Power - Line As Access Medium – A Survey

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Abstract

While PLCC (Power Line Carrier Communication) over HT Lines is an old and established practice, use of the LT segment (110/220/440 volts) below the Distribution Transformer for Communication purposes represents altogether new challenges that are just beginning to be addressed. Some of the problem areas are : Unpredictable Frequency and Time dependence of Impedance, Attenuation and Transmission Characteristics; Impulse and Background Noise and their wide variability; Limited Bandwidth; Harmonic Interference. These issues have to be addressed before the power line can become a reliable communication medium. The communication potential of Power lines can be assessed only through elaborate measurements, modeling and characterization carried out over representative line segments, to arrive at average behavioral patterns. Work in this area (carried out largely in Europe , US, Canada, and Japan) is examined and their results summarized in this paper. It appears from reported results that up to 2Mbps data rates should be realizable, with possible applications to Automatic Meter Reading,

Data Communications and Networking, Internet Access, Voice Communication etc.

The paper also presents data on the available and emerging range of Components, Products, Standards and Applications, as well as the extent of their proven–ness at present. Of course significance is the availability of a range of ASICs (both Spread–Spectrum and conventional narrow–band) designed for specific power line applications such as AMR, Power Line Modems and Transceivers, LAN and Home bus, Internet Distribution, Local Telephony etc. Information is also provided about the Companies that provide these Products and Services as well as the Standards being followed/evolved. Also surveyed is the range of other Components needed to connect to the power lines, such as couplers, filters, bridges etc.

The paper makes out a case for a serious examination of this technology for local loop applications in countries like India where, over seventy percent of households have power line connections already in place. Even a fraction of this Conductor–Capacity made usable for additional Communication purposes would represent a significant enhancement in the availability of Access medium.

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1 Introduction

The National Power Distribution System can be broadly segmented into three parts: The E(V)HT segment (110KV and above) bringing power from the generating stations to the major consumption zones, typically over hundreds of kilometers; HT segment (6KV-33KV typically) that fanout from the substations taking power to the consumer localities, typically tens of kilometers long; the LT segment (110/220/440V) from the distribution transformer (DT) to the buildings of the consumer, typically around one kilometer or less. The intra-building wiring then distributes the power to different points of the building where appliances are connected. The traditional PLCC (Power Line Carrier Communication) system operated at the first level serving the communication, monitoring and control purposes of the power system utility companies themselves. With long stretches of wires having very few interruptions or connections between, this segment is the most benign part of the Power Line Network for communication purposes. The second segment is typically characterized by scores of branchings, interconnects, loadings through DTs, changes in conductor sizes etc, making it a very hostile communication medium. A very low data rate (< 120 bps) ASK system with a carrier under 3 KHz, called the Ripple Communication System (RCS) used by the utility companies, has been the only use of this segment for communication purposes. The customer premises cabling below the DT, the last-mile part of the Power System Network, or the Intrabuilding wiring has not seen any serious communications applications until the last decade or two [1,2].

The problems associated with use of power lines for communication purposes do not originate from the transmission conductor system per-se, but from the fact that a wide range and variety of loads are continuously being connected/disconnected to the network by large numbers of independent customers at their will, making the medium non-linear, dispersive, randomly time-varying, noisy, lossy, and entirely beyond control of the communications engineer - all of which in turn stemming from the fact that its use for communication purposes was never a part of its designer's objective or inkling! Despite this, serious efforts have been afoot since last one-two decades to use the enormous potential of this near-ubiquitous conductor-network for communication applications. Some major applications driving the Power Line Communication (PLC) technologies are :

- Automatic Meter Reading (AMR) - readings of Electricity, Water, Gas or any other meters in the customer premises to be transmitted to a central base-station for further processing, billing etc. With tens of millions of meters to be read periodically and regularly, this alone represents an enormous market justifying huge investments in Technology Development. This would typically use the LT segment below the D.T.
- Home-Bus for making the buildings "Intelligent" - all appliances to be monitored/controlled continuously and automatically for convenience comfort, safety and energy - saving. This makes use of the intra-building wiring.
- Voice and Data Two-way Communication - using the LT segment below the DT as the communications last mile part. Internet Distribution is the most tempting of these applications.
- Distribution Automation, and Supervisory Control and Distribution Automation (DA and SCADA) - this is for the utility companies themselves to monitor and control the Power Distribution Process. Typically

the HT and EHT parts are involved, and is to replace the systems that now use the PSTN or dedicated RF networks for this purpose.

- Rural Communication applications where user densities are low and distances are large which makes installation of fresh infrastructure expensive/non-profitable.

This paper surveys the problems associated with realising PLC over the LT segment, solutions being proposed and realised, products and applications that are emerging, and comments on its possible scope in the Indian Context.

2 The Nature and Characteristics of the L.T. Line Segment and Domestic Wiring System [3-13]

An LT segment typically has hundreds of customers connected to it, each of whom loads it with scores of appliances (lights, Fans, Airconditioners, Heaters, TV, PCs, Ovens, Mixies, Dryers, Vacuum Cleaners, Water Pumps, etc), each appliance having its own electrical characteristics. Consequently, a communication device connected to the line sees a very hostile environment which keeps changing with time as customers switch their loads on and off the line-the time variation being primarly random as the customers are independent and do not coordinate, their operations among themselves. Definite patterns, however, can be discerned in the time-dependence of the line properties, patterns over a 24-hr cycle, 7-day week cycle, seasonal patterns, etc. This implies that all characteristics of the line have to be measured and understood under its worst-case condition, best-case condition, as well as typical conditions. The fact that the variations away from "typical" can be very large makes any design approach very difficult.

From the communications point of view, there are three major aspects of the power line that must be measured, modelled and characterised - the Noise behaviour, the Impedance characteristics, and the Attenuation characteristics. These are discussed below.

2.1 Noise Behaviour

Each load causes its own characteristic current/voltage fluctuations and disturbances on the line which appears as noise to the communication equipment. This is a very complex process, and detailed measurements, carried out all over the world over time have established the existence of five types of Noise behaviour observed on the line.

Background Noise

This is what every subscriber sees as already present on the line, and not caused by subscribers' appliances. Typically, this originates from the Distribution Transformer, public lighting systems etc, and can vary from -90 dBW/Hz (worst case : - 80 dBW/Hz) at 10 KHz to -125 dBW/Hz (worst case : - 90 dBW/Hz) at 100 KHz.

Noise Synchronous with Power Frequency

This is caused by Power Supplies, SCRs etc connected to the line, can be significant (-100 dBW/Hz) in the 60-95 KHz region.

Impulsive Noise

This is the most severe communications impairment encountered on the line, can be of a variety of types interms of the amplitudes, widths and inter-arrival times of the noise pulses. There are two major sources for this type of noise. One-single impulse associated with manual ON-OFF of domestic loads such as lamps, TVs, etc, which can typically cause 1V amplitude pulses lasting 1 mS or more. The second type is caused by those loads that themselves generate impulse-trains like Triac-controlled fan-regulator, light-dimmers, thermostats etc. 20 volt peaks lasting over tens of microseconds being common. The spectral densities associated with such noise can be in the range -50 to -80 dBW/Hz, and can extend up to 1 MHz if SMPS, fluorescent lamp Ballasts etc are involved. More than the average noise spectral densities involved, the impulsive noise amplitudes can kill the data signals during its peak excursion - a fact that has to be borne in mind while determining the bit-interleaving periods.

Noise with Smooth Spectra

This is caused by Universal Motors, loads, not synchronous with the power line frequencies, etc, and is nearly white. Their values can be as higher as -40dBw/Hz at 100Khz.

Narrow - Band Noise

Believed to be induced by Radio Transmitters etc, these appear as narrow spikes in frequency - 75 to 80 Khz being a region they are predominantly observed, with powers of - 80 BW/Hz or more.

2.2 Impedance Behaviour

Single - phase lines behave largely as inductive loads, impedance magnitudes going up with frequency, in the range below 100Khz, variation being typically from 1-2 ohms at 10 Khz to 10-20 ohms at 100 Khz. In this range, the impedance is largely that of the DT which can be approximated by an inductance of about 25 μH shunting a series connection of 8 ohms resistance and 50 nF capacitance. Other loads appearance as shunt impedances across this connection. Beyond 100 KHz, repeated series and parallel resonances are observed depending on the loads, impedances often becoming as high as 100 ohms at 100 Mhz. The line itself typically has a capacitance of 30-60 pF/m, inductance of 0.3-0.6 μH/m, and resistance of 0.040 ohms/m, leading to a characteristics impedance of 75-150 ohms. Typical loads like TV, Heater etc have impedances much less than the line impedance. As expected, resistive loads like heaters dominate the low-frequency region, and reactive loads, like motors, TV, PCs etc dominate the higher end of the spectrum. Other than day - night variation average impedance behaviour have not shown much time-dependence.

2.3 Attenuation Behaviour

The line itself causes little attenuation or its variation with frequency - typical estimates being 0.5dB/Km at 9 Khz and 1.5dB/Km at 95 Khz. It is the connected loads and their variation that makes the line highly dispersive (both amplitude and phase distortion). Below about 100Khz, the dispersion is rather low, with a near constant attenuation of some 20 dBs. Above 100Khz, sharply resonant behaviours are observed, 3-6 pairs of series - parallel resonances occurring in the 100Khz to 1Mhz range itself, with attenuation peaks in excess of 80dBs even seen. Variation of Attenuation with time even by 20 dBs at a given frequency leads to severe signal fades, and is a major communication impairment.

3 Communication System Design and Performance Issues (14-19)

In this section, we touch upon on those issues that determine the performance of the power line as a viable communication medium - coding and modulation schemes, error performance, capacity prediction etc. Commercial communication practice over any medium is normally governed by Standards Specifications that spell out the details that all designers have to abide by. The status of Standards in PLC domain would first be touched upon, followed by other details.

3.1 PLC Standards

This is an area that is lagging behind the most, there still being no easily accessible documents that laydown the detailed practices that need to be complied with while designing PLC systems. There two sets of standards at various stages of evoluation.

- CENELEC Standards of EEC (European Standards)
- CE Bus Standards of EIA (North American)

Not much is known about the CE Bus specifications for PLC, excepting that it has set aside the range 100 KHz - 400 KHz for this application, and that a maximum signalling rate of 6.6K baud is permitted. Also, it has spelt out some of the issues relating to the Chirp modulation version of Spread - Spectrum practice of PLC. A little more is known about the CENELEC Standards and is summarized below .

CENELEC permits the use of 3-148.5KHz band for PLC, the range being divided into five regions :

3-9 KHz for use by energy providers

9 - 95 KHz (A-band) for use of energy providers

95 - 125 KHz (B-band) for use of consumers

125 - 140 KHz (C-band) for use of consumers, CSMA protocol defined

140-148.5 KHz (D-band) for use of consumers.

A-band specifies maximum permissible signal amplitudes for two types of modulations : 5 V at 9 Khz to 1 V at 95 Khz for Narrow - Band users; 5 V peak for Broad-Band uses, with a maximumof 0.75 V in a 200 Hz band. The signal amplitudes are limited to 0.63 Volts for B, C and D bands.

CENELEC Standards also specify three types of customer equipments (Types 1, 2 and 3) depending on the intended application environments, and their Immunity requirements have also been spelt out in detail.

3.2 Modulation Techniques for PLC

Both types of modulation have been utilised for PLCs - Narrow Band such as ASK, Non-Coherent FSK, and DPSK, as well as Spread-Spectrum Schemes such as DS/SS, FH/FSK as well as Chirp modulation. It's spectrum allocation being narrow, CENELEC generally favours Narrow-Band Schemes, where as CE Bus permits Spread Spectrum Schemes. Combinations of the two are also in use. Some of the more widely used ones are spelt out below.

ASK (Ripple - Carrier Signalling)

This is a very low data rate (less than 120 bps) scheme evolved in 1930s and uses carrier frequencies below 3KHz meant primarly for AMR. This is nearly obsolete now.

Non-Coherent FSK

This is the conventional schemes, preferred for its relative robustness. On the power line, however, signal fades are known to limit it's use, and a variation of its called SFSK has been proposed where two narrow badns located close to each other (separation of about 10 Khz) is used, giving a type of Spectral diversity. Its performance against selective fading has been shown to be good, giving 1200 bps over the 9-95 Khz A-band.

DS/SS

One system uses Gold codes with chipping rates of 14.4 KHz and carrier of 28.8 Khz, and works up to 9.6 Kbps data rates with a received power of 50 mw and BER 10^{-4}. Another version of this scheme called PC/SS is reported to give 64 Kbps at 440 Khz Band width with a BER better than 10^{-3}.

FH/FSK

Two schemes have been reported. An Indoor application at 300 bps in the 30-146 Khz region, using 900 Khz hopping rate and 0.35 volts signal amplitude; and a similar outdoor application at 60 bps using 300 Hz hopping rate.

Chirp or Spread Spectrum Carrier Modulation

This has been proposed to overcome the difficulties associated with the conventional Spread Spectrum that need to acquire and track the code which makes it problematic for CSMA Schemes. Chrip that sweeps from 100 to

400 KHz is used, with signal encoding done by PWM with each symbol having an integral number of unit Symbol Times (USTs) - there being four such symbols : 0, 1, EOF and EOP.

The synchronization requirements of the Spread Spectrum Systems are derived from the 60/50 Hz power line frequencies themselves, and for the European and North American Systems with their tight regulations (synchronization error under 60-70 μsecs) there is a penalty in SNR of under one dBs only due to this.

3.4 BER Performance and Channel Capacity [20-21]

A typical DS/CDMA systems discussed gave BER values below 10^{-7} most of the time, with bursts of higher BER (10^{-5} - 10^{-4}) occuring periodically in a 24 hour cycle. Average performance specifications of such a system would thus be very good, though the error burst periods will have to be properly handled. Received signal powers of 40 dBm gave high BER of 10^{-2} whereas it went down to 10^{-7} for 46 dBm. Some of the DS/SS experiments yielded BER of 10^{-4} at E_b/N_o of 15dB, and showed no further improvements for higher E_b/N_o values. It is evident that BER performance would be strong function of the specific context as well as implementation details. A recent simplified sermi-analytical investigation [21] on the channel capacity of single phase power lines under AWGN assumption predicts a capacity limit of some 3 Mbps. The following tables summarises the results, reported for two types of lines, one with attenuation of 40 dB/Km and the other with 100 dB/Km, as a function of the line lengths.

Line Lengths (Km)		**0**	**0.25**	**0.50**	**0.75**	**1.0**	**2.0**	**3.0**
Capacity (Mbps)	40dB/Km line	3.0	2.5	2.2	2.0	1.5	0.5	6×10^{-4}
	100 dB/Km line	1.0	0.7	0.02	10^{-4}	-	-	-

Considering the various simplifying assumptions that have gone into it, it would be necessary to confirm the above with detailed numerical simulations before confirming their validity.

4 Products and Applications

Perhaps the most significant push that the PLC sector has received recently is the availability of a range of ASICs and other products from a number of vendors in the last 3-4 years; products with which designers can implement applications. These are briefly surveyed here.

The ASICs can be classified in a number of ways-depending on the modulation schemes used (Spread Spectrum or otherwise), depending on the function intented (LAN Chips, Modems, Transceivers etc), depending on the applications targetted (AMR, Telephony, Data Communication, Networking etc), and so on. Instead of attempting these different classifications an indicative list of some representative products are given below to convey an idea of the range available at present. While some of the products reveal the technologies used in them, some do not, and this is reflected in the listing given here also.

AN-1000 (LAN Chipset) from Adaptive Networks

Meant to be used on intrabuilding wiring, it is a DS/SS product at a carrier frequency of 535 KHz, giving user data rates of 100 kbps at 10^{-9} BER, with raw transmission rates of 268.8 kbps. The AN 1000CS chipset is made of three chips - two physical layer controller chips PLC 1000A and PLC 1000D, and one DLP Data Link Layer plus application processor chip. The PLC chips provide the power line transceiver functions and implement SS synchronization, equalisation, modulation/demodulation, and FEC function. DLP is a network Communications microcontroller using an enhanced 6502 core, and manages the PLC chips as well as the protocols. There is also a lower version of LAN chipset at 19.2. kbps (AN 192M) smiliar to the AN 1000 set. (www.adaptivenetwork.com). Altcom makes modules using the AN chipsets-see www.alt_com.com

ICSSXXXX (LAN Chipset) from Itran and Cyplex

3 chip solution implements FH/SS technology in the 9-95 KHz band in compliance with CENELEC standards. Data rate variable in the 300 bps to 3.2 kpbs range, dynamic range of 93 dBs- meant for AMR, DA, Intrabuilding LAN etc. (www.nsc.com)

MAVERICK (Modem chipset) from IC COM

Meets CENELEC and CE Bus standards, and implements DS/SS. Can give upto 1 Mbps data rates useable for Internet distribution, AMR etc, and transmits 2 walts of power. (www.iccom.com)

PL^2 (Power Line local loop Modem chipset) from Keyin Systems

2Mbps data rates for 10 base-T Ethernet, ADPCM voice at 32K/24K/16K (selectable) rates, AMR (5-10 Kbps) Internet Distribution, etc. (www.keyin.co.kr).

ITM-10 (Transceiver chip) from Itran comm.

DS/SS system, up to 10Mbps data rates, supports CSMA/CD, 802.11 compatible and implements IP protocols. Ideal for Internet distribution over the LT line.

Itran also makes ITM 5000 (50 kbps, CE-Bus compatible, telephony chip), IT 800 PL (8kbps, for AMR, security, DA etc) and ITM1PL (2.5 Mbps chip for Internet over power line). (www.it rancomm.com)

SSC PXXX (Transceiver + controller chips) from Intellon

DS/SS chips for Distributed control and sensing over powerline P111, P200, P300 and P400. P111 is a SS-based Media Interface IC to work with the other PXXX chips, and has a dynamic range of 75 dBs. (www.intellon.com)

PLT 22 (Transceiver) from Echelon

CENELEC A-band compatible, raw data rate 5Kbps, operates at two carriers 132KHz (primary) ad 115 KHz (secondary) (www.echelon.com)

ASSET LAN (LAN Transceiver) from Acquila

Meant for Home Networking, variable data rates of 0-115.2 Kbps, operates at 3MHz (www.acquila.com).

CD 8000 (Power line modem) from Compu-Mech

FSK modem at 125 KHz outputs 1 w and receives upto 5mv (66dBs of attenuation from T_x to R_x). Signaling rates of 300-19.2 kbps selectable (webmaster @sysalt.com)

SMART PLUG (Transceiver unit) from Teamware

FSK modem operating at 132.45 KHz, data rates of 1200/2400 bps, half - duplex mode, upto 500m distance. (www.teamware.com)

MDL 500 Modem from Data Linc

FSK modem at 100/106.5 KHz and 150/156.5 KHz-9600 baud, full duplex (www.datalinc.com)

TDA 5051 (Modem chip) from Michat

ASK at 132.45 KHz, compliant with CENELEC specifications. 600 or 1200 bauds (webmaster @ michat.com)

Most of the above are chips or chipsets that can be used by system designers to realise specific solutions. Presented below are two examples of such system realisations.

DPL 1000 (Digital Power line) from NORWEB

NORWEB, formed as a subsidiary of Nortel to specifically focus on PLC area, came up with the DPL 1000 System used for Internet Distribution in the wellknown "Manchester Experiment" during 1997-99. The complete solution consists of 4 units - DPL 1000 Main Station, DPL 1000 Substation, DPL coupling unit, and the DPL 1000 communication module. The first two are located at the DT, and the last two at the subscriber premise. 2Mbps Internet access was provided over the line in a stable and trouble free manner in perhaps the best - known demonstration of the technology. (Internet document by Philip Sinfield, sinfield @fit. qut.edu.au. Also see comments on DPL in section V)

Power net (LAN)

Total solution for an intrabuilding LAN to which can be connected 64 nodes. Since the total rate is only 57.6 kbps, useful only for simple applications (Internet document : www . ngcan .dom /datacomm)powenet)

AMR System from Intra Coastal

SS technology for AMR from over 300 subscriber meters over the powerline. The readings are Concentrated at the DT base station, and sent to the central data base using a modem. Claimed to be highly cost effective, undergoing field trials (www.intracoastal.com)

Special units are needed to connect the Communications terminal to the powerline, taking care of issues such as isolation, noise removal, impedance matching etc. Blocking Couplers, Bridges, Attenuators, Filters etc are available for this purpose. Leviton PLC signal conditioning devices are a typical range of such products available (hometech @gohts.com). The Insulated Coupling Network of Michat electronique is another example, which operates at 115 KHz with 35 ohms impedance, and has 3dB - Band width of 100 KHz, 50Hz signal is attenuated by more than 90dBs (web master @ michat.com)

5 Summary and Conclusions

The current status of the PLC area may be summarised as below:

- The issues and problems involved in implementing PLC over the LT and Home segments are largely understood, and solutions of a certain level are available, adequate to address a wide range of applications.
- Increasing number of products and tools are getting into the market for designers to build applications and offer services - and consequently the range and numbers of such PLC applications that have been realised are growing steadily.
- PLC over Intra-Building wiring for Home Automation has fairly stabilised and faces little competition from any quarters as of now.
- Some standards have been evolving over time, though it has been far behind the rate at which products and applications are making their appearances.
- Whether PLCs would have any significant future in the communications last-mile role (increasingly becoming Broad-Band) would depend on the extent to which it is able to handle the Competition from DSL as well as Wireless access technologies.
- The role of PLCs in DA/SCADA applications over the HT segment remains largely unexplored.

In this connection, the calling off the well-advertised "Manchester Experiment" of 2Mbps Internet distribution over the LT segment by NORWEB last year has some significance. In fact, NORWEB site no more makes any mention of any of their DPL (Digital Power Line) products!

A query to them elicited the following response from Nortel. ".... NOR.WEB DPL Ltd, a joint venture between Nortel and United Utilities was closed on 30th Sept 1999... This decision was based on an evaluation of the future volume market potential for the DPL solutions, although the technology itself had been well proven in the field. With in the very Competitive Broad Band Access arena; where large - scale deployments of high speed technologies are in progress and Nortel has a strong portfolio, the market potential for DPL, based on current forecasts, can not justify continued focus".

It still follows that the technology may hold promise in those application areas that are not necessarily Broad-band and High Density; Scenarios such as typical Indian rural environments may still find the medium Band width, Low-density solution that PLC can provide attractive for some more time to come. A conceivable scenario is that of some 15-25 rural customers having 64 Kbps Voice/data access over an LT lime of some 1-5 km length, with the DT installation also serving as the Base Station whose equipment may be quite similar to the ones used in today's WILL technologies. Development of this solution needs detailed studies, modelling and characterisation of our LT system under our operating environments, and than designing appropriate PLC systems matched to their characteristics, and aimed to meet performance requirements specific to our context. The authors form part of a team that is presently addressing this issue.

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