Data Communications Via Powerlines

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The views expressed in this paper are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. government.

The hunger for increased bandwidth is driving individuals, corporations, and organizations to seek new methods for delivering Internet service to customers. Many of these methods are well known: radio-frequency (or wireless) communications (such as the IEEE 802.11 Wireless LAN, Bluetooth, and the HomeRF and SWAP Protocols), infrared communications (IrDA), fiber-optic channels, high-speed telephone connections (such as DSL and ISDN or the more modern Home Phoneline Networking Alliance (HomePNA) system).[1] One approach that is still receiving a cool reception in the United States is a highly discussed option in Europe and the rest of the world using the power grid as a delivery conduit for high-speed data communications. This paper provides a brief introduction to High-Speed Powerline Communications (HSPLC): the technologies, political struggles, and future look.

The Electric Power Grid Design

Before discussing HSPLC, it is informative to outline the construction of the power delivery systems in the United States and Europe. In the United States, electric power is transferred from the power producer to the power user via a three-stage delivery system. Electric power is generated at a moderately high voltage (typically around 4.16 – 13.8 kilovolts (kV); 1 kV = 1000 volts)[2] at the power plant (using either a high-speed turbine, such as in nuclear- or coal-powered electric power plants, or a low-speed turbine, such as is used in hydroelectric power plants). The power is transferred to the transmission system via a voltage step-up transformer.[3] Typical voltages in this stage range from 138 kV to 500 kV or more. Bulk power is delivered from the generating plants via this intercity transmission system (which can span several states) to the transmission substations where the power is transferred to a subtransmission system whose voltages range from 38 kV to 138 kV; power transference is made via a step-down transformer. The subtransmission system delivers the high voltage throughout a city or large region. Power is delivered to the consumers via the distribution system. Transference from the subtransmission system to the distribution system is made within regions called distribution substations, likewise using step-down transformers. Output cables from the distribution substations are typically called feeders.

In the United States, the distribution system is subdivided into two components: the primary distribution system (the voltages of which run from 4.6 kV to 12.47 kV)[4] and the secondary distribution system (the voltages of which are the typical 120/240/208 voltages in houses and offices). Power from the primary distribution system to the secondary distribution system is transferred via the distribution transformers commonly seen on top of power poles or in large metal boxes near offices and apartment complexes. A typical arrangement for suburban power connections has four houses connected in a secondary distribution system, being served by a single distribution transformer. At best, a secondary distribution system in the U.S. services only a few apartments with a single transformer.

Europe and most of the rest of the world use a single layer distribution system. Output voltages from the subtransmission substations range from 200 to 300 volts, depending on the country. The reasons for the differing philosophies are not important to this paper, but it is important to recognize that in the United States usually only a handful of consumers connected are in a single (secondary) distribution system while in the rest of the world hundreds of consumers can be connected in a single distribution system. As will be seen later, these facts partially answer the question of why HSPLC is of great interest in Europe but of only mild interest in the U.S.

Low-speed Powerline Communications Protocols

Using the electric powerline to send information is not a new idea. Sweden has used its electric power grid for telephone communications for many years. Further, electric power lines have been used throughout the world for low-frequency communications by the electric power industry, for baby monitors, or simple control functions, using protocols such as X10® Home Automation, Intellon CEBus®, Echelon LONWorks®, or Intelogis PLUG-IN®.[5] These proprietary protocols are low speed and are used solely for controlling consumer systems, such as lights, appliances or simple electronics. In addition to these consumer-oriented protocols, the power industry has a separate protocol for using powerlines to communicate system control (SCADA) data. In the past, signals used by the electric utilities for controlling signal powerline communication have been analog. Data are transmitted using either amplitude modulation (either double-sideband or single-sideband) or frequency-shift (ON-OFF) keying on carrier frequencies from 30 kHz to 500 kHz in the U.S. and from 10 kHz to 490 kHz in Canada.[6] Because the power industry worldwide is changing its protocols for all SCADA communications, this report does not examine the power utility protocols.

X10,[7] the granddaddy of powerline protocols, uses amplitude modulation to send binary information from a controller/transmitter to X10 modules that are plugged into a standard electrical outlet. The control pulses consist of 120 kHz bursts with a 1ms envelope: the presence of a burst signals a logical "1" while the absence of a burst is a logical "0."[8] A single bit is transmitted twice (for reliability)[9] on each cycle of the 60 Hz AC power sine-wave; the bursts are synchronized to within 200ms of the zero-voltage crossing point of the AC power sine-wave. As a result, its transmission rate is limited to 60 bits per second (bps). Further, a complete X-10 command consists of two packets, each containing two identical messages of 11 bits (voltage cycles); each packet is separated by a 3-cycle gap[10] (again, redundancy for reliability). The result is that a single X-10 command takes approximately 47 cycles of the 60 Hz signal or 0.8 seconds to send.

The developers of the CEBus standard (EIA-600) state that they use spread-spectrum technology to transmit data.[11] However, unlike traditional spread-spectrum techniques such as frequency-hopping or direct-sequence spreading, the spread-spectrum of CEBus sweeps the signal frequency from 100 Hz to 400 Hz for each bit. According to the developers, this overcomes some of the inherent noise problems associated with higher speed powerline communications. Like X10, CEBus has two fundamental components: a transceiver and a microcontroller. Unlike X10, CEBus is not restricted to powerline communications but can use any communication media, including RF.[12] At its higher level, CEBus uses its own Common Application Language (CAL) to ensure that CEBus compliant systems made by different manufacturers can exchange commands and status requests.[13] CAL creates device "contexts" and object classes to communicate a given command to the appropriate device.[14] The CEBus protocol is similar to Ethernet in that (a) it is peer-to-peer and (b) it uses a Carrier Sense Multiple Access/Collision Detection and Resolution (CSMA/CDCR) protocol to avoid data collisions.[15] This protocol requires a network node to wait until the line is clear so that there will be no simultaneous transmission on the line. Data are transmitted at the rate of approximately 10 kilobits per second (kbps). Standard EIA 709.2 defines the specifications to use either CEBus for sending data over two- and three-phase electrical powerlines. The standard restricts the powerline channel to a spectral bandwidth from 125 kHz to 140 kHz and specifies data communication rates of 5.65 kbps while providing a narrow-band power line signaling technology that meets North American and European regulations.[16]

LONWorks[17] (ANSI/EIA 701.9-A-1999) is similar to CEBus: it works as either a peer-to-peer or a master-slave data communication system; it uses spread spectrum technology to transmit data; and it uses a CSMA technique for data collision avoidance. Additionally, LONWorks also supports many communication media including twisted pair, power line, fiber-optics, coaxial cable, radio frequency, and infrared.[18] Unlike CEBus, LONWorks supports higher data rates: from 610 bps up to 1.25 Mbps[19] and is a proprietary protocol, requiring a license for operation. However, if used for data transmission over powerlines, LONWorks is restricted by EIA 709.2, just like CEBus. The LONWorks standard implements a control system communication network using an open communications protocol, LONTalk, and LONWorks Network Services (LNS), in addition to a proprietary MAC protocol to provide the peer-to-peer networking layer. A key feature of LONWorks is the LNS, which provides an object-oriented method to connect networked control devices. LNS clients can run on any platform (PC, MAC, UNIX, embedded, etc.). LNS Server supports both LONTALK and TCP/IP protocols at the transport layer.

PLUG-IN[20] is based on the Open System Interconnection (OSI) model and defines several protocols: at the Application Layer, PLUG-IN uses either the proprietary Intelogis Common Application Layer (iCAL) Protocol (for client/server operation) or the CEBus Generic Common Application Language (CAL, for peer-to-peer operation); at the Network, Transport, and Data Link Layers, PLUG-IN defines the Power Line Exchange (PLX) Protocol while at the Physical Layer PLUG-IN uses the Digital Power Line (DPL) Protocol. Using DPL, PLUG-IN boasts data transmission rates of up to 350 kbps using a single channel frequency. PLUG-IN uses Frequency-Shift-Keying (FSK) to encode the data onto the signal carrier. A proposed version of PLUG-IN DPL (for Digital Power Line) is to use multiple signal channels to produce speeds of over 1 Mbps. Bit error rates for DPL are in the range of 10^{-9} with 80 dB of dynamic range. The FSK scheme encodes the digital data onto the power line by using two or more separate frequencies that are in a fairly narrow frequency band. Like the other low-speed powerline communications protocols, PLUG-IN is intended for control system communication signals. However, the success of DPL has led other companies to attempt to modify it for carrying high-speed data communications over powerlines.

High-speed Powerline Communications Protocols

There are many difficulties in using powerlines for High Speed Powerline Communications (HSPLC), including the wide variation in the line impedance as a function of frequency, the high attenuation and interference problems, and the signal reflections caused by signal mismatches.[21] Each developer of HSPLC products has attempted to solve these difficulties by proposing different protocols. While many companies and organizations have been (and still are) pushing their concept, only four primary protocols are actively competing to become THE protocol for HSPLC. These are Intellon's PowerPacket™ protocol, Intelogis' Plug-In PLX™, Digital Powerline™ (DPL), and Adaptive Networks' AN1000 Power Line Communication system.

The HomePlug (Powerline) Alliance consists of over forty members who are major manufacturers of computers and data communication equipment, including 3Com, CISCO, Compaq, Intel, Motorola, Panasonic, Radio Shack and Texas Instruments. On June 5, 2000, PowerPacket was selected by the HomePlug Alliance to become the basis for an industrial specification in home powerline networking.[22] As a result, most of the manufacturers who were developing the other protocols (with the exception of Adaptive Networks) are moving away from their original developments and turning their attention to creating products that will conform to the new HomePlug standard.

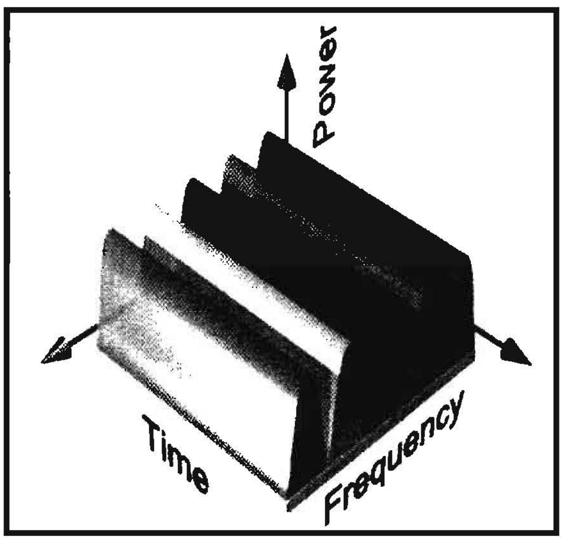

Fig. 1. Time-Frequency Spectra of OFDM
From Lawrey, Chapter 1.

PowerPacket, now referred to as HomePlug 1.0, uses Orthogonal Frequency Division Multiplexing (OFDM) technology to transmit data at up to 5 Megabits per second (Mbps)[23] in the 4- to 20-MHz frequency band of the powerline.[24] OFDM is a multicarrier transmission technique, similar to Frequency Division Multiple Access (FDMA).[25] Both of these techniques divide the available spectrum into many carriers and modulate each carrier by a separate low-rate data stream. However, where FDMA allocates each subchannel (which are typically 10 kHz to 30 kHz wide) to separate users, OFDM uses all the subchannels (OFDM typically has 100-1000 subchannels, each around 1 kHz wide)[26] to broadcast a single message, thus allowing more data to be transmitted faster with a lower symbol rate than in FDMA. Figure 1 is a graph of a typical OFDM/FDMA spectrum. Coded Orthogonal Frequency Division Multiplexing (COFDM) is the same as OFDM except that forward error correction is applied to the signal before transmission.

One problem encountered with power line communications is aliasing (distortion of a signal due to the interference of the signals from adjacent channels). As data rates increase and channel bandwidths narrow, aliasing increases. In order to prevent aliasing, guard frequency bands are included in each subchannel. This means that a portion of the spectrum allocated to each subchannel is a "dead zone" of no signal. The guard bands in FDMA are large (typically up to 50 percent of the total spectrum),[27] whereas in OFDM the guard bands are much smaller resulting in the spacing between channels being closer in OFDM than in FDMA. By setting all the subcarriers orthogonal to each (hence, the definition of Orthogonal Frequency Division Multiplexing), interference is reduced between the closely spaced carriers.

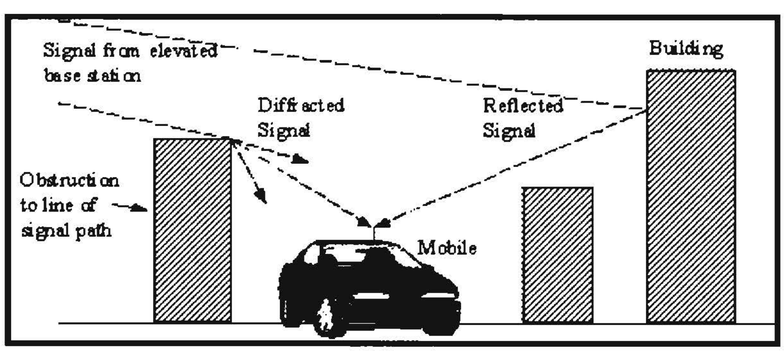

Fig. 2. Multipath Interference
From Lawrey, Chapter 1.

Another of the problems with HSPLC is that of multipath reflections. Figure 2 below indicates the concept of multipath reflections in the case of radio communications.

Multipath interference, also called "ghosting," results when a signal travels from a transmitter to a receiver via multiple possible signal paths. Since the time required for a signal to travel a finite distance varies directly with the distance, a signal that travels over multiple paths will result in a multitude of signals being presented at the receiver, each received signal slightly time-shifted with respect to each other (i.e., having phase shifts with respect to each other). These multiple paths can be created by reflections (in a powerline, reflections are the result of impedance mismatches between the transmission line and the loads attached to the line) or diffractions around obstacles (in a powerline, diffractions are caused by imperfections, such as "kinks" or cracks in the transmission line). For powerline communications, multipath distortion results in digital intersymbol interference. Like aliasing, multipath interference increases with frequency.

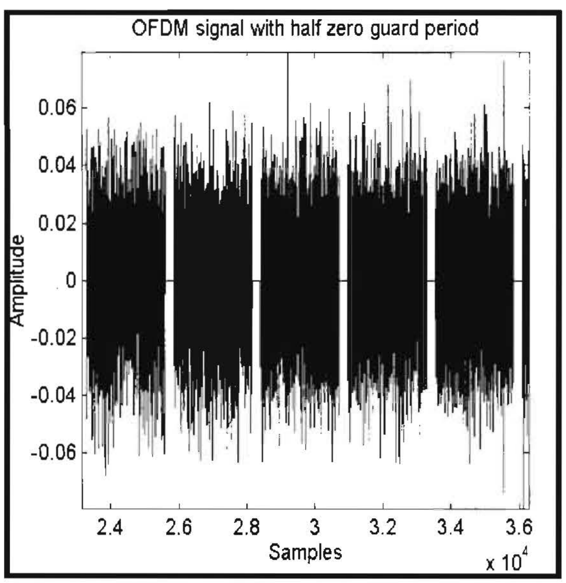

Fig. 3. OFDM Signal With Guard Period From Lawrey, Chapter 1.

Because of their low symbol rates, ODFM signals are highly resistant to multipath interference.[28] Additionally, a time domain guard period, shown in figure 3, is added to reduce the possibility of interference due to the symbol spreading caused by the multiple paths.[29]

Theoretically, the OFDM protocol should be able to operate at up to 100 Mbps, although most devices operate at around 14 Mbps.[30] Since the RF characteristics of a powerline vary as a function of frequency, using different modulations would allow the channel efficiency to be optimized to its maximum potential.[31] Because the subchannel carriers are orthogonal to each other, each subcarrier in OFDM can be modulated with a separate modulation scheme such as any combination of coherent or differential, phase or amplitude modulation schemes, including BPSK, QPSK, 8PSK, 16QAM, 64QAM or others. Normally, this is not done, but the same modulation scheme is used on all subchannels for the sake of economy of design. The choice of the modulation scheme depends on how much noise is in the channel.[32]

While the HomePlug Alliance has chosen ODFM to be the standard powerline communication protocol, not everyone agrees that it is the best. Michael Propp, president of rival Adaptive Networks Inc., claims that the HomePlug protocol "enables a PC-centric, point-to-point unicasting network" and that such a network is "not a usable home network."[33] A rival consortium, the Consumer Electronics Association (CEA) R7.3 Committee, argues that, for it to be applicable for home use, a powerline network must be able to support a large number of nodes and "simultaneous entertainment activities such as streaming audio and video, plus provisions for multicasting and broadcasting," something PowerPacket does not provide.[34] However, an interesting feature of the 14 Mbps PowerPacket chips currently being produced by Intellon (INT5130) is that they come equipped with real-time 56-bit DES encryption of data packets,[35] a feature that has been identified as a major need in powerline communications but has not been stressed in design circles.

Propp argues that home networks need a wideband spread-spectrum transmission and adaptive equalization to ensure that some portion of the transmitted spectrum is received without distortion due to "the multiple peaks and valleys of the power line transfer function."[36] As shown in figure 4,[37] the transmission line attenuation (the dark line) is not constant but varies with frequency. A narrowband spread-spectrum signal

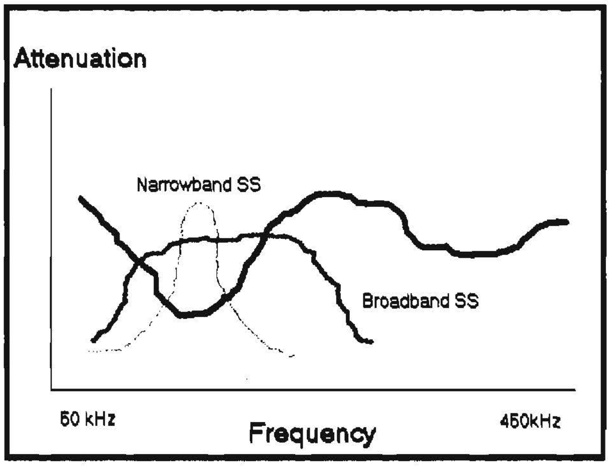

Fig. 4. Powerline Attenuation and Spread Spectrum. From Adaptive Networks.

(shown with the light colored line) may not pass some frequencies while a wideband spread-spectrum signal (the medium colored line) will allow some portion of the signal to pass. However, since the attenuation varies with frequency (as well as time and distance between the source and the receiver), the receiver must adapt to the changing conditions.

Propp's own corporation, Adaptive Networks, Inc., just happens to manufacture a product that provides these features: the AN1000 Power Line Communication system. Adaptive Network's protocol, which is being considered by the CEA R7.3 Committee for its specification, pushes wideband spread spectrum and adaptive control of the receiver.

The other major HSPLC technologies, Plug-In PLX and Digital Powerline, are similar in technical content and were discussed earlier in the low-frequency protocols. They both operate around 1-2 Mbps and use frequency-shift key (FSK) techniques.

Regulatory Issues of Powerline Communications

There is a spirited debate raging in Europe over HSPLC (the topic is hot in Europe, since the technology there is capable of being cost effective. In the U.S., the market has yet to develop so the issue is not as hotly pursued.) The debate centers mostly on the electromagnetic compatibility/electromagnetic interference (EMC/EMI) issues associated with HSPLC. Key players in this arena are the International Powerline Communications Forum (IPCF), the European Telecommunications Standards Institute (ETSI), the International Telecommunication Union (ITU), the European Radiocommunications Office (ERO), a subcommittee of the European Conference of Postal and Telecommunications Administrations (CEPT) (ERO coordinates radiofrequency spectrum allocations in Europe),[38] the European Committee for Electrotechnical Standardization (CENELEC),[39] and the Comité Internationale Spécial des Perturbations Radioelectrotechnique (CISPR), a committee of the International Electrotechnical Commission (IEC) dealing with the technical issues of EMC and other related matters. The IEC itself is the worldwide standards-setting institution concerned with all aspects of electrical technology (CENELEC is the European member of the IEC, just like the ISO is the U.S. member of the IEC).

In a nutshell, the problem is that HSPLC radiates electromagnetic energy off the power transmission lines. Depending on the data rate, signal frequencies of HSPLC can vary from 100 kHz to 30 MHz, a band of frequencies that is highly used for mobile, marine and aeronautical distress and calling, for time signals used by radio astronomers, by airports for civil defense communications – in short, a wide variety of critical communications. Currently, spectral usage in this area is set by ERO and the radiation limits are established by CISPR.[40] The IPCF has been lobbying the IEC to change the standards for radiation in the frequency bands. Needless to say, the massive amount of coordination between the ETSI/ITU, CISPR/IEC, ERO/CEPT and CENELEC is slowing the regulatory aspects of HSPLC adoption. Additionally, there is massive resistance by the current users of the proposed frequency band (coming from civil defense organizations, military, scientific (astronomy) organizations – everyone who has a stake in the outcome). However, the current state of HSPLC regulation is a declaration by the IEC that there WILL be a revision of the frequency band and EMC limits in order to accommodate HSPLC.[41] ETSI and CENELEC are jointly developing a new standard to accommodate everyone, but there will be much effort before everyone is satisfied.[42]

Summary

The growing digital revolution is creating an ever-increasing demand for bandwidth. Many products and services are being introduced to fulfill this demand, one of which is the use of powerlines to transport data, whether by low-speed or high-speed data transmission. Many companies are working to create what they consider to be the ideal approach to using powerlines for data transmission. In the low-speed powerline communications arena, used primarily for simple functions such as simple system control and low-frequency communications (e.g., baby monitors), proprietary protocols still dominate. These systems are well established, and the only new innovations are to add more products to the line. On the other hand, high-speed powerline communications is just entering the respectability phase of product design. The signaling characteristics of the differing protocols are proprietary, but the higher-level communications protocols are proposed to be of the UDP/TCP/IP suite. New products and new concepts are constantly being added.

That said, there are many critics of the entire concept of powerline data transmission, particularly high-speed powerline communications (HSPLC). Some of the problems and criticisms to be resolved are as follows:

HSPLC is unfeasible and inefficient for data transmission. This argument is losing ground as practical devices capable of operating at tens of megabits per second are appearing. Tests have shown that the new devices have overcome some of the limitations inherent in older HSPLC designs and that high data rates with low bit-error rates are possible.

HSPLC is impractical, especially in the United States, due to signal blockage by the power transformers. As discussed earlier, only a few consumers are linked together in the U.S. by the power distribution system while many consumers are linked together by the distribution system in the rest of the world. These power transformers in the U.S. distribution system thus inhibit potential Internet communication. Supporters have countered by noting two areas HSPLC can serve: as a local area network within a home, building, or small office (where being able to plug-and-play a device using a standard power plug is a great attraction for the consumer) and as a bulk carrier between regions (using the transmission grid of the power industry). Further, the supporters have argued that contemporary systems are just as impractical: the cost of laying optical fiber to the door of each consumer makes that option unlikely; that DSL doesn't reach every home, particularly in the U.S.; that telephone modems rely on multiplexing in order to extend access to more persons (i.e., technology used in telecommunications today can be easily and cheaply adapted to HSPLC at the distribution transformer to multiplex the users onto the rest of the network); and that all telecommunication options suffer degradation as the number of users increases.

The biggest headache is the regulatory limits imposed by EMC/EMI considerations. There are many opponents to HSPLC as a result of this issue. However, regulations change, and the more that industry desires the introduction of HSPLC, the more likely the existing regulations will be modified.

Security issues have been little addressed. There is a growing recognition that HSPLC has a serious security vulnerability, particularly in Europe, due to the interconnectedness of the network and the open protocols (UDP/TCP/IP) being proposed. Industry is starting to address these issues, but *caveat emptor.*

Powerline carrier communications is here to stay. It may be limited to a local area network within the home or office, or it may become another medium like telephone modem communications, but it will be used in the future. The only real obstacle to its full development is the lack of a standard around which the entire industry can rally. The future holds the answer.

Notes

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2. Theodore R. Bosela, *Introduction to Electrical Power System Technology* (Upper Saddle River, NJ: Prentice Hall, 1997), 81. Cited hereafter as Bosela.

3. A transformer is essentially a large block of iron whose purpose is to "transform" the voltages and currents from one system to another. A "Step-up" transformer means that the output voltages of the transformer are higher than the input voltages. A "Step-down" transformer means that the output voltages of the transformer are lower than the input voltages. Transformers have great impact on data communications.

4. Bosela, 89.

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39. "Info – About CENELEC", http://www.cenelec.org/Info/about.htm (7 August 2001).

40. http://www.emclab.umr.edu/cispr.html (7 August 2001).

41. John Newbury, IEEE representative to the ITU, in a public address at the 2001 IEEE Summer Power Meeting, Vancouver, BC, 15 - 19 July 2001.

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