2 to 210 ohms with a median value of 48 ohms. The median impedance values are very close to the source impedances of the signal injector for symmetric and asymmetric signal injection, respectively.

It should be noted that the impedance values in the plot include the feed lines connecting from the balun to the mains outlet. These feed lines were estimated to have 0.38 uH of asymmetric-mode inductance, which corresponds to a reactance of 72 ohms at 30 MHz.

Figure 9 shows balance measurements derived from the conducted measurements. The plotted values were obtained as follows:

- TCL is the ratio of applied symmetric voltage to asymmetric voltage from Figure 6 (with symmetric signal injection);
- LCL is the ratio of applied asymmetric voltage to symmetric voltage from Figure 7 (with asymmetric signal injection); and,
- The current ratio is the ratio of asymmetric (common mode) current to symmetric (differential mode) current from Figure 7 (with asymmetric signal injection).

The current ratio for symmetric injection was not computed because the high asymmetric impedance of the source (baluns with the asymmetric input unterminated) results in very low symmetric current.

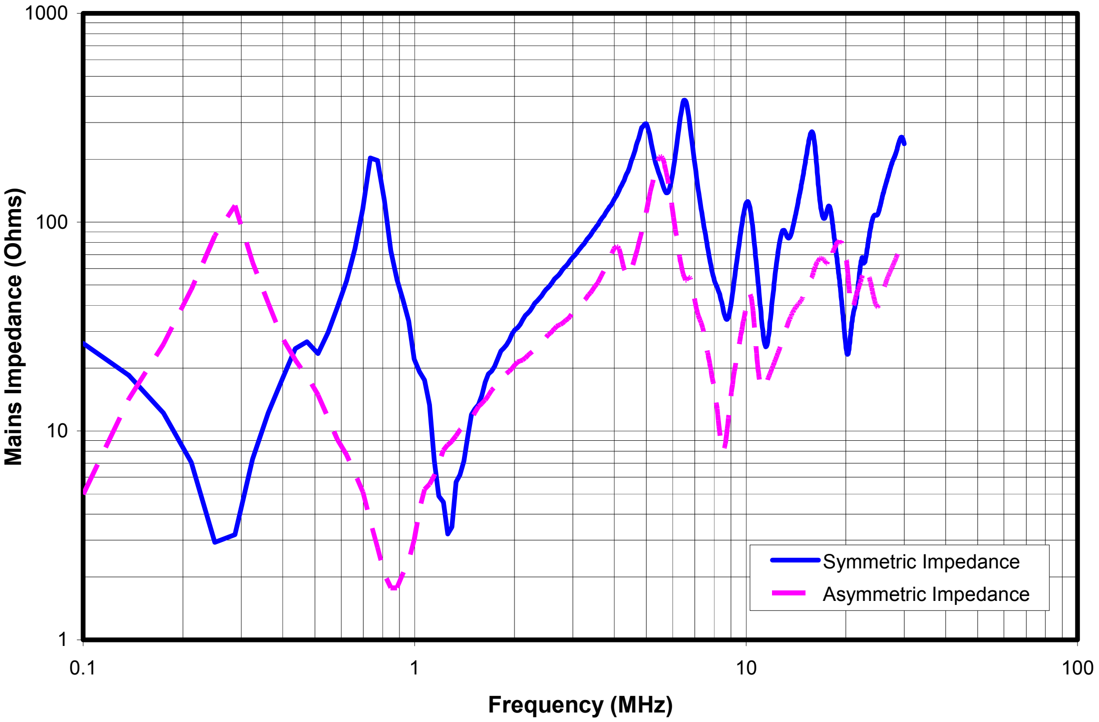


Figure 8. Magnitude of Mains Impedance

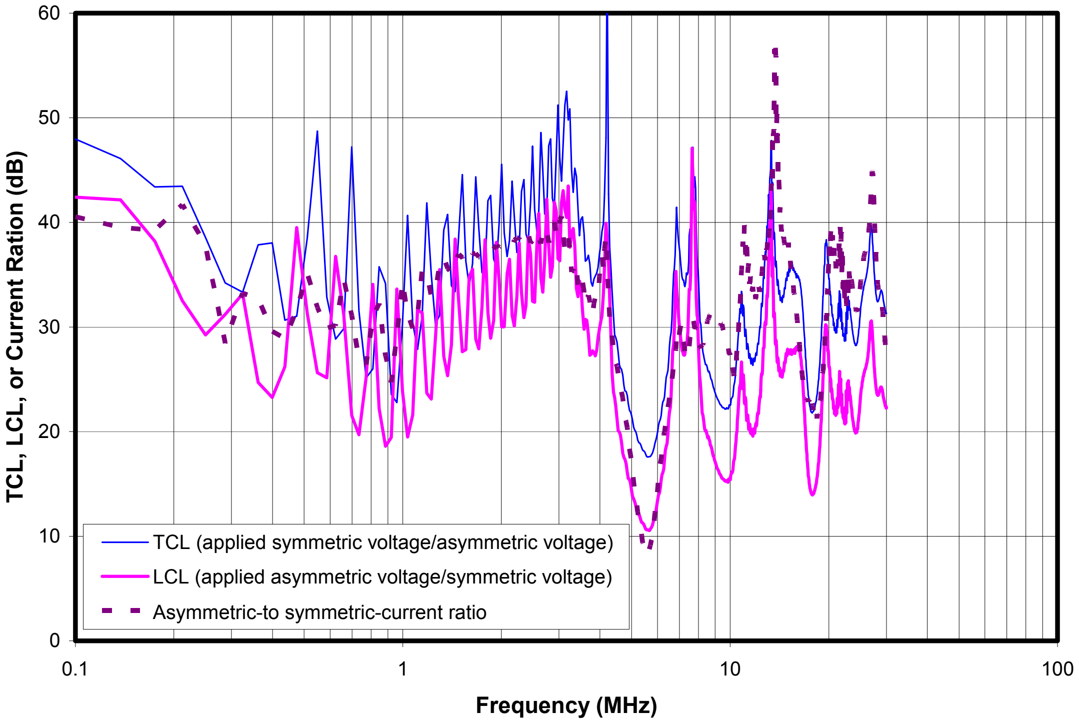


Figure 9. Balance Measurements

The voltage used in the numerator when computing TCL or LCL was the "applied" voltage (i.e., the voltage that would have been seen if the mains were replaced by a load that matches the impedance of the balun assembly). If the actual voltage across the mains were used in the calculations, the lower minimum values would have been obtained. In particular, LCL would have dropped below 0 dB at 0.9 MHz because resonances in the mains caused the actual symmetric voltage to drop below the asymmetric voltage at this frequency, as shown in Figure 7.

Median values TCL, LCL, and the current ratio across the frequency range tested are 32, 24, and 33 dB, respectively. 80 percent of the TCL, LCL, and current ratio measurements are above 27, 20, and 27 dB, respectively.

It should be noted that the measurements above 10 MHz may be affected by the asymmetric mode inductance described in the "Test Description" section of this report.

Radiated Measurements

Figure 10 shows the 16 radiated emission curves that were measured with symmetric signal injection into the mains. The curves correspond to eight antenna locations (each 10 meters from the house) and two antenna orientations. The maximum noise floor observed across the 16 measurements in eight antenna locations is also shown. All data is plotted relative to the applied symmetric voltage.

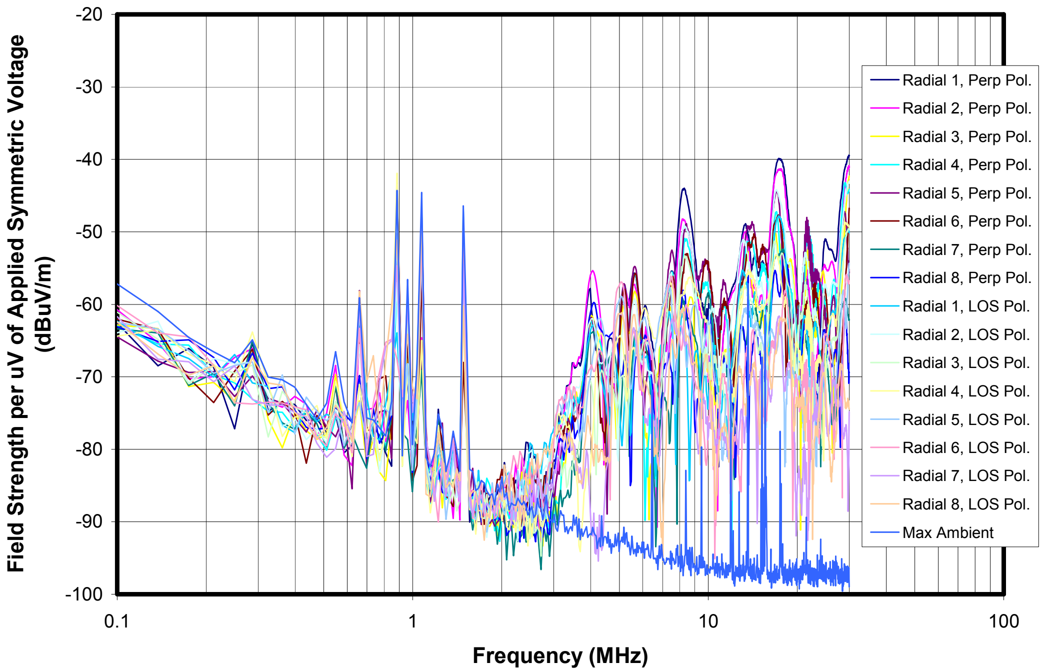


Figure 10. Radiated Emissions Measurements with Symmetric Signal Injection

Figure 11 shows the 16 radiated emissions curves that were measured with asymmetric signal injection into the mains. The maximum noise floor is also shown. All data is plotted relative to the applied asymmetric voltage.

Figure 12 summarizes the radiated emissions measurements relative to applied asymmetric and symmetric voltages. At each antenna location and each frequency, the antenna orientation resulting in the highest emission measurement was selected. The median and maximum these values across the eight antenna locations were then determined. The plot shows the maximum and median field strengths for both symmetric and asymmetric signal injection. Data is shown only for frequencies where the maximum field strength exceeded the maximum ambient field by at least 10 dB. Maximum field strength resulting from asymmetric signal injection is 16 dB higher than that resulting from symmetric injection at the same voltage level.

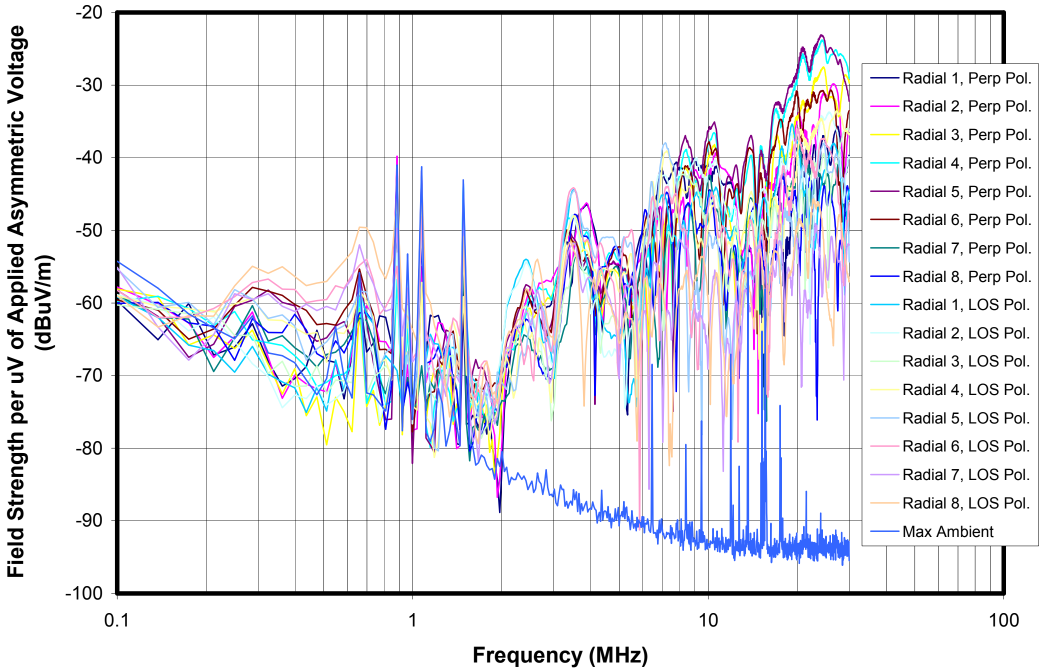


Figure 11. Radiated Emissions Measurements with Asymmetric Signal Injection

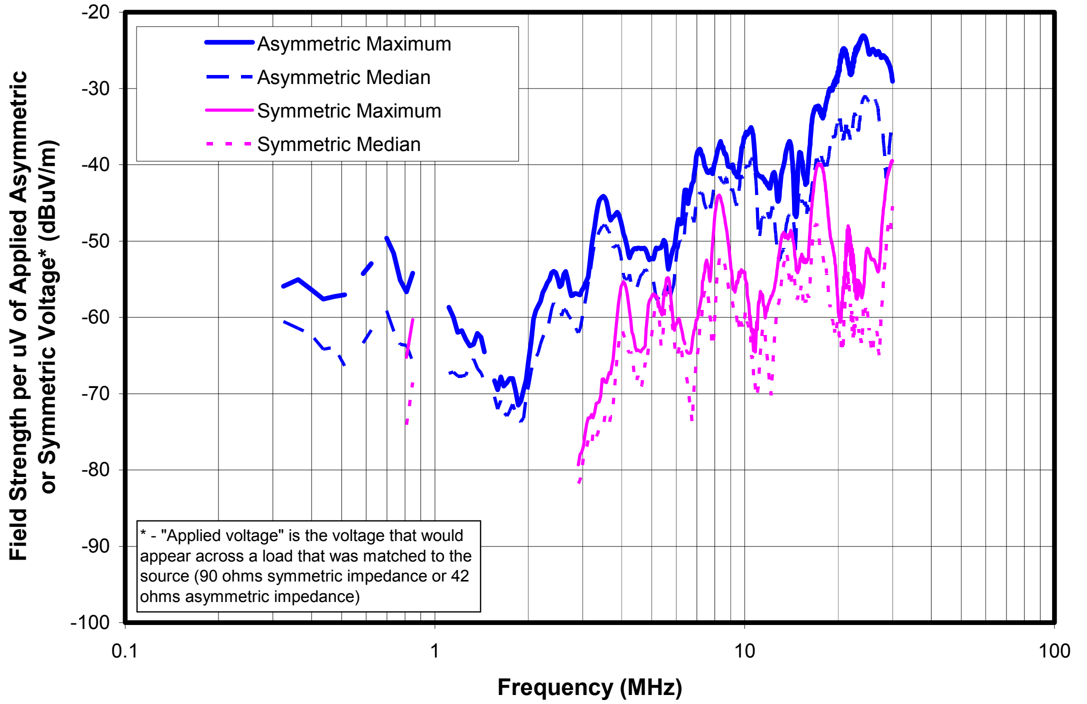


Figure 12. Radiated Emissions Measurement Summary (Relative to "Applied Voltage")

Figure 13 shows radiated emission levels relative to the actual asymmetric and symmetric voltages on the mains (but including voltage developed across the inductance of the feed lines). These plots differ from those in Figure 11 due to the fact that actual voltage across the line varies with line impedance. Again, the maximum field strength resulting from asymmetric signal injection is 16 dB higher than that resulting from symmetric injection at the same voltage level.

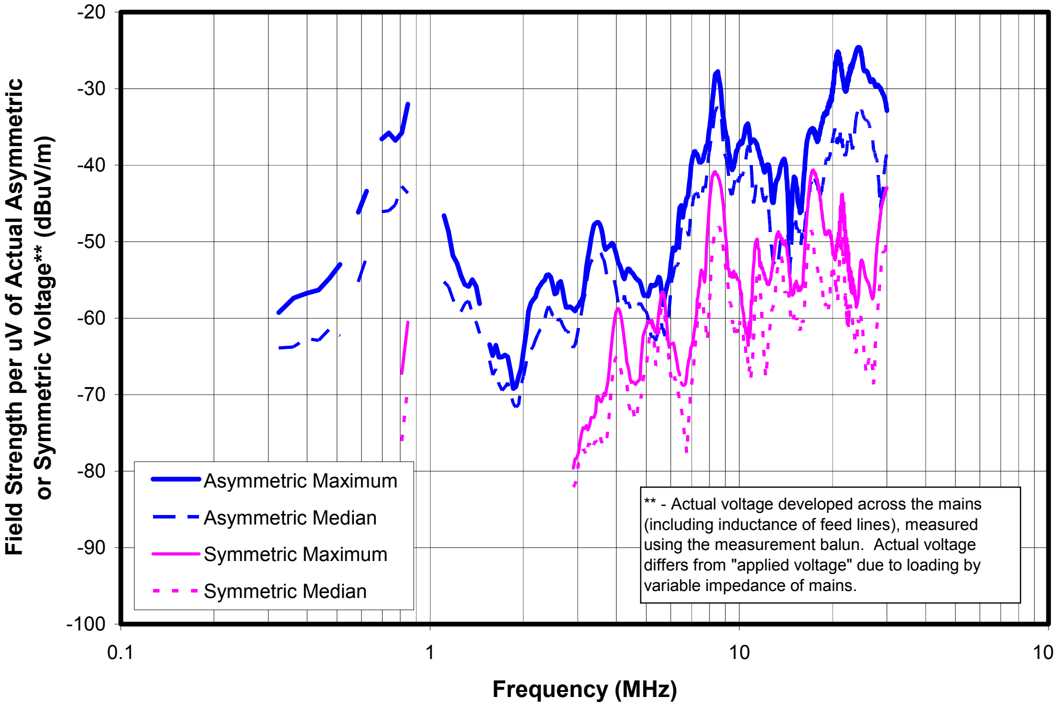


Figure 13. Radiated Emissions Measurement Summary (Relative to Actual Voltage)

5. Emissions under CISPR/I/44/CD

CISPR/I/44/CD proposes applying the CISPR 22 telecommunication port conducted limits to PLC. For frequencies from 0.5 to 30 MHz, the quasi-peak asymmetric-mode conducted limits are 87 dBuV for class A equipment and 74 dBuV for class B equipment—to be measured using a T-ISN having LCL and impedances that are derived from the characteristics of the network. If one assumes that the PLC equipment exhibits perfect balance, is matched to the differential mode impedance of the T-ISN, and has a high asymmetric (common mode) source impedance, then the asymmetric mode disturbance measured using a T-ISN is less than the symmetric output voltage of the PLC device by an amount given by[*]:

$$20 \cdot \log_{10}\left|\frac{E_S}{V_{CM}}\right| \approx LCL - 20 \cdot \log_{10}\left|\frac{2Z_{CM}}{Z_0} + \frac{1}{2}\right|$$

where

E_S	is symmetric (differential mode) output voltage of the telecommunications device;
V_{CM}	is the common mode voltage resulting from imbalance of the T-ISN;
Z_{CM}	is the common mode impedance of the T-ISN; and,
Z_0	is the differential mode impedance of the telecommunications device and of the network to which the T-ISN connects.

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[*] Stephen Martin, "*Relationship between common mode voltage, differential mode voltage, and LCL for telecommunications networks*", CISPR/I/WG3/ISN Task Force (Martin) 03-02, September 4, 2003

For PLC, the network differential mode impedance is assumed to be 100 ohms. CISPR/I/44/CD initially called for a T-ISN having an LCL of 36 dB +/- 3 dB and a common mode impedance of 150 ohms but recommended further study to finalize the values. Subsequently, the LCL Task Force recommended an LCL of 30 dB +/- 6 dB and a common mode impedance of 150 ohms. Applying the formula above using the nominal value of LCL, one finds that:

$$20 \cdot \log_{10}\left|\frac{E_S}{V_{CM}}\right| \approx 19.1 \text{ dB}$$

This value is consistent with data measured when driving such a T-ISN with a balun.[†]

Thus one can conclude that the differential mode voltage that would produce common mode voltages corresponding to the telecommunications port limits of 87 dBuV for class A equipment and 74 dBuV for class B equipment would nominally be 106 dBuV and 93 dBuV, respectively.

Figure 14 shows the maximum quasi-peak field strength that would be observed 10 meters from the tested house with symmetric signals injected at these levels. The current FCC's rules limit radiated emissions from PLC devices to a quasi-peak level of 30 uV/m at a distance of 30 meters over the frequency range shown in the plot. With the distance extrapolation formulas allowed by the rules, this is equivalent to a quasi-peak field strength of 49 dBuV/m at 10 meters. The FCC requires that emissions must be below the limit in all directions, at all frequencies from 1.7 to 30 MHz, in each of three representative installations. The illustration indicates that the thresholds and the nominal design specifications for the recommended T-ISN would appear to permit higher radiated emissions than the current FCC limits. In the case of the measurements taken for the test house, the predicted radiated levels exceeded current FCC limit by 18 dB for a class A device and 5 dB for class B device; however, testing in more houses will be necessary to determine whether this result is typical.

It should be noted that the prediction of Figure 14 is based on the nominal T-ISN LCL value of 30 dB; variations in T-ISNs allowed by the +/- 6 dB tolerance of the LCL could allow for a +/- 6 dB variation in the allowable output of the PLC device and a corresponding +/- 6 dB variation in the corresponding radiated emission levels relative to those shown in the figure. It should also be observed that the radiated emissions predictions are based on FCC emission measurements with asymmetric mode signal injection; consequently, the results are not affected by the asymmetric mode inductance discussed earlier.

[†] Bernd Wirth and Holger Hirsch, CISPR/I/WG3/(Wirth/Hirsch)03/01, August 6, 2003.

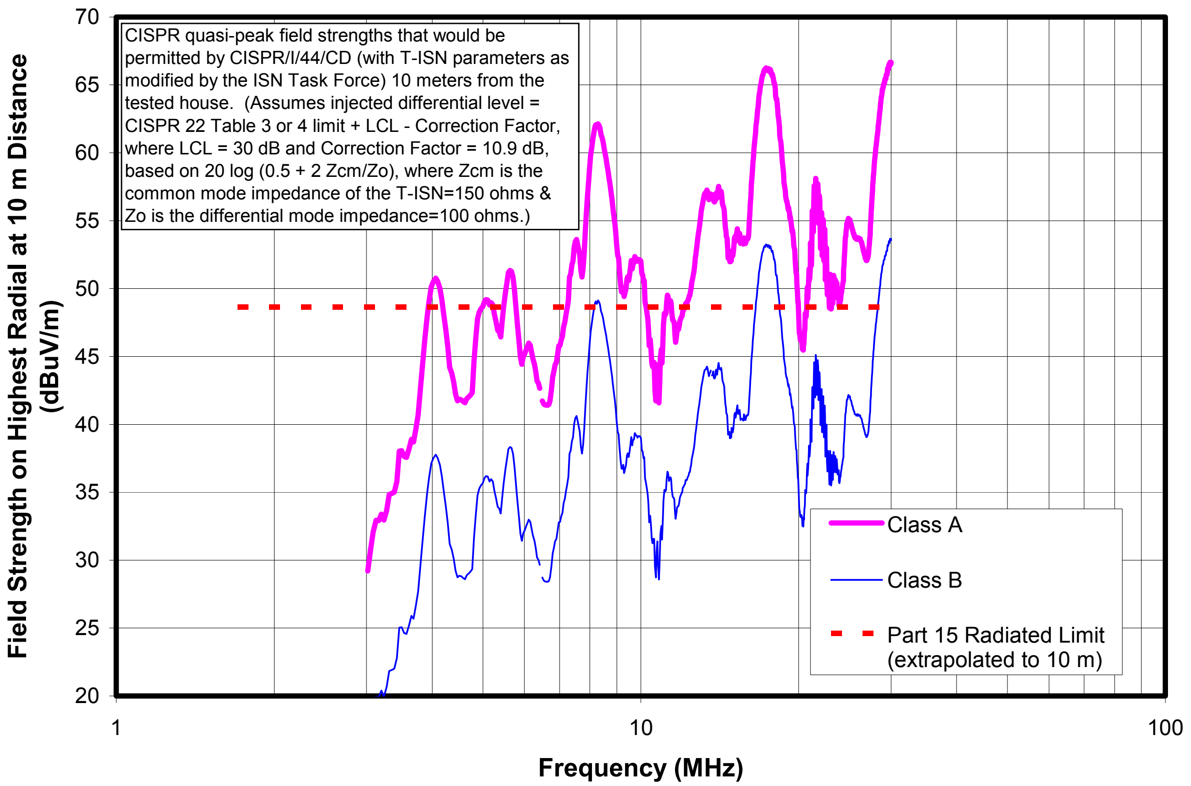

Figure 14. Predicted Radiated Emissions From Tested House Under CISPR/I/44/CD

6. Conclusions

Because of the likely variability between houses, a test on a single house cannot be presumed to adequately establish the relationship between conducted and radiated emissions for the mains networks of houses in the U.S. Furthermore, even with the relatively short lead lengths used in the test, asymmetric mode inductance was found to be a potentially significant source of error in asymmetric mode measurements. Testing at additional houses is planned after refinement of the test methods.

Despite these shortcomings, some conclusions are possible from the testing conducted to date.

(1) It is clear that inductance of feed lines can have a significant effect on any measurements made with asymmetric injection and can affect asymmetric measurements even when signals are injected symmetrically. These effects may not be unique to the FCC test setup. Short lead lengths are critical.

(2) For the specific house and outlet tested, asymmetric injection of signals resulted in higher emissions than symmetric injection—by about 16 dB.

(3) Radiated emissions predictions based on measurements at the specific house and outlet tested suggest that a somewhat lower value of either the T-ISN's LCL or of the compliance threshold recommended in CISPR/I/44/CD may be required for compliance with current FCC Part 15.209 radiated emission limits; however, testing in more houses will be necessary to confirm this conclusion. It would also be desirable to confirm these results by subjecting actual PLC devices to both radiated emissions testing in houses and conducted emissions testing with a T-ISN having appropriate parameters.