A Power Line Communication Tutorial - Challenges and Technologies

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Keywords: Communication, Spread Spectrum, Digital Signal Processing

Abstract - This paper reviews the sources of attenuation, noise and distortion encountered when communicating over AC power wiring. Various technologies which have been used to address these challenges, such as spread spectrum and digital signal processing, are then examined in light of the known channel conditions.

Introduction

While the idea of sending communication signals on the same pair of wires as are used for power distribution is as old as the telegraph itself, the number of communication devices installed on dedicated wiring far exceeds the number installed on AC mains wiring. The reason for this is not, as one might think, the result of having overlooked the possibility of AC mains communication until recent decades. In the 1920's at least two patents were issued to the American Telephone and Telegraph Company in the field of "Carrier Transmission Over Power Circuits". United States Patents numbers 1,607,668 and 1,672,940, filed in 1924 show systems for transmitting and receiving communication signals over three phase AC power wiring. Others have suggested that what was required for power line communication to move into the main stream was a commercialized version of military spread spectrum technology. It has been suggested that this is what was needed in order to overcome the harsh and unpredictable characteristics of the power line environment. Commercial spread spectrum power line communication has been the focus of research and product development at a number of companies since the early 1980's. After nearly two decades of development, spread spectrum technology has still not delivered on its promise to provide the products required for the proliferation of power line communication. This paper, after reviewing basic power line communication characteristics, examines the advantages and disadvantages of various power line communication technologies from the perspective of extensive research and field experience with each prospective technology. While earlier thoughts that a new technology was needed to overcome communications challenges were correct, it is the intent of this paper to demonstrate that the key technology required is digital signal processing technology (DSP) and that the application of spread spectrum techniques actually decreases reliability in many common situations.

Power Line Characteristics

Evaluation of any communication technology is only relevant in the context of the operating environment. This seemingly obvious point, frequently bypassed in textbook analysis, can not be overlooked in the field of power line communications. We begin by examining three common assumptions which must be modified in order to be applicable to power line analysis.

The majority of engineering texts rely heavily on the principle of superposition. Unfortunately, the conditions required for superposition to be applicable (i.e., linearity and time invariance) are not met for the majority of power line networks. One cause of nonlinearity is when a packet's signal voltage adds to the AC line voltage and causes power supply diodes to turn on and off at the packet carrier frequency. A common example of time variance is when the impedance at a point of a power line network varies with time as appliances on the network are alternately drawing and then not drawing power from the network at twice the AC line frequency.

Another area of confusion arises from the common view that wiring capacitance dominates signal propagation effects. This simplified view is rooted in assumptions which do not accurately reflect power wiring environments. While it is true that wire capacitance is dominant for cases where the termination or load impedance is much greater than the characteristic impedance of the wire, power lines are frequently loaded with impedances significantly below the characteristic impedance of the wire. Common examples of loads which present a low network impedance at communication frequencies include capacitors used within computers and television sets to meet electromagnetic emission regulations and resistive heating elements found in cooking ovens, space heaters and the like. The impedance of these devices is typically an order of magnitude, or more, below the characteristic impedance of power wiring. This can be seen quantitatively by comparing the entries in tables 1 and 2.

Wire Type	Z_0 ohms	c/ft (pF)	L/ft (mH)	r/ft ohm @130kHz	v ft/ns
12-2 BX metal clad	74.2	22.7	0.13	.0132	.594
12-2G Romex NM-B	143	10.4	.214	.0136	.670
18-2 Lamp cord	124	13.2	.203	.0235	.610
18-3 IEC power cord	79.6	30.8	.195	.0315	.408

Table 1: Power wire characteristics

Low Impedance load	Impedance at 100kHz
0.1uF EMC capacitor	16 Ohms
2kW 240VAC space heater	30 Ohms

Table 2: Low impedance power line loads

While a full transmission line model, complete with high frequency models of each load, is required to fully characterize power line attenuation, there is one simplification which can be used as a first order approximation. For cases where wire runs are less than 1/8 of a wavelength (approximately 250 meters at 100kHz) and communication is confined to a single power phase, the presence of low impedance loads causes wire inductance to dominate. In many instances a lumped model which includes only wire inductance and low impedance loads closely approximates actual signal attenuation. Frequently the only other effect which must be considered in order to match measured values is the loss encountered when the communication signal must cross power phases. This loss, typically in the range of 5 to 25dB, is influenced by a number of variables including distribution transformer coupling, distribution wire cross-coupling, multi-phase load impedance and circuits which are explicitly installed to reduce this loss. Combining the above effects we find that 96% of the time the attenuation within a single residence falls in the range of 6-54dB near 100kHz. A distribution of power line attenuations measured at 130kHz using thousands of randomly selected socket pairs in hundreds of homes from 5 different countries is shown in figure 1.

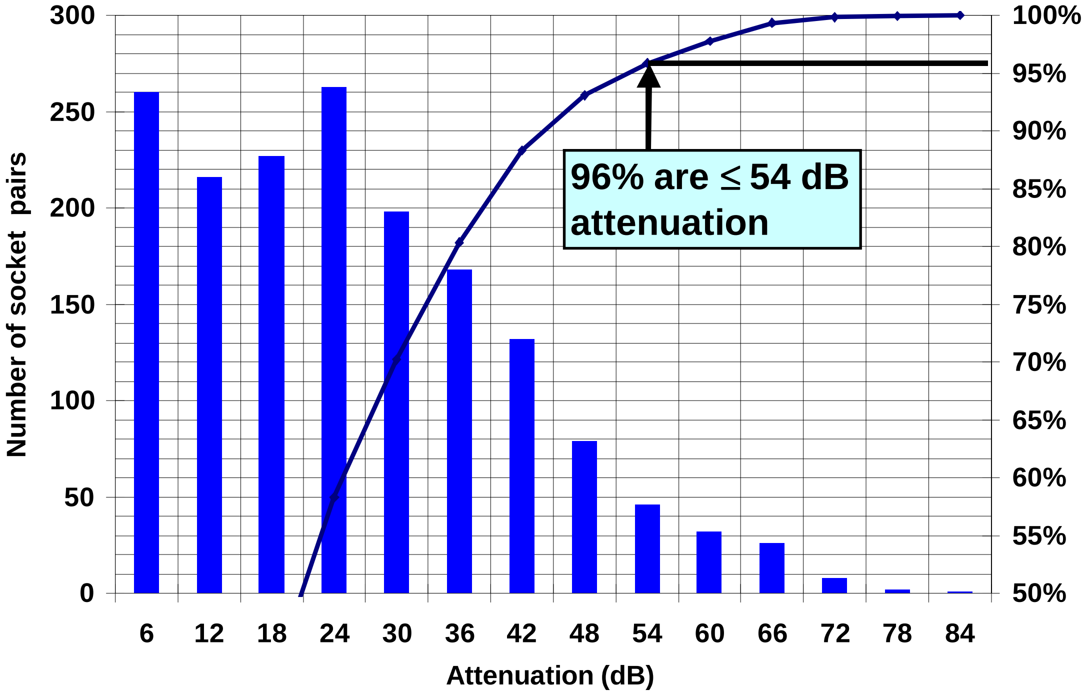

Figure 1 Attenuation in homes at 130 kHz

If attenuation were the only impairment, then receiver gain could simply compensate for this signal loss. Both the noise and distortion characteristics of the power line must also be considered before we have a picture of the operating environment which is adequate for use in technology comparison.

Many electrical devices which are connected to the power mains inject significant noise back onto network. The characteristics of the noise from these devices varies widely. Examination of the noise from a wide range of devices leads to the observation that the noise can be classified into just a few categories:

Impulse noise (at twice the AC line frequency)
Tonal noise
High frequency impulse noise

The most common impulse noise sources are triac-controlled light dimmers. These devices introduce noise as they connect the lamp to the AC line part way through each half AC cycle. When the lamp is set to medium brightness the inrush current is at a maximum and impulses of several tens of volts are imposed on the power network. These impulses occur at twice the AC line frequency as this process is repeated in every 1/2 AC cycle. Figure 2 shows an example of this kind of noise after the a high pass filter has removed the AC power distribution frequency.

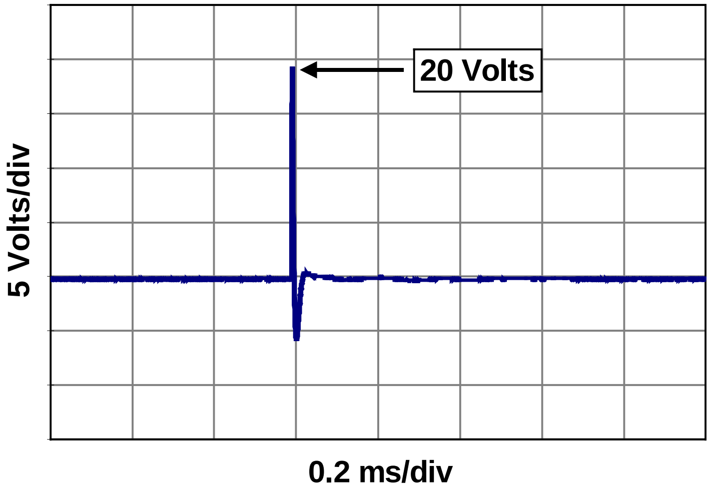

Figure 2 Lamp dimmer impulse noise

It is often useful to divide tonal noise into the two sub-categories of unintended and intended interference. The most common sources of unintended tonal noise are switching power supplies. These supplies are present in numerous electronic devices such as personal computers and electronic fluorescent ballasts. The fundamental frequency of these supplies may be anywhere in the range from 20kHz to >1MHz. The noise that these devices inject back onto the power mains is typically rich in harmonics of the switching frequency. Noise from the charging stand of an electronic toothbrush is shown in the plot of figure 3. Note the similarity between the switching supply noise and an ideal sawtooth waveform.

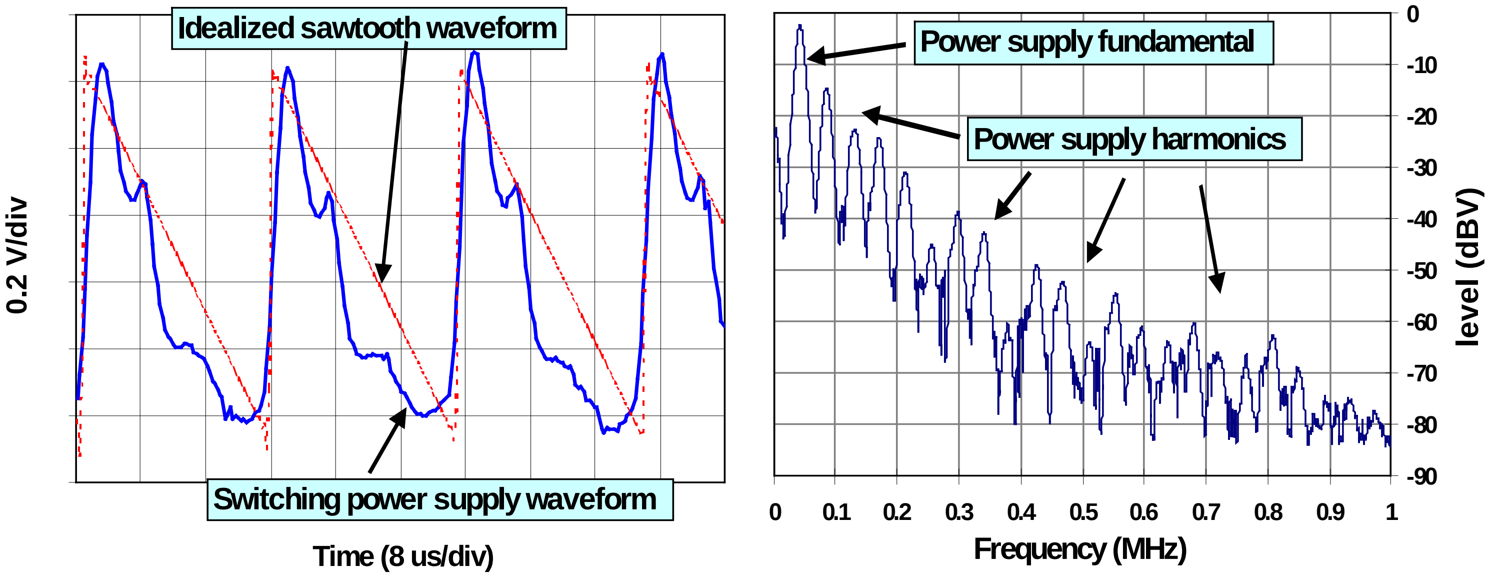

Figure 3 Noise from electric toothbrush charging stand

Intentional tonal noise can result from devices such as power line intercoms and baby monitors. In the United States and Japan these devices generally operate at frequencies between 150kHz to 400kHz; injecting signals of several volts peak to peak onto the power line. Figure 4 shows a spectral plot of a typical power line intercom. A second source of intentional tonal noise results from pickup of commercial radio broadcasts. Power wiring acts an antenna to pick up signals from these mulit-thousand watt transmitters. Interference on the order of a volt peak-to-peak at frequencies just above the communication band is not uncommon. Note that this interference has very specific implications for the filtering requirements of any power line transceiver.

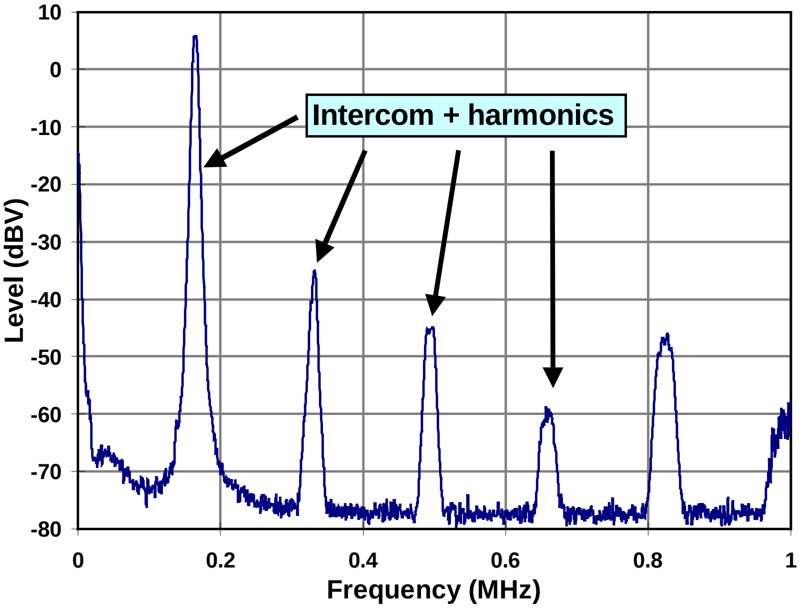

Figure 4 Power line intercom spectrum

High frequency impulse noise finds its source in a variety of series-wound AC motors. This type of motor is found in devices such as vacuum cleaners, electric shavers and many common kitchen appliances. Commutator arcing from these motors produces impulses at repetition rates in the several kilohertz range. Figure 5 is an oscilloscope plot of noise from a household vacuum cleaner on the left and on the right amplitude distribution plots of three common types of impairments. An ideal guassian distribution fitted to the vacuum distribution is also shown.

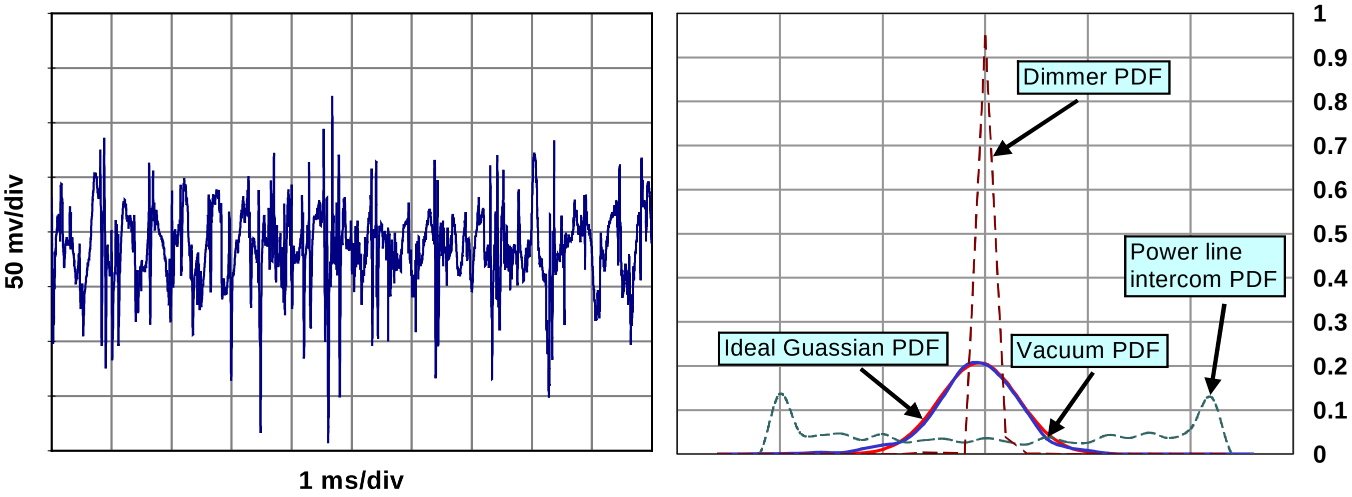

Figure 5 Vacuum cleaner noise and amlitude distributions for common impairments

Figure 6 is a frequency domain view of the noise from the same vacuum cleaner showing the wide band spectrum on the left and a close up of the part of the spectrum typically used for power line communications on the right. Note that, of the various categories of power line noise, this motor noise is the only type which bears even a remote resemblance to white gaussian noise commonly used to analyze many communication systems.

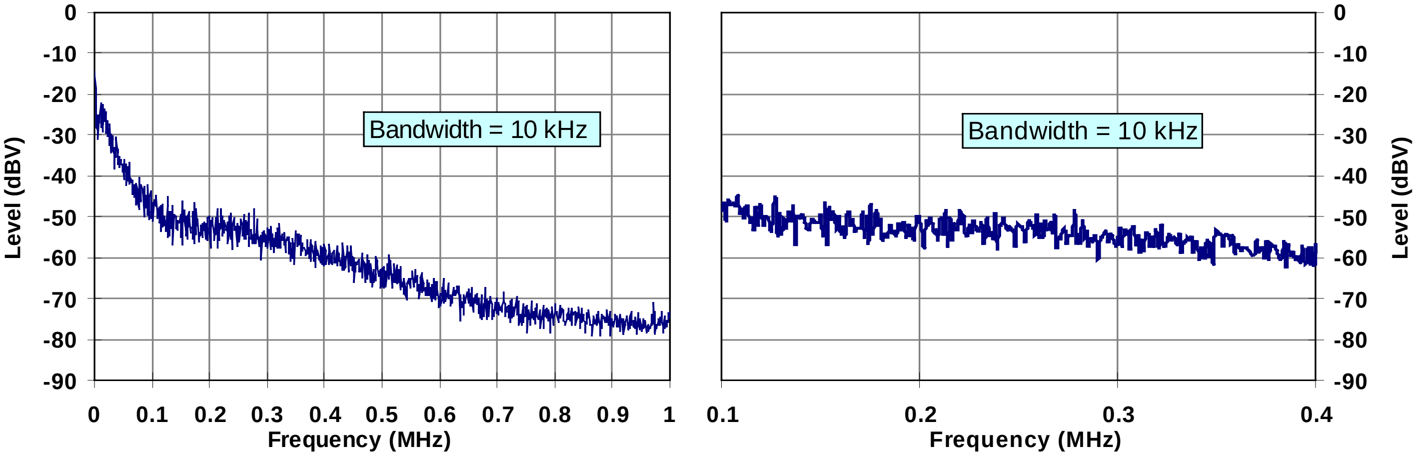

Figure 6 Vacuum cleaner noise spectrum

As mentioned earlier a complete analysis of power line characteristics must include an analysis of the distortion characteristics of the channel. Various reactive loads and wire characteristics combine to create a channel with highly distorted (and time varying) frequency response. Figure 7 illustrates this point showing the magnitude and phase characteristics between two points of a sample power line network.

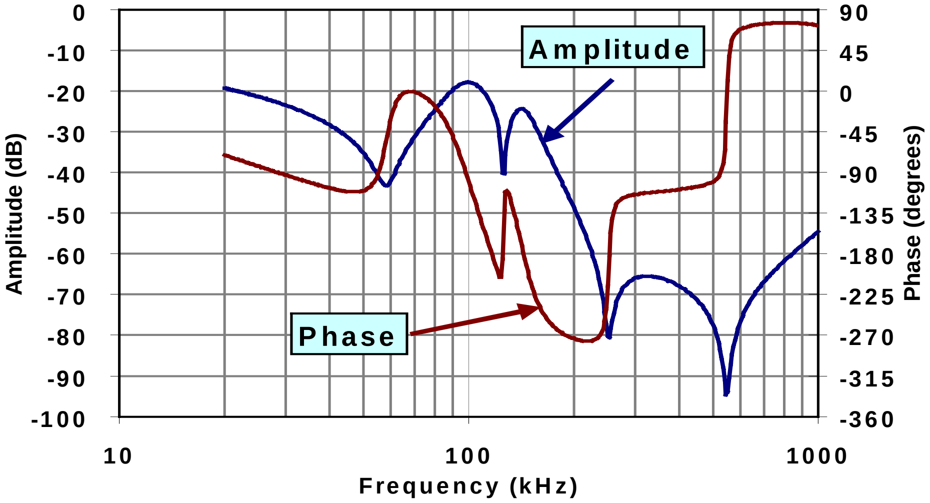

Figure 7 Example of power line frequency distortion

Communication Technologies

Having reviewed the characteristics of the power line, we are now in a position to compare various communication technologies within the context of their true operating environment. We will begin by examining three technologies in order of historical significance. Many early power line communication devices used narrow band transmission combined with a phase-locked-loop type receiver. Three variations of narrow band transmission are illustrated in figure 8. For clarity these illustrations do not include wave shaping which is typically applied to remove abrupt transitions and limit signal spreading.

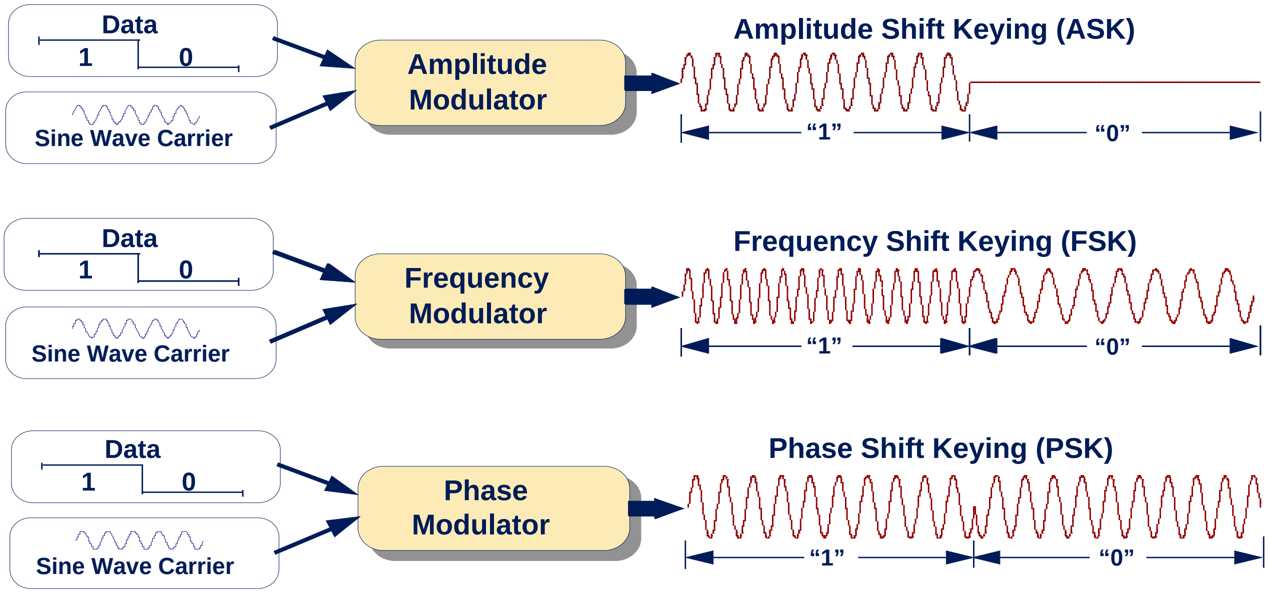

Figure 8 Methods of narrow band modulation

A phase-locked-loop receiver which can be used to receive any of these three transmissions is illustrated in Figure 9. With this technology the PLL typically adjusts the phase of the receiver's local oscillator until the down converted and filtered signal in the quadrature (Q) channel is nulled out. The filtered "I" channel signal is then used as a recovered representation of the transmitted data.

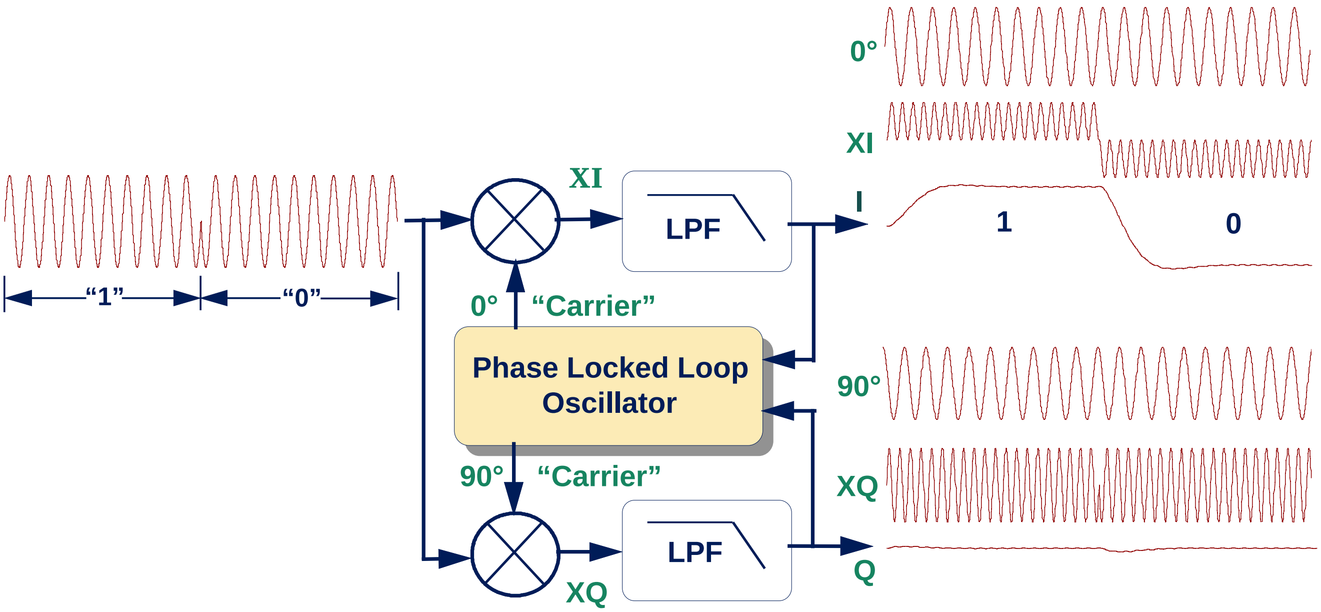

Figure 9 A phase locked loop receiver

A serious limitation with this approach emerges when it is evaluated in light of typical power line noise. Impulse noise from light dimmers is spread over several bit times by the required narrow receive filter. Figure 10 is an oscilloscope plot of the output from one of these receivers with a 66dB attenuated input signal - disturbed by an impulse from a light dimmer located next to the receiver. As the graph shows, two of the received bits are in error. This and other limitations have caused many companies to abandon this technology for use in power line communication.

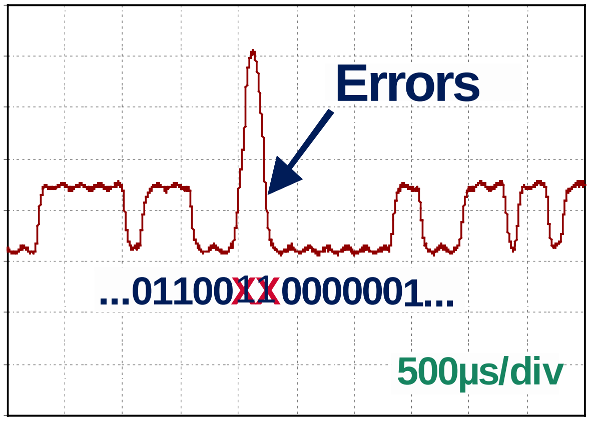

Figure 10 Errors in PLL recovered signal due to impulse noise

Another technology to draw the interest of power line communication developers is spread spectrum technology. Lets begin this analysis with a definition: Spread spectrum transmission is a method of signal modulation where the transmitted signal occupies a bandwidth considerably greater than the minimum necessary to send the information and some function other than the information being sent is used to increase this bandwidth [1]. This simply means that the transmitted signal is subjected to a second modulation step using a wide-band signal other than the transmitted data as the modulation source. Figure 11 illustrates this process for direct sequence, chirp, and frequency hop spread spectrum signaling. This type of transmitter is typically no more complicated than its narrow band counterpart. In practice the extra modulation step is simply performed prior to storing a "pre-spread" carrier into read only memory.

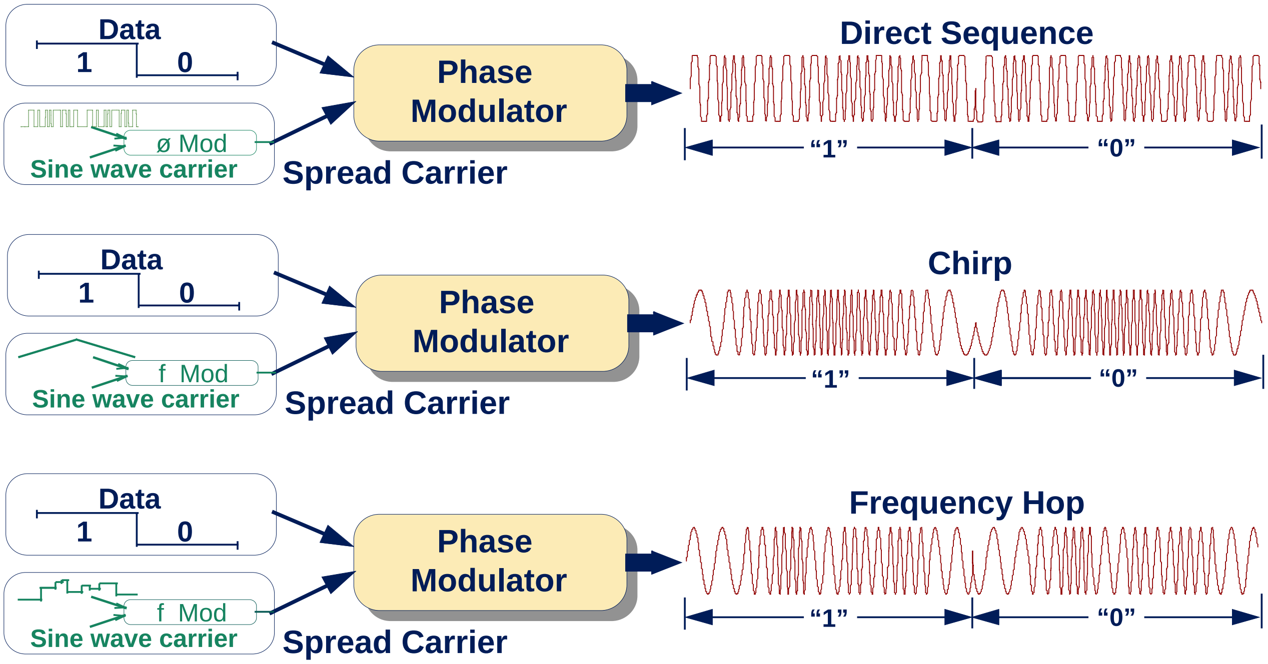

Figure 11 Methods of spread spectrum modulation

Spread spectrum reception is then performed by correlating the received spread spectrum signal with a replica of the expected waveform. This process is shown in figure 12.

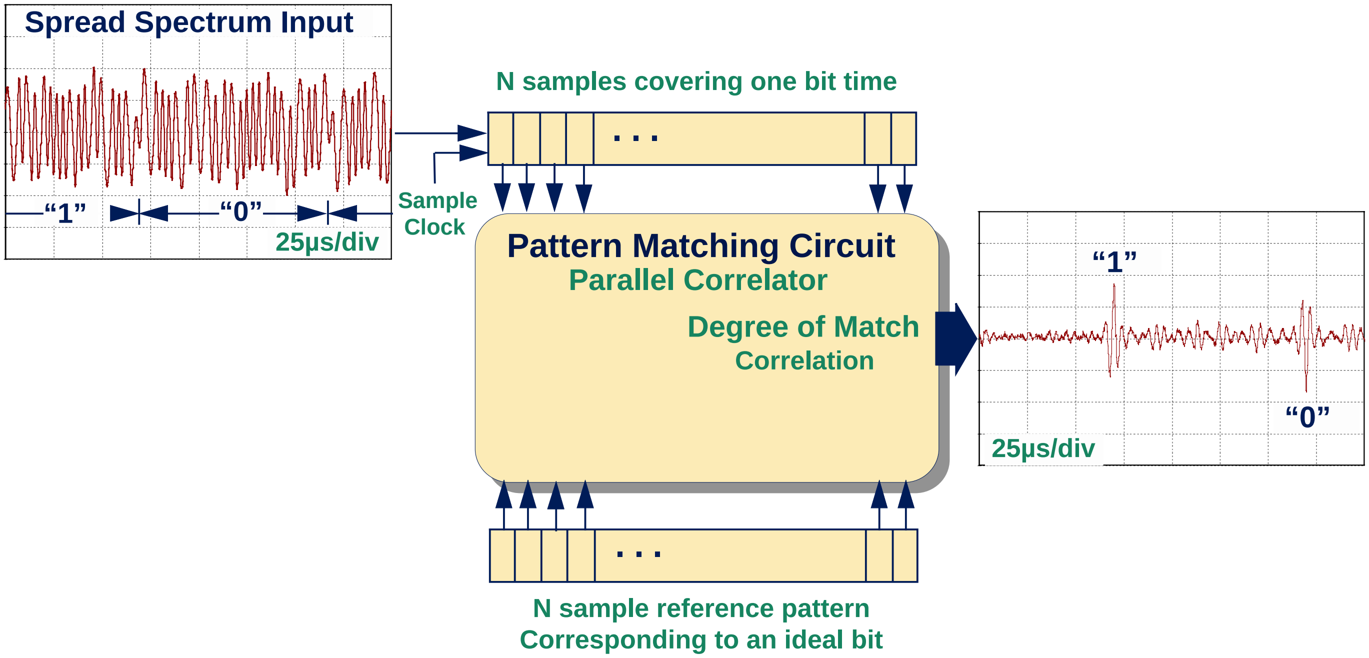

Figure 12 A spread spectrum receiver

Another characteristic of spread spectrum technology which must be considered relates to the bandwidth consumed by a spread signal. European regulations (EN-50065-1) prohibit power line signaling above 150kHz due to potential interference with low frequency licensed radio services. Furthermore the European community has viewed power line bandwidth as a resource to be shared between all interested parties. European band allocations are illustrated in figure 13. The result of these regulations is that the consumer use bands are too narrow for the effective use of spread spectrum technology.

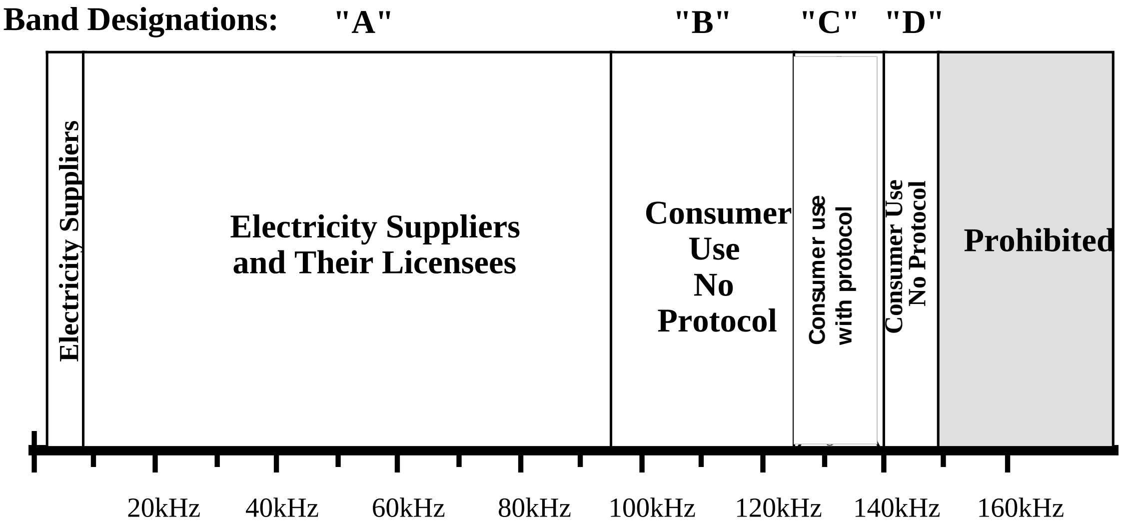

Figure 13 European power line communication frequency allocation

Current US and Japanese regulations allow the use of somewhat broader spectrum transmissions. For instance in the US and Japan transmissions are allowed up to approximately 525 kHz where the AM broadcast band begins. This may change, however, due to the recent discovery that power line communication signals above 180kHz can interfere with aircraft navigation systems. Canada has been the first to respond to investigations of airline crashes which traced the cause of the crash to power line communication equipment radiating above 180kHz. Operation above the AM broadcast is problematic due to the fact that band there are many licensed services which cannot be disturbed.

Thus far we have considered the mechanics of spread spectrum technology and are now in a position to consider its behavior. Most communication text books point out that spread spectrum communication techniques can be used to improve performance in the presence of tonal noise. The maximum improvement is set by the degree of spreading which in turn is set by available bandwidth and desired data rate. For instance, the value of this theoretical gain for a 10kbit/sec information signal spread over a 100kHz-400kHz bandwidth is 30 (15dB in logarithmic terms). Realization of even this modest gain depends on implementation and for most practical receivers the processing gain is reduced to few dB as will be seen shortly.

When examined in the light of power line tonal interference, we see that spread spectrum technology is significantly inferior to narrow band technology. The problem is that the processing gain available to the power line spread spectrum signals is not enough to overcome the levels of tonal noise from switching power supplies and other common consumer products seen on the power line. The left side of Figure 14 shows a spread spectrum signal attenuated by just 40 dB relative to the switching power supply from figure 3. It can be seen that much more than 15 dB of processing gain (the maximum available to the 10 kbps spread spectrum receiver) would be required to overcome the level of interference resulting from even this moderate attenuation case. Some advanced spread spectrum systems use digital signal processing to filter out tonal noise which is present at levels above where the processing gain of the receiver can overcome it. The right of figure 14 shows the largest power supply harmonic being eliminated with a notch filter (which also eliminates a small part of the signal). It can be seen that since other harmonics are nearly the same amplitude as the notched tone the net performance increase is only 1 or 2 dB.

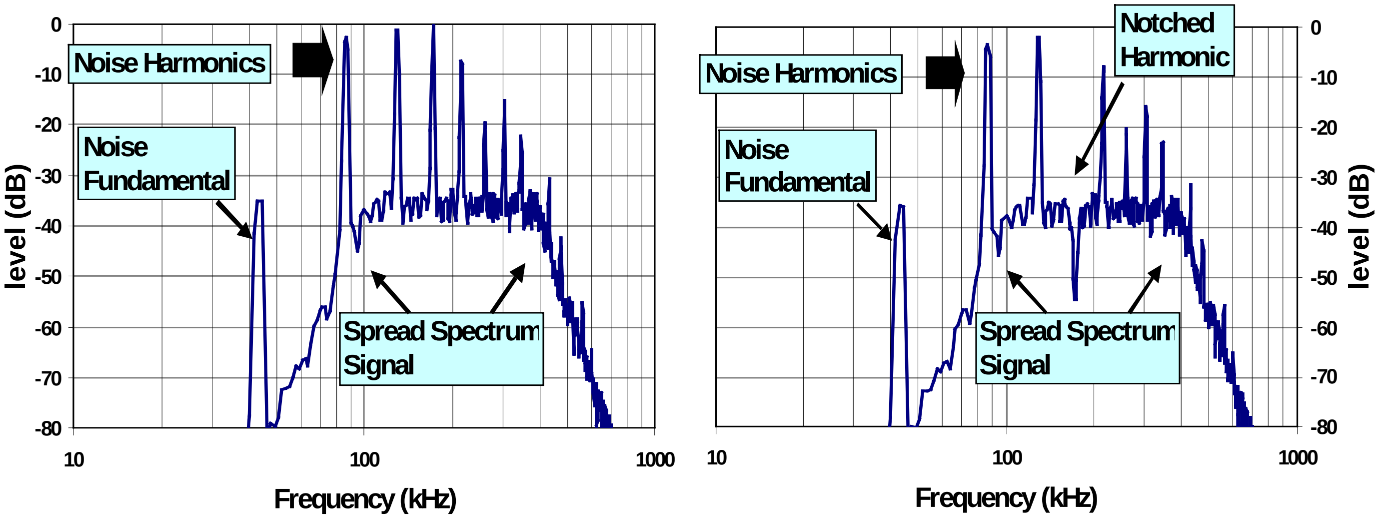

Figure 14 Spread spectrum signal with power supply noise

To further illustrate this phenomenon a simulation was performed comparing a spread spectrum system to a narrow band system in the presence of switching power supply like noise. Both systems were assumed to operate at 5kbps. The spread spectrum system used a frequency chirp to spread its signal between 100k-400kHz (below the AM band in the US and Japan). It used a floating point correlator and DSP tuneable notch which automatically filters out the largest tone. Two narrow band systems were simulated, one with a single carrier at 132kHz and and one with dual carriers at 115kHz and 132kHz. The narrowband systems used BPSK modulated carriers each with a bandwidth of 6kHz. A sawtooth wave was introduced at the same level that the toothbrush switching power supply that was measured earlier. To simulate different brands of power supplies with different switching frequencies the sawtooth waveform was swept in frequency from 25kHz to 200kHz. At each frequency the received signal was attenuated relative to the noise until the bits could no longer be decoded for each system. The resulting attenuation tolerance plots are shown in figure 15. It can be seen that the spread spectrum receiver has significantly lower tolerance to switching supply noise than the dual carrier narrow band receiver at all frequencies. Even the single carrier receiver is better at the vast majority of frequencies.

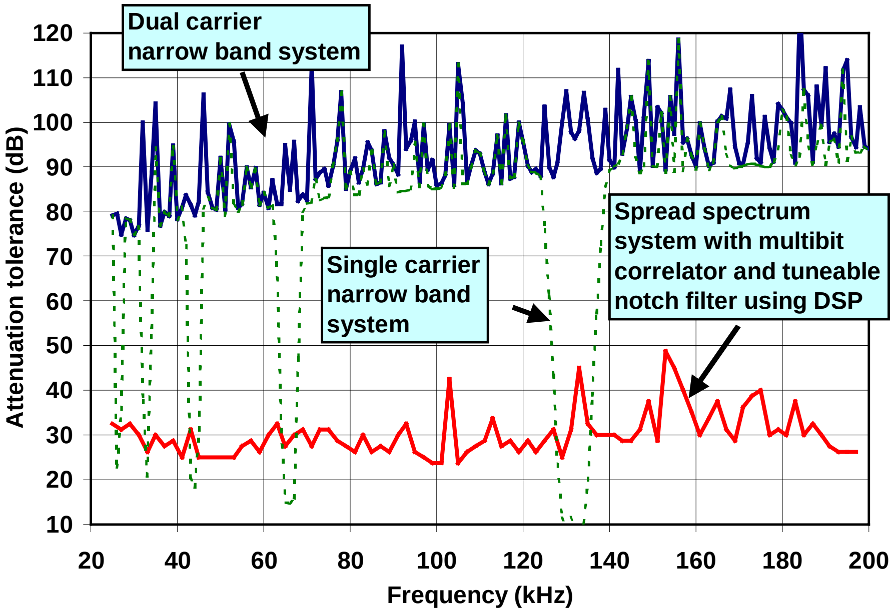

Figure 15 Simulated performance with sawtooth interference

Another disadvantage of spread spectrum technology is that it has been found to degrade performance in the presence of common power line channel distortion. This can be understood by examining the plot of figure 16. This plot is an expanded view of figure 7, showing only the frequency range which is commonly used for spread spectrum communication. Examination of this plot reveals a phase response which differs by more than 180 degrees across the communication bandwidth. The right side of figure 16 shows the decoder's correlation waveforms with an undistorted channel and for a channel distorted by the frequency plot shown. In effect, this kind of response causes part of the received correlation signal to be out of phase with the rest of it. This can result in correlation signals which are nulled out causing missed messages. Techniques to overcome this limitation have been explored with varying degrees of success and complexity. To date channel distortion remains as a serious limitation for all peer-to-peer spread spectrum power line communication products evaluated by these authors.

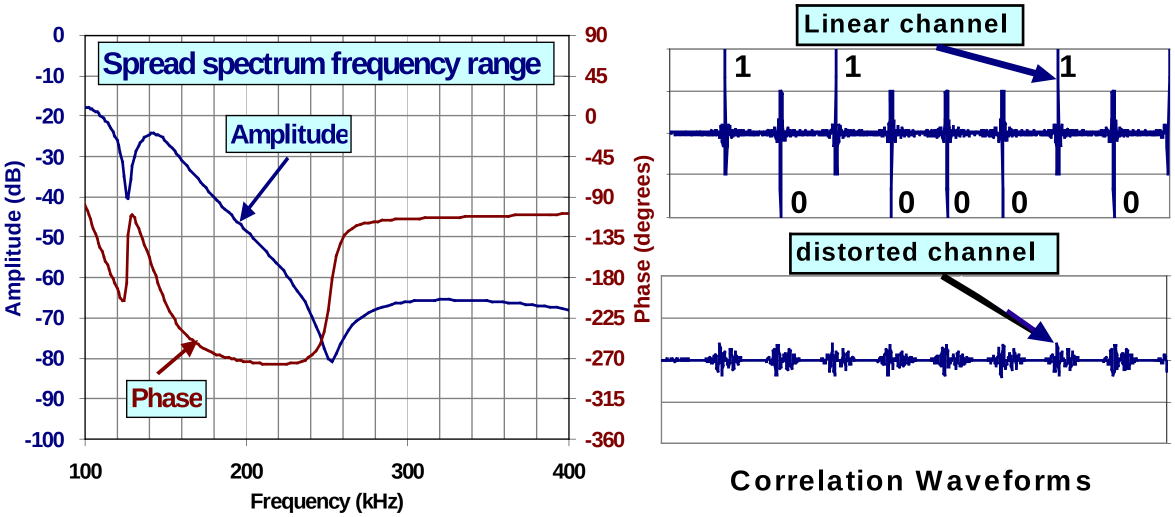

Figure 16 Frequency distortion over a spread spectrum bandwidth

For the multiplicity of reasons listed above, power line communication equipment suppliers are considering techniques other than spread spectrum in order to overcome the challenges of power line communication.

While digital signal processing has been around for many years it is only within the last few years that IC technology has advanced to the point where it is economically feasible to implement significant power line communication enhancements. We have considered application of DSP to spread spectrum systems with little resulting improvement. Lets now examine what can be done with digital signal processing to overcome the limitations of PLL-based narrow band systems. In the past narrow band transmission has been abandoned due to its poor performance when faced with impulse noise. By combining narrow band transmission with digital signal processing we find that the limitations typically associated with a narrow band receiver can be fully eliminated. Figure 17 is a oscilloscope plot taken under the exact same conditions as figure 10 (66dB of message attenuation with an impulse producing dimmer located directly next to the receiver). The ability of the digital signal processing algorithm to completely remove the effects of the impulse can be seen by comparing figures 17 and 10.

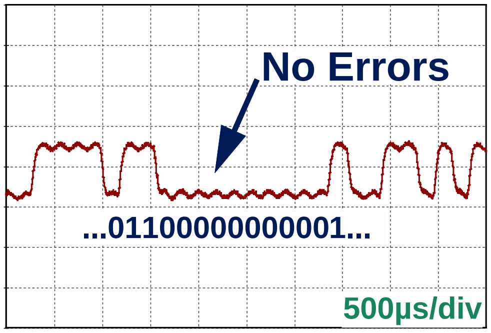

Figure 17 A DSP-based receiver’s output with impulse noise interference

Lets further consider the use of DSP to address channel distortion characteristics. It is, of course, possible for channel distortion to impair narrow band transmission as in the case of figure 7 where a 127kHz to 135kHz bandwidth signal falls on the steepest portion of the notch centered at 127kHz. Expanding the plot of figure 7 to include only this receiver's band (in figure 18) we see that the distortion here is far lower than was the case when figure 7 was expanded to the spread spectrum receiver's bandwidth (figure 16). The decoder's waveforms are shown on the right where it can be seen that the effect on decoding the correct bits is minimal. While digital signal processing can be applied to either case, there is a fundamental difference in the ability of DSP to correct these two vastly different cases.

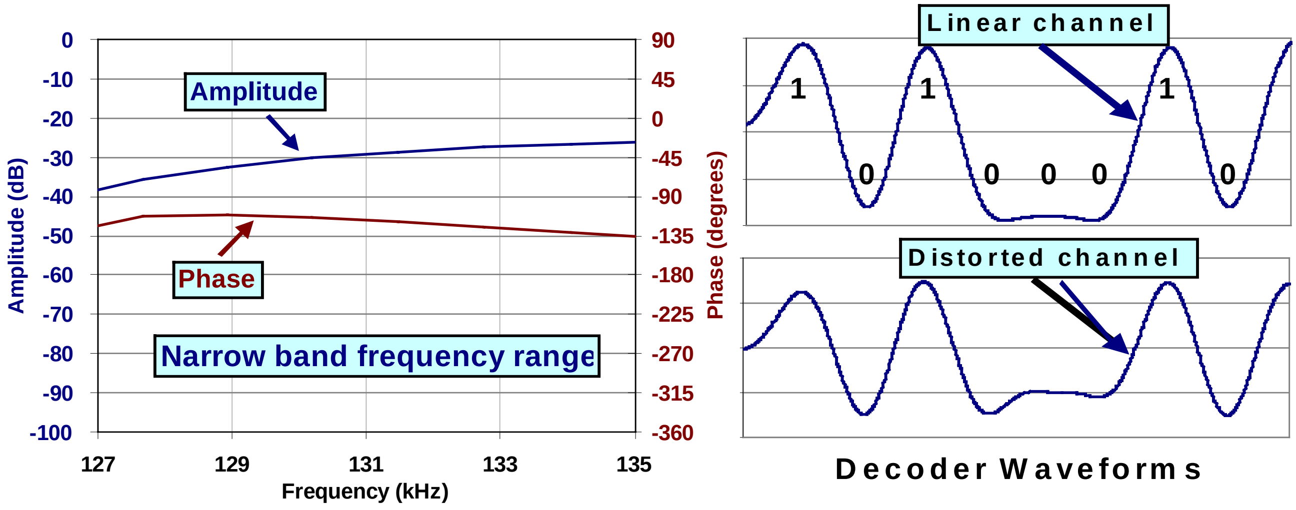

Figure 18 Frequency and phase distortion over a narrow bandwidth

One further point needs to be made with respect to the effect of frequency notches. The question is often raised as to whether it is possible on real power line networks for the deep notches to occur near 100kHz (as they do at higher frequencies). There is a physical reason why higher frequency notches are deeper than those near 100kHz. There are two primary sources of power line frequency notches. The first source is from EMC filter capacitors resonating with line inductance. For reasons of cost, size, and high frequency effectiveness, the maximum practical value for one of these capacitors is about 0.47uF. The most common value is probably 0.1uF. The length of wire required to resonate with 0.1uF at 132kHz is over 20 meters. The high frequency resistance of this length of wire, while low, limits the depth of lower frequency notches. The second source of frequency notches is unterminated and lightly loaded wiring of 1/4 wavelength (~500 meters at 100kHz). Once again wire resistance limits these notches to be much shallower than higher frequency instances which occur with shorter lengths of wire.

For the reasons outlined above the application of digital signal processing to narrow band transmission is drawing increasing interest as a technology well suited to the power line environment.

Performance Comparisons

Having reviewed how each of these technologies theoretically responds to the impairments found on power line networks it is helpful to compare their measured performance with several impairments. Testing was done with commercially available tranceiver products and impairments. The narrow band system tested was the Echelon PLT-22 power line transceiver which has two carriers at 115kHz and 132kHz and operates at 5.4kbps. Three spread spectrum systems were tested. The spread spectrum transceivers used waveforms signaling at 10 kbps and occupying bandwidth from 100kHz to 400kHz. Unless otherwise noted the performance graphs are shown with the spread spectrum system which used digital signal processing to enhance its performance. Figure 19 shows a comparison of error rate vs. attenuation when a light dimmer is located next to the receiver. The line on the graph for the DSP based PLT-22 transceiver shows that the digital signal processing has completely overcome the previous limitations of narrow band signaling.

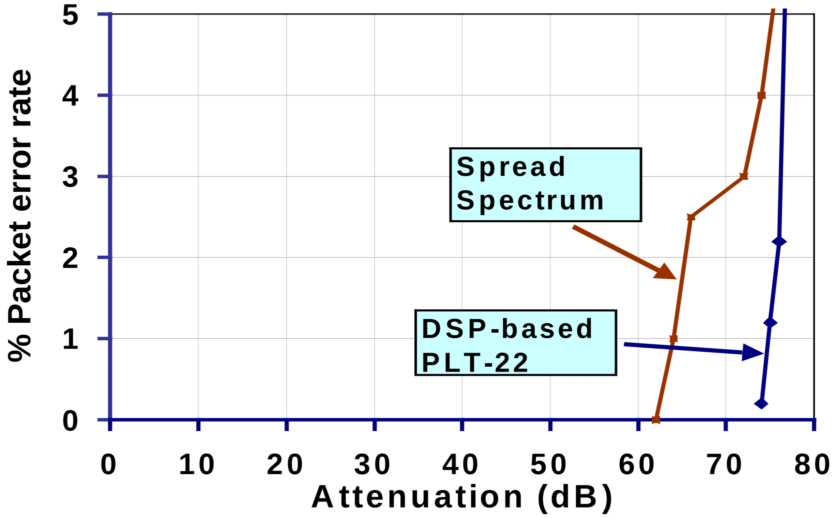

Figure 19 Communication performance with a lamp dimmer

Figure 20 shows a comparison of error rate vs. attenuation with a vacuum cleaner located next to the receiver.

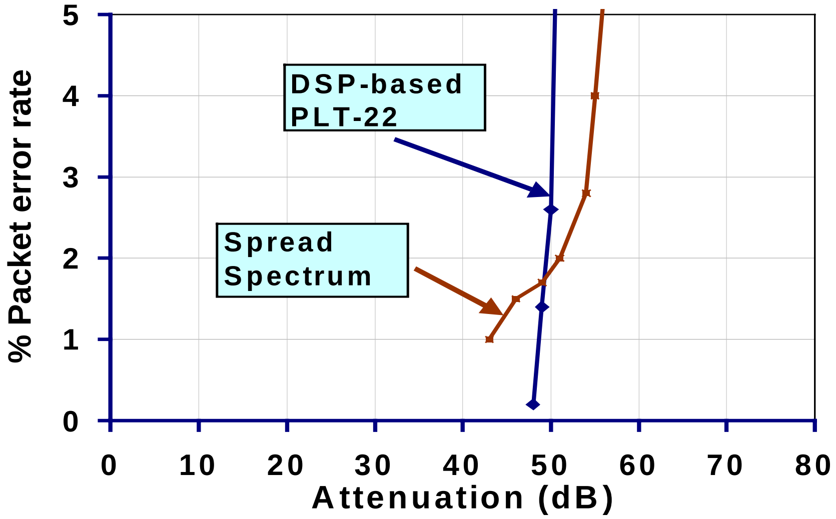

Figure 20 Communication performance with a vacuum cleaner

Although there are minor performance differences when tested with impulse noise and vacuum noise, both types of systems peform well with these impairments. Figure 21 shows the measured performance with the switching power supply based toothbrush charging stand which was shown in figure 3. The graph shows the spread spectrum system failing at a very low attenuation despite the fact that the spread spectrum system tested had DSP enhancements for better tone immunity. Note that the narrowband system has superior performance even though this impairment has a switching frequency where the third harmonic falls in the center of the narrowband system's primary carrier band.

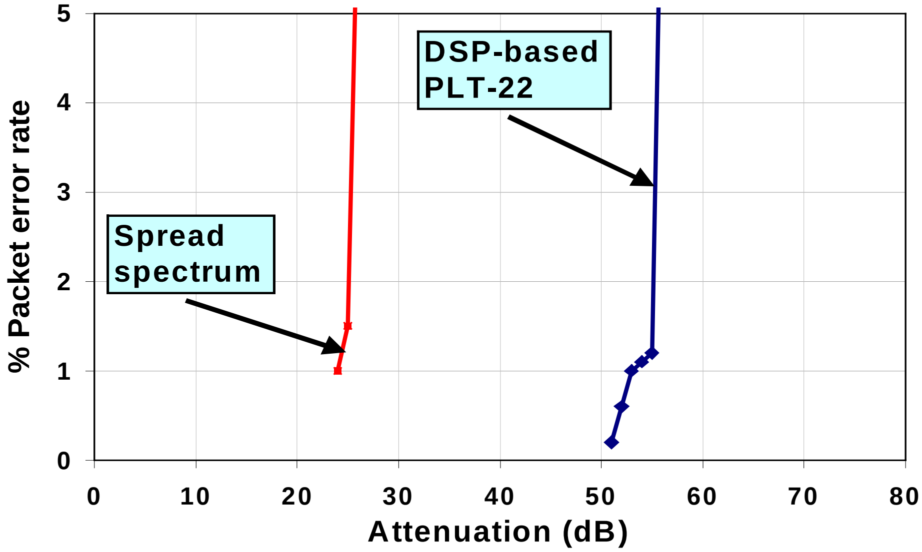

Figure 21 Communication performance with a noisy switch mode power supply

Since switch mode power supplies are becoming very common in consumer products and can use a range of switching frequencies, additional testing was done to characterize transceiver performance over a very wide range of frequencies. Figure 22 shows actual measured tonal immunity results for two different power line transceivers. For this test a transmitter and receiver were separated by 55dB of attenuation while sinusoidal interference was injected at the receive location. The frequency and amplitude of this noise was then varied to determine the level of interfering tone which could be tolerated at each frequency. We see from this plot that the spread spectrum transceiver has dramatically inferior tonal interference characteristics over a very broad range of frequencies. This limitation has serious consequences when high amplitude noise such as from switch mode power supplies, baby monitors or radio transmission pickup is present on the power line.

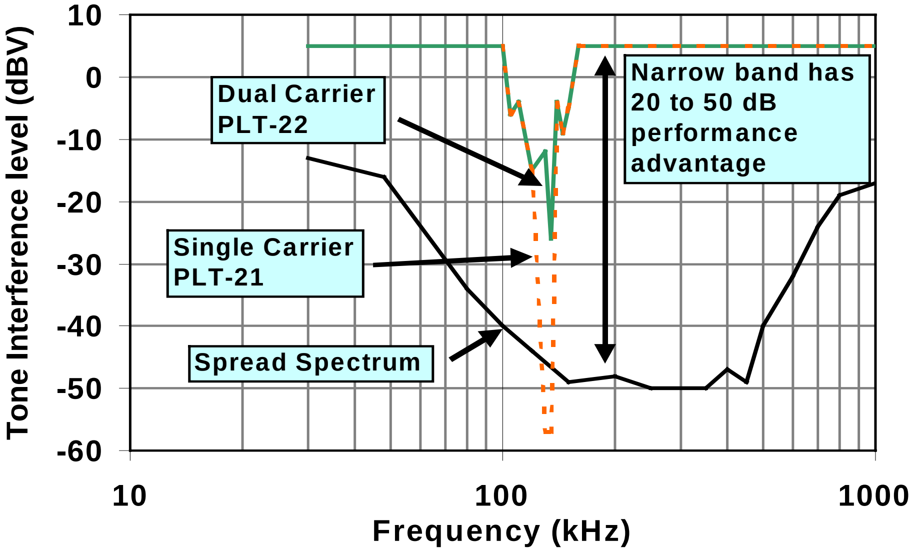

Figure 22 Measured tone immunity

Table 3 shows a comparison in the level of attenuation which can be tolerated (for less than 10% packet error rate) with tone producing intercoms placed next to the receiver. Note that results for this case are shown for the normal as well as the enhanced spread sprectrum systems.

Intercom	DSP-based PLT-22	Spread Spectrum	"Enhanced" Spread Spectrum
Realistic 43-218B	52dB	8dB	6dB
Command WI-3SS	58dB	6dB	4dB
Radio Shack 43-207C	55dB	6dB	5dB
ComTalk GEE-825	53dB	9dB	10dB

Table 3: Attenuation tolerated with intercom at the receiver

Television sets are a very common source of power line signal distortion. Figure 23 shows a test setup used for the evaluation of power line technologies with 28 randomly selected TVs.

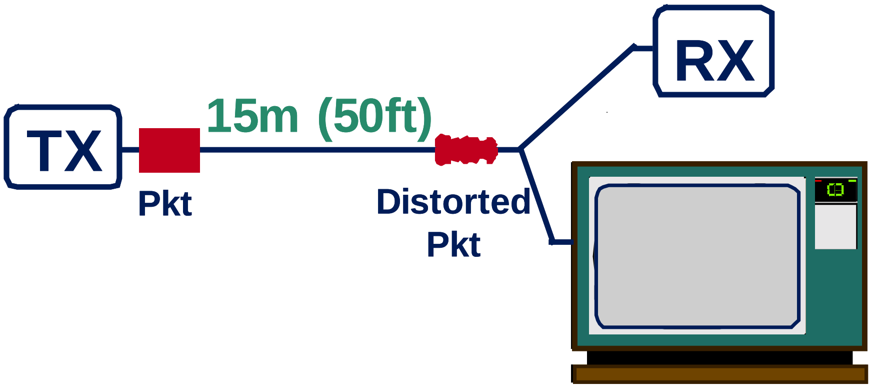

Figure 23 Test conditions for measuring communication performance with TVs

The results of these tests showed that the spread spectrum transceiver had >25% packet error rate with 1 out of every four TVs while the DSP based narrow band transceiver had less than 1% packet error rate with all 28 TVs.

Conclusion

A review of various technologies which can be applied to power line communication leads to the conclusion that the digital signal processing is key to overcoming the harsh conditions of the power line environment. Furthermore spread spectrum technology was found to be a detriment rather than a benefit in overcoming these challenges. Since no technology is static, one must ask whether the clear advantage demonstrated by DSP-based narrow band transmission will continue in the future. This question can only be answered with the benefit of research and extensive field experience with each technology. From the perspective of a company which sells both spread spectrum and DSP-based narrow band power line communication transceivers, DSP-based narrow band is a clear winner for most all power line applications. The only possible exception to this conclusion is a dedicated power line environment devoid of distortion producing TVs or computers and isolated from common power line tonal noise sources. From the perspective of a company with over 30 patented inventions developed to address the weakest aspects of both spread spectrum and DSP-based narrow band communication, DSP based narrow band is the clear winner for today and for the future.

Reference

[1] R.C. Dixon, *Spread Spectrum Systems*, Second Edition, John Wiley and Sons, Inc., New York (1984).