

Power Line Communications

Performance Overview of the Physical Layer of Available protocols

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Abstract: The Power Line has been extensively studied as the media for high frequency signal transmission for use as a communications environment. In recent years, development of several power line communications protocols, namely X-10, CEBus and LonWorks, renewed the interest on this matter.

This paper gives a brief description of the spectral behavior of these protocols' physical layer, analyzes the findings of previous research on power line and applies their conclusion to the protocol characteristics. A verification method of this behavior is suggested.

1. Introduction

Up until recently, most home and building automation was done using proprietary systems that required special wiring such as twisted pairs, coaxial and fiber optic. Recent technological developments have enabled the emergence of devices that utilize the power line to send and receive control signals with some degree of reliability. However, there are concerns in using this medium, since the power line was only devised for transmission of power at 50-60 Hz and at most 400 Hz. To make matters worse, the power line is one of the most electronically contaminated environments and the signal attenuation at the frequencies of interest is fairly high, which makes it more challenging to achieve dependable results.

The main advantage of power line communications is the fact that the physical network is already installed, making it a very attractive option. Given the physical drawbacks of the network, it becomes necessary to install repeaters of some sort if the distances are appreciable and bridges over distribution transformers if there is a need to go over that boundary [1].

Another aspect that needs to be considered is the difference in standardization according to the part of the world where the technology is to be set. The most important parameters specified by the different standards are the maximum transmitted power and the allowable bandwidth. The restriction is imposed to limit the interference with other telecommunication services and maybe as a measure to avoid further spectrum contamination. Figure 1 shows the frequency spectrum limitation imposed by the regulatory agencies in the two most important markets: North America and Europe.

It is important to note the stricter limitation put into effect by Europe's CENELEC EN 50065-1 [1] and the narrower bandwidth allowed for power line communications. This could preclude the use of one of the standards as will be described later. The bottom line is that in

Europe, power line communication is restricted to operate in the frequency spectrum ranging from 85 to 150 kHz, while in North America the spectrum is wider (540 kHz).

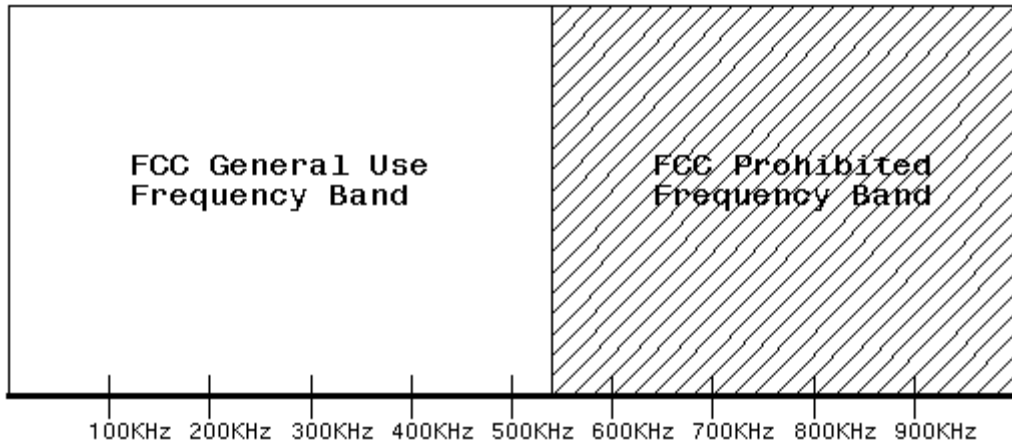


Figure 1a. FCC Frequency Band Allocation for North America

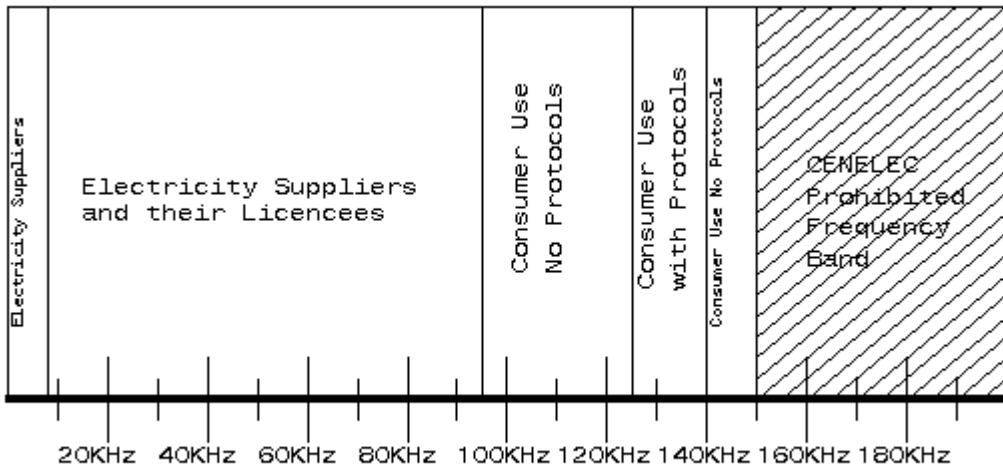


Figure 1b. CENELEC Frequency Band Allocation for Europe

Based on the references found on the subject, the following aspects will be studied: Characteristic Impedance of the power line at high frequencies, noise sources and their effect on power line communications signal coupling to the power line and how the available protocols fare under the studied parameters.

2. The Protocols

Since the purpose of this paper is to analyze the performance of the protocols under the characteristics to be described, a brief description of the physical aspect of the communication signal interface with the power line is discussed.

2.1 X-10

The X-10 technology is one of the oldest power line communications protocol and uses a form of Amplitude Modulation (ASK Modulation) to transmit information. Although it was originally unidirectional (controller to controlled modules) recent developments indicate that some bi-directional products are being implemented. X-10 controllers send their signals over the power line to simple receivers that are used mainly to control lighting and other appliances. Some controllers available today implement some sort of gateway between the power line and other medium such as RF and infrared.

A 120 kHz AM carrier, 0.5 watts signal is superimposed into the ac power line at zero crossing to minimize the noise interference. Information is coded by way of bursts of this high frequency signal. To increase communications reliability, every bit of information is sent twice, requiring a full line cycle, which limits the transmission rate to 60 BPS (in a 60 Hz line). A normal X-10 command consists of two packets with a 3-cycle gap between packets. As mentioned, each packet contains two identical messages of 11 bits each, which yields a 48-cycle command length of about 0.8 second. This represents a poor bandwidth while the reliability of the transmission is severely compromised in a noisy environment. These are the main reasons why this technology has limited applications.

2.2 CEBus

The CEBus protocol uses a peer-to-peer communications model so that any node on the network has access to the media at any time. To avoid data collisions, it uses a Carrier Sense Multiple Access/Collision Detection and Collision Resolution (CSMA/CDCR) protocol. Basically, this Media Access Control (MAC) protocol requires a network node to wait until the line is clear, which means that no other packet is being transmitted before it can send its own. The goal of CSMA/CDCR is to optimize channel access by allowing as many nodes to use the medium as possible without interfering with each other. Data packets are transmitted by the transceiver at about 10 Kilobits per second (KBPS), employing a patented spread spectrum technology. Each packet contains the necessary sender and receiver addresses.

The Power Line physical layer of the CEBus communication protocol is based on a spread spectrum technology patented by Intellon Corp. of Ocala, FL. Unlike traditional spread spectrum techniques (that use frequency hopping or direct sequence spreading), the CEBus power line carrier sweeps through a range of frequencies as it is transmitted. The waveform is synthesized from a table of 360 digitized values given in the standard. According to the patent, “the points were chosen to maximize in-band energy while keeping harmonic out-of-band content to a minimum”. The waveform frequency starts at 200 kHz and sweeps to 400 kHz, jumps to 100 kHz and then sweeps back to 200 kHz. The complete 200-400/100-200 kHz

frequency sweep (called chirp) takes 25 cycles in 100 μ sec. Figure 2 shows actual samples of these chirps.

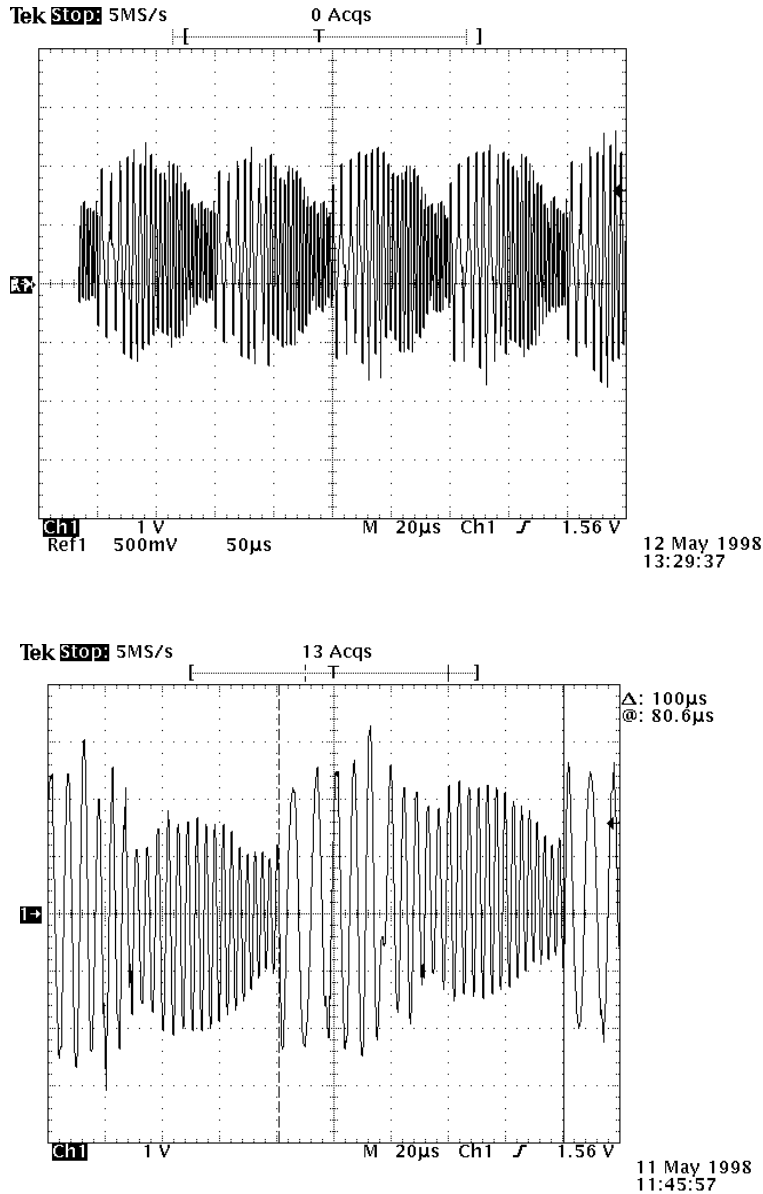


Figure 2 Chirp waveform

Chirps are self-synchronizing, data bit in length and detectable by all network nodes, to allow contention resolution and collision detection needed to support this carrier sense based network protocol. The ability to reject high levels of interfering signals is one of the primary benefits of spread spectrum communications.

As mentioned, data packets are transmitted using spread spectrum chirps. A first sequence of chirps forms a contention resolution preamble that transmitters use to resolve

conflicting contentions for access to the communication media. This preamble is followed by a set of chirps that form the start of the packet symbol used to mark the start of the data within the packet. To differentiate the preamble from the data, preamble chirps are transmitted at a different pitch. (114 vs. 110 μ sec.) The receivers have a correlator or matched filter that produces a pulse when a chirp is detected, producing the self-synchronization specified. Complete details of this discussion can be found in references [3] and [4]. Other details of the protocol are of little interest to the main purpose of this paper and are not discussed here. See reference [10] for more details. In summary, this protocol uses a pre-spread carrier stored in ROM, and the transmitted signal uses a bandwidth considerably greater than the minimum necessary to send information. This method introduces a gain of about 15 dB (improvement in S/N ratio) at 10 Kbps.

2.3 LonWorks

LonWorks is a technology developed by Echelon Corporation and provides a peer-to-peer communication protocol, implementing Carrier Sense Multiple Access (CSMA) techniques. Unlike CEBus, LonWorks is a narrow band spread spectrum modulation scheme (125-140 kHz, BPSK), that uses a multi-bit correlator intended to preserve data in the presence of interference noise [12], with a patented impulse noise cancellation. Since this technology uses a narrower band, transmitted signals are subject to much lower levels of distortion than wide band spread spectrum.

The use of Digital Signal Processing techniques for the receiver achieves the above mentioned characteristics as well as the digital filtering of out of band noise and higher dynamic range (claimed to be as high as 80 dB). The transceiver recommended for these applications is referenced as the PLT-21, which features an internal amplifier that boosts the output signal to 7 Vp-p. Its 1 Ω output impedance and 1A-p-p current capability allows the transceiver to drive high output levels into low impedance circuits. Figure 3 shows a block diagram of this transceiver and its use in a PLC node.

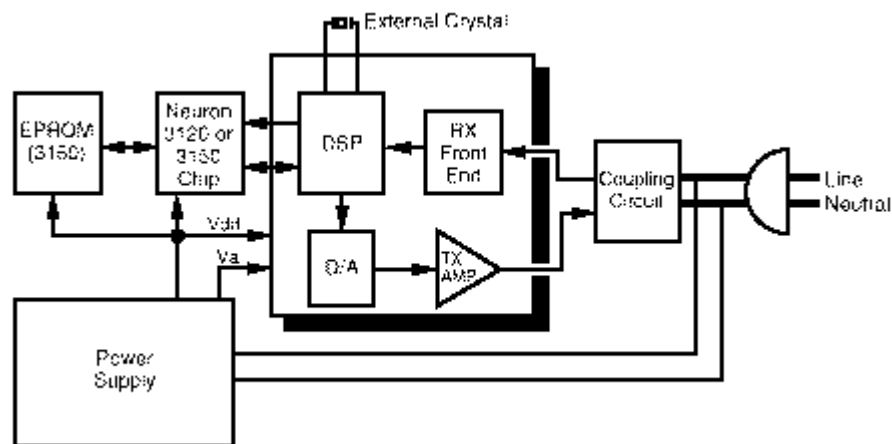


Figure 3 PLT-21 Power Line Node Block Diagram

An advantage of the narrower band used by LonWorks is that it can be used almost world-wide unlike CEBus that has limited application in Europe since the spread is out of the

spectrum allowed by CENELEC as shown in figure 1.b. The PLT-21 transceiver implements the CENELEC access protocol, which can be enabled or disabled by the user, eliminating the need to develop the complex timing and access algorithms mandated by CENELEC 50065-1 [13]. Its main disadvantage is the reduction in transmission rate to 5.5Kbps, which corresponds to a net bit rate of 4Kbps after accounting for error correction overhead.

3. Power Line Characteristics

The distribution transformer secondary windings, entrance cables, house wiring and electric loads determine residential impedance. The characterization of this impedance is important to the design of Power Line Carrier (PLC) systems. For them, this impedance is the driving point into which the transmitter operates and from which the receiver extracts the signal.

One of the earlier studies of power line impedance characteristics conducted by Nicholson and Malack [2] gives a frequency response plot of the power line as shown in Figure 4. Although this paper is geared toward the validation of proposed characteristics of Line Impedance Stabilization Networks (LISN), used for measurements of conducted EMI, the results shown are applicable to the scope of this paper.

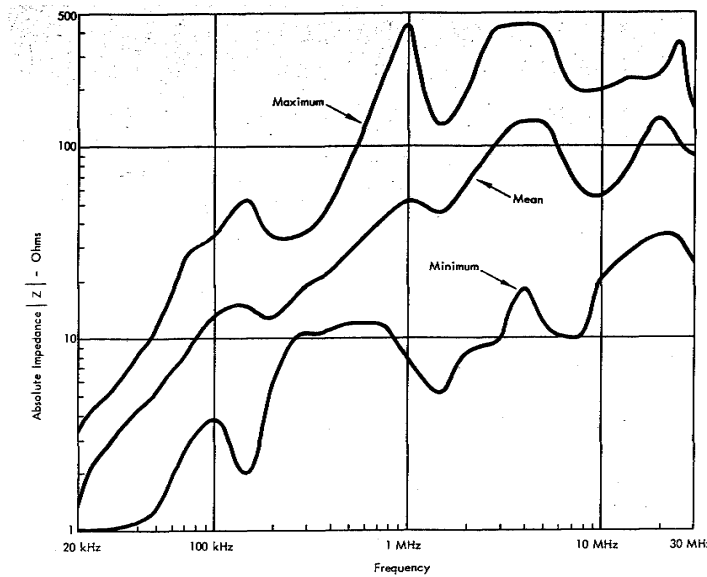


Figure 4 Power Line Impedance Measurements by Nicholson and Malak [2].

A method to measure power line impedance reported by Vines [6] that validates in part the results obtained by Nicholson and Malack (it only covers frequencies up to 20 kHz), consists of forcing a voltage signal at the frequency of interest (through a filter) and measuring both the voltage and current into the filter. One important point in this report is the conclusion that measurements can be made without the 60Hz power signal present, simplifying the test set up. The presence of the 60Hz signal has no effect at kHz frequencies. This and some other studies

have proven that the residential power line can be modeled as distributed impedance with a characteristic value:

$$Z_c := \sqrt{\frac{L}{C}} \quad (1)$$

where L is $\mu\text{H}/\text{foot}$ and μC is F/foot . Vines reports a characteristic impedance varying from 70 to 100Ω for different types of wires. The impedance of the 120 and 240 Volt residential power circuits increases with frequency, thus indicating a clearly inductive behavior as expected. From Figure 3 it can be seen that the power line impedance ranges from 5 to 32Ω at 100 kHz. One interesting finding reported by Tanaka [7] indicates a drastic increase in the overall line inductance due to the outlet termination (commonly known as J-box). Each J-box termination increases the power line inductance by about $1.5 \mu\text{H}$, with this inductance increasing as the length of the termination is increased. This affects the overall network performance, and careful termination methods are recommended to minimize this problem.

One of the concerns when considering the impedance of the power line is the affect of the household loads in the overall residential impedance. Vines have reported that the impedance of most electrical loads around the house is relatively high (with the exception of high resistive loads) when compared to the unloaded power line impedance. There are however, some loads that cause resonance (either series or parallel) with the power line impedance, at frequencies above 40 kHz. This is a matter of concern, since the protocols of interest operate at frequencies above 100 kHz. In particular, Switched Mode Power Supplies (SMPS) are somewhat troublesome because of their EMI filtering. The capacitors used for the implementation of this filter bypass the communication signal, and users must avoid the connection of PLC nodes at these locations.

A study made by Dostert [8], reports a 15 dB mean attenuation in a typical single residence for frequencies below 150 kHz, while the attenuation of signal is close to 50 dB in external power line (distribution level) up to 0.7 miles cable length. Due to restrictions on the carrier level, in some instances the interference exceeds the transmission signal, creating unreliable links. The conclusion of this study is that narrowband modulation techniques constitute a poor choice for PLC, because it yields unreliable data links. A Frequency Hopping Spread Spectrum (FHSS) communication technique similar to that used by CEBus was proposed. One drawback of some of these FHSS methods is that jitter caused by frequency variations may cause synchronization problems, with a subsequent communications reliability problem. Test results in the paper indicate that this type of errors are tolerable.

3.1 Equivalent Circuit for the Power Line

Several studies made on the physical characteristics of the power line medium indicate that it can be represented as an R-L-C circuit. However, since the capacitance value is negligible, some authors choose to ignore it. Forti [14] concludes that the power line can be represented as frequency-dependent resistance in series with a constant inductance:

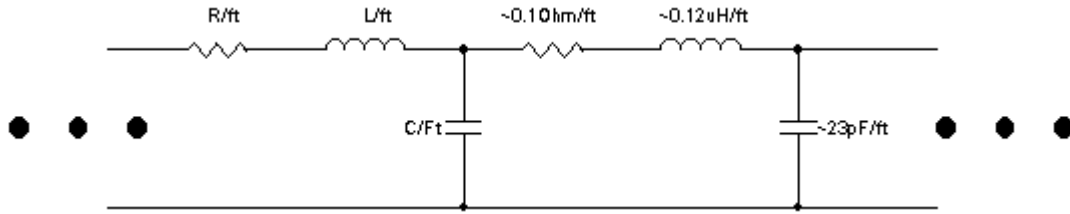


Figure 5 Power Line Model by Downey and Sutterlin [12]

$$Z = R(f) + sL \quad (2)$$

A more practical approach is given by Downey and Sutterlin [12], in which the power line modeled as a distributed R-L-C network as shown in Figure 5. Using the model above for a 30 ft length of 12-2 BX cable, yields the following values: Series inductance: 3.6 μ H, Shunt Capacitance: 690pF, and Series Resistance: 0.3 Ω . With the values given above and using the expression (1), $Z_c = \sim 74\Omega$.

The significance of this information is that the power line circuit will exhibit a different characteristic depending of the type of impedance (load) into which it is terminated: It will look inductive when terminated with a low impedance and it will look capacitive when terminated with a high impedance. Also, it can be seen that the power line acts as a voltage divider (attenuates the communication signal), together with the different loads that are connected to the network, with the attenuation increasing with frequency for frequencies above 100 kHz (increase of 0.25 dB/kHz is reported) [1]. The power of the signal at the receiver side is maximum when the impedance of the transmitter, receiver and the power line are matched. Therefore it is important to study carefully the signal coupling mechanisms that optimize the transfer of information.

Considering all the facts already discussed, it is almost impossible to decide which is the best value of the power line impedance to use for the design of the coupling circuit, since this value depends on the type of wire, the length of the cable and the type of loads connected to it. However, the range of values given by Nicholson and Malack [2] are a good starting point.

3.2 Noise On Power Line Circuits.

Noise that affects communications on the power line circuit is due mainly to light dimmers, universal motors and some power line based intercom modules. Recent development of Audio and Video transmitters that use the power line as the signal transport media have made matters worse. It has been found that dimmer generated noise is much greater and harmful than that generated by universal motors. Moreover, dimmers generate both odd and even harmonics of 60 Hz which can severely impair the PLC network if they are not properly filtered, although some manufacturers argue that this noise attenuates very fast as frequency increases, becoming harmless at the frequencies of interest. Practical experiments demonstrate quite the opposite. Jitter can be considered as another source of noise as mentioned before.

Television receivers and computer monitors are another cause for concern since they produce a significant amount of line noise at multiples of the horizontal sweep frequency. Therefore, transmission frequencies multiples of these should be avoided when implementing the network. Low cost power line surge suppressors, used today as temporary power strips, are a great cause of network degradation, since they are built to filter the same frequency spectrum that most of the PLC protocols use for communication.

Noise that is aperiodic in nature such as impulse noise caused by thermostats or lightning [1] can be overcome by use of an appropriate error correction code. The important point here is that all these common sources of noise have to be analyzed and dealt with when a PLC network is being implemented, otherwise, the network will not operate reliably. Vines [5], [6] and O'Neal [9] make an excellent study of the noise generating devices and their influence in the power line communications network.

3.3 Power Line Coupling Methods.

There are two choices for signal coupling to the power line: Differential or Line -to-Neutral mode [1], [12], in which the line to neutral pair is used to inject the signal. This method can be used only if the neutral line is available (not always the case in residential applications). Common or Line -to-Earth mode uses the ground wire as the second terminal. This second method has less attenuation and less noise (neutral line is the return for all the noise present in the power line), but may have potential dangers and is not always allowed by the safety regulation agencies. Most manufacturers use the first coupling method for these reasons.

Another aspect to consider is the signal transfer between the two phases. As the inter-wiring capacitance is negligible, and the distribution transformer is not designed for the high frequencies used, other means of signal transfer must be implemented. A sizable load connected from L1 to L2 (240 Volts) will generally cause an increase in signal transfer, but a reliable network can not depend on the presence of such loads, as they might not be continuously connected, prompting for the use of a different mechanism. A capacitor of the right size for the frequencies of interest would suffice. This method is not advisable if there are communication nodes operating between the two lines (240 v-ac in residential circuits), since the capacitor will shunt the signal to be received or sent by this node. A circuit that overcomes this problem and presents a low attenuation path (~3dB) for the signal between phases is shown in Figure 6.

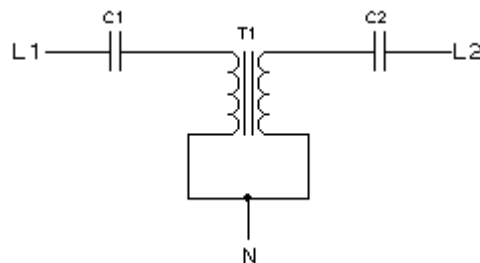


Figure 6 Recommended Phase Coupling Circuit

Injecting a communication signal operating at the frequencies already described is generally realized by capacitively coupling the transceiver's output to the power line. For safety reasons, a transformer is almost always present. Some manufacturers use non-isolated circuits whenever possible to minimize transfer losses. The inductance of the transformer should be designed such that the L-C circuit thus formed acts as a high-pass filter for the incoming signal. Also, in order to minimize attenuation due to the different loads connected to the power line, especially the kind that has EMI filtering such as switching power supplies (found in PCs), some isolation is required. The inductance of the power line wire is usually sufficient since its impedance is about 10Ω per 100 feet at the frequencies of interest. Therefore, moving the node some feet away from the offending load often solves the problem. The following figures illustrate some of the topologies used to couple the communication circuitry to the power line medium.

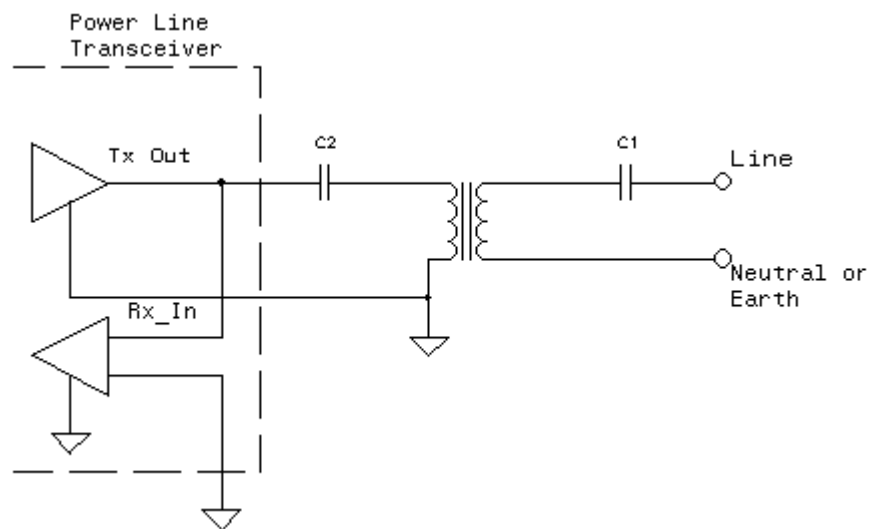


Figure 7 Transformer Isolated Coupling Circuit for Power Line Communications

The different protocols utilize variations of the circuit shown in Figure 7. In the X-10 case, the transformer is an IF transformer centered on 120 kHz, and giving a 3dB bandwidth of approximately 10 kHz. Since X-10 uses zero crossing detection, additional circuitry that perform that function is implemented. The coupling circuit found on most X-10 devices is shown in Figure 8. Typical values for the components are listed in [15].

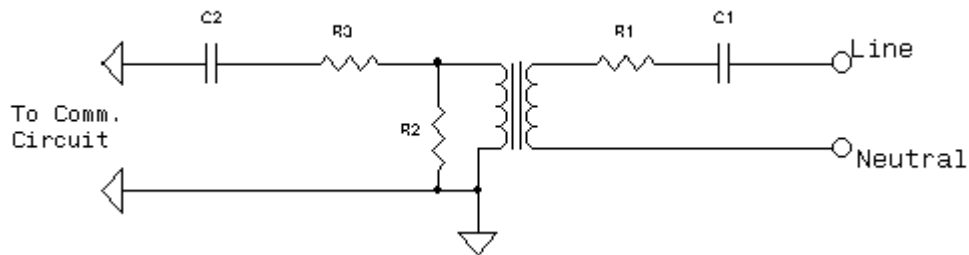


Figure 8 Power Line Coupling Circuit found in X-10 Devices

Intellon, one of the manufacturers of CEBus transceivers, recommends the use of a power amplifier to boost the spread spectrum signal before it is coupled to the power line [16]. This amplifier is a class AB configuration that produces a 6Vp-p into a 10Ω load, to increase performance under low line impedance conditions. Since CEBus uses all the frequency spectrum from 100 to 400 kHz, the coupling circuit must include a bandpass filter for that frequency range. In theory, such a wide window makes this protocol more susceptible to noise interference, making the filter requirements more challenging. However, the spread spectrum technology used makes the receiver immune to a large range of impairments, due to the fact that only a portion of the signal is required for detection. Figure 9 contains a typical power line coupling circuit as suggested by Intellon.

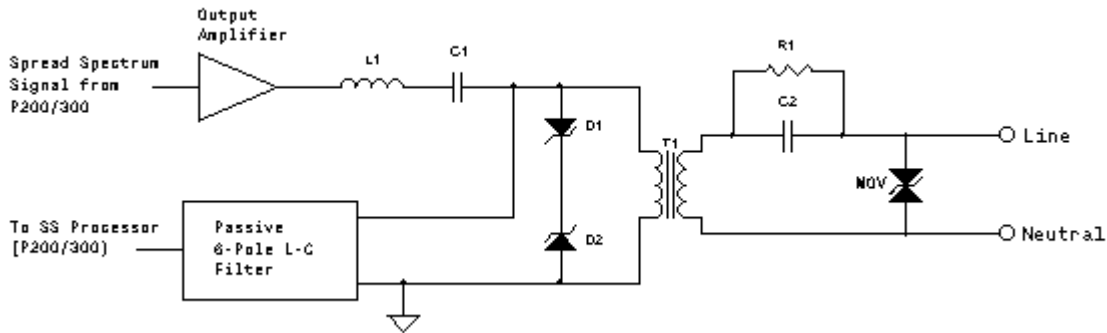


Figure 9 Power Line Coupling for CEBus Devices suggested by Intellon Corp.

Transformer T1 provides a linear function for the 100-400 kHz Spread Spectrum Carrier; capacitor C2 blocks the 60 Hz signal and avoids transformer saturation. The MOV provides protection against line transients and the zener diodes D1 and D2 serve to clamp the voltage level applied to the input of the SS processor IC. The passive 6-pole filter is designed to provide a -3dB point at 100 and 400 kHz, with a 30 dB attenuation at 40KHz and 1000MHz respectively. The circuit formed by L1-C1 is used to reduce conducted EMI noise to within FCC regulations. More detail information is provided in [16].

The power line transceivers for a LonWorks network operate on a narrower frequency band, and the filter requirements are different to those used in CEBus applications. Circuit in Figure 10 shows the main components of a power line coupling circuit used by Echelon's PLT-21 transceiver [13]. One of the most important aspects of this circuit is the requirement for values of capacitors C1 and C2, which must have low impedance at the frequency of transmission (125-140 KHz). The output impedance of the transceiver is of the order on 1Ω. Capacitors C1 and C2 are expected to have impedance of the same order at these frequencies, in order to minimize the overall output impedance of the transmitting circuit. This condition requires a large capacitance value and the capacitor C1 connected to the power line might become expensive for volume production. To reduce this impedance, the isolation transformer's inductance provides some help. This inductance forms a series-resonant circuit with C1 and C2 that should be tuned to the communication frequencies of the transceiver. The R-L-C network comprised of R2-L4-C4 is recommended when the node contains SCR, triacs, or operates below 12 Vdc. Diode D3 in conjunction with capacitor C3 is used to protect the inputs of the

transceiver from large transients. C3 also integrates excessive overshoots that might be present when these transients occur.

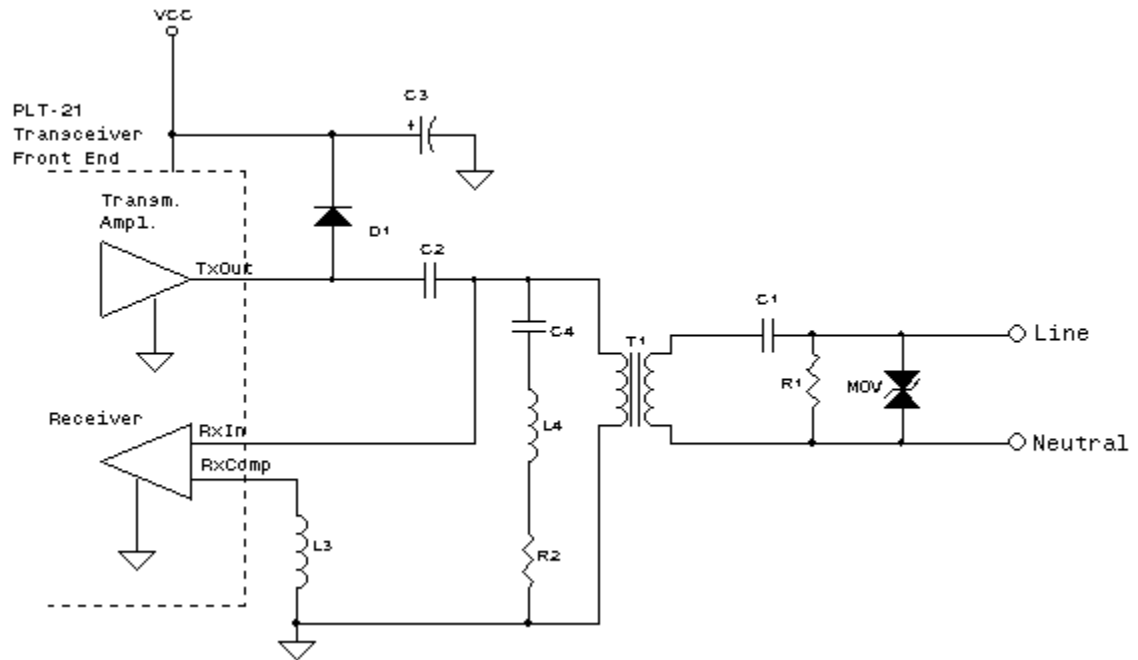


Figure 10 Coupling Circuit for LonWorks PLT-21 Transceiver

4. Testing the Power Line Characteristics

When designing a Power Line Communication System, there must be a clear understanding of the limitations and challenges it represents. The previous sections have outlined the most important aspects of this type of network. The testing of these characteristics must be performed in a way that allows the equipment to simulate the conditions found in the real world. Several manufacturers have developed test methods intended to show the benefits of their own protocol [13], [17]. Reference [17] provides useful circuits that simulate some of the impairments described in this paper.

A method presented in [18] uses a Digitally Implemented Network Analyzer that excites the power line to measure its impedance-versus-frequency characteristic. The advantage of this method is that measurements are performed on energized systems, with real load conditions present. Although the study limits the frequencies of interest to below 24 kHz, it seems possible to extend the frequency range to 500 kHz and cover the protocols described in this paper. The equipment used here makes use of a digital signal processor to perform a single discrete Fourier transform to find the real and imaginary components of the voltage and current signals at the same frequency of the injected test signal. Impedance is calculated from the current actually injected into the system and the voltage produced. The instrumentation characterizes the line impedance as a function of frequency by repeating the measurement over a series of values over the desired frequency range. The authors claim that this measurement technique is independent

of the harmonic distortion or the noise introduced by the loads connected to the tested line. Further study of this test method is needed before it can be recommended for the applications outlined in this paper. However, some of the procedures described and results showed agree with previous studies.

5. Conclusion

Power line communications is a viable technology as demonstrated by several commercial products available today. Advances in signal processing and semiconductor development have made this concept a reality. The technologies described in this paper obtain data transfer speeds of up to 10 KBPS, with some others being announced with speeds above 100 KBPS. The concepts outlined here intend to create a basic understanding of some of the technologies used for this application and point the limitations and drawbacks of some of them. There is no clear winner, and their coexistence in a very unfriendly environment is the more reasonable approach. The need for gateways between these protocols is an urgent need for the very same reason, and the views expressed here form a base for their design.

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