Review of Power Line Communications System Emissions Standards

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1 Introduction

At the present time, the regulatory and standards organisations are in the process of determining what the appropriate standards should be for High Speed Power Line Communications (HS PLC) products and systems. There are many interest groups that are lobbying these organisations to either relax or tighten the limits for the new standards. The new emission limits for HS PLC systems should be of the same order as the limits for existing standards for consumer and other communications products. Setting limits for HS PLC networks that are orders of magnitude below existing limits can only be viewed as a deliberate attempt to undermine the viability of HS PLC systems as a broadband communications alternative to other technologies such as xDSL.

General guidelines for formulating a set of standards for PLC products and networks are:

- Broadband communications systems should be allowed to perform at the maximum capacity possible without disturbing radio services due to unintentional radiation;
- All broadband communications should comply with the same limits;
- The limits should allow existing systems (e.g., LANs, televisions, halogen lamps, inductive ovens, etc.) to operate without any modifications;
- The limits should preferably be flat with respect to frequency (as is the case for FCC Part15);
- A spectral power mask may be necessary to protect existing services. This should be applied locally where there may be a problem rather than nationally where all PLC users would be penalised;
- The present emission limits of FCC Part15 have proved to be acceptable in the many trials that have been and are in operation at the present time. There have been no cases of complaints due to unintentional radiations reported from these sites;
- Adoption of product standards like CISPR22 (presently under review to include PLC) with some modifications, if needed, will be the most expedient;
- Set a reasonable frequency for the coexistence of Access and In-House PLC systems.

In the past regulatory standards have been set to meet advances in technology and commercial developments. The most recent case of this is the proposed amendments to FCC Part15 in the USA. In February of 2004 the FCC in the USA released document number FCC04-29 “Notice of proposed rule making” which is a proposal to amend FCC Part15 to include BPL (Broadband Power Line) carrier current systems.

The proposed changes to the US regulations have placed pressure on the European regulators to set European standards that have similar limits.

Australia is closely aligned to the European standards and adopts the CISPR standards sometimes with minor changes. It is very likely that Australia will adopt any changes to CISPR22 and also any new PLC System emissions standards that are legislated in the EC.

2 Introduction to PLC Standards

2.1 InovaTech Products and Standards Compliance

InovaTech's PLC products comply with the European Commission EMC Directive:

- EN55022 B Limits & Methods of Measurement of Radio Interference Characteristics of IT Equipment
- EN55024 A IT equipment – Immunity Characteristic Limits & Methods of Measurement
- EN61000-3-2 EMC - Limits for Harmonic Current Emissions
- EN61000-3-3 Limitation of Voltage Fluctuations and Flicker in Low Voltage Supply Systems
- EN55082-1 Generic Immunity Standard – Domestic, Commercial and Light Industrial

InovaTech's products comply with the European Commission Safety Directive:

- UL1950 Safety of IT Equipment, including Electrical Business Equipment
- EN60950 Safety of IT Equipment, including Electrical Business Equipment
- EN41003 Particular Safety Requirements for Equipment to be connected to Telecommunication Networks
- IEC60664-1 Insulation Coordination for Equipment within Low Voltage Systems

In addition to the above, the HS PLC system emissions can be adjusted to meet:

- FCC-Part 15 Code of Federal Regulations 47: Telecommunication – RF Devices
- Reg TP 1/99 (NB30)

2.2 Emission Standards Comparison

Given the significant activities in research, development, trials and commercial deployment of broadband PLC systems in the past three years, the regulatory bodies in a number of countries are reviewing their existing EMI/EMC equipment standards (e.g., CISPR22, FCC Part15) with the aim of including high speed (HS) PLC.

A significant amount of effort has also been put into establishing new standards (e.g., NB30, MPT1520, BBC, etc.) specifically for setting limits principally for HS PLC networks and other broadband technologies (e.g. xDSL).

Figure 2-1 provides a comparison of some of the emission limits that are either in force at the present time or have been proposed and are under review. More detailed information about these standards will be found in Sections 4 onwards. Appendix C provides some explanation of the reasoning behind the emission limit levels that have been proposed.

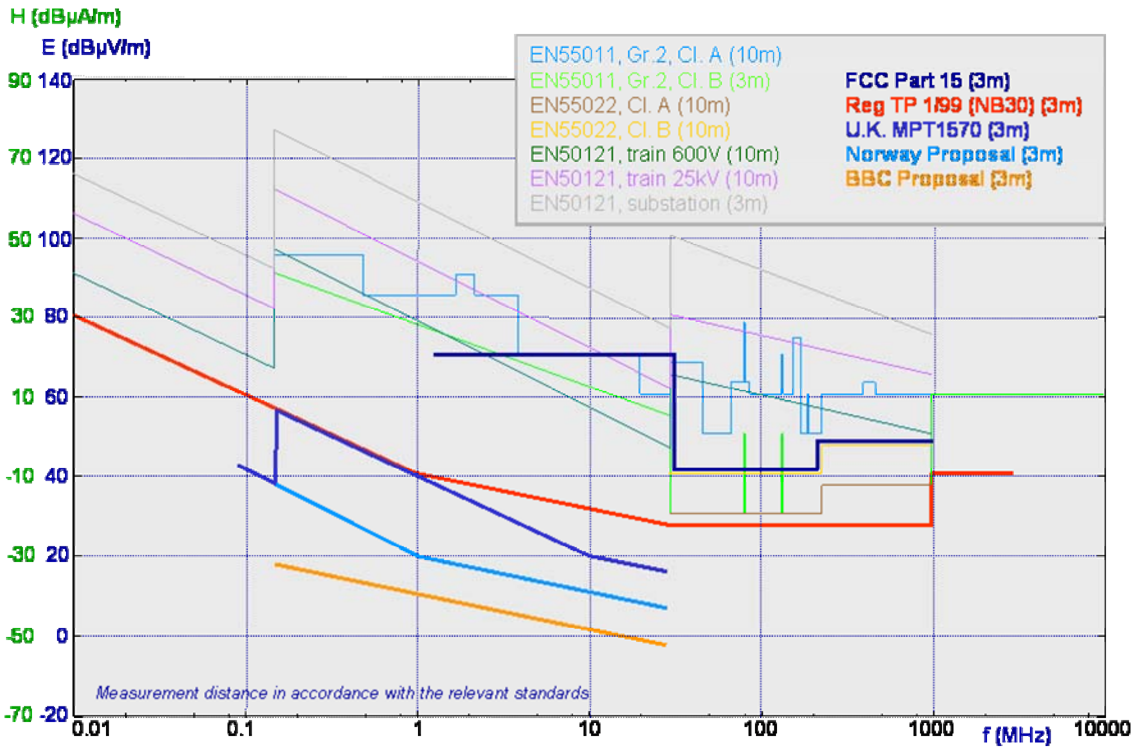

Figure 2-1 Comparison of Emission Limits for EMC Equipment Standards and Proposed PLC Systems

To put the limits proposed by the standards organisations in to perspective, Figure 2-2 shows the results of two measurements of emissions that were made at the University of Dortmund of a Local Area Network (LAN) consisting of about 200 PCs interconnected with CAT-5 cable and using Ethernet. The diagram also shows the proposed NB30 limit. Emissions from the LAN exceed the proposed NB30 limit by more than 20dB at some frequencies.

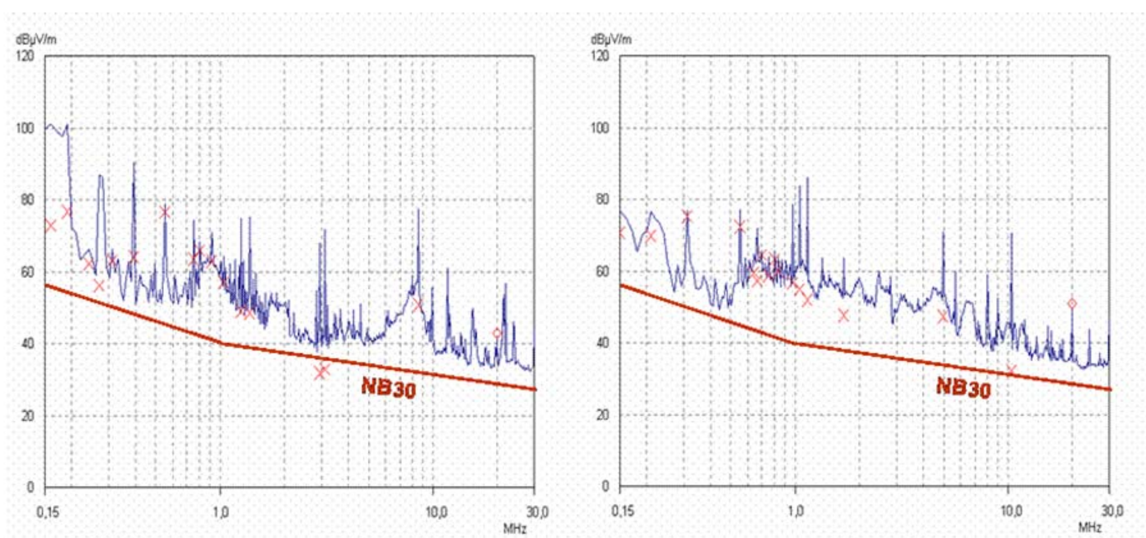

Figure 2-2 Emission measured of Ambient Noise Environment – NB30/MV05 (3 m distance, 60-cm BB magnetic loop) method inside a building at the University of Dortmund. About 200 PCs and workstations operate in this building.

Network: Ethernet with Cat 5-Cabling *(Ref. PLCforum)*

3 Standards Implementation Recommendations

Consideration should be given to leaving some latitude in the legislated standards to allow for:

- Advances in technology
    - For example, use of higher carrier frequencies.
- Improvements in performance
    - For example, denser modulation schemes.
- Changes to algorithms
    - For example, channel coding, encryption, channel adaptation, etc.
- Multiple technology providers
    - InovaTech is currently using DS2 as its technology provider. In the future there may be other vendors with competitive technologies that could be incorporated in to the InovaTech products.

The following sub-sections provide recommendations for EMI-EMC emissions standards for implementation. The sub-sections are organised in the following way:

- Level 1 – Equipment / Products
- Level 2 – Systems: Frequencies, Modulation and Protocols

3.1 Level 1 – Equipment / Products

The standards organisations listed below control the relevant EMI-EMC standards in the appropriate countries or regions:

- International Recommendations (IEC - CISPR)
- European Standards (CENELEC, ETSI)
- United States Standards (Federal Communications Commission - FCC Part15)
- German Standards (Reg TP – NB30)
- UK Standards (Radio Communications Agency – MPT1570)

The present emission standards in any country may already be aligned with standards from one or more of the above regulatory organisations. If there are no standards in place at the present time, adopting existing overseas standards and introducing some additional local restrictions or relaxations may be the most convenient way to proceed.

Some relaxation of present emission limits (if they exist) may be necessary to make HS PLC a viable technology for the provision of broadband Access services.

Emission levels set at or close to the limits prescribed in FCC Part15 are recommended.

3.2 Level 2 – Systems: Frequencies, Modulation and Protocols

Access & In-House Coexistence

Figure 3.1 summarises the frequency bands of use for the major PLC technology providers including InovaTech which uses DS2 technology.

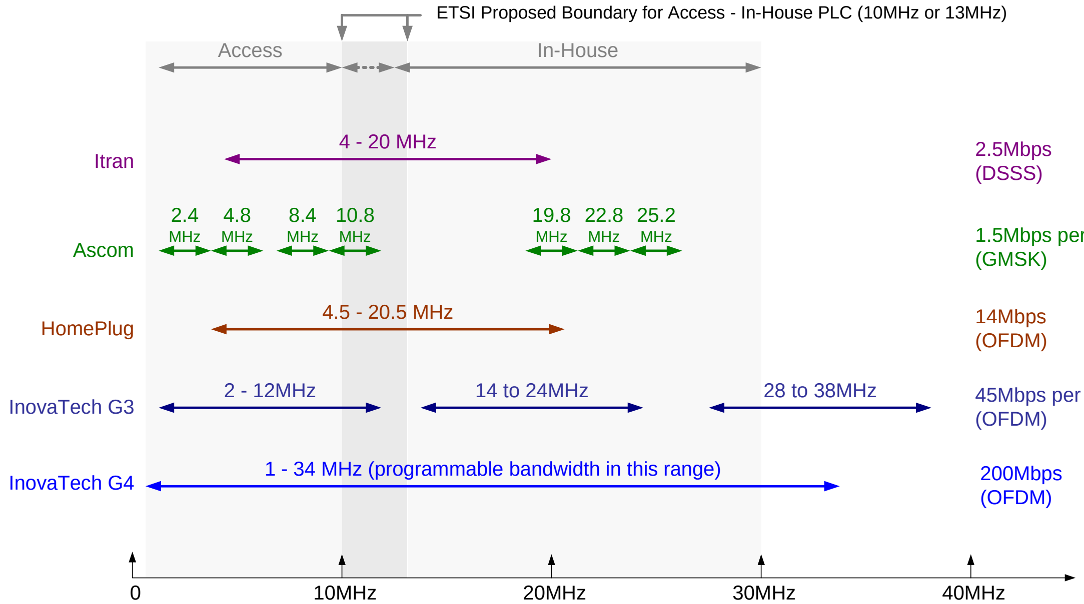

Figure 3-1 *Comparison of Frequency of Operation, Physical Layer data rates and modulation scheme for HS PLC technologies together with the ETSI proposed frequency allocation(s) for Access and In-House PLC.*

Figure 3-2 shows the division of responsibility between CENELEC and ETSI for the preparation and maintenance of HS PLC standards.

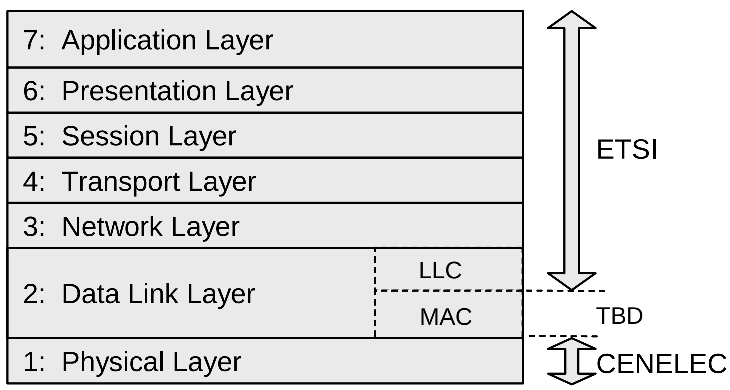

Figure 3-2 *ETSI – CENELEC Division of Responsibility (OSI Reference Model)*

The coexistence issue is handled by setting operational frequency bands for Access and In-House PLC. This is described in the following section.

Operational Frequencies for Access and In-House PLC

The European Technical Standards Institute (ETSI) has proposed that the boundary between Access and In-House PLC systems be set at either 10MHz or 13MHz. The final decision has not been made at the present time and is still under consideration.

Setting the boundary at 13MHz is recommended because gives Access PLC systems more of the sought after lower frequencies which have better propagation characteristics.

Modulation Scheme

The three main modulations schemes that are used for HS PLC are Gaussian Minimum Shift Keying (GMSK), Direct Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multiplexing (OFDM).

After many years of HS PLC development and operation, OFDM has emerged as the most suitable for communications over the power lines. OFDM is the most resilient to noise, changing line conditions and provides the highest modulation density (bits per second per Hz of bandwidth).

InovaTech's G3 products have 1280 carriers with up to 8 bits per carrier (8bps/Hz). The G4 products have 1536 carriers and 10 bits per carrier (10bps/Hz).

Coding and Channel Quality Monitoring and Adaptation

InovaTech's G3 and G4 products have the following:

- Adaptive Per Carrier Modulation
- Reed Solomon Forward Error Correction
- Interleaving
- Trellis coded Modulation

The optimum coding mechanism is determined automatically based the channel characteristics and available SNR at the receiver. The modulation parameters per carrier are adjusted to maintain the required BER. The BER can be set to be 10E-3, 10E-6 or 10E-9.

MAC (Medium Access Control) Layer Protocols

The InovaTech G3 products use a Master – Slave (M-S) protocol where the Head End (MultiCAT) is the Master and all of the registered Repeaters (PurCAT) or CPEs (IPCAT) are the Slaves. The M-S protocol is used for both Access and In-House PLC.

Inovatech's G4 products can be configured to have either a M-S or Peer to Peer MAC layer protocol. The M-S protocol is usually used for Access and the PtP is used for In-House PLC. M-S can be used on the In-House network. It is not recommended to use PtP on the Access network.

The G3 and G4 products support the IEEE802.1q standard for VLAN and also the DS2 proprietary Optimised VLAN (OVLAN).

Quality of Service (QoS)

The InovaTech G3 and G4 products comply with the IEEE802.1p standard for prioritisation of data packets.

Each user can be configured to have:

- Guaranteed bandwidth
- Bounded Latency (e.g., VoIP or video)
- Low BER
- Guaranteed availability (e.g., critical services)

Encryption and Security

InovaTech's G3 and G4 products support the IEEE802.1q standard for VLAN and also the DS2 proprietary Optimised VLAN (OVLAN). Both generations of product can have encrypted VPN if required for extremely sensitive applications.

The G4 products also support DES and triple DES encryption.

4 Low Speed PLC

4.1 Introduction

Low speed PLC systems have been in use for many years primarily for electric utility telemetry applications over HV and MV power lines and also for home and building control, monitoring and automation systems.

4.2 EN50065 / IEC61000-3-8

Some powerline communications systems terminal devices are currently regulated under the EMC regime. Specifically, powerline communications systems using frequencies in the range 3 kHz - 525 kHz must meet the requirements of one of two standards:

- EN 50065-1 Signalling on low voltage electrical installations in the frequency range 3 kHz to 148.5 kHz- Part 1; or
- IEC 61000-3-8 Electromagnetic Compatibility (EMC) – Part 3: Limits, Section 8: Signaling on low voltage electrical installations using signals in the frequency range 3 kHz to 525 kHz.

These standards for powerline communications systems do not apply to broadband powerline communications systems, which utilise HF frequencies (3 MHz to 30 MHz) and above. At the present time there are no mandatory standards for PLC equipment using frequencies above 525 kHz.

4.3 Japan

The Japanese Ministry of Telecommunications is the regulator of the postal system, telecommunications systems and radio frequency usage in Japan. Currently, systems are limited to the use of systems with operating frequencies below 450 kHz.

Systems using frequencies below 10 kHz require permission from the Minister and systems operating on frequencies between 10 – 450 kHz require notification to be given the Ministry.

Efforts have been made by the Association of Radio Industries and Business (ARIB) over the last few years to gain access to frequencies between 2 and 30 MHz for broadband powerline systems in Japan. This has included trials in Akagi held in January 2002 and further trials held in June 2002. The Ministry currently has a conservative view and considers the risk of interference to radio communications services from these systems too great to permit widespread use.

On November 7, 2003, the Japanese Ministry of Public Management, Home Affairs, Posts and Telecommunications (MPHPT) announced the results of an invitation for comments concerning drafting partial amendments to Regulations for the Enforcement of the Radio Law for the introduction of a testing system for PLC facilities. The MPHPT had invited comments from the public from August 29 until September 26, 2003, concerning drafting partial amendments to the Regulations for the Enforcement of the Radio Law, in preparation for the introduction of a testing system for PLC facilities using 2MHz to 30MHz.

The comments were received on an inquiry made to the Radio Regulatory Council on September 10, 2003, concerning the partial amendment of regulations for radio equipment. The MPHPT will prepare for the introduction of this testing system, taking into consideration a report that will be received from the Council along with the comments received from the public.

The MPHPT explained that BPL operations are permitted on an experimental basis for the purpose of developing technologies that reduce the emissions from BPL operations.

4.4 IEC

The IEC is the leading global organisation that prepares and publishes international standards for all electrical, electronic, and related technologies. Work related to broadband powerline communications systems is currently being undertaken by the IEC International Special Committee on Radio Interference (CISPR).

4.5 CENELEC / ETSI

European Committee for Electrotechnical Standardisation (CENELEC)

- Sets standards for power industry
- Defines frequency spectrum for power lines used by utilities for network management
- Present PLC standard is EN50065-1 for LS PLC

European Technical Standards Institute (ETSI)

- Sets standards for telecommunications industry
- Defines frequency spectrum allocation for telecommunications usage
- ETSI defined modulation frequency bands in October 2000
    - 1.5 – 10 (or 13) MHz for Access
    - 10 (or 13) – 40 MHz for In-House

Present CENELEC PLC standard EN 50065-1 for operating, controlling, measuring, and, in particular, switching of the mains signalling receivers for low tariff heating systems has upper limit of 148.5 kHz.

Ongoing discussions via Powerline Telecommunication Forum (PLCforum) to resolve boundary between Access and In-House PLC frequency bands for Europe

Germany legislated NB30 in 2001 (revoked) and the UK proposed MPT1570 as the PLC network emissions standards, but both of these are now used only to resolve any EMI/EMC problem or complaint

European Commission gave directive to ETSI and CENELEC to prepare a common PLC network emission standard with a preference for limits to be at or near the US standard FCC Part15

Operational frequencies and emission levels of HomePlug standard may conflict with ETSI/CENELEC PLC network standard, which may mean HomePlug compatible systems unable to obtain approval to operate in Europe or in countries adopting the European standard

OFDM-based systems with selectable sub-carrier frequencies will have a significant advantage over other modulation schemes because of the ability to suppress problem emission frequencies

International Special Committee on Radio Interference (CISPR) is reviewing EN 55022 (formerly CISPR22) to include powerline communications equipment and the necessary test procedures

General electronic equipment as well as PLC equipment will have to be compliant with EN55022 for sale in Europe and countries adopting the European standards, which may cause a problem for HomePlug equipment developed for sale in the USA

The ETSI Technical Committee TC PLT has already produced standards for reference network architecture (TS 1010896) and coexistence (sharing) arrangements between in-house and last-mile systems (TS 101867). Other standards in development cover detailed in-house architecture and protocols. It should be noted that all of these standards are dealing with telecommunications aspects and that none directly address potential interference issues for radio communications systems.

The Technical Committee is working through CENELEC with the International Electrotechnical Committee (IEC) specialist body CISPR (the International Special Committee on Radio Interference), on EMC issues related to powerline systems. The CISPR standard for information technology equipment conducted limits at mains terminals and telecommunications ports (CISPR 22), together with its European counterpart EN 55022, are in the process of being updated to include changes clarifying their application to powerline systems.

Currently, several European countries have adopted their own requirements for powerline communications systems. These include: Germany, where limits for emissions from all cable systems are set out in NB30; and the United Kingdom - covered by MPT 1570, which has been recently updated. There is also a limit proposed by Norway and the BBC in the UK.

In summary, the European Communications Committee has identified a significant risk of interference to HF radio communications services (ECC Report 24). Based on these findings, Europe is currently developing a range of telecommunications and other harmonised standards specifically covering broadband powerline communications systems. There are, however, a growing number of systems already being deployed in Europe and surrounding countries to provide last-mile broadband services using devices compliant with EN 55022.

4.6 PLC Forum

PLCforum is an international industry association representing the interests of manufacturers, energy utilities and research organisations active in the field of last-mile and in-home power line type systems. PLCforum was established in March 2000 in Interlaken, Switzerland through the merger of two existing associations to lobby for satisfactory regulatory frameworks for PLC, to pursue coexistence and interoperability standardisation and support the marketing and financial models of its members.

The forum organised a world summit of PLC Associations in Brussels in June 2003 to discuss aspects of international standardisation and the need to lobby for a common regulatory approach by regulators.

The PLCforum board has nine members, including the chairman, drawn from different sectors, e.g. utilities, manufacturers, developers, et al.

The PLCforum is principally interested in Access PLC standards. It has working groups for many aspects of PLC, including:

- Modulation techniques
- Transfer from existing technologies (xDSL, cellular, etc)
- Electromagnetic compatibility
- Interface requirements
- Frequency allocation
- Licensing procedures
- Telecommunications and energy law
- Definition of regulatory framework

4.7 HomePlug

The HomePlug power line alliance is an industry grouping in the USA consisting of five sponsoring companies including Intellon, Panasonic, RadioShack Corp. and Sharp. The alliance has nineteen participating members including Motorola, Philips Electronics, Sony Corp. and France Telecom. The alliance has developed the HomePlug standard specifically for In-House PLC systems and meets the current FCC Part 15 requirements for current carrier systems.

The HomePlug standard strives to provide interoperability between consumer devices by setting out a MAC protocol as well as the physical signalling techniques to be used by devices. The media access control allows multiple devices to be connected to the network within the building. The media access control specification includes data encryption levels, priority communications and latency control. The physical signalling uses a form of orthogonal frequency division multiplexing (OFDM) modulation using up to 76 carriers in the band 4.5MHz to 21MHz.

The HomePlug standard provides for a typical throughput rate of 14 Mbps with the potential for up to 20 Mbps when all carriers are in use. The physical layer standard provides for carrier channel selection (channel adaptation) and carrier modulation selection (DBPSK/DQPSK) in conjunction with variable levels of forward error coding to allow adaptation to the transmission path between devices. Devices complying with the HomePlug standard are supposed to meet FCC Part 15 requirements.

HomePlug compatible modems have an injection power spectral density (PSD) of -50dBm/Hz over the frequency range of 4.5 MHz to 21 MHz.

The measurements made by the IEEE/ANSI C63 Standards committee PLC Working Group have shown that the field strength at 30 meters can be expected to be as much as 20 dB over the FCC limits.

A power spectral mask has been introduced in to the HomePlug standard to reduce the PLC signal injection level by 30dB (i.e. PSD of -80dBm) within the Amateur frequency bands. The measured PSD at the transmitter for the HomePlug standard modems is shown in Figure 5-1 below.

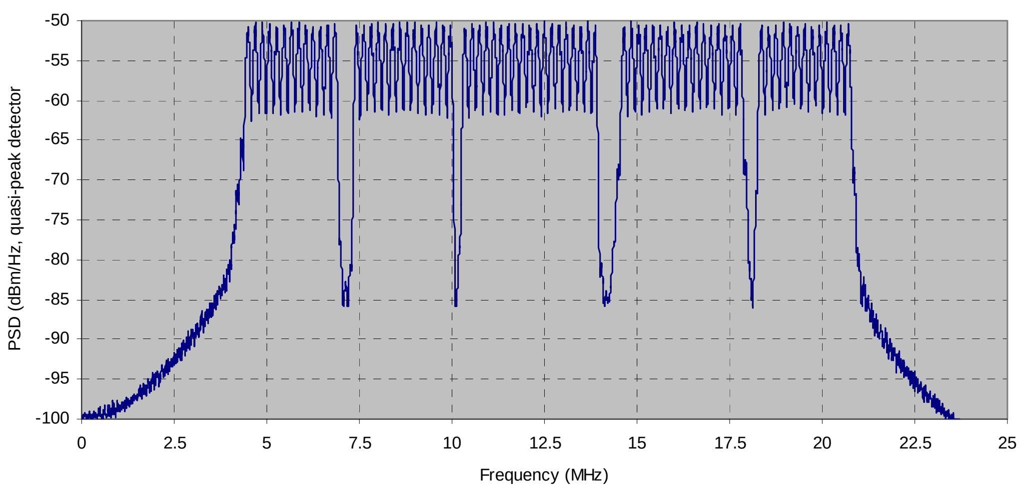

Figure 5-1 *HomePlug Injection PSD measured at the transmitter and showing notches of ~30dB introduced to protect Amateur Frequency Bands*

4.8 CISPR22

CISPR has developed a range of EMC standards for electronic equipment that have been widely adopted by regulatory authorities around the world. CISPR Standard 22 on the limits and measurements of emissions from information technology equipment is currently in the process of being updated. The CISPR 22 work program includes a project to provide clarification of the application of CISPR 22 to PLC equipment (project number: CISPR 22 Amd.2 f9 Ed.3). This work was scheduled for completion in August 2003; however, due to the level of debate regarding the impact on radio communications services from powerline systems the work is still uncompleted.

The debate is centred on the appropriateness of the conducted signal measurement methods and limits in CISPR 22 (which are intended to limit the amount of radiofrequency energy finding its way from information technology equipment onto mains power networks). (The radiated signal limits and measurements methods would only be applicable to the cases of powerline communications terminal devices and radiation from the case of these terminal devices does not present a significant interference risk.)

The applicability of CISPR 22 as a standard for devices used in broadband powerline communications systems is currently being debated. The proposal is to amend the scope of CISPR 22 to include PLC and to prescribe conducted limits for these devices that are considerably higher than the current restrictions.

4.9 FCC Part 15

Powerline communications systems have developed in the USA under Part 15 of the FCC Rules and Regulations. This part of the FCC Rules and Regulations relates to requirements for unlicensed low power radio communications devices and emissions from non-radio communications digital equipment that might otherwise cause electromagnetic interference (EMI) to radio communications services.

Powerline communications systems are treated in Part 15 as non-radio communications digital equipment. They are referred to in this Part as current carrier systems and specific arrangements are in place for systems operating on frequencies in the band 9 kHz to 30 MHz. The FCC Rules and Regulations specify limits for both conducted and radiated emissions for current carrier systems. Section 15.107 sets out the conducted emission limits for all Part 15 devices connected to the AC power supply, including devices used in current carrier systems. It appears that these requirements apply to the terminal devices only.

The radiated emission limits for current carrier systems [15.107(c)(3)] [15.109(e)] (See Appendix B) are the general radiated emission limits for non-specified devices that radiate either intentionally or unintentionally. The limits for conducted emissions set out in FCC Rules and Regulations section 15.107 and the limits for radiated emissions set out in section 15.109 are reproduced in Appendix A. These limits are significantly higher (> 100 times) than limits found in the regulation of other countries for these devices at HF frequencies.

The FCC in April 2003 [ET docket No.03-104] (See Appendix A) initiated an enquiry into current carrier systems, including broadband-over-powerline systems, to obtain information on a variety of issues relating to these systems. The enquiry sought technical information and data to allow an evaluation of the current state of the technology and to determine whether changes to Part 15 are necessary to facilitate the deployment of this technology.

The closing date for comment was initially set as 7 July 2003 but was later extended to 20 August 2003 due to the large number of comments (filings) made. The period in which responses to the filings can be made is expected to close in late September 2003.
The FCC initiated this enquiry as part of its statutory mandate to encourage new technologies. (Renewed world wide interest in powerline communications systems seems in part to be a consequence of these developments in the USA.)

A brief examination of some of the initial comment filings made to the FCC indicates that various respondents are concerned about the risk of interference from powerline communications systems to radio communications, including the NTIA and the amateur radio community. Concerns have also been expressed regarding possible interference to cable television services and digital subscriber line services using aerial cables in close proximity to powerlines.

In February 2004 the FCC released a formal document proposing amendments to the existing regulations under FCC Part15 to include Broadband Power Line (BPL) systems. A few excerpts of this document can be found in Appendix C.

5 Appendix A: FCC Docket No. 03-104

FOR IMMEDIATE RELEASE
April 23, 2003

Media Contact:
M. Van Wazer
(202) 418-0030

FCC BEGINS INQUIRY REGARDING BROADBAND OVER POWER LINE (BPL)

Washington, DC – As part of its ongoing effort to promote spectrum flexibility and access to broadband services for all Americans, and to encourage multiple platforms for broadband, especially new facilities-based platforms, the FCC today issued a Notice of Inquiry seeking public comment on using existing electrical power lines to provide Internet and broadband services to homes and offices.

Broadband over Power Line (BPL) can provide consumers with the freedom to access broadband services from any room in the house without adding or paying for additional connections by simply plugging a BPL device into an existing electrical outlet. BPL may be able to provide an additional means for "last-mile" delivery of broadband services and may offer a competitive alternative to digital subscriber line (DSL) and cable modem services. This will also enable access to communications services in rural and remote areas of the country. In addition, BPL systems can be used by electric utility companies to more effectively manage their electric power networks.

The inquiry addresses the two types of BPL: Access and In-House. Access BPL uses medium voltage (1,000 to 40,000 volts) power lines to bring Internet and other broadband applications to homes and offices. In-House BPL uses existing electric utility wiring to network computers and printers, as well as smart appliances, within a building. The Commission noted that existing rules for unlicensed *carrier current* systems, which couple radio frequency (RF) energy to the alternating current (AC) electrical wiring for the purpose of communications have been successful. However, these carrier current systems have operated with relatively limited communications capability on frequencies below 2 MHz, over a narrow spectrum bandwidth. Now, the availability of faster chip sets and the development of sophisticated modulation techniques have produced new digital power line designs that use multiple carriers, spread over a wide frequency range (*e.g.*, 2 - 80 MHz) and are capable of high data rates. The Commission further noted that providers of broadband over power line equipment are free to continue to deploy their networks in conformance with existing Part 15 rules, and potential rule changes as a result of this proceeding will address prospective compliance.

The Commission, in this inquiry, seeks information, comment, and technical data on issues concerning Broadband over Power Line, specifically:

- The current state of high speed BPL technology
- The potential interference effects, if any, on authorized spectrum users
- Test results from BPL experimental sites
- The appropriate measurement procedure for testing emission characteristics for all types of carrier current systems
- Changes that may be needed in Part 15 technical rules and the equipment approval process to foster the development of BPL and to ensure that interference is not caused to other services as a result of this technology.

Action by the Commission April 23, 2003, by Notice of Inquiry (FCC 03-100). Chairman Powell, Commissioners Abernanthy, Copps, Martin, and Adelstein. Separate statements issued by Chairman Powell, Commissioners Abernathy, Copps, and Adelstein.

Office of Engineering & Technology Contact: Anh T. Wride (202) 418-0577

6 Appendix B: FCC Part 15 - Rules applicable to PLC Systems

Current Carrier Systems

15.107 Conducted Limits–
This section sets out the conducted limits of devices connected to the AC mains supply.

15.107(a) Limits for all devices except Class A digital devices and the current carrier systems in part (c).

Frequency (MHz)	Quasi-peak (dBmV)	Average (dBmV)
0.15-0.5	66 to 56	56 to 46
0.5-5	56	46
5-30	60	50

15.107(b) Limits for Class A digital devices

Frequency (MHz)	Quasi-peak (dBmV)	Average (dBmV)
0.15-0.5	79	66
0.5-30	73	60

15.107(c) Current Carrier Systems
The limits shown in paragraphs (a) and (b) of this section shall not apply to current carrier systems operating as unintentional radiators on frequencies below 30 MHz. In Lieu thereof, these current carrier systems shall be subject to the following standards:

(1) For current carrier systems intended to be received using a standard AM broadcast receiver (Not a PLC system as considered in this report.)
(2) For all other current carrier systems within the frequency band 535-1705 kHz 1000 mV.
(3) Carrier current systems are also subject to radiated emission limits.

15.107(d) Measurements to demonstrate compliance

15.109 Radiated Emission Limits
15.109(a) Limits for all devices except Class A digital above 30 MHz
15.109(b) Limits for Class A above 30 MHz
15.109(c) Band edge values
15.109(d) CB receivers
15.109(e) Current carrier systems are subject to the radiated limits in 15.209 between 9 kHz and 30 MHz.
15.109(f) Receiver terminals
15.109(g) Acceptance of devices which comply with CISPR 22

15.209 Radiated emission limits, general requirements

Frequency(MHz)	Field Strength(uV/m)	Measurement Distance (m)
0.009-0.490	2400/ F(kHz)	300
0.490-1.705	24000/ F(kHz)	30
1.705-30.0	30	30
30-88	100	3

7 Appendix C: Excerpts from FCC04-29, 23FEB04 (Proposed amendments to include BPL)

Below are some excerpts from the document FCC04-29.

Page 2:

"I. INTRODUCTION

By this action, we are proposing to amend Part 15 of our rules to adopt new requirements and measurement guidelines for a new type of carrier current system that provides access to broadband services using electric utility companies' power lines. Because power lines reach virtually every home and community in the country, we believe that these new systems, known as Access broadband over power line or Access BPL, could play an important role in providing additional competition in the offering of broadband services to the American home and consumers, and in bringing Internet and high-speed broadband access to rural and underserved areas. At the same time, we are cognizant that the possibility of widespread operation of Access BPL raises interference concerns and that we must protect licensed radio services from any harmful interference that might occur. In this regard, we are proposing to require that BPL systems and devices incorporate capabilities to mitigate harmful interference should it occur. We are also proposing to adopt administrative requirements to aid in the identification and resolution of harmful interference from Access BPL systems. Finally, we are proposing to clarify certain measurement guidelines for all types of carrier current systems that use electric wiring and electrical outlets within homes and buildings to transfer information between computers and other electronic devices. With these proposals, we take an important step towards promoting the deployment of new broadband networks that are expected to enhance the economic, educational and social well-being of all Americans. Specifically, we believe that the proposed changes will remove regulatory uncertainties and facilitate the introduction and use of this promising new technology."

Pages 13 & 14:

"III. Discussion

30. As indicated in the *Notice of Inquiry* and supported by the responsive comments, we believe that Access BPL offers the promise of a new method for delivery of broadband services to residential, institutional, and commercial users. Because power lines reach virtually every home, school, and business in the United States, Access BPL technology could play an important role in providing high-speed Internet and broadband services to rural and remote areas of the country. Thus, significant areas of the country still lack broadband access and many others lack competition for such services, and we believe that Access BPL could serve as a means to reach those areas. Since Access BPL uses the same power lines that carry electricity virtually everywhere, much of the infrastructure needed to operate this technology is already in place, so that major savings in deployment costs and capital may be realized in its deployment. Access BPL could also serve to provide new competition to existing broadband services, such as cable and DSL. In addition, Access BPL may allow electric utilities to improve the safety and efficiency of the electric power distribution system and also further our national homeland security by protecting this vital element of the U.S. critical infrastructure. Moreover, Access BPL is being developed worldwide, and encouraging the deployment of the technology in the United States will support globalization of products and services, promote continued U.S. leadership in broadband technology, and bring important benefits to the American public.

31. We recognize the significant concerns of existing radio users regarding the potential for harmful interference from Access BPL operations. After careful consideration, however, we believe that these interference concerns can be adequately addressed. We believe that Access BPL systems can operate successfully under the non-interference requirements of the Part 15 rules. Under these rules, operators of Access BPL systems will be responsible for eliminating any harmful interference that may occur. Furthermore, we believe that the current Part 15 emission limits for carrier current

systems in conjunction with certain additional requirements specific to Access BPL operations will be adequate to ensure that existing radio operations are protected against harmful interference from such operations. We therefore are proposing changes to our Part 15 rules that we believe will facilitate the deployment of Access BPL technology while protecting licensed users of the spectrum. Specifically, we are proposing to: 1) define Access BPL for purposes of our rules; 2) maintain the existing Part 15 emission limits for Access BPL; 3) require that Access BPL devices employ adaptive interference mitigation techniques; 4) require that Access BPL providers maintain a database of installation locations and technical information; and 5) adopt specific measurement guidelines for both Access BPL and other carrier current systems to ensure that measurements are made in a consistent manner and provide for repeatable results in determining compliance with our rules. These proposals are discussed more fully below. "

Pages 15, 16 & 17:

34. While we appreciate the interference concerns raised by existing radio users, we note that Access BPL will operate in compliance with the current Part 15 rules that limit emissions from unlicensed carrier current systems to very low power levels in comparison to licensed radio operations. We believe that the current Part 15 levels will limit the harmful interference potential of Access BPL devices to relatively short distances around these devices. In this regard, we note that hundreds of kinds of unlicensed devices are successfully operating under the current Part 15 limits without causing harmful interference to licensed operations. Furthermore, all unlicensed devices operating under Part 15 are subject to the condition that they not cause harmful interference and that they cease operation if they do cause such interference.

35. We recognize that amateur operations are likely to present a difficult challenge in the deployment of Access BPL in cases where amateurs use high gain outdoor antennas that are located near power lines. In considering this interference potential, we note that ARRL acknowledges that noise from power lines, absent any Access BPL signals, already presents a significant problem for amateur communications. We therefore would expect that, in practice, many amateurs already orient their antennas to minimize the reception of emissions from nearby electric power lines. Further, we note that many Access BPL technologies have the capability to avoid using specific frequencies, if necessary, to avoid interference. This would permit Access BPL devices to avoid the use of amateur frequencies when in close proximity to amateur outdoor antennas.

36. We also disagree with ARRL and others that suggest that interference caused to amateur and other radio operations by Access BPL systems complying with our Part 15 limits will be widespread. Although we agree with ARRL that Access BPL on overhead lines is not a traditional point-source emitter, we do not believe that Access BPL devices will cause the power lines to act as countless miles of transmission lines all radiating RF energy along their full length. Rather, the primary source of emissions will be the individual couplers, repeaters and other devices and, to a lesser extent, the power line immediately adjacent thereto. Regarding the cumulative interference effect of Access BPL across wide geographic areas, data submitted by Access BPL proponents, such as AEC and Current Technologies, show that radiation would be the highest in the vicinity of an Access BPL emissions source. In addition, as indicated above, Current Technologies, Main.Net and other Access BPL equipment manufacturers state that in their implementations only a limited number of devices transmit simultaneously on the same frequency in the same geographic area and that there is no cumulative effect from multiple Access BPL devices transmitting

at the same time in the same area. Nevertheless, to ensure that any effect of the power line is taken into consideration when testing for compliance with our Part 15 rules, we are proposing to modify the measurement procedures for Access BPL systems, as set forth in Appendix C, to specify that emission measurements be made at several specific distances from the Access BPL equipment source, and that measurements be taken parallel to the power line to find the maximum emissions from the BPL system. We seek comment on our proposed measurement guidelines.

37. With regard to potential interference to the non-amateur radio services, such as public safety, maritime and other operations, we believe that the risk of harmful interference from Access BPL operations is low. In general, we believe that a properly designed and operated BPL system will pose little interference hazard to non-amateur services such as aeronautical, maritime and public safety. However, we recognize in our analysis that public safety systems merit particular attention because of the often critical nature of their communications. In analyzing the potential for harmful interference to public safety systems we took into account the fact that low-level Part 15 signals from Access BPL devices attenuate rapidly as the distance from the device increases; and that most public safety systems are designed so that mobile and portable units receive a signal level significantly above the noise floor. From an interference analysis standpoint, this latter characteristic distinguishes public safety systems from amateur radio stations using high-sensitivity receivers to receive signals from transmitters often thousands of miles away. However, it is foreseeable that under certain rare circumstances a public safety unit could: (a) operate in close proximity to an Access BPL device; (b) be tuned to a frequency radiated by the Access BPL device; and (c) be receiving a weak signal from a distant, or obstructed, public safety base station. In general, potential harmful interference under these conditions would be limited to public safety units operating on systems using low-band VHF channels (25-50 MHz). Therefore, it appears that the interference protections we propose herein -- and the strict "no interference" restriction inherent in the Part 15 rules -- will be adequate to foreclose such rare instances of harmful interference to public safety systems. While we tentatively conclude that the measures proposed herein are adequate, we request comment on whether any additional measures are needed to protect particular operations, such as public safety. For example, should we require Access BPL system to coordinate with public safety agencies that use the HF band for state-wide public safety communications?

38. Accordingly, we are proposing to maintain the existing Part 15 radiated emission limits for Access BPL systems and devices. In addition, we are proposing to exempt Access BPL systems from the existing conducted emission limits of Section 15.107(c). Because Access BPL systems are installed on power lines that can carry 1,000 volts to 40,000 volts, conducted emission measurements are very difficult to measure, and present safety hazards in connecting test equipment to these lines. We do not believe that this exemption would have any impact on interference potential since Access BPL would still be required to comply with our radiated emissions rules. We seek comment on these proposals. We further seek comment on whether Access BPL would in some instances operate in the AM broadcast band (from 535 to 1705 kHz), and whether specific conducted requirements are needed in such situations.

Access BPL Operational Requirements

39. Notwithstanding compliance with the Part 15 emission limits, we wish to emphasize that Access BPL would also operate under our Part 15 non-interference conditions. Thus, operations must cease if harmful interference to licensed services is caused. Given that there is significant investment in the deployment of the service, we agree with several commenters that Access BPL providers would have a strong incentive to

exercise the utmost caution in installing their systems to avoid harmful interference and ensure uninterrupted service to their customers. In addition, given the typical attachment of BPL products to medium voltage lines and the possible use of BPL systems to control and monitor the electrical system, we believe that Access BPL systems likely will be managed on a more controlled basis as compared to other typical Part 15 operations.

40. To further address the interference concerns raised in the *Inquiry*, we are proposing certain additional technical and administrative requirements for Access BPL. First, we are proposing to require that Access BPL systems and devices incorporate capabilities that would allow the operator to modify system performance to mitigate or avoid harmful interference to radio services. Such adaptive interference mitigation techniques would include, for example, the capability to reduce power levels on a dynamic or remote controlled basis, and the ability to include or exclude specific operating frequencies or bands. This capability would allow operators to avoid localized and site-specific harmful interference.

41. We believe that this requirement is reasonable and practicable for Access BPL operators and equipment manufacturers to implement. We observe that a number of Access BPL devices currently employ OFDM modulation techniques, which facilitate the ability to dynamically select the specific frequencies used to provide service and to avoid use of specific frequencies where operation might result in harmful interference. In this regard, we note that PowerWAN states that "notching" of specific frequency is technically feasible. Ambient indicates that its equipment will be able to notch out individual frequencies "on the fly," in response to short term changes in the RF environment. Main.Net states that it already has the capability to remotely control the operating frequencies and power of their installations."

8 Appendix D: Excerpt from CENELEC/ETSI JWG on EMC of wire-line telecommunications networks

A: Information on RF signal levels used for planning purposes for LF, MF, and HF broadcast radio services in the frequency range under consideration

The minimum duty field strength used for planning purposes for public broadcast radio services in the LF, MF, and HF range which should be protected are indicated in figure A.1.

The ITU recommendations specify a typical signal-to-noise ratio of 30 dB within the broadcasting radio frequency bands in the LF, MF and HF range.

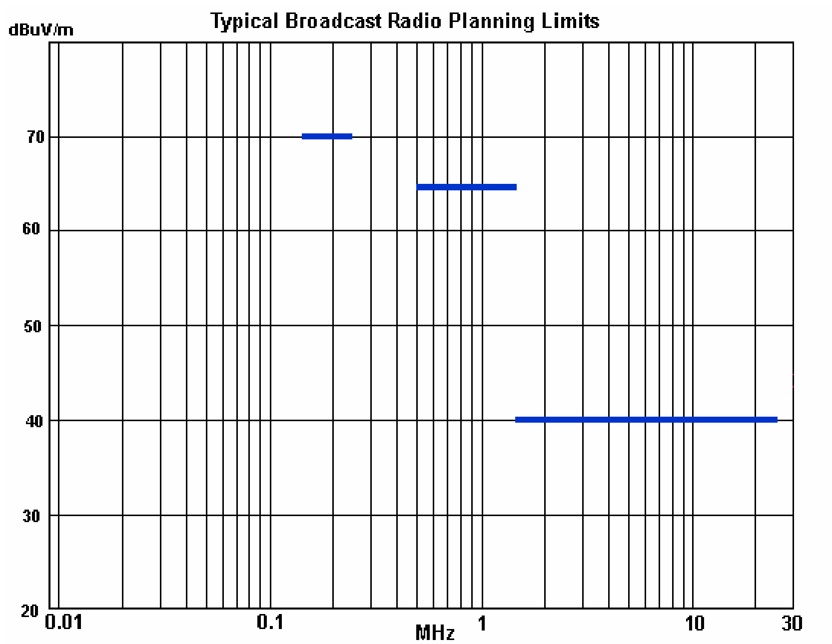

Figure A.1: Graph showing typical planning field strengths for broadcast radio services allocated in the frequency range 150 kHz – 30 MHz

B: Individual justifications for the limits proposed by the various parties contributing to the work of the JWG

Parties that contributed to the discussion on limits for disturbance emissions were invited to submit a brief reasoning for their proposals. These reasons are set out hereafter. Please note that the different reasons may not allow for direct comparison one another since being based on different coupling models and perspectives.

B.1 Reasoning for the proposal from CENELEC SC 205A to use limits derived from FCC Rules Part 15

The limits of the FCC Rules Part 15 have been applied in the USA and other countries of the American continent (e.g. Canada, Brazil, etc.) for many years. It has been proven that these limits work quite well and no problems have been reported with these limits to date. Many wire-bound broadband telecommunication systems comply with the same limits, e.g. Ethernet systems.

This is why CENELEC SC 205A proposes a flat limit, in the frequency range from 1,6 MHz - 30 MHz, based on the FCC Part 15 limit (i.e. 30 dB(µV/m) @ 30 m distance). As the CENELEC/ETSI JWG decided to define the standard measurement distance as 3 m, the limit is converted to 63 dB(µV/m) @ 3 m distance. The conversion was calculated based on an extrapolation factor of 33 dB per decade, which is actually lower than the FCC Part 15 extrapolation factor of 40 dB per decade, but is in line with CISPR 18.

Please note that the literal application of the extrapolation factor given in FCC Rules Part 15 would lead to a limit of 70 dB(µV/m) @ 3 m distance, for application to the telecommunication network.

Networks are not products and in order to be coherent with existing harmonised EMC product standards, the emission limit for incorporation into the network standard has to be a few dB above the existing limits for products, apparatus, or equipment. More stringent limits will never be recognized as being too stringent, but will only hinder access to the products' market and in consequence the market growth and development of the Information Society. Therefore it is the aim to propose realistic values for the emission limits.

However, if interference problems should arise, the limits could be corrected afterwards, e.g. during the maintenance of the generic emission standard for telecommunication networks.

B.2 Reasoning for the proposal to stay in line with the limits specified in EN 55022

This set of limits is proposed as the mandate M/313 requests that any standard produced under this mandate should be coherent with existing applicable harmonised product standards. The harmonised standard EN 55022 (used directly or referenced by EN 300 386) is the relevant standard for equipment used in a telecommunications network.

For frequencies below 30 MHz EN 55022 does not contain any radiated emission limits but specifies conducted limits at the telecommunications port for the common mode voltage or current. The measurement technique used further defines certain critical parameters (such as LCL and common mode impedance) to ensure that the influence of the network cabling, to which the product will be attached, is accounted for. These additional factors enable the interference potential to be assessed.

In order to relate these requirements to a radiated measurement under in-situ conditions a limit for the radiated magnetic field strength has been derived. The starting point for this derivation is the Class B telecommunications port common mode current limit. This limit has been selected as it is the one applicable to telecommunication ports and defines a limit for the maximum common mode current, and hence radiation, that could exist on the network cable due to unwanted common mode signals launched directly from the product and signals converted by the network cable from the wanted differential mode signals.

For a given common mode current (I) the resulting magnetic field (H) at a distance (r) from the cable has been calculated by:

$$H = I / (2 \cdot \pi \cdot r)$$

Note: all values are in linear units.

The magnetic field is then converted to an equivalent electric field strength using the far field relation of 51,5 dB.

B.3 Reasoning for the proposal to use the limits derived by Guellemann

Guellemann derived the limits based on considerations about the interference potential of point sources embedded in a given network or installation. The limits were discussed with the German telecommunication industry and network provider and were eventually taken onboard in a national standard dealing with the emissions from telecommunication networks and installations. However, their application remained in the voluntary domain. During that period in the Nineteen Seventies and Eighties, Guellemann's limits were actively and successfully used for the assessment and resolution of radio interferences caused by telecommunication networks or installations.

It is assumed that Guellemann's limits for radiated disturbance emissions in the frequency range 9 kHz to 30 MHz are approximately in line with the limits for conducted disturbance specified for the mains port in EN 55022 for class B equipment. Several studies conducted in Germany in the last years verify that the coupling model used by Guellemann is still valid and applicable.

B.4 Reasoning for the proposal to use the limits of NB 30

In the frequency range 9 kHz to 30 MHz, the limits of NB 30 were derived from the limits specified by Guellemann in the Nineteen Seventies. The NB 30 limits are 10 dB more stringent than Guellemann's limits in order to adapt to the evolving deployment of broadband communications.

B.5 Reasoning for the limits proposed by Norway

The limit proposed by Norway is derived from the limits for the AC mains port of class B equipment in the scope of EN 55022. On-site measurements were conducted in order to check the relationship between the asymmetric mode disturbance voltage present at the AC mains port (i.e. the voltage between phase and earth) and the resulting radiated field. It could be proven that an average conversion factor of -40 dB to -30 dB exists between the conducted voltages at the AC mains port and the resulting fields. It should be noted that the measurements were made while transmitting a broadband signal via the AC mains leads (phase/phase). More information on the measuring equipment and measurements is found in the report of CEPT/ERC Project Team SE35 "Power Lines Telecommunications (PLT) and cable transmissions in general".

B.6 Reasoning for the limits proposed by the BBC

This limit is derived from the concept of a permissible increase of 0,5 dB in the noise floor for outdoor reception at 10 m distance caused by a potentially interfering cable*. The pre-existing noise floor is defined as intermediate between the "Rural" and "Quiet rural", cases given in ITU-R Rec. P372, being considered to be typical of the RF noise levels found in suburban housing areas.

The limit is then derived assuming that the measurement distance is 1 m from the cable to the centre of the loop used to measure magnetic field strength:

The magnetic field strength is defined as

$$H_n \text{ (dB}\mu\text{A/m in 9 kHz, peak)} = -29{,}7 - 8{,}15 \log[10, f \text{ in MHz}]$$

Expressed as an electric field strength, the limit is defined as:

$$E_n \text{ (dB}\mu\text{V/m in 9 kHz, peak)} = 21{,}8 - 8{,}15 \log[10, f \text{ in MHz}]$$

The electric field limit is shown in the figure normalised to a measurement distance 3 metres rather than 1 metre, i.e. it is some 10 dB lower than the mathematical definition given above.

* It should be noted that for indoor reception the distance to the source of the interference is likely to be very much less than 10 m, leading to a noise floor increase substantially greater than 0,5dB.

C: Information on typical performance characteristics of CISPR measuring receivers in the frequency range up to 30 MHz which meet the requirements specified in CISPR 16

Figure C.1 shows the typical intrinsic noise figure of EMC emission measuring equipment meeting the requirements of CISPR 16. The graph shows the internal noise level indicated by a radio disturbance measurement receiver ESCS 30 combined with an active loop antenna HFH2-Z2. The measuring time is 1 s, the step width 6.3%, and the internal preamplifier of the measuring receiver is switched off.

The increase in sensitivity of the measuring receiver in the frequency range below 150 kHz is caused by switch over of the RF bandwidth from 9 kHz to 200 Hz. Due to the tightening of this bandwidth, the noise figure reduces by 16,53 dB:

$$L_{diff} \text{ (dB)} = -10 \log (9 \text{ kHz} / 0{,}2 \text{ kHz})$$

$$\text{Noise figure (dB}\mu\text{V/m) @ 200 Hz BW} = \text{Noise figure (dB/}\mu\text{V/m) @ 9 kHz BW} - L_{diff} \text{ (dB)}$$

Please note that EMC measuring equipment has been developed to deal with input signals normally higher than those occurring at antenna ports of receivers. Standard communications receivers with resonant input circuits achieve higher sensitivities than typical measurement equipment. CISPR based measurement equipment may therefore not be appropriate for measuring low signal levels.

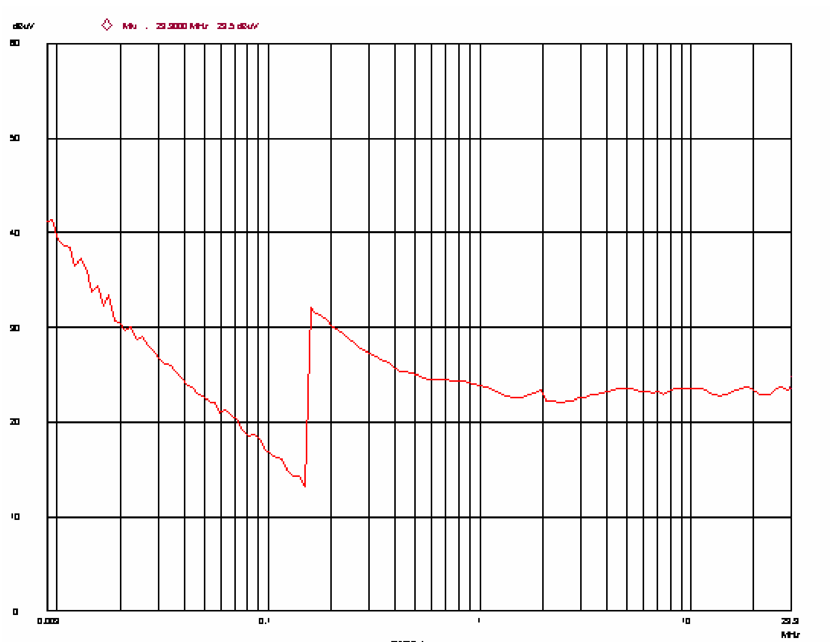

Figure C.1: Graph showing the internal noise level of a radio disturbance measuring receiver ESCS 30 combined with an active loop antenna HFH2-Z2

9 Appendix E: Excerpt from European Commission Radio Spectrum Committee Document: RSCM03-12, Date: 21May03

Introduction

Powerline Communication (PLC) systems have the potential to provide an alternative broadband infrastructure competing with local fixed telephony and cable networks. A faster roll-out of competitive broadband infrastructure will contribute to achieve the ten-year goal set at the Lisbon European Council for the EU to become the most competitive and dynamic knowledge-based economy in the world and, in this context, to achieve the commitment in the *e*Europe action plan for greater competition in local access networks.

The debate about PLC has been centred on interference aspects. However, assessments made using radio-regulatory interference models developed to co-ordinate between radio systems may not be appropriate. PLC as a guided medium has different interference properties, typically with larger statistical variations. Modern PLC systems do not seem to give rise to the same interference problems that characterised the first generation PLC systems and are flexible to adapt to interference situations, if and when such situations arise.

PLC cuts across the field of expertise and responsibility of different regulators and authorities and its deployment depends on overcoming regulatory barriers and finding a new balance between the interests of existing players and new entrants, allowing a co-existence of users of radio and guided media with the least possible restrictions on either side. This will need to include consideration of, on the one hand, the potential contribution of PLC towards realising the Lisbon goals, and, on the other hand, the need to avoid interference with existing services, in particular radio services.

This Working Document was developed by DG Information Society and DG Enterprise to allow an exchange of view on the barriers that are currently holding up the deployment of PLC services in the EU and to explore ways to achieve the co-existence of PLC systems with other systems.

DRAFT

Annex: Radiated emission level of PLC equipment

The emissions from a PLC-equipment in the frequency range 1,6 MHz to 30 MHz shall not exceed the field strength level of [ ] [1].

The limits are based on measuring equipment employing a CISPR quasi-peak detector function and a measurement bandwidth of 9 kHz. The quasi-peak measuring receiver shall be in accordance with subclause 4.1 of CISPR 16-1[2].

Measurements shall be made on an open field site and shall be performed at a minimum of three installations that can be demonstrated to be representative of typical installation sites.

To the extent practicable, the device under test shall be measured at the distance specified, which corresponds to the horizontal distance between the measurement antenna and the closest point of the equipment under test, support equipment or interconnecting cables as determined by the boundary defined by an imaginary straight line periphery describing a simple geometric configuration enclosing the system containing the equipment under test. The equipment under test, support equipment and any interconnecting cables shall be included within this boundary.

Measurements may be performed at a distance closer than that specified above; however, an attempt should be made to avoid making measurements in the near field. When performing measurements at a closer distance than specified, the results shall be extrapolated to the specified distance by either making measurements at a minimum of two distances on at least one radial to determine the proper extrapolation factor or by using the square of an inverse linear distance extrapolation factor [ ][3].

The extrapolation method used shall be specified in the Declaration of Conformity together with the measurement data.

Measurements shall be performed at a sufficient number of radials around the equipment under test to determine the radial at which the field strength values of the radiated emissions are maximized. The maximum field strength at the frequency being measured shall be reported in the Declaration of Conformity.

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1 The draft network standard developed by the JWG ETSI/CENELEC establishes a level of 22,5 dBµV/m at a measurement distance of 30 meters. This figure is derived from CISPR22 (or EN55022) for telecom ports which leads to a limit for radiated emissions of 55,5 dBµV at a measurement distance of 3 meters (or 22,5 dBµV/m at 30 meters using the extrapolation factor in footnote 3).

2 CISPR 16-1:1999, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1: Radio disturbance and immunity measuring apparatus*

3 CISPR 18-3: 1986*, Radio interference characteristics of overhead power lines and high-voltage equipment. Part 3: Code of practice for minimizing the generation of radio noise* – "high voltage power line", section 3.2.5 establishes an extrapolation factor of 33 dB/decade. This gives an appropriate description of the mixed behaviour of a powerline between a line and a point source.

10 Appendix F: Modulation - OFDM

The Orthogonal Frequency Division Multiplexing (OFDM) modulation technique employs methods that allow high speed data transmission over a noisy and unpredictable mediums (such as wireless or powerline) while maintaining low Bit Error Rates (BER) at relatively low Signal to Noise Ratios (SNR).

OFDM allows a transmitter to "pack" a relatively high data transmission rate into a relatively low frequency band. The table below provides an example of possible raw bit rates achievable with various modulation methods (given a 15MHz frequency band (between 5MHz and 20MHz).

Modulation Method	Raw Bandwidth (approximately)
BPSK	10 MBPS
QPSK	20 MBPS
16-QAM	40 MBPS
64-QAM	60 MBPS

OFDM transmits a high-speed bit stream by de-multiplexing it into multiple parallel lower-rate streams, each of which modulates separate but closely spaced carriers. When the carrier spacing is set equal to the inverse of the bit rate on each carrier, the signals on each carrier are orthogonal.

In practical terms, if a receiver performs an FFT of the received waveform over a time span equal to the bit rate on an individual carrier, the value of each point in the FFT output is a function only of the bit (or bits) that modulated the corresponding carrier, and is not impacted at all by the data modulating any other carrier.

The motivation for using multiple carriers comes from the frequency-selective nature of the communication channel. While single-carrier modulations can be used for such channels, they require complicated adaptive equalizers to correct the channel, and, in an environment where the source of a given transmission is not immediately known, training the equalizer can be challenging.

In the general case, OFDM has the advantage that when carrier spacing is small, the channel equalization problem becomes a simple scaling.

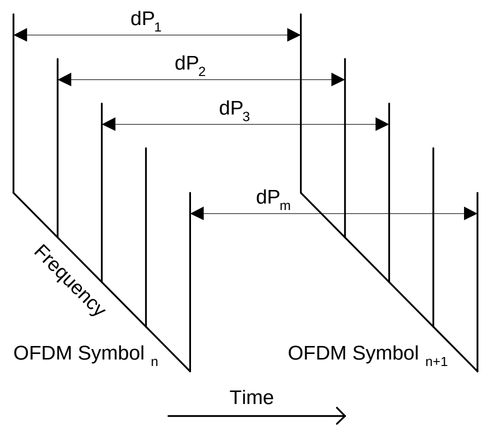

Figure 1. Differential phase encoding across symbols

Most OFDM implementations use an inverse FFT (IFFT) to generate the waveform samples. The frequency domain points input to the IFFT consist of the set of complex symbols that modulate each carrier. The output of the IFFT is a set of time domain samples that span an interval of time equal to the inverse of the carrier spacing. Figure 1 shows the process of conversion between the frequency domain and the time domain.

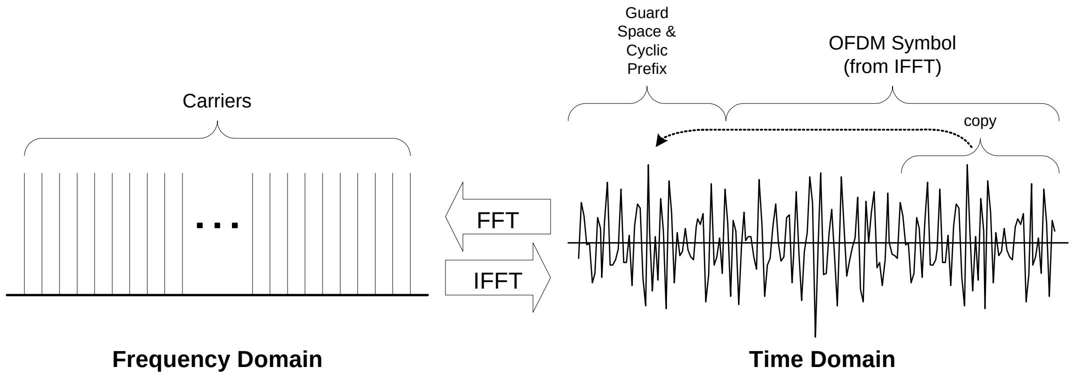

Figure 2. Transform from the frequency to the time domain and adding the cyclic prefix

In many cases, the channel introduces group delay distortion. This means that signals at some frequencies encounter more delay than signals at other frequencies.

In the absence of any measures to mitigate against group delay variation, the interval used by the receiver to form its FFT would be unable to avoid containing energy from symbols other than the desired symbol. The “cyclic prefix” (shown in Figure 2) is part of a technique that solves this problem, although at the expense of some throughput.

The transmitter copies a section of the end of the sample’s output by the IFFT, and places them at the beginning of the time domain sample set prior to transmission. If the duration of this prefix exceeds the variation in delay across the frequency band of interest, then it will be possible to form an FFT over samples that are not influenced by the previous or following OFDM symbols.