BS EN 62488-1:2013

BSI Standards Publication

Power line communication systems for power utility applications

Part 1: Planning of analogue and digital power line carrier systems operating over EHV/HV/MV electricity grids

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National foreword

This British Standard is the UK implementation of EN 62488-1:2013. It is identical to IEC 62488-1:2012. It supersedes BS EN 60495:1994 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/57, Power systems management and associated information exchange.

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English version

Power line communication systems for power utility applications - Part 1: Planning of analogue and digital power line carrier systems operating over EHV/HV/MV electricity grids

(IEC 62488-1:2012)

Systèmes de communication sur lignes d'énergie pour les applications des compagnies d'électricité -
Partie 1: Conception des systèmes à courants porteurs de lignes d'énergie analogiques et numériques fonctionnant sur des réseaux d'électricité EHT/HT/MT
(CEI 62488-1:2012)

Systeme zur Kommunikation über Hochspannungsleitungen für Anwendungen der elektrischen Energieversorgung -
Teil 1: Planung von Systemen zur analogen und digitalen Nachrichtenübertragung über Hochspannungsleitungen
(IEC 62488-1:2012)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
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Foreword

The text of document 57/1279/FDIS, future edition 1 of IEC 62488-1, prepared by IEC/TC 57 "Power systems management and associated information exchange" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62488-1:2013.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2013-10-03
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2016-01-03

This document supersedes EN 60495:1994.

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In the official version, for Bibliography, the following notes have to be added for the standards indicated:

CISPR 22:2008	NOTE	Harmonised as EN 55022:2010 (modified).
IEC 60038:2009	NOTE	Harmonised as EN 60038:2011 (modified).
IEC 60044-1:1996	NOTE	Harmonised as EN 60044-1:1999 (modified).
IEC 60255-5:2000	NOTE	Harmonised as EN 60255-5:2001 (not modified).
IEC 60255-22-1:2007	NOTE	Harmonised as EN 60255-22-1:2008 (not modified).
IEC 60255-151:2009	NOTE	Harmonised as EN 60255-151:2009 (not modified).
IEC 60358-1:2012	NOTE	Harmonised as EN 60358-1:2012 (not modified).
IEC 60721-3-1:1987 + A1:1991	NOTE	Harmonised as EN 60721-3-1:1993 (not modified).
IEC 60721-3-2:1997	NOTE	Harmonised as EN 60721-3-2:1997 (not modified).
IEC 60721-3-3:1994	NOTE	Harmonised as EN 60721-3-3:1995 (not modified).
IEC 60721-3-4:1995	NOTE	Harmonised as EN 60721-3-4:1995 (not modified).
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IEC 61000-4-2	NOTE	Harmonised as EN 61000-4-2.
IEC 61000-4-3	NOTE	Harmonised as EN 61000-4-3.
IEC 61000-4-4	NOTE	Harmonised as EN 61000-4-4.
IEC 61000-4-5	NOTE	Harmonised as EN 61000-4-5.

CONTENTS

INTRODUCTION

The complexity and extensive size of present-day electricity generation, transmission and distribution systems are such that it is possible to control them only by means of an associated and often equally large and complex telecommunication system having a high order of reliability.

The control of electrical networks and transmission and reception of data are through a combination of analogue and digital communication systems controlling devices and systems distributed throughout the electrical network.

The emergence of digital communication systems for controlling the devices of the electrical distribution network enables faster data transmission. The ability to represent the various electrical parameters as an analogue signal and or digital signal ensures the quality and quantitative aspects of seamless communication to be maintained throughout the electrical power network.

Therefore, by using either analogue power line communication (APLC) or digital power line communication (DPLC) or a combination of both types of system, seamless efficient communication may be maintained throughout the power network.

The development of digital techniques for communications in the electrical distribution networks is now very widespread along with other applications in electronics. This is especially relevant for the electrical distribution network where many of the devices have built into them analogue to digital converters, together with digital signal processing enabling them to perform many functions and offer fast seamless communication. The conversion of the analogue signal into a binary signal requires the binary digits to be formed into a code for the transmission of the information. These codes take different forms to represent the information to be transmitted. However, the main advantage for this is that digital signals compared with analogue signals provide for virtually error free transmission and the minimum errors that do arise may be detected and corrected by using suitable data encoding techniques. Further, digital transmission circuits generally are compatible with the digital devices in the communications circuit. The most commonly used multiplex systems are frequency division multiplex (FDM) and time division multiplex (TDM).

The development of the technical report “Planning of power line carrier systems” was first produced by the International Electrotechnical Commission through publication IEC 60663 in 1980 entitled Planning of (single sideband) power line carrier systems. In 1993, the International Electrotechnical Commission produced IEC 60495 “Single sideband power-line carrier terminals”. In the intervening years, electronic systems and the associated communications systems for electronic devices evolved and developed considerably. The introduction of digital transmission and reception techniques improved the quality of transmission and reception within electronic devices, enabling them to provide more detailed quality analysis and control of the data being communicated throughout the electricity distribution network, from control centre to service provider.

Both of these standards, IEC 60663 and IEC 60495, are being updated and replaced by the following: IEC 60663 is replaced by IEC 62488-1 and IEC 60495 is replaced by IEC 62488-2, IEC 62488-3, IEC 62488-4, covering respectively analogue, digital power line carrier and broadband power line terminals.

The first part of this series is IEC 62488-1. Following this standard, parts IEC 62488-2, IEC 62488-3, IEC 62488-4 will follow. During the development of the above mentioned standards, the existing standards IEC 60663 and IEC 60495 will be maintained in use. They will be subsequently phased out at a date to be agreed by the International Electrotechnical Commission in conjunction with IEC technical committee 57.

These international standards apply to power line carrier (PLC) terminals used to transmit information over power networks including extra high, high and medium voltage (EHV/HV/MV) power lines. Both analogue and digital modulation systems will be included.

IEC 62488 series consists of the following parts under the general title: Power line communication systems for power utility applications:

Part 1: Planning of analogue and digital power line carrier systems operating over EHV/HV/MV electricity grids;

Part 2: Analogue power line terminals or APLC;

Part 3: Digital power line carrier terminals or DPLC;

Part 4: Broadband power line systems or BPL.

POWER LINE COMMUNICATION SYSTEMS FOR POWER UTILITY APPLICATIONS –

Part 1: Planning of analogue and digital power line carrier systems operating over EHV/HV/MV electricity grids

1 Scope

This part of IEC 62488 applies to the planning of analogue and digital power line carrier systems operating over EHV/HV/MV electricity grids. The object of this standard is to establish the planning of the services and performance parameters for the operational requirements to transmit and receive data efficiently over Power Networks.

The transmission media used by the different electricity supply industries will include analogue and digital systems together with more common communication services including national telecommunications authorities, radio links and fibre optic networks and satellite networks. With the developments in communication infrastructures over the last two decades and the ability of devices connected in the electricity communications network to internally and externally communicate, there is a variety of architectures to use in the electricity distribution network to provide efficient seamless communications.

These series of standards for the planning of power line carrier systems will also be an integral part of the development of the overall architecture, standard IEC 61850 developed within IEC TC57 which provides the fundamental architecture for the formation of the smart grid.

2 Terms, definitions and abbreviations

2.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

NOTE Other terms used in this standard and not defined in this clause have the meaning attributed to them according to the International Electrotechnical Vocabulary (IEV).

2.1.1
amplitude modulation
AM
modulation technique in which information is transmitted through amplitude variation of a carrier wave

2.1.2
analogue interface
interface dedicated to the processing of voiceband analogue signals

2.1.3
anomaly
small discrepancy between the actually received and the desired data

Note 1 to entry: The occurrence of a single anomaly does not cause interruptions of the applications using the transmitted data.

2.1.4
attenuation
power reduction along a transmission line for the mode or modes under consideration, quantitatively expressed either by the ratio or the logarithm of the ratio of an input power at the initial point to the corresponding output power at the final point

2.1.5
availability
time or fraction of time a system is operational over a given time interval

2.1.6
background noise
noise present over all real high voltage power-line channels due mainly to corona and, partial discharges and electromagnetic interference with other PLC equipments operated over the same electricity grid and other interferences due to radio stations working in the same radio frequency spectrum

2.1.7
bit error ratio
BER
ratio of the number of bits errors received divided by the total number of bits sent

2.1.8
bit error ratio test
BERT
set of instruments and measurement methodology to be adopted to evaluate the BER of a transmission system

2.1.9
broadband over power line
BPL
technology that allows data to be transmitted over utility power lines using bandwidths of several MHz

Note 1 to entry: These systems typically run over a frequency spectrum in a range from 1 MHz to 30 MHz allowing the transmission of broadband communications. These systems can be found on all the range of power lines from LV to MV. The BPL systems are means to deliver broadband communications to homes and business facilities. Among the BPL systems, we can distinguish the systems used outsides the homes or offices (to-the-home-internet access also called access BPL or smart-grid applications operated by the electricity companies) and the “in-home” or “in-house” applications used for home networking (Generally using an Ethernet network technology) and automation. These applications are generally called Home Plug applications.

2.1.10
carrier-frequency range
bandwidth available for a specific power line carrier communication technology

Note 1 to entry: In Europe, the typical carrier-frequency range for narrowband HV PLC is 3 kHz to 148,5 kHz or for broadband PLC is 1,6 MHz to 30 MHz. For the USA IEEE PLC standard the frequency range is 45 kHz to 450 kHz. Parts of the range may be barred by national regulations.

2.1.11
channelling
elementary subdivision of the carrier frequency range or part thereof allocated to a single PLC transmits and receive channel (bidirectional)

2.1.12
code division multiple access
CDMA
multiple access technique in which a number of transmitters modulate their data on pseudo random signals which are orthogonal to each other, which prevents the demodulators from seeing signals other than their own

2.1.13
coloured noise
non-white noise or any wideband noise whose spectrum has a non-flat shape

Note 1 to entry: Also called non-white noise; examples are pink noise, brown noise and autoregressive noise.

2.1.14
corona noise
noise caused by partial discharges on insulators and in air surrounding electrical conductors of overhead power lines

Note 1 to entry: Discharges occur on the three different phase conductors at different times. The corona noise level is considerably dependent on weather conditions. The effect of the corona noise is particularly strong under foul weather conditions.

2.1.15
coupling capacitor
capacitor used for the coupling of the carrier signal to the power line in a PLC system

2.1.16
coupling system
group of devices used to couple the PLC high frequency signals to the power line

2.1.17
defect
large discrepancy between the actually received and the desired data

Note 1 to entry: Defects cause interruptions of the applications using the transmitted data and are used as input for performance monitoring, the control of consequent actions, and the determination of fault causes.
Examples are: loss of signal, sync loss, alarm indication signal, slip, loss of frame alignment.

2.1.18
distribution line carrier
DLC
system for communication over the distribution power lines

Note 1 to entry: They DLC systems can be narrow band high speed communication systems on the medium voltage distribution network, or broadband/narrow band communication systems on the low voltage distribution network.

2.1.19
effectively transmitted signal-frequency band
that part of the frequency band used for the transmission of the baseband signal

2.1.20
environment
external conditions in which a system operates

Note 1 to entry: Different classes of constraints and limits for EMC/EMI are defined for environment classes such as industrial, commercial, domestic.

2.1.21
error free second
EFS
a one second period without bit error

2.1.22
errored second
ES
a one-second period in which one or more bits are in error

2.1.23
errored second ratio
ESR
ratio of errored seconds ES to total seconds in available time during a fixed measurement interval

2.1.24
Ethernet interface
interface dedicated to the processing of data signals in accordance with the recommendation IEEE 802.3 (2000)

2.1.25
forward error correction
technique used for correcting errors in data transmission over unreliable or noisy communication channels by encoding the message at the sender in a redundant way by using an error-correcting code so as to enable the receiver to correct a limited number of bit errors

2.1.26
frame check sequence
FCS
extra bits or characters added to a data frame for error detection

2.1.27
frame loss rate
the number of frames that never reached the destination divided by the number of frames transmitted successfully by the source

Note 1 to entry: It is usually expressed as a percentage.

2.1.28
frequency division multiplexing
FDM
multiplexing technique in which several transmitters are allotted separate frequency bands for transmission over a common channel

2.1.29
frequency shift keying modulation
FSK
a frequency modulation technique in which coded information is transmitted through discrete frequency changes of a carrier wave

2.1.30
gross data rate
number of bits per unit of time exchanged between the terminals of a PLC link

2.1.31
group delay
propagation time of a narrowband signal from input to output of a linear system

Note 1 to entry: Mathematically, group delay equals the negative derivative of the phase shift in radians between input and output of a linear system versus angular frequency.

2.1.32
impulsive noise
noise consisting of short-duration pulses of random amplitude and random duration

2.1.33
jitter
short-term variations of the significant instants of a timing signal from their ideal positions in time (where short-term implies that these variations are of frequency greater than or equal to 10 Hz)

2.1.34
latency
time from the source sending a packet into a packet switched network to the destination receiving it

Note 1 to entry: One-way latency is distinguished from round trip latency, which is the one-way latency from source to destination plus the one-way latency from the destination back to the source. Round-trip latency is more often quoted, because it can be measured from a single point. Note that round trip latency excludes the amount of time that a destination system spends processing the packet.

2.1.35
line matching unit
LMU
unit which interfaces the EHV/HV side of power line with the PLC equipment

Note 1 to entry: It usually consists of a box mounted near the coupling capacitor. Its characteristics are normalized by IEC 60481.

2.1.36
line trap
a device presenting high impedance at the carrier frequency band while introducing negligible impedance at the power frequency

Note 1 to entry: The high impedance limits the power of the carrier signal within the power system. Line traps are connected in series with transmission lines. In most cases the Line trap is mounted directly on top of the coupling capacitor. Its characteristics are normalized by IEC 60353.

2.1.37
modulation scheme
technique used to convert a baseband signal into a high frequency carrier signal suitable for transmission over power line

Note 1 to entry: Examples are: AM-SSB, Spread Spectrum, QAM, OFDM.

2.1.38
multiplexing techniques
method by which multiple analog message signals or digital data streams are combined into one signal over a shared medium

2.1.39
narrowband noise
noise process with a narrow bandwidth such as a 50/60 Hz ‘hum’ from the electricity supply

2.1.40
nominal high frequency band
frequency band in which a particular PLC transmitter or receiver is operating within the carrier-frequency range

2.1.41
nominal impedance
value of impedance for which an input or output circuit has been designed and for which the prescribed requirements apply

2.1.42
operating conditions
set of conditions (e.g., voltage, temperature, humidity, and the like) over which the specified parameters maintain their stated performance rating

2.1.43
orthogonal frequency division multiplexing
OFDM
modulation scheme that distributes the data over a large number of sub-carriers with frequencies such that the sub-carriers are orthogonal, which prevents the demodulators from seeing sub-carriers other than their own

Note 1 to entry: Each sub-carrier is modulated with a conventional modulation scheme (such as QAM or PSK) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

2.1.44
peak envelope power
PEP
average power of a carrier signal present during one cycle of the carrier-frequency at the highest crest of the modulation

Note 1 to entry: It is recommended that in order to determine the peak envelope power, the transmitter should be modulated by two sinusoidal voice-frequency signals of equal amplitude, located within the effectively transmitted frequency band. The transmitter is terminated by a resistive load equal to its nominal impedance and the limiter is not in operation. The amplitude of the modulation signals must be chosen as to satisfy the requirements for spurious emissions. The peak envelope power is then considered to be four times the power of one of these signals, selectively measured (CCIR Recommendation 326-1, point 3.1.3.1).

2.1.45
peak to average power ratio
PAPR
peak power of a signal divided by its average power

2.1.46
phase shift keying
PSK
modulation scheme that conveys data by changing, or modulating, the phase carrier signal

2.1.47
PLC mean output power
output power of a PLC terminal averaged over a time sufficiently long compared with the cycle time of the lowest modulating frequency and during which this average power assumes the highest value for which the equipment has been designed

2.1.48
PLC nominal output power
output power of a PLC terminal expressed as the peak envelope power (PEP) for which the equipment has been designed, compatible with the requirements for spurious emissions, available at the carrier frequency output across a resistive load equal to the nominal impedance

2.1.49
PLC terminal equipment
equipment able to manage a telecommunication link over a high voltage power line, mainly used to reliably transmit speech, data and power system protection signals

2.1.50
power line
installation used to transfer electric energy from one point to another in an electric power system

2.1.51
quadrature amplitude modulation
QAM
analog or digital modulation scheme conveying two analog message signals, or two digital bit streams, by changing (modulating) the amplitudes of two carrier waves with 90° phase difference, using the amplitude-shift keying (ASK) digital modulation scheme or amplitude modulation (AM) analog modulation scheme

2.1.52
quality objective
specified level of quality that shall be met by a system to be deemed acceptable

Note 1 to entry: In speech communication, quality objectives can be subjective when listeners judge transmission quality by qualifiers such as excellent, good, fair, poor or unsatisfactory.

2.1.53
quality of service
QoS
defined measure of performance in a data communications system

2.1.54
reliability
degree of the ability of a system to consistently perform according to its specifications

2.1.55
return loss
loss of signal power resulting from the reflection caused by impedance mismatch

Note 1 to entry: The return loss is usually expressed as a ratio in decibels (dB).

2.1.56
sensitivity level
minimum power level of an HF signal to be applied at the receiver input in order to sustain the maximum specified data throughput affected by a predefined BER

Note 1 to entry: Example: sensitivity level = –60 dBm at 64 kb/s and BER=10^{-6}.

2.1.57
serial interface
interface dedicated to the processing of serial type data signals

2.1.58
severely errored second
SES
a one-second period which has a bit error ratio $\geq 10^{-3}$ or during which loss of signal (LOS) or alarm indication signal (AIS) is detected

2.1.59
severely errored second ratio
SESR
ratio of severely errored seconds SES to total seconds in available time during a fixed measurement interval

2.1.60
single side band modulation
AM-SSB
refinement of amplitude modulation that more efficiently uses electrical power and bandwidth

2.1.61
signal to noise ratio
SNR
ratio between the signal power and the noise power

2.1.62
smart grid
application of computer intelligence and networking abilities to the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements, from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances and other household devices

2.1.63
spurious emissions
emissions at one or more frequencies, which are located outside the nominal carrier-frequency band

Note 1 to entry: Spurious emissions comprise harmonics, parasitic signals and intermodulation products.

2.1.64
tapping loss
measure of the loss of power sustained by a carrier frequency signal when connected to the carrier output of a PLC equipment

2.1.65
telecommunication management network
TMN
architecture for management, including planning, provisioning, installation, maintenance, operation and administration of telecommunications equipment, networks and services

Note 1 to entry: TMN uses the OSI management standards as its framework and applies to all telecommunication technologies: wired, wireless as well as to private and public networks.

2.1.66
throughput
number of bits per unit of time available at the user data interface of a PLC link

2.1.67
time division multiple access
TDMA
multiple access technique using TDM

2.1.68
time division multiplexing
TDM
multiplexing technique in which several transmitters are allocated separate periodic time intervals for transmission over a common channel

2.1.69
transient noise
noise consisting of relatively long duration noise pulses

2.1.70
wander
long-term variations of the significant instants of a digital signal from their ideal position in time (where long-term implies that these variations are of frequency less than 10 Hz)

2.1.71
white noise
purely random noise that has a flat power spectrum

Note 1 to entry: Band limited white noise refers to noise with a flat spectrum and a limited bandwidth.

2.2 Abbreviations

ADSL	asymmetrical digital subscriber line
AGC	automatic gain control
AIS	alarm indication signal
AM	amplitude modulation
APLC	analogue power line carrier
AWGN	additive white Gaussian noise
BER	bit error rate
BERT	bit error rate test
BPL	broadband over power line
CC	coupling capacitor
CDMA	code division multiple access
CENELEC	comité européen de normalisation électrotechnique
CF	carrier frequency
CISPR	comité international spécial des perturbations radioélectrotechniques
CSMA/CD	carrier sense multiple access with collision detection
CVT	capacitor voltage transformer
DLC	distribution line carrier
DPLC	digital power line carrier
E&M	ear and mouth (telephone signalling wires)
EFS	error free second
EHV	extra high voltage
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EPS	electricity power system
ES	errored second
ESR	errored second ratio
ETH	Ethernet
ETSI	European telecommunications standards institute
FCS	frame check sequence
FDM	frequency division multiplexing
FIR	finite impulse response
FSK	frequency shift keying
FXO	foreign exchange office
FXS	foreign exchange subscriber
GMR	geometric mean radius
HF	high frequency
HTTP	hypertext transfer protocol
HV	high voltage

ICAO	international civil aviation organization
IEEE	institute of electrical and electronics engineers
IETF	internet engineering task force
IEV	International Electrotechnical Vocabulary
IP	internet protocol
ISO	international organisation for standardisation
ITU	international telecommunications union
LAN	local area network
LMS	least mean squares
LMU	line matching unit
LOS	loss of signal
LV	low voltage
MAC	media access control
MOS	mean opinion score
MV	medium voltage
NAT	network address translation
NIC	network information center
OFDM	orthogonal frequency-division multiplexing
OPGW	optical ground wire
OSI	open system interconnection
OSPF	open shortest path first
PABX	private automatic branch exchange
PAM	pulse amplitude modulation
PAPR	peak to average power ratio
PEP	peak envelope power
PESQ	perceptual evaluation of speech quality
PLC	power line carrier
PLCS	power line communication system
PLT	power line telecommunications
PSK	phase shift keying
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
REN	renewable energy
RIP	routing information protocol
RMS	root mean square
RTU	remote terminal unit
Rx	receive(r)
SCADA	supervisory control and data acquisition
SDA	synchronous digital hierarchy
SES	severely errored second
SESR	severely errored second ratio
SNMP	simple network management protocol

SNR	signal to noise ratio
SSB	single side band
TCP	transmission control protocol
TDM	time division multiplexing
TDMA	time division multiple access
Tx	transmit(ter)
UDP	user datagram protocol
VDSL	very-high-bit-rate digital subscriber line
VoIP	voice over IP
WAN	wide area network
Wi-Fi	Wireless Fidelity

3 Power line communication systems

3.1 Introduction to PLC

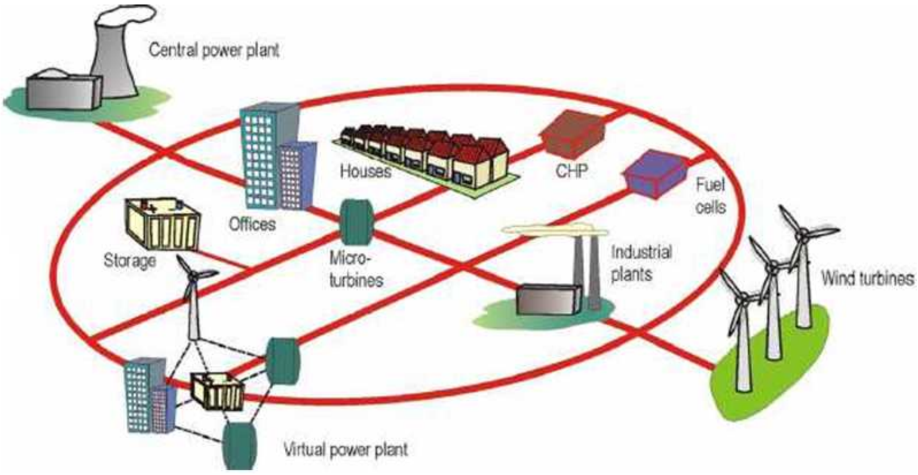
3.2 PLC usage

The electrical grids have been relatively steady from the middle of the 20th century until the 1980's when the digital processing techniques began to be of common use.

Since that time, the constant evolution in the telecom electronic and the need for more reliable power network have brought the PLC from single point to point link equipment used mainly for supporting teleprotection service and simple PABX interconnection to extend telephony service to modern networking equipment that can be used in service oriented telecom architectures.

The modern power line carrier system can be integrated into IP communication network interconnecting nodes at data link level as point to point links (on HV and EHV networks) or as part of the network itself (multipoint broadband applications on the MV and LV networks).

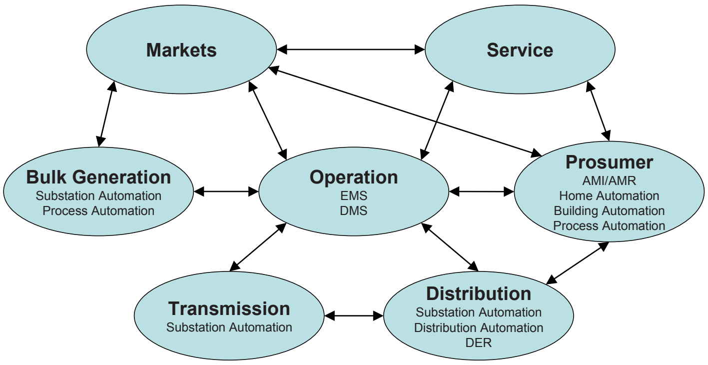
In addition, this new architecture provides solutions for management, control and monitoring of the equipment (SNMP capabilities mainly) that reduce the cost of commissioning and maintenance.



(Source: COM/2006/0105 final GREEN PAPER – A European Strategy for Sustainable, Competitive and Secure Energy)

Figure 1 – Smart grid vision

Current electricity grids are developing into smart grids, increasing the number of electricity business players' demand for an improvement in terms of communication resources. PLC will play a key role on this arena. An example of the smart grid is shown in Figure 1.



(Source: IEC SMB/SG3 SMART GRID Survey – 2009)

Figure 2 – Smart grid players

They are ubiquitous and represent a well proven technology since long time exploited in any segment of the electricity grids from EHV/HV/MV to LV providing for very successful applications. An example is shown in Figure 2.

3.3 PLC telecommunication system

A PLC telecommunication system consists of one of more PLC links together with other telecommunications such as SDH communications. They can form a network of PLC or part of it. An example is shown in Figure 3.

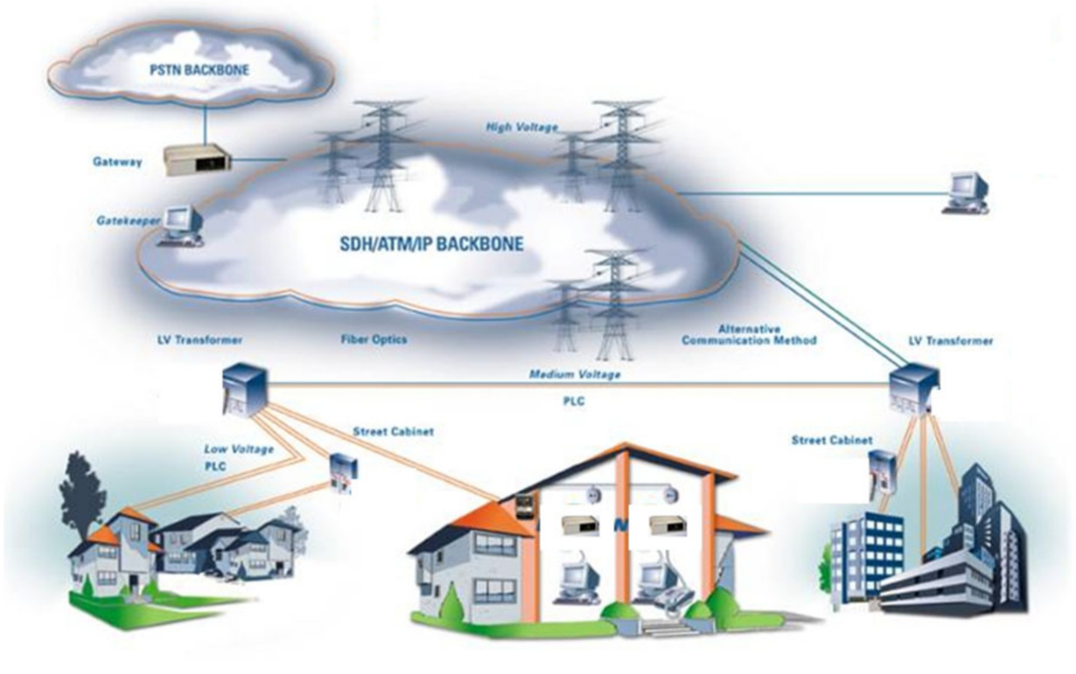


Figure 3 – Complex PLC telecommunication system

According to the definition each PLC telecommunication link consists of:

- two PLC terminals,
- two coupling systems,

– an electricity power line (EHV/HV/MV).

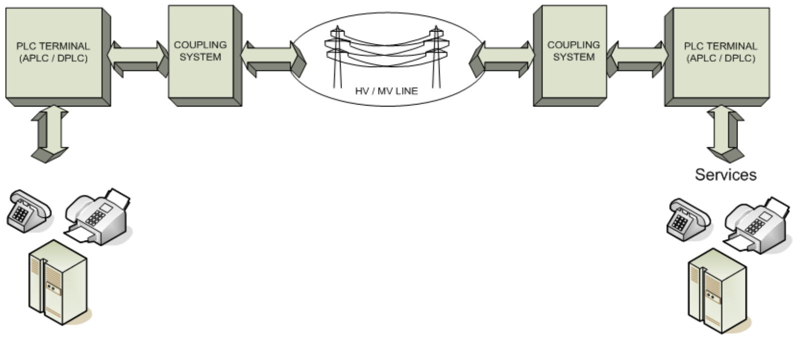


Figure 4 – PLC telecommunication link

Terminal equipments can be divided in two categories: Analogue PLC equipments and Digital PLC equipments respectively named APLC and DPLC systems. A general description of such equipments focusing on their main technical features is provided in the followings paragraphs. An example of this type of link is shown in Figure 4.

Detailed aspects concerning the power line transmission media and coupling systems are described in Clause 5.

Refer to Annex A regarding environmental conditions and Annex B regarding EMC for PLC equipment.

3.4 Analogue and digital PLC systems (APLC & DPLC)

3.4.1 APLC systems

APLC systems, as shown in Figure 5 have been in use from the 1930s and are commonly used by the electricity utilities for their communication (teleprotection, telephone and data, fax) mainly on the EHV and HV electricity transmission grid.

The modulation scheme generally used for these systems is the single sideband (SSB) amplitude modulation to carry one or several basic telephone channels in the carrier range from 20 kHz to 500 kHz (sometimes extended to 1 MHz).

When more than one service is required, the services are mixed using frequency-division multiplexing. The main limitation of APLC systems is the data rate which is limited to some hundred bps per service because of the limited bandwidth and the nature of the modulation.

In the following, some of the most used technologies within APLC systems are listed:

- Frequency-division multiplexing;
- Single sideband modulation;
- Channel equalisation;
- FSK modem (rates $\leq$ 2 400 bit/s);
- PSK or QPSK modem (rates $>$ 600 bit/s).

A typical APLC terminal equipment structure is given in Figure 5.

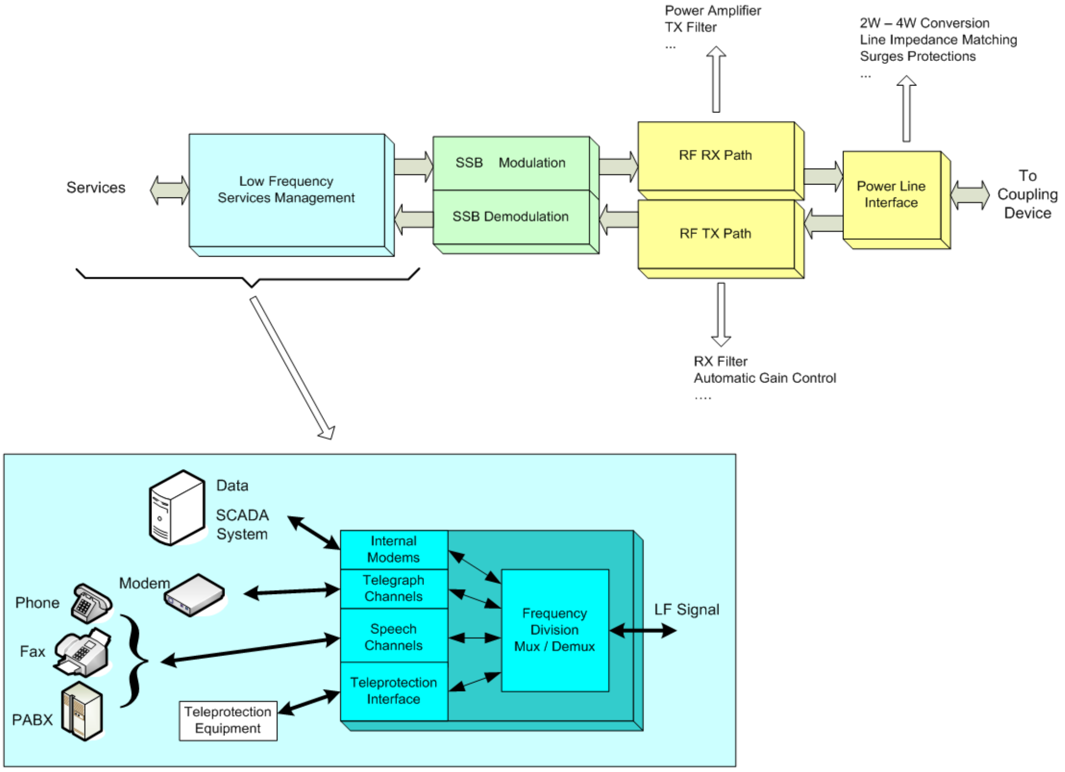


Figure 5 – Typical structure of an APLC terminal equipment

3.4.2 DPLC systems

From the early 1980s, there has been a wide interest in developing PLC systems based on digital modulation schemes. The original information can be either data in its original format or digitised signals, such as speech, fax or others.

When more than one service is to be transmitted, digital PLC makes use of time division multiplexing to arrange the different services into a single stream.

The main advantage of digital PLC links as compared to analogue PLC links are the following:

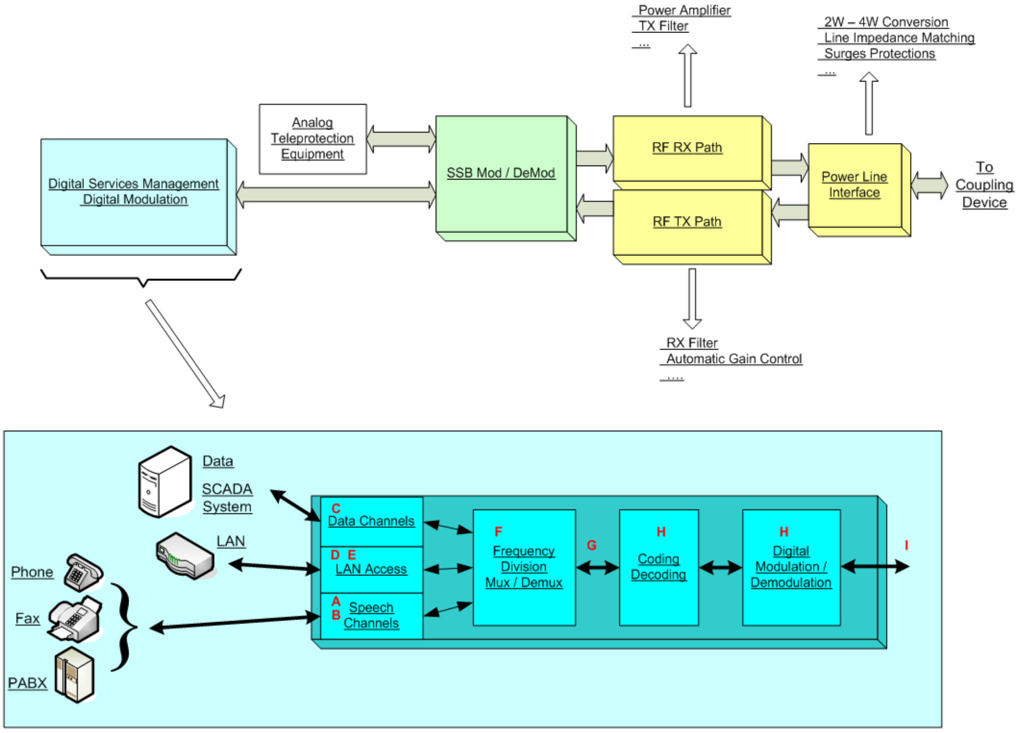
a) Enhancing the transmission capacity compared with traditional analogue PLC links for the same channel bandwidth:
   - more data channels (or data channels running at higher rates);
   - more speech channels using vocoding techniques.
b) Easy integration of the PLC network into a larger digital network (digital PLC as an embedded component of a digital telecommunications network):
   - n × 64 kbps channel as a tributary channel of a digital telecom network;
   - Digital data interfaces for lower speed data avoiding intermediate modems;
   - Data rate of DPLC allow their use for LAN to LAN connection (typically through an Ethernet access);
   - A native network access provide an easy way to integrate the DPLC links in a network management system.
c) The use of time-division multiplexing provides greater degrees of flexibility as compared to frequency-division multiplexing.

Digital PLC links can be used in access links or network internal links, for the transmission of speech, data and teleprotection related signals.

In the following, some of the most used technologies within DPLC systems are listed:

- Quadrature-amplitude modulation;
- Multicarrier modulation (OFDM);
- Trellis coding;
- Echo cancellation;
- Adaptive equalisation;
- Time-division Multiplexing;
- Speech compression.

A typical DPLC terminal equipment structure is given in Figure 6.



Key

A	Speech/telephone interfaces: 2 wires or 4 wires with E&M signalling, FXO, and FXS
B	Speech coding and management includes speech compression decompression, echo cancellation, digital management of signalling and call progress, FAX, etc.
C	Interfaces for data service: V.24/V.28, V11 (X21, X24), G.703, etc.
D	LAN interface; mainly Ethernet interface
E	TCP or UDP /IP for LAN to LAN communication. Can also be at applicative level (FTP, SNMP.)
F	Digital time division multiplexer; multiplexes a number of channels into an aggregate serial bit stream.
G	Digital interface, aggregate multiplexed serial data running at a given gross bit rate. The specific value of this gross bit rate depends on the implementation. For a given implementation it may have different possible values.
H	Signal converter; converts the digital data into a signal which is suitable for transmission over band limited PLC channels, using a given modulation format. The two main modulation schemes currently used are QAM and OFDM.
I	Band limited signal carrying the digital information of G.

Figure 6 – Typical structure of a DPLC terminal equipment

It is important to note that the teleprotection functionality currently is still managed as analogue service.

Depending from the design, it can be an access for an external analogue teleprotection, as well as a teleprotection device integrated into the PLC system.

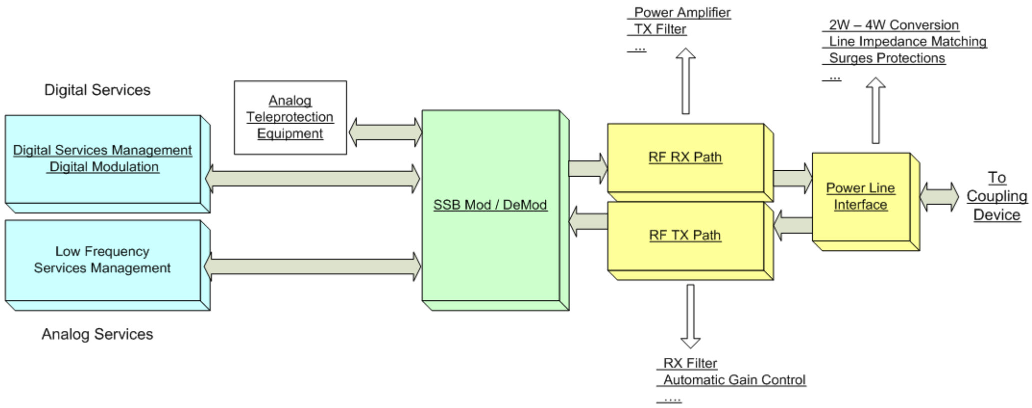


Figure 7 – APLC/DPLC terminal equipment structure

PLC systems can also be composed by a mix of APLC/DPLC terminals. Figure 7 gives an example of such a PLC System.

A typical APLC/DPLC link carrying telecontrol, teleprotection and telephony services is shown in Figure 8.

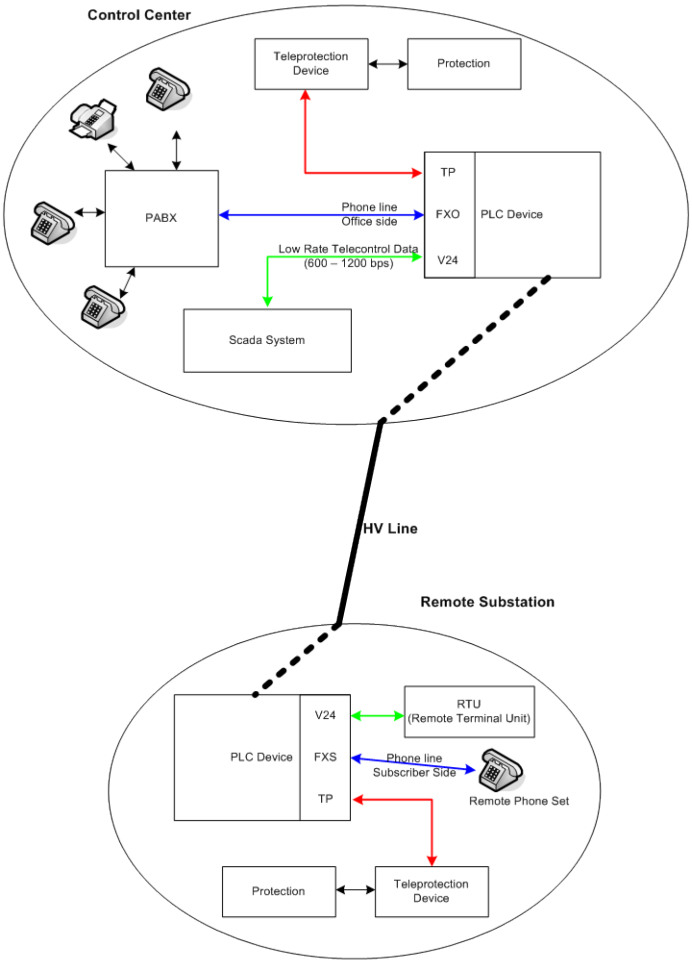


Figure 8 – APLC/DPLC link carrying telecontrol, teleprotection and telephony services

3.5 PLC modulation schemes

3.5.1 General

The modulation technique to be adopted for PLC equipment is a design issue depending on several factors. In the following are summarized the key features and parameters to be considered to perform an evaluation and comparison of the most commonly used modulation techniques in the PLC field.

3.5.2 **AM-SSB** (Refer to Table 1)

AM-SSB stands for amplitude modulation with single sideband. It is used as the modulation method in the analogue PLC terminal equipments (IEC 60495:1993). It can also be used as the final high frequency modulation in a digital PLC terminal. The conventional amplitude modulation scheme (with both sidebands and full carrier transmission) was used in the early years of analogue PLC, but has been replaced by the SSB modulation to provide a better efficiency of the transmission. Actually, the suppression of one of the sidebands and the suppression of the carrier (or the transmission of a reduced amplitude carrier) allows a significant reduction of the transmitted power to achieve the same quality of service with the same signal to noise ratio.

3.5.3 **QAM** (Refer to Table 1)

Quadrature Amplitude Modulations are in fact combinations of ASK and PSK modulations. Often a geometric representation of these amplitude factors is used. This geometric representation is called signal space, and each waveform is represented by a dot in the signal space. The spectral efficiency, i.e. the number of bits/sec that can be transmitted for each Hz of bandwidth, is high; this leads to high transmission rates (bits/s) in a narrow bandwidth (Hz).

In a practical implementation the input binary stream to be transmitted is grouped into symbols of n bits. A symbol of n bits is used to address one out of the 2^n points in the signal space, in a process called “symbol mapping”. A simple example for n = 4 (16-QAM) is shown in Figure 9.

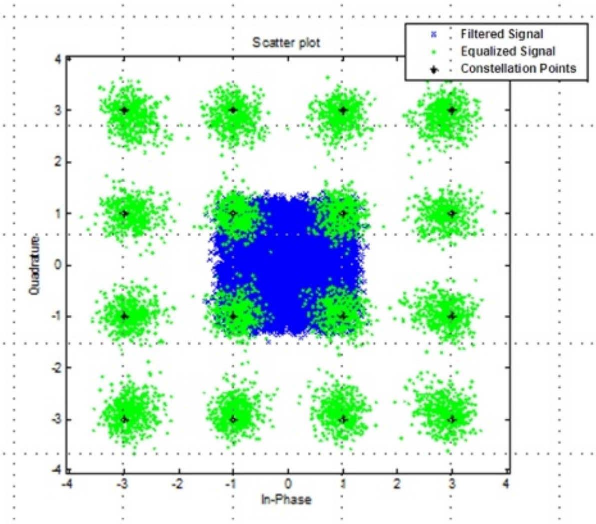


Figure 9 – Signal space for a 16-QAM constellation

It can be shown that the performance of a QAM modem depends basically on the geometry of the signal space. Robustness against noise, for instance, depends on the euclidean distance between points. The goal of the receiver is to detect the received points and decode the corresponding bits, but the received signal will be corrupted by channel noise and other impairments. The effect of noise on the signal space is that the points will not be clearly defined but will be scattered over areas within which the received signal may lie. The receiver then defines a decision area around every theoretical point; if the received signal lies within the decision area the corresponding theoretical point will be decoded as valid. If, because of the noise, the received signal crosses the decision threshold, the wrong point will be decoded and subsequently the wrong information bits will be delivered to the user.

As with most digital transmission systems, there is a trade-off between bandwidth, probability of error and system complexity. For a given transmission rate, the higher the number of points in the signal space (2^n), the narrower the channel bandwidth but the greater the receiver complexity and the higher the probability of error for the same SNR.

3.5.4 **OFDM** (Refer to Table 1)

Known also as multicarrier modulation, it transmits the information by using many carriers, which are located in a limited frequency band.

In a conventional frequency division multiplex system, each of the modulated carriers are separated by filtering, so that there is no spectral overlap of the carriers. This means there is no interference between the carriers, and each carrier can be demodulated individually.

The multicarrier modulation, however, uses spacing between the carriers following special rules, so that the information of each carrier can be detected at the receiver, even if there is a spectral overlap of the carriers.

Data to be transmitted are grouped into blocks of K bits. This number of bits is distributed to the carriers and each carrier is modulated with a group of bits. A 2^n-QAM (quadrature amplitude modulation) is used to encode the data into the phase and magnitude of the carrier, where m is the number of the bits assigned to the carrier.

In a simple implementation, every carrier is modulated with the same number of bits. This is a sufficient method, if the transmission characteristics are the same for each carrier. Transmitting via the power line, however, means having complex channel characteristics where the amplitude response is not flat and/or the group delay is not constant. By measuring the channel characteristics it is possible to determine the transmission characteristics for each carrier. The distribution of the bits to the carriers is done according to the results of this measurement such that a carrier with good conditions for the transmission gets more bits to transmit than a carrier with bad conditions. Using this method, a good adaptation to the characteristics of the transmission channel is possible.

The advantages of the multicarrier modulation are good protection against impulsive noise (such as that produced by switching in the power network) and the efficient use of the bandwidth. By splitting the channel into many narrowband subchannels, the multicarrier modulation is resistant against frequency response distortion and does not rely on sophisticated equalisation techniques.

The simultaneous processing of many QAM-signals increases the complexity of the implementation and may be considered as a disadvantage of the multicarrier modulation.

3.5.5 Other modulation schemes

The other class of modulation scheme that can be used for digital power lines communication are spread spectrum modulation techniques. They are characterized by the use of a bandwidth much greater than the one required by the original signal to transmit. This is generally done by using a long pseudo-random code to spread the data into a large coded stream using a wide bandwidth (direct sequence spread spectrum). The inherent advantages of these techniques are:

a) The resulting signal is a wide band “noise like” signal generally with a low level. This characteristic makes it difficult to be detected and therefore decoded.

b) The messages privacy is ensured as long as the pseudo random code is long enough. The spreading of the signal on a wide bandwidth makes it robust to narrow band noise and to multipath interference.

c) Different signals, each one with its own pseudo-random code can be superposed on the channel allowing many users to access simultaneously to the communication channel (code division multiple access CDMA).

The spread spectrum modulation, because of its wide bandwidth, is not used on HV power line carrier equipment; it is used in broadband power line communication over the distribution network in competition with OFDM modulation.

Table 1 – Characteristics of DPLC modulation schemes

Modulation schemes	Characteristics
Single carrier Typical QAM	• Good spectral efficiency • Good peak to average ratio • Low complexity • Susceptible to multipath interferences ➔ Needs equalization • Needs specific techniques to reduce impact of impulse noise and narrow band interference
Multi carrier Typical OFDM	• Robustness to multi path interference ➔ No equalization required • Good spectral efficiency • Robustness to narrow band interference by deactivation of sub-channels • High complexity • Susceptible to frequency offset • Susceptible to phase noise High peak to average ratio
Spread spectrum	• High immunity to noise and interferences • Large bandwidth ➔ Not applicable for HV PLC

The modulation technique used for PLC equipments is not the only element to take into account to evaluate the performance of the system. A number of techniques have been developed to take advantage of the pros and to avoid the theoretical disadvantages of the cons. This is shown in Table 2, where the pros and cons are indicated with “+” and “–“, respectively.

Table 2 – QAM and OFDM DPLC modulation scheme characteristics

DPLC modulation scheme	Single carrier modulations e.g. QAM	Multi carrier modulations e.g. OFDM
Peak to average ratio	+	–
Complexity of basic modem	+	–
Data delay	+	–
Sensitivity to frequency jitter	+	–
Sensitivity to phase noise	+	–
Complexity of echo cancellation	+	–
Spectral efficiency	–	+
Channel equalization	–	+
Data rate adaptation in small steps	–	+

DPLC modulation scheme	Single carrier modulations e.g. QAM	Multi carrier modulations e.g. OFDM
Susceptibility to multipath interference	–	+
Susceptibility to narrowband interference	–	+
Susceptibility to impulsive noise	–	+

3.5.6 Echo cancellation

In order to reduce the bandwidth needed for a PLC link, it is possible to superimpose the transmission and reception bandwidth allocated to a DPLC communication using echo cancellation techniques. In fact, echo cancellation enables transmission in two directions simultaneously using the same frequency band, thereby reducing the bandwidth requirements in half relative to systems without echo cancellation. Therefore, both directions of transmission share the same bandwidth with echo cancellation used to separate the two directions.

When we transmit full-duplex data over the same PLC bandwidth, the main problem is undesired feed-through of the transmitted signal into the receiver due to the impedance mismatch between the two-wires cable and the hybrid, which is used to provide a virtual four-wires connection between the transmitter on each end and the receiver on the opposite end. This reflection of the transmitted signal is called echo and so an echo canceller is necessary to detect the received data.

The main functionalities of echo cancellation are the following:

- to recognize the originally transmitted signal that re-appears with some delay in the received signal; to synthesize an estimate of the echo of the transmitted signal;
- to remove the echo by subtracting that synthesis from the received signal.

As shown in Figure 10, the near-end transmitted signal can be used to eliminate its own echo at each receiver of the full-duplex link. The echo canceller takes advantage of its knowledge of the local transmitter signal in order to generate a replica of the echo. This replica is subtracted from the echo plus far transmitter signal to yield an echo-free signal which ideally contains the far transmitter signal alone.

Typically, the core of an echo canceller is a discrete-time FIR (Finite Impulse Response) filter. This filter is adapted to match the impulse response of the environment being cancelled and it shall be long enough to adequately cover the duration of that impulse response. This technique requires adaptive signal processing to generate a signal accurate enough to effectively cancel the echo, where the echo can differ from the original due to various kinds of degradation along the way. The FIR filter can be adapted using the LMS (least mean squares) algorithm.

When adapted, the typical performance of an echo canceller is 50 dB of echo attenuation. So, with a good approximation, we can say the DPLC link performances with overlapped bandwidth and echo cancellation are the same of a link with transmission and reception in different bands.

In conclusion, echo cancellation technique allows a great data-rate increase with the same bandwidth requirements because it doubles the system spectral efficiency.

Teleprotection transmission shall not rely on adaptive echo cancellers, because of their poor performance during line faults changing the channel impulse response temporarily.

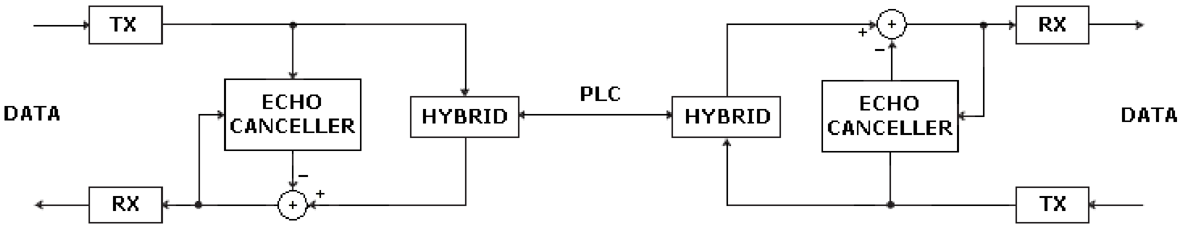


Figure 10 – Echo cancellation method for a DPLC link

4 Frequency bands for PLC systems

4.1 Introduction to the characteristics of PLC systems for EHV, HV and MV networks

There is a growing demand for data transmission networks throughout the World. The initiative for these demands in data services comes from an increase in internet services, which need to be available throughout the day and available to companies and residential homes.

This demand in data communication services is supported by an increase in traditional communications networks of fibre optic communications, adoption of the abundant telephone services through asymmetrical digital subscriber line (ADSL) and higher speed variants such as VDSL. These services are also supported by cable local area network technologies and satellite networks. In more recent years, Wireless networks and Wi-Fi have shown considerable prominence in networking. All these types of networks are dedicated and designed to a particular architecture and topology. They also require cables to be installed and configured to specific equipment. Consequently, any further increase in such networks requires further installation of the different types of cables and this can be a prohibitive cost.

Although these traditional communications networks are in abundance, the most ubiquitous wire network available throughout the world is the electricity distribution network. Although designed to supply power at a range of voltages, normally 110 V or 240 V at either 60 Hz or 50 Hz, respectively, there is the potential of simultaneously transmitting and receiving data traffic over these power distribution lines. The data traffic may be either for home or business services or for internal telecommunication services within the electricity supply industry.

The simultaneous use of the power distribution network for both energy transmission and data communication is unique and reduces the costs of installing two services over one transmission path. Consequently this allows the control of devices in all aspects of the infrastructure of the world from businesses to homes without the inherent costs of installing cables in the ground. For these fundamental reasons a new transmission network of data communications technology has evolved called generically power line communications technology.

The first application of power communications was the form of ripple control technology within a Swiss electricity distribution system in 1893. The aim was the application of a control single to switch a remote circuit breaker. The voltage of the signal was the order of millivolts and frequency of the signal in the kilohertz range. From this initial trial and application, the frequency ranges have increased, allowing high data rates of the order Megabytes per second. The developments of this form of communication over the last 100 years have been significant mainly because of the structure of power cables used in the low, medium and high voltage systems of our buildings and homes. Further, the developments in communications technology from analogue to digital systems, signal processing, modulation systems and data processing have enhanced the transmission services available to customers both industrial, residential but also the internal communications network of an electricity distribution network.

The power distribution network is very diverse ranging from high voltage operating at the order of 100 kV, medium voltage at below 100 kV and low voltage below 1 kV. For power line communications, the focus is on the low voltage distribution network which is the widest geographically spread in the majority of countries. Further, it has the convenient connection point to the range of buildings and homes and their different infrastructures.

Signalling over the low voltage in the early years concentrated on low speed data rates and consequently low frequency applications with the classical application of meter reading for electricity, gas, water and heat meters. Other applications included load monitoring and shedding together with connection and disconnection services. In the 1990s there was the demand for more services which involved higher data rates of the order of 1 Megabytes and higher and consequently higher bandwidths and frequencies in the 1 MHz to 30 MHz range. It is this latter development that evolved into the new term of “Broadband Power Line communications” technology.

This broadband power line communications allows high speed data transmission services such as data and voice over the internet protocol known as “VoIP”. These services are distributed through normal electrical power lines that are incorporated into every house hold socket .Further this data is shared among simultaneous users. For this reason, the concept of data services to every plug in the home or building gives the concept of “Internet to and from the socket”. The consequence of this is the transmission and reception for any socket in the home or building without additional wiring. Therefore the power line is feeding a high speed data signal into a local mains power supply network to every socket in that electrical network. Therefore the transmission capacity is shared between the users.

However, although there is considerable potential for power line carrier communications at both low frequency and high frequency for the range of different services, there are potential problems with the power line that shall be taken into consideration and investigated on every type of electrical distribution network within any country and area within a country. Therefore the performance of a power communications service may experience different communications conditions for the same type of network but in different geographical environments and countries.

There are a number of particular conditions that affect the power communications network. The impedance of the power distribution network varies considerably according to the type of power cable and network topology, according to the configuration being a single phase, ring main or a three phase tree and branch network. Also the frequency of transmission will determine the impedance values of the circuit. This leads to the cable attenuation which may be very high according to the frequency of operation. This can also lead to standing waves on long cables and may lead to frequency nulls in the frequency response. In addition the interfacing of the equipment to the power line will introduce attenuation and noise to the circuit which is affected to by the impedance of the line which varies according to the frequency of operation. Further as devices are switched in and out of the circuit the noise of the line will vary and the attenuation will vary in an unpredictable manner. Although only as a figure of merit operating power line systems in the low frequency range provides more stable conditions and therefore a more seamless communications throughout the system. Further, due to these electrical and communication impairments of the system a potentially more serious problem arises and that is due to potential electromagnetic emission from the power lines when operated in the high frequency range 1,6 MHz to 30 MHz and higher. These frequencies that emanate from the power line have the ability to cause interference to established radio frequency services. Although this does raise cause for concern there are a number of devices and methods available to potentially compensate and overcome these electrical problems. These include using repeaters, amplifiers, isolators, line traps, and couplers. The particular line shall be analysed to decide the type of device to be used and where it is placed in the circuit .These techniques work, however the control of the energy injected into the power line from the modem will establish the potentially radiated emission from the power line and the amount of interference caused to other established radio services.

The radio spectrum is a unique resource that has considerable demands made on it by companies and users. Further, the frequency range from 1,6 MHz to 30 MHz has special propagation conditions allowing long range communications services around the world. Further it is utilised very efficiently by low frequency power communications. Therefore this part of the spectrum requires special protection by choosing an appropriate emission limit for interference. To provide total protection of radio services is not possible principally because it would require a very low radiating limit which consequently would limit high data rate communication services. In addition, it should be recognised that electronic equipment of any kind is a potential source of interference once placed in the power line which again would make any decision in favour of very tightly radiated limits completely uneconomic. There are other safety-of-life services with respect to human life and property that shall also be protected. Also manufacturers should develop procedures enabling reduction of emissions in cases of interference through reduced power levels for specific frequencies. The risk of potential interference to radio services depends not only on the different users of the power line agreeing a strategy but also on the different network structures and technologies and the frequency ranges used. For power line communication systems compared to DSL systems or cable TV systems, the risk of interference for the same radiated emission level is considerably higher. Therefore considering the higher densities of deployment for power line networks there is a potential risk of a rise in the noise floor level for that locality. Due to the wide geographical coverage of power line networks throughout each country standards bodies have introduced and formulated specifications to restrict the bandwidth and power levels of communication systems for one main reason and that is of avoiding or reducing the interference with respect to other radio users who use the same part of the spectrum. This is essentially the aim of the different national and international standards bodies.

4.2 Frequency bands for power line systems

Signalling over the power line has existed for many years. The early transmission systems from the 1900s used extremely low date rates and consequently low transmission frequencies of the order of Kilohertz. However, as more applications demand higher data rates, the frequency of transmission increased.

Therefore according to the data services available to customers on the network determines the frequencies and bandwidth of the transmission system. The frequency used is directly related to the application and local environment. Table 3 provides the typical power communication technique and representative frequency band for the particular system.

Table 3 – Early power communications techniques and frequencies

PLT technique	Frequency range
Ultra narrow band(UNB)	10 Hz
Power frequency	60 Hz
Ripple control	100 Hz to 1 000 Hz
Distribution PLT	3 kHz to 148,5 kHz
Transmission PLT	30 kHz to 500 kHz
Local PLT	40 kHz to 30 MHz

The early techniques of ultra narrow band operating at extremely low frequency of 10 Hz through to ripple control operating in the frequency band from 100 Hz to 1000 Hz are used for basic switching of equipment in the electricity distribution network. However, as applications of remote meter reading and data transmission developed, higher frequencies came into use including distribution PLT, transmission PLT and local PLT.

In the late 1990s there was a considerable development in providing high data rate transmission systems for internet services to residential and industrial customers. These new services introduced data and voice over the internet protocol “VoIP” which provided a common communication service to all residential and industrial customers. These services demand the higher data rates and hence bandwidth. The characteristics of such services ranging from security of service through to signal error are shown in Table 4.

Table 4 – Parameters of power communications systems

Parameter	Ultra narrow band	Distribution PLT	Broadband PLT
Range	Excellent	Very good	Very good
Data Rate	Low	High	Excellent
Security	Good	Good	Good
Line Conditioning	Minimal	Excellent	Excellent
Latency(time delay)	Good	Medium	Low
Error rate	Low	Excellent	Good

Table 4 demonstrates that there is no ideal PLT communication system. Good quality parameters include the range the system will operate over, however for the broadband PLT system the data rate is excellent and current systems operate at 250 Mbyte and higher speeds are becoming available. In comparison for the low data rate system a longer range is achievable. Therefore it is important to determine the exact services that will be transmitted over the power line network.

Table 5 details the early power line carrier frequencies, many of which are still operational today. However, manufacturers and utility companies have combined to develop power line systems for greater range and higher speed and consequently services such as video on demand. Also the national and international standards bodies have become involved to provide neutrality to the vast range of services being developed throughout the World and potentially coexistence between the operations of such systems.

Today, the operational frequency bands used throughout the world have specific frequency ranges for data signals being transmitted between the backbone network and the home or building, known as the “Access network” and the data network inside the home or building known as the “In-house network.” Further, the networks are classified as low frequency and high frequency systems.

Table 5 – Frequency bands in power line communication systems

Architecture	Underground	Underground	Underground/Overhead
	Low frequency systems standards organisation		
	IEEE	**CENELEC/ETSI**	**IEC CISPR 22**
Frequency range	45 kHz to 450 kHz	3 kHz to 148,5 kHz	1,6 MHz to 30 MHz
Access band	45 kHz to 450 kHz	3 kHz to 90 kHz	1,6 MHz to 10 MHz
In-house band	45 kHz to 450 kHz	95 kHz to 140 kHz	10 MHz to 30 MHz
Architecture	**Overhead/underground**	**Underground**	**Underground**
	High frequency systems		
Frequency range	1,6 MHz to 80 MHz	1,6 MHz to 30 MHz	1,6 MHz to 30 MHz
Access band	10 MHz to 80 MHz	1,6 MHz to 10 MHz	1,6 MHz to 10 MHz
In-house band	1,6 MHz to 10 MHz	10 MHz to 30 MHz	0 MHz to 30 MHz

4.3 Channel plans

4.3.1 General

There are different channel plans for PLC communication systems depending on the level of voltage of the electrical power line used, international standards and local regulation, and type of transmission i.e. narrowband or broadband.

4.3.2 EHV/HV/MV narrowband PLC channel plan

Most of the multi-purpose APLC systems require a bandwidth of 4 kHz for each direction of transmission; therefore, the available range of frequencies (24 kHz to 1 MHz) is divided into a number of channels each 4 kHz wide. Two of these will be required for each two-way carrier circuit but they need not necessarily be adjacent.

In order to assure compatibility and coexistence with other systems in operation new DPLC systems will use basically the same channelling approach. Depending on the technology used it is common to have adjacent, non-contiguous and superimposed bidirectional transmission channel grouping a number of 4 kHz channels.

Other channel widths have also been adopted in some countries to suit their special needs.

The frequency ranges and standards applied in Europe, USA and other countries are shown in Table 6. Further, Figure 11 shows the APLC narrowband channel plan.

Table 6 – HF spectrum allocated for PLC systems

	Europe	USA	Other Countries
Reference standard	IEC 62488	IEEE 643	-
Frequency range	40 kHz to 500 kHz	24 kHz to 1 MHz	24 kHz to 1 MHz

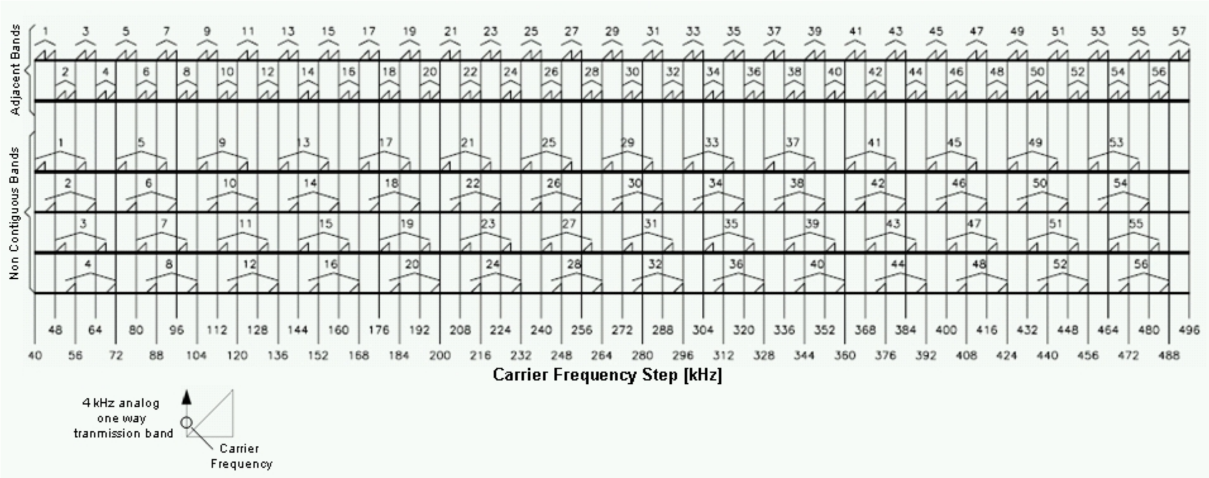


Figure 11 – APLC narrowband channel plan

4.3.3 MV/LV narrowband DLC channel plan

DLC is mostly used over MV/LV underground cables as shown in Table 7. Also, Figure 12 shows the situation in Europe and the USA.

Table 7 – HF spectrum allocation for narrowband PLC

	CENELEC (EUROPE)			USA	Other countries
Reference standard	**EN 50065-1**			**IEE 643**	**-**
Frequency range	***3 kHz to 148,5 kHz***	A band (3 kHz to 95 kHz)	Utilities access	50 kHz to 450 kHz	-
		B band (95 kHz to 125 kHz)	Consumer in-house		
		C band (125 kHz to 140 kHz)			
		D band (140 kHz to 148,5 kHz)			

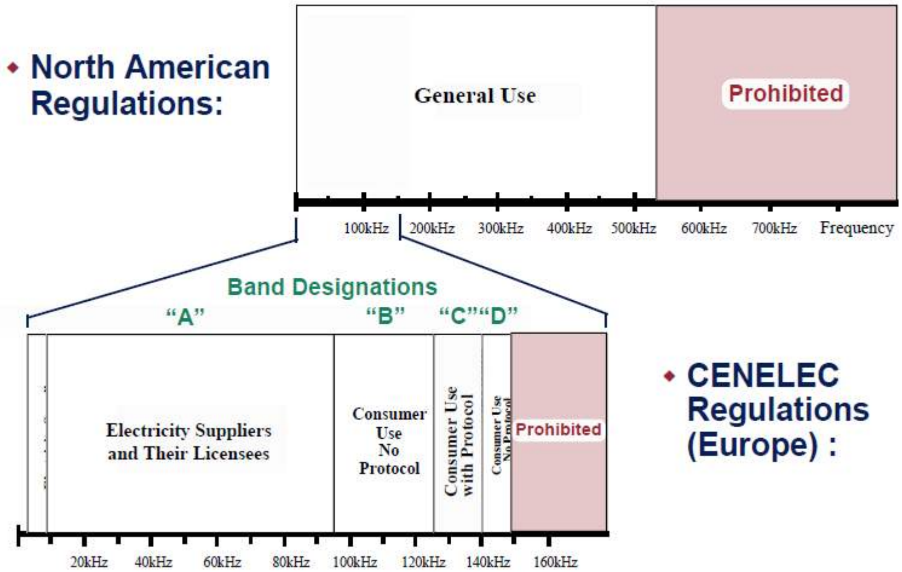


Figure 12 – DLC narrowband channel plans Europe vs. North America

4.4 High frequency spectral characteristics

APLC systems generate discrete frequencies (pilots, maintenance signals, guard signals for teleprotection), speech signals and narrowband spectra from modems using typically Frequency Shift Keying (FSK) as the modulation method.

DPLC systems generate a modulated signal with a continuous spectrum p(f) and possibly additional tones with discrete frequencies f_i used for auxiliary functions (pilots, maintenance signals, guard signals for teleprotection). Generally during synchronisation of a DPLC link, the characteristics of the signal spectrum changes until synchronisation is achieved and data is transmitted, and therefore the spectral characteristics are stable.

The signal spectrum of combined APLC/DPLC systems can be split into sub-bands allocated either to the APLC or the DPLC sub-system of the combined APLC/DPLC system. The spectral characteristics of the signals in the sub-bands are those of pure APLC or DPLC systems, respectively.

4.5 Regulation and emission limits for PLC

4.5.1 Extra high voltage, high voltage for narrowband systems

The regulation and emission limits for narrowband communications are determined and limited by local national regulations for conducted and radiated electromagnetic field.

4.5.2 Medium voltage and low voltage narrowband systems

Refer to 4.3.2 for operating frequency bands for Cenelec standard, EN 50065-1.

4.5.3 Medium voltage and low voltage broadband systems

These systems are limited by the conducted and radiated electromagnetic field as designated in CISPR 22. This standard is currently under review.

4.6 Selection of the frequency bands for HV PLC systems

4.6.1 General

This subclause gives considerations and advices taking into account signal power of the HF modulated signal in order to meet the constraints and requirements for channelling, frequency allocation and paralleling of APLC/DPLC systems.

4.6.2 Maximum power of PLC signal

The relevant power quantities to be distinguished are:

P_{Peak} [W_{Peak}] = Peak power of the PLC signal. It is usually limited by the power amplifier of the PLC terminal.

P_{PEP} [W_{PEP}] = Peak envelope power [W_{PEP}] corresponds to the power of a sinusoidal signal with peak power P_{Peak}. The relation to P_{Peak} is

$$P_{PEP} = \frac{P_{Peak}}{2} . \tag{1}$$

P_{PEP} is usually limited by the power amplifier of the PLC terminal.

$p_{RMS}(f)$ [W_RHz] = Power density of the continuous signal spectrum. It may be limited by national regulations.

$P_i(f_i)$ [W_{RMS}] = Power of discrete tones at frequencies f_i. National regulations may specify the maximum power of individual discrete frequencies $P_{cont\ max}$ [W_{RMS}] that are continuously present within the nominal frequency band:

$$P_{cont\max} \geq P_i(f_i). \tag{2}$$

For individual discrete frequencies only appearing for a given period of time – as is the case for short duration teleprotection signals – a higher limit $P_{temp\ max} \geq P_{cont\ max}$ might be allowed.

P_{RMS} [W_{RMS}] = RMS Power of the PLC signal. It may be limited by thermal constraints of the PLC power amplifier. P_{RMS} is the sum of the powers of individual discrete frequencies and the power of the continuous part of the spectrum in the nominal frequency band:

$$P_{RMS} = \sum_i P_i(f_i) + \int_{Bn} p_{RMS}(f)df , \tag{3}$$

where Bn [Hz] is the used PLC band.

A further important quantity is the ratio between the peak power and the RMS power,

$$P_{PeakToRMS} = \frac{P_{Peak}}{P_{RMS}} . \tag{4}$$

The value of $R_{PeakToRMS}$ – also called peak to average power ratio (PAPR) – is typically around 7 dB to 13 dB for APLC and DPLC systems in the stationary state. For DPLC systems, it depends on the type of modulation, while for APLC systems, it is mainly influenced by the number of channels and the number of services carried by these channels.

4.6.3 Channelling

As shown in Figure 13, the nominal carrier-frequency bands, B_n, used by APLC systems are equal to a basic carrier-frequency band B_0 of 4 kHz or 2,5 kHz in case of single-channel terminals or to a multiple thereof in case of multi-channel terminals. DPLC systems generally use the same divisions for compatibility and coexistence with APLC systems in existing networks.

The frequency spacing between the transmitter and the receiver of one PLC link traditionally used to be a multiple m of B0, with m depending essentially on the design of the transmission and reception filters of the PLC terminal. As today’s technology allows shifting the nominal band of the PLC systems in fine increments down to 1 kHz or even lower, there is no reason to maintain this restriction. The transmitter (Tx) and the receiver (Rx) bands may either be adjacent (G = 0 Hz) or separated by a frequency gap (G > 0 Hz) as shown in Figure 13. The minimum value of G in case of non-adjacent channels is specified by the manufacturer.

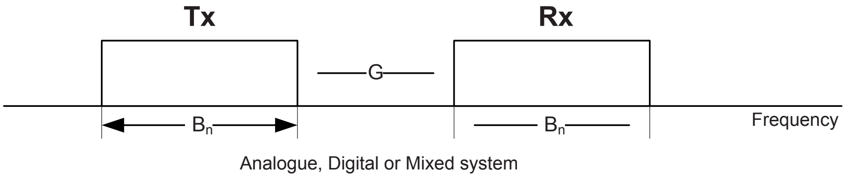


Figure 13 – Minimum frequency gap

There is no particular advice concerning the respective placement of analogue/digital bands in mixed systems. The recommendations given by the manufacturers should be followed.

NOTE The Tx and Rx bands of pure of DPLC systems or the Tx and Rx bands allocated to the DPLC subsystem of combined APLC/DPLC systems can be superimposed using echo cancelling techniques. This is a method to reduce the bandwidth needed for a link.

4.6.4 Frequency allocation

The frequency allocation of the channel in the PLC band mainly depends on:

– existing links in the network. It is generally recommended to have at least two or three line sections between links using the same frequency band, each section being terminated with line traps. In case of a two line section separation, measurements should be made to ensure that the interference level is low enough. The interference level depends on the impedance of the line traps installed on the lines. Where two power lines are near each other and run in parallel for a few kilometres, there is a signal coupling between these lines and consequently, channels operating on the same frequencies may interfere with each other;

– national or international regulations restricting the use of frequencies e.g. to limit emissions likely to disturb the primary user of the radio spectrum i.e. air control beacons. For instance, in Canada and in France, limited use is made of frequencies above 200 kHz;

– the line attenuation, which is generally better at lower frequencies. Therefore, lower frequencies will preferably be used on lines with higher attenuation.

4.6.5 Paralleling

It is necessary to provide enough frequency space between parallel links, i.e. links operated over the same line. The required frequency space depends on two quantities: a) the tapping loss and b) the spurious emission level.

a) When a second PLC terminal is connected to a line equipped with an already installed first PLC terminal, the transmitted signal level of the first PLC terminal is reduced due to the finite impedance of the second PLC terminal outside its frequency band. This level reduction is called tapping loss and depends on the design of the transmission filters.
b) Unwanted emissions outside the nominal Tx band of a PLC terminal are called spurious emissions. Their level can be lowered by reducing the power of the PLC signal.

Tapping loss and spurious emission levels have to be known to determine the minimum required frequency gaps between parallel links. Manufacturers therefore have to specify these quantities.

For frequency planning, a convenient rule is to choose the gap between the frequency bands of parallel equipment at least equal to the nominal bandwidth of the link with the wider bandwidth.

5 Media for DPLC and APLC systems

5.1 General

As mentioned in previous clause, basically a PLC communication system consists of three distinct parts: the terminal assemblies, the coupling system, and the power line media acting as transmission line, as shown in Figure 14.

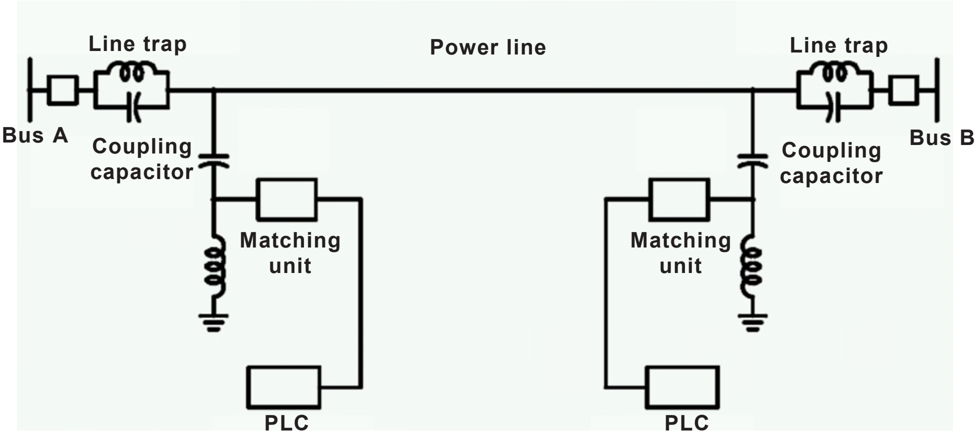


Figure 14 – PLC communication system

- The transmission line actually the media provides a suitable path for the transmission of carrier energy between terminals in the PLC band of frequencies.
- The coupling system provides a means of connecting the terminals to selected points on the power transmission line.
- Terminal assemblies consist of transmitters, receivers, and often in addition they also include teleprotection.

5.2 The electricity grid

Electricity power system or EPS is a complex system where several parts interact to reach a common goal: delivering efficiently at competitive costs energy from generation plants to the final customers. The architecture of the EPS includes several components: generation plants, power lines at various voltage levels, electrical switching and/or transformer stations and substations, operators, market and customers.

For our purposes, we should consider exclusively the electricity grid which can be simply divided into the transmission and sub-transmission and distribution systems as a collection of power line cables, operated at any voltage level, which we would like to use as physical transmission media. Nevertheless, it should be remarked that they were not designed in order to satisfy this task.

Thinking at the topology of the traditional grids, we can see the Transmission segment as the central trunk of the electricity grid. Thousands of distribution grids branch off from this central trunk and fork and diverge into tens of thousands of feeder lines reaching into homes, buildings, and industries. This is often known as ubiquitous property of the electricity grid and may be exploited from telecommunication point of view to deploy access networks.

For our scope, it is worth to consider that due the development of smart grids, the electricity infrastructure will change: from a centralized to a complex distributed architecture. This means an increasing need of bidirectional communication to ensure the control and signal exchange among new players such as distributed energy resources (DER), renewable energy (REN) resources, smart metering infrastructure, market, aggregators, prosumers.

5.3 Extra and high voltage electricity power lines

In most countries, the networks at 220 kV and above are defined as the extra high voltage network (EHV) also named as the transmission grid. Most of the high voltage (HV) sub-transmission grid is related to power lines of 50 kV to 220 kV.

Electrical transmission lines are used to send electricity over long distances to minimize electrical losses, national and regional backbones, from the point of generation to subordinate distribution grids. A traditional transmission line is conceived as a sequence of self-supporting rigid towers, each one supporting the conductors and shield-wires of the two adjacent spans.

Most of the EHV-HV network is overhead line; underground cables are an alternative but a more expensive form of transmitting electricity. The conductors transmitting electricity at 380 kV are usually made from aluminium.

Some conductors are often reinforced with steel to withstand inclement weather conditions including ice, frost and wind, although all aluminium alloy conductors have a better resistance to corrosion.

The conductors need to be insulated from the ground and overhead lines use air as the principal insulator although the live conductors are hung from a string of toughened glass (or porcelain) insulating chains that are suspended from the pylons.

Other equipment that is used on transmission lines includes dampers, to avoid conductor damage in windy conditions, spacers, which maintain conductor separation at intervals along the span between towers, clamps, jumpers and dampers.

There is also usually an earth wire strung between the top of the pylons which protects the conductors from lightening. The earth wire may also host optical fibre cables, i.e. OPGW, to carry telecommunication signals.

5.4 Medium voltage electricity power lines

Electricity distribution grid is the stage with the task of delivering (before retail) the electricity to end users.

It is generally considered to include medium-voltage (less than 50 kV) power lines, electrical substations and pole-mounted transformers, low-voltage (less than 1 000 V) distribution wiring and sometimes electricity meters.

MV power lines include overhead and buried cables. The latter made with copper are generally laid in a trench about 1 m below ground.

5.5 Electricity power lines as transmission media

5.5.1 Coupling system

5.5.1.1 General

To enable the conductors of a power line to be employed for communication purposes, coupling equipment is required allowing the injection of the high-frequency carrier signal without undue loss and at the same time de-couple the communication equipment from the power line in so far as the power system power-frequency voltage, switching surges, lightning surges, load variations are concerned.

Basically, to couple the signal to the power line we can use a capacitive or inductive approach. While the first is the most used for narrowband PLC communications, the latter find application mainly for broadband PLC communications to couple with MV/LV buried or suspended power cables. An example of capacitive coupling is shown in Figure 15.

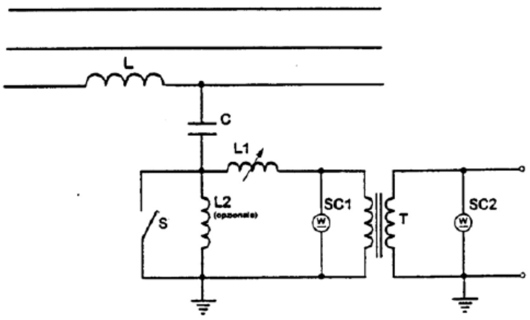


Figure 15 – Capacitive coupling system

A capacitive coupling system includes also the following additional elements:

- Line trap with tuning device;
- Line matching unit.

Nowadays, to couple to MV/LV cables inductive coupling systems are available as shown in Figure 16. Basically, the coupler consists of a closed toroid or clamp of material with high magnetic permeability which is posed around the cable. The coupling exploits inductive effect to inject signal into the cable.

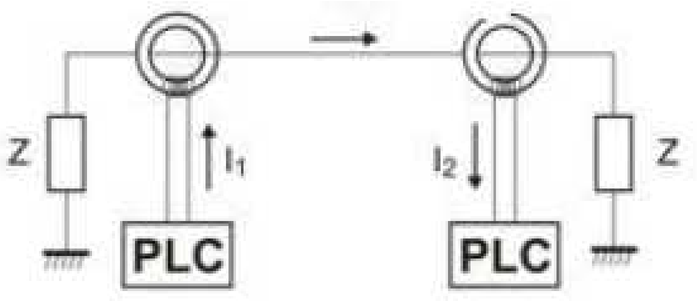


Figure 16 – PLC link exploiting inductive coupling system

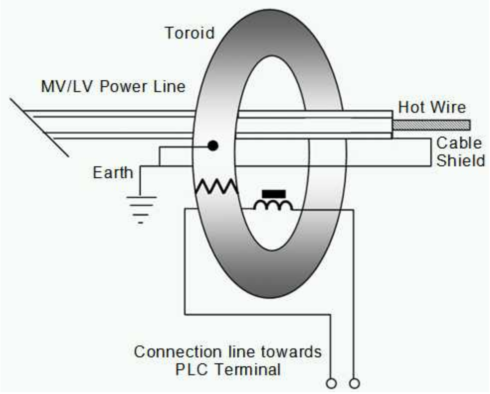


Figure 17 – Principle of inductive coupling system

The principle of the inductive coupling system is shown in Figure 17. The coupling system is also required to minimize the shunt loss caused by the substation equipment, and to render the impedance at carrier frequencies reasonably independent of switching conditions at the substation.

5.5.1.2 Coupling capacitor

The coupling capacitor is the physical link to the transmission line that has a high impedance to the power frequency and a low impedance to carrier frequencies as shown in Figure 18.

Coupling capacitor or capacitor voltage transformer (CVT) of suitable voltage withstand properties which is inserted between the coupling device and the high-voltage conductor. Values are of the order of 1 000 pF to 10 000 pF. Figure 19 shows a typical arrangement of devices for a capacitive coupling system.

Consideration shall be given to the choice of the coupler design to ensure an optimum selection based on capacitor cost versus bandwidth requirements. Reference should also be made to IEC 60358.

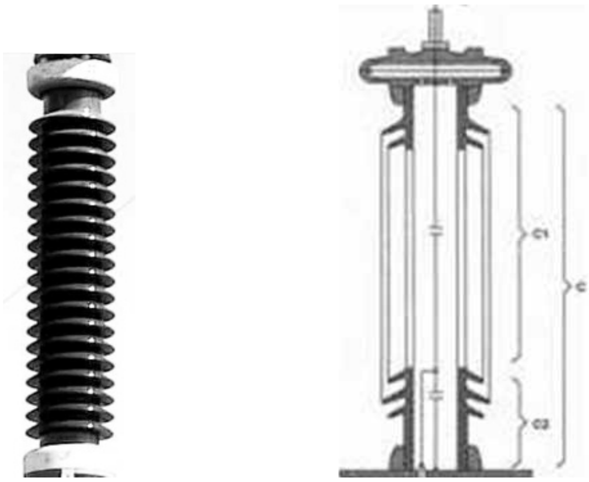


Figure 18 – EHV/HV typical coupling capacitor (CVT)

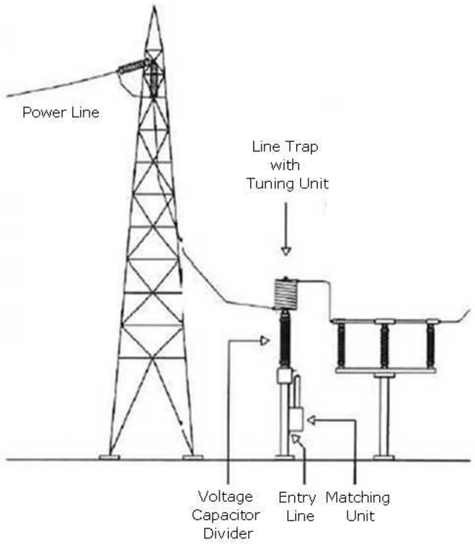


Figure 19 – EHV/HV typical capacitive coupling system
(single phase to earth)

The equipment side of the matching transformer is generally only connected to earth, via the coaxial cable sheath to avoid the possibility of circulating currents, under fault conditions, saturating the transformer and effectively disabling the carrier channel. It shall however be borne in mind that unsafe voltages could then transiently exist at the line matching equipment. Some utilities may insist on connecting the coaxial cable sheath to earth at both the LMU and PLC equipment ends as shown in Figure 20.

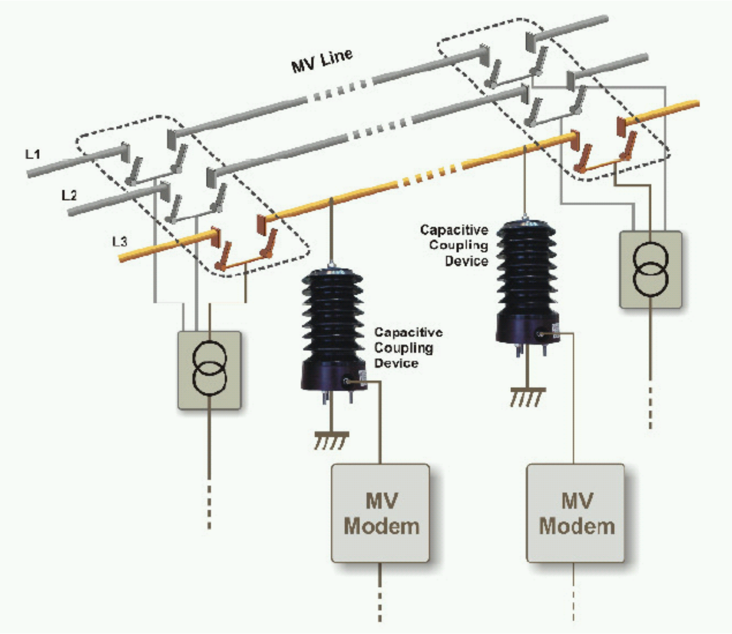


Figure 20 – MV capacitive coupling system

5.5.1.3 Coupling inductor

The inductive couplers currently on the market are made up of a main toroidal magnetic split core in nanocrystalline material. The main core has been chosen to work without becoming saturated in the event of strong currents at mains frequency.

The effect of these currents is negligible at the coupling frequency range of operation.

The coupler shall finally be encapsulated in such a way that it withstands the electric tests of IEC 60044-1. An example is shown in Figure 21.

Figure 21 – MV coupling inductor

5.5.1.4 Line trap

The line trap is inserted into the EHV/HV power lines to minimize the loss of carrier energy and to prevent external faults from shorting the carrier signal on the unfaulted line.

Basically, the line trap (or "wave trap") consists of a choke coil, rated to carry the full line current, a tuning and protective device as shown in Figure 22.

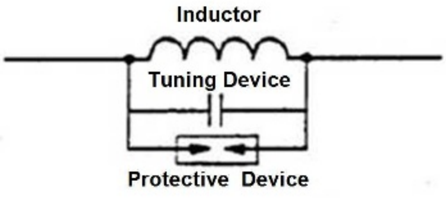


Figure 22 – Line trap electrical scheme

Figure 23 – HV line trap

Figure 23 shows an example of a HV line trap. This device is connected in series with the power line between the point of connection of the coupling capacitor and the substation, or at the line trap.

Line traps are available in various inductance ratings and continuous power-frequency current ranges. The value of line trap inductance is of the order of 0,1 mH to 2,0 mH as shown in Figure 24.

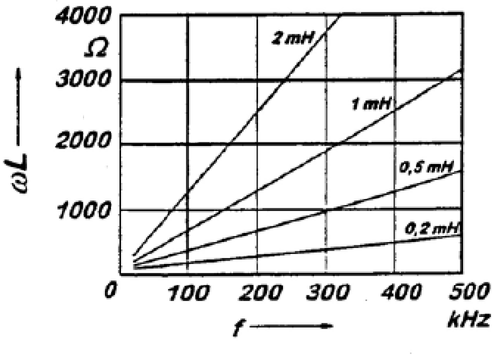


Figure 24 – Line trap impedance versus frequency

Line traps provide blocking of the carrier signal, preventing it from continuing into other transmission line sections.

The typical blocking impedance characteristic of a narrowband line trap is shown in Figure 25. Single and two-frequency line traps are parallel L-C circuits with parameters of variable inductances and capacitances selected so as to resonate at a specific frequency (or at two frequencies) thus blocking the carrier frequency.

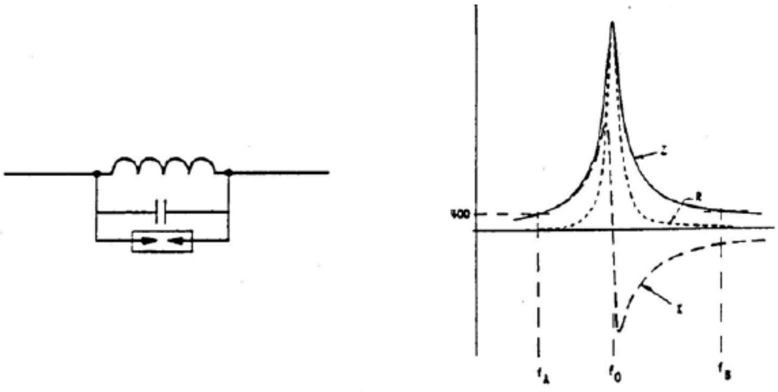


Figure 25 – Blocking impedance characteristic of a narrowband line trap

The tuning devices, used to improve the blocking efficiency of line traps, may be of different types. Those with narrow-band characteristics ensure a high blocking impedance for one carrier frequency (CF) channel.

Those with double-band characteristics present a high blocking impedance for two non-adjacent CF channels as shown in Figure 26, and those with broad-band characteristics present a blocking impedance for several CF channels as shown in Figure 26. The latter is typically tuned for a specified minimum resistive component as shown in Figure 27.

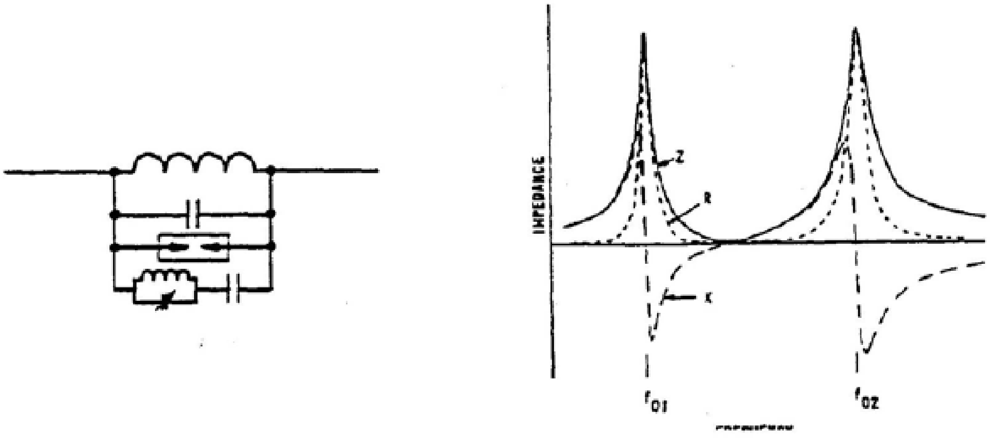


Figure 26 – Blocking impedance characteristic of a double band line trap

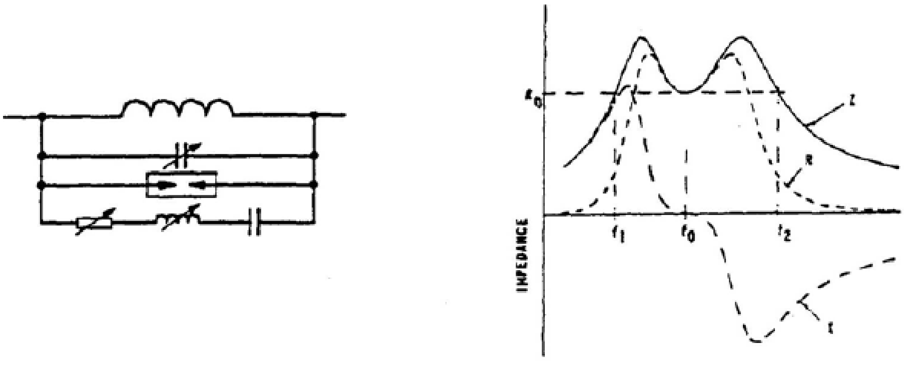


Figure 27 – Blocking impedance characteristic of a broadband line trap

5.5.1.5 Line matching unit

The line matching unit (LMU) as shown in Figure 28 provides a low impedance path to ground for power frequencies and a high impedance path for carrier frequencies. Moreover, it matches the impedance of the PLC to the HV line.

The LMU is inserted between the low-voltage side of the coupling capacitor and the cable connecting the PLC terminal.

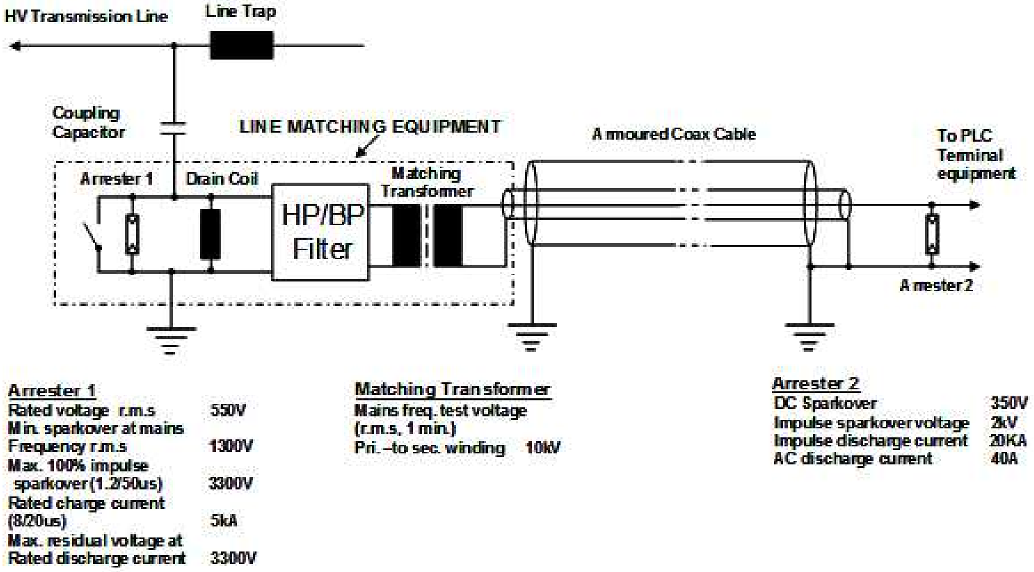


Figure 28 – LMU components and electric scheme

It comprises a drain coil, a surge arrester, and a matching transformer, which in some equipment is also designed as a drain coil to the power-frequency current. The surge arrester, inserted between the low-voltage side of the coupling capacitor and earth, absorbs high transient voltages for protection of the LMU.

The function of the drain coil is to offer a low impedance at power frequency and high impedance at CF frequencies. It is designed to provide a path to earth for the power frequency current through the capacitor and so limit the potential of the capacitor terminal at the point of connection to the carrier equipment, in the interest of safety.

The requirements for coupling devices are covered by IEC 60481. Typical LMU characteristics for coupling attenuation A and return loss R are shown in Figure 29.

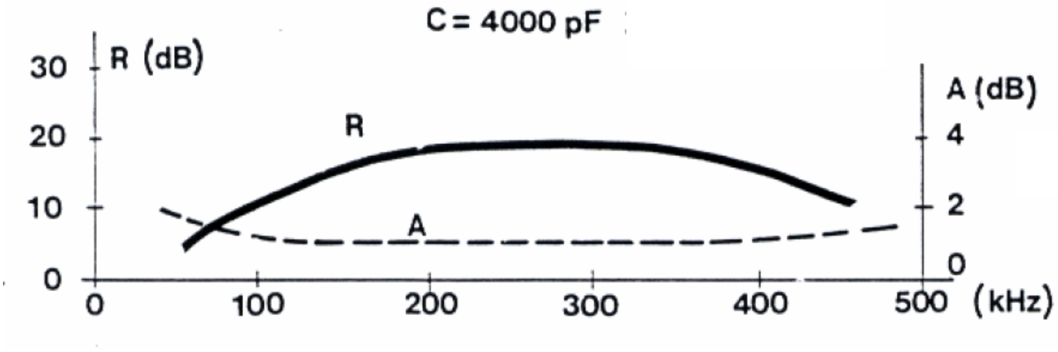


Figure 29 – LMU characteristics with a coupling capacitor of 4 000 pF

As the LMU is inserted between the low-voltage terminal of the coupling capacitor and earth, a switch (blade earthed) is provided to ensure direct earth connection of the coupling capacitor during maintenance or commissioning.

Statutory safety rules may require different procedures for the operation of this earthing switch and typical arrangements are as follows:

An earthing switch earths the low voltage side of the coupling capacitor when the LMU housing is opened. A manually-operated switch interlock may be provided which does not allow the cover to be removed before the switch is operated to the earthed position.

A pole-operated earthing switch with suitable warning notice may be provided. Whichever arrangement is used, it is recommended that an indication of the earthed position of the earthing switch should be clearly visible.

5.5.2 Coupling configuration for overhead cables EHV/HV/MV

5.5.2.1 General

With regard to the type of coupling used, coupling devices may be of the phase-to-earth, or of the phase-to-phase types.

In the case of the latter, the coupling may be made with either a single phase-to-phase device or with two phase-to-earth devices properly connected. If the first arrangement is used, the distance between the low-voltage terminals of the capacitors and the coupling device is generally greater than with the second arrangement with a greater possibility of damage and interruption.

Consequently, in order to achieve higher security, use of phase-to-phase coupling should be made with two phase-to-earth units, with the connection between them made on the secondary side of the matching transformer.

5.5.2.2 Phase-to-earth coupling

In this type of coupling the PLC terminal is connected between one phase conductor and earth as shown in Figure 30. Only one coupling capacitor and one line trap is required at each coupling point, so that this system offers economies in coupling equipment but it normally results in higher attenuation than phase-to-phase coupling and less security in the event of an earth fault on the coupled phase. It is to be noted that although the coupling takes place between one phase and earth, the actual transmission involves the two remaining phase conductors in a complex manner.

Figure 30 – Phase-to-earth coupling

Because of the economic advantages, phase-to-earth coupling may be employed where high reliability in the presence of line faults is not essential.

5.5.2.3 Phase-to-phase coupling

In this case, as shown in Figure 31, two coupling capacitors and two line traps are required at each coupling point, so the cost of the coupling equipment will be approximately twice that of phase-to-earth coupling. Phase-to-phase coupling however offers a number of important advantages, including lower attenuation, greater security against communication failure due to line faults, and less interference, both radiated and picked up.

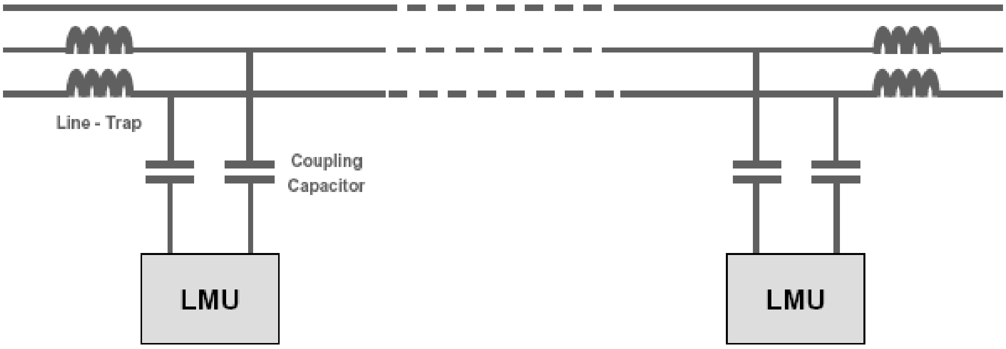


Figure 31 – Phase-to-phase coupling

The coupling may be made with either a single phase-to-phase device or with two phase-to-earth devices properly connected. If the first arrangement is used, the distance between the low-voltage terminals of the capacitors and the coupling device is generally greater than with the second arrangement, leading to a greater possibility of damage and interruption. Consequently, in order to achieve higher security, use of phase-to-phase coupling should be made with two phase-to-earth units, with the connection between them made on the secondary side of the matching transformer.

As approximately 80 % of all line faults are single-phase, this arrangement may be expected to give higher security.

5.5.2.4 Inter-circuit coupling

When two parallel high-voltage circuits are run without discontinuity on the same poles or towers, it is possible to utilize one phase on each of the circuits to provide the equivalent of phase-to-phase coupling on a single circuit line or two phases on each circuit to provide a double differential form of coupling. With this form of coupling, communication is maintained even if one power circuit is taken out of service and earthed. The lines and cables at both ends should be equal in length to avoid the possibility of phase cancellation.

5.5.2.5 Insulated earth wire coupling

It is customary on high-voltage lines, particularly those above 110 kV, to provide one or two earth wires above the phase conductors. These are primarily intended to protect the lines against lightning strokes, but they also serve to reduce the step voltage which would otherwise exist at the towers and substations under earth fault conditions on the lines. In addition, the earth wires help to minimize induction effects on nearby telecommunication circuits during earth faults on the power lines.

The earth wires are normally in metallic contact with the line towers, but it is known that their efficiency as lightning protectors is not affected if they are insulated from the towers, the insulators being by-passed by spark gaps rated to flash over at about 15 kV to 30 kV. This fact has led to the utilization of insulated earth wires for communication purposes, the principal advantage being the saving in coupling equipment since although coupling capacitors and choke coils are still required they need not be rated for the full operating voltage and current of the line.

The method has, however, a number of disadvantages:

a) The attenuation at carrier frequencies is, in general, appreciably greater than that of the power line, where multi-strand steel conductor is employed for the earth wire. However, where composite conductors are used for the earth wire(s) the attenuation is more acceptable.
b) The need for insulating the earth wires at each tower and at the terminal points adds to the costs, and for longer distances the additional costs may exceed the savings in coupling equipment.
c) The effectiveness of the earth wires in their protective role under line fault conditions is reduced to some extent by the insulation at each tower.
d) Insulated earth wire links are not recommended for teleprotection.

Because of these drawbacks, the use of insulated earth wires for carrier communications has so far found only limited application.

5.5.3 Connecting cable

5.5.3.1 General

A “connecting cable” inserted between the secondary terminals of the coupling device and the PLC terminal. This connection may be made with either a balanced or unbalanced (coaxial) cable depending on the impedance of the carrier terminal.

Commonly used values for the impedance of the cable are 150 Ω for the balanced cable and 75 Ω for the coaxial type.

5.5.3.2 Coaxial or shielded cable earthing methods

When coaxial cable is employed, different methods of earthing the screen may be used depending if the coupling device and PLC terminal are or not part of the same earth mesh.

For cables lying within the same earth mesh, different methods could apply:

- Earthing at both ends of the coaxial cable: This method ensures the safety of maintenance personnel, as there will never be potential differences between local earth and the cable screen. Obviously, during faults, this connection may allow power-frequency currents to circulate in the screen and in the “hot” conductor;
- Earthing only one side of the screen at the PLC equipment end: This method of earthing may be used to avoid secondary problems due to i.e. coils and windings having magnetic cores. This practice, whilst eliminating power-frequency current circulation, may cause high voltage across the windings of the coupling transformer which will need to be designed for this duty. Consequently, maintenance personnel will need to take precautions against the possibility of potential differences, during faults, between cable screen and local earth.

For cables ending over different earth meshes different methods could apply:

- Earthing only one side of the screen at the PLC equipment end: This method of earthing may be used to avoid earth potential differences may be high in the case of a fault and circulating currents in the screen of the coaxial cable may be dangerous.

Similar problems can arise in the case of armoured and/or shielded cables, except that secondary problems are unlikely to occur, and the same considerations apply. By the use of balanced cables some of the above problems can be avoided.

It is good engineering practice to use for the interconnection between LMU and CC/CVT a solid, uninsulated, large diameter copper rod, or something similarly robust, positioned at least 10 cm away from the supporting steel structure.

5.6 Transmission parameters of electricity power line channel

5.6.1 General

PLC communications works over channels solely designed for optimal electrical power transportation, completely disregarding signal transmission at high frequencies.

Like any other transmission line a set of typical parameters have to be considered to characterize the behaviour of the electricity power line when used as transmission media enabling technicians to evaluate correctly the link budget and estimate the reachable performance and quality.

Basic assumptions valid for all power line channels are as follows:

Low pass characteristics: cables of the mains network are built for energy transfer with little losses, but are not optimal for data transfer. Multiple measurements showed that these cables have a strong low pass characteristic depending on the type of cable, the length of the cable and the frequencies of the signal;

- Selective fading: Each of the transitions at the connections between cables along the propagation path represents changes of impedance and causes reflections. Due to branches and reflection points the signal not only propagates on the direct connection between transmitter and receiver, but also additional propagation paths have to be considered. Those usually have longer path ways and cause time delayed echoes. The result is multi-path signal propagation with frequency selective fading.

The main physical parameters to be considered are as follows:

- Characteristic impedance;
- Overall link attenuation;
- Impulsive and frequency response.

Other relevant aspects concern:

- Noise, reflections, multipath, non-linearity/stationary channel behaviour, interferences, and crosstalk.

5.6.2 Characteristic impedance of power line

The characteristic impedance of a uniform transmission line, usually written Z_0, is the ratio of the amplitudes of a single pair of voltage and current waves propagating along the line in the absence of reflections. The characteristic impedance is expressed in ohms.

Applying the transmission line model based on the telegrapher's equations, the general expression for the characteristic impedance of a generic transmission line is shown in equation (5):

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad [\Omega], \tag{5}$$

where

R is the resistance per unit length;

L is the inductance per unit length;

G is the conductance of the dielectric per unit length;

C is the capacitance per unit length;

j is the imaginary unit, and

ω is the angular frequency.

In practice, at PLC frequencies, the quantities jωL and jωC are large by comparison with R and G, so that the latter can be neglected, and the expression for characteristic impedance can be reduced to equation (6):

$$Z_0 = \sqrt{\frac{L}{C}} \qquad [\Omega]. \tag{6}$$

By applying conventional formulas for L and C to the above equation, Z_0 is shown in equation (7):

$$Z_0 = 276 \cdot \log\left(\frac{d}{r}\right) \quad for\ \frac{d}{r} \geq 20 \qquad [\Omega] \tag{7}$$

is obtained, where d is the distance between conductors and r is their radius in the same units. The achieved equation expresses the characteristic impedance of a line consisting of two aerial wires. For a single aerial conductor at a height h above ground and radius r, the characteristic impedance is shown in equation (8):

$$Z_0 = 138 \cdot \log\left(\frac{2h}{r}\right) \qquad [\Omega]. \tag{8}$$

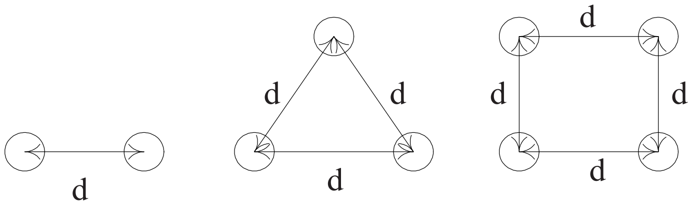
For bundled conductors, the geometric mean radius (GMR) is used for r in previous equations.

The GMR is defined as in Figure 32 and equations (9) for three arrangements, where GMR_c is the GMR of a single conductor.

Two wire bundles $GMR = \sqrt{GMR_c \cdot d}$

Three wire bundles $GMR = \sqrt[3]{GMR_c \cdot d^2}$ (9)

Four wire bundles $GMR = \sqrt[4]{GMR_c \cdot \sqrt{2} \cdot d^3}$



$$GMR_x = \sqrt[n^2]{(D_{aa}D_{ab}...D_{an})...(D_{na}D_{nb}...D_{nn})}$$

for the two – subconductor bundle

$$D_s^b = \sqrt[4]{(D_s \times d)^2} = \sqrt{D_s \times d}$$

for the three – subconductor bundle

$$D_s^b = \sqrt[9]{(D_s \times d \times d)^3} = \sqrt[3]{D_s \times d^2}$$

for the four – subconductor bundle

$$D_s^b = \sqrt[16]{(D_s \times d \times d \times d \times 2^{1/2})^4} = 1{,}09\sqrt[4]{D_s \times d^3}$$

Figure 32 – GMR of conductor bundles

In the case of a three-phase transmission line, the calculation of the characteristic impedance is more involved and is further complicated by the use of bundled conductors. If a transmission line is terminated in its characteristic impedance, no energy will be reflected from the termination, and the sending-end behaviour is the same as though the line was infinitely long.

An impedance network of six impedances, as shown in Figure 33, is required to terminate a three-phase line in its characteristic impedance. Because a transmission line is seldom, if ever, terminated in its characteristic impedance network, the impedance observed by a set of coupling equipment connected to the transmission line, either phase-to-phase or phase-to-ground, will be affected by reflected energy on the uncoupled phases.

Another and more practical value frequently called characteristic impedance is the value of the impedance to which the carrier coupling equipment is matched to obtain minimum mismatch and thus achieve maximum power transfer. This value of characteristic impedance is affected by the terminating impedance of the phase(s) not used in the coupling circuit. Measurements indicate that for phase-to-phase coupling, as the terminating impedance of the uncoupled phases varies from an open circuit to a short circuit, the characteristic impedance varies slightly. However, much larger differences occur for phase-to-ground coupling.

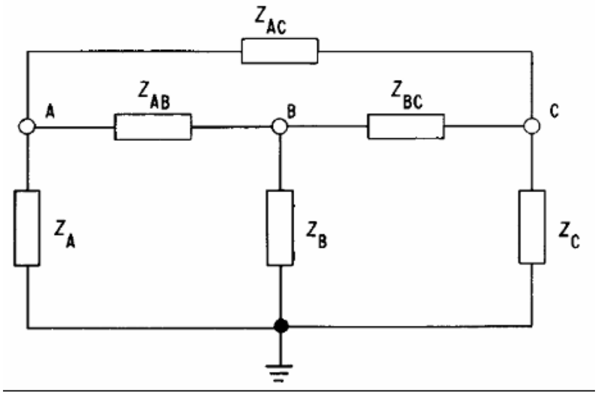


Figure 33 – Terminating network for a three-phase line

As shown, the characteristic impedance is based on the radius of the conductors and the distance between conductors. In general, both dimensions increase with higher voltages so that the ratio remains nearly the same. Therefore, there is very little difference in the characteristic impedances of lines of various voltages as long as only one conductor is used for each phase.

Lower values of characteristic impedance will exist on extra-high-voltage (EHV) transmission lines where bundled conductors are used with an effective radius that is much larger than the radius of a single conductor. Table 8 shows the range of values that can be expected from a wide variety of lines.

Table 8 – Range of characteristic impedances for PLC circuits on EHV/HV overhead lines

Transmission line conductor (each phase)	Characteristic impedance (phase-to-ground) Ω	Characteristic impedance (phase-to-phase) Ω
Single wire	350 to 500	650 to 800
Bundled (two-wire)	250 to 400	500 to 600
Bundled (four-wire)	200 to 350	420 to 500

It should be noted that the figures quoted are mean values calculated over the entire frequency range allocated for particular PLC technology and for all possible terminations of the uncoupled phases. Thus the actual values may differ considerably from the mean but this is generally not significant from the system design point of view, as it only increases the overall loss by some tenths of a decibel.

In comparison to overhead lines, the characteristic impedance of power cables is smaller by a factor of 10 to 20. Consequently, the inductance of the line traps decreases, the capacitance of the coupling capacitors increases by the same figure for equal frequency bands compared with overhead lines.

The values of the characteristic impedance of power cables vary greatly depending from different types of cables. In general, there has not been much information published on power cables, such as the high-frequency characteristic impedance, and it may be required to perform measurements on the actual cable used for a particular circuit. Generally, the characteristic impedance of a power cable will be between 10 Ω and 60 Ω.

5.6.3 Overall link attenuation

5.6.3.1 General

For our purposes it is convenient to simplify the propagation model and consider the overall link attenuation as the one present among the end sides of PLC circuit. It is due mainly to three components: the connecting cable, the coupling systems and the power line. It is expressed in decibel versus frequency as shown in equation (10):

$$A_{OL} = A_{Powerline} + A_{CouplingSystem1} + A_{CouplingSystem2} + A_{ConectingCable1} + A_{ConectingCable2} \text{ [dB]}. \qquad (10)$$

5.6.3.2 Power line attenuation

The line attenuation represents the loss in dB that will be experienced by the signal when in transit over the line. It is measured in [dB/km]. It is primarily a function of the following parameters:

- Line length and conductor configuration,
- Structure of the phase conductors, material, etc.,
- Structure of the earth wire(s), material, etc.,
- Carrier frequency,
- Earth resistivity.

Its effective value depends also from:

- Coupling configuration adopted,
- Tower disposition effects,
- Weather conditions.

5.6.3.3 Modal analysis

Analysis of a multi-conductor line shows that several modes of carrier signal propagation take place simultaneously. It can be shown that the number of natural modes is equal to the number of conductors involved in the propagation (e.g. three modes in the case of a single-circuit line with two earth-wires grounded at each tower, and seven modes in the case of double-circuit line with one insulated earth-wire).

The main characteristics of natural modes are:

a) each mode has its own specific propagation loss, velocity and characteristic impedance;
b) the modes are independent of each other;
c) the phase voltage at any location is the vector sum of the phase-mode voltages at that location, similarly the phase current is the vector sum of the phase-mode currents.

Modal analysis shows that the coupling arrangement should be chosen in such a way that the whole transmitter power is injected into the line in the form of the lowest loss mode. For practical coupling arrangements, such as phase-to-earth, phase-to-phase or inter-circuit coupling, the transmitter power is generally injected in the form of a mode-mixture, part of it in a high loss (ground) mode, this resulting in a certain modal conversion loss a_c.

The line attenuation a_line can be calculated as follows through equation (11):

$$a_\text{line} = \alpha_1 \cdot l + 2 \cdot a_\text{c} + a_\text{add}, \tag{11}$$

where

a_line is the line attenuation (dB);

α_1 is the attenuation constant of the lowest loss mode (dB/km);

a_c is the modal conversion loss (dB) (refer to Figure 34),

$$a_\text{c} = 10 \cdot \log\left(\frac{P\ \text{total}}{P\ \text{total} - P\ \text{ground mode}}\right);$$

a_add is the additional loss caused by discontinuities, e.g. coupling circuit, transposition, in dB;

l is the line length (km).

From the analysis of a considerable amount of experimental material and computer calculation, the following approximation for α_1 was found:

$$\alpha_1 \approx 7 \cdot 10^{-2}\left[\frac{\sqrt{f}}{d_\text{c} \cdot \sqrt{n}} + 10^{-3} \cdot f\right], \tag{12}$$

where

α_1 is the attenuation constant of lowest loss mode (dB/km);

f is the frequency (kHz);

d_c is the diameter of phase conductor (mm);

n is the number of phase conductors in bundle.

This formula will give a good approximation (approximately ± 10 % up to 300 kHz, ± 20 % up to 500 kHz) for most cases with line voltages above 150 kV and earth resistivity's around 100 Ωm to 300 Ωm.

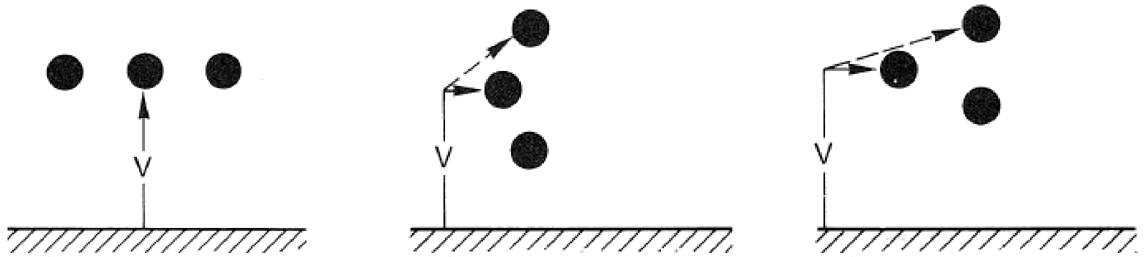
5.6.3.4 Homogeneous lines

The choice of coupling arrangement is less critical for vertical and triangular single-circuit lines than for double-circuit lines, but is essential for horizontal line configurations. Optimum coupling arrangements and modal conversion loss a_c for horizontal and triangular lines are shown in Figure 34.

The following approximate figures for the additional loss a_{add} can be applied to different line configurations, provided that optimum coupling arrangements are as shown in Table 9:

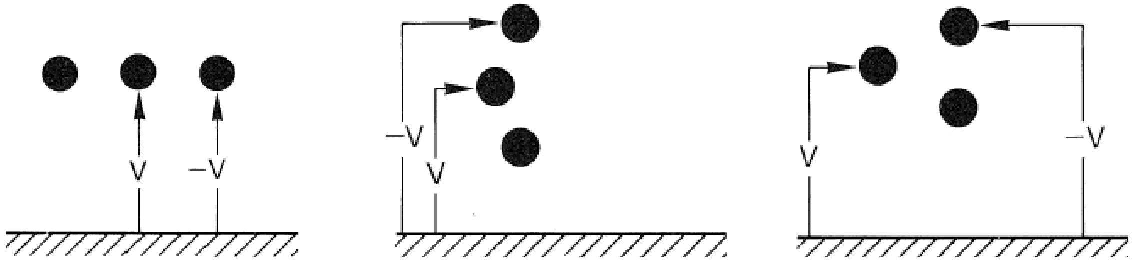
- single-circuit, vertical or triangular:
  $a_{add} \leq 3$ dB for phase-to-earth and phase-to-phase coupling;
- double-circuit, vertical or triangular:
  $a_{add} = 2$ dB to 10 dB for phase-to-earth and phase-to-phase coupling;
  $a_{add} \leq 1$ dB for double differential coupling;
- single-circuit, horizontal:
  $a_{add} = 0$ dB for phase-to-earth coupling;
  $a_{add} = 0$ to 6 dB for phase-to-phase coupling.

Single circuit lines – phase to earth coupling



a) a_c = 1,5 … 2 dB b) a_c = 1,5 … 3,5 dB c) a_c = 1,5 … 3,5 dB

Single circuit lines – phase to phase coupling

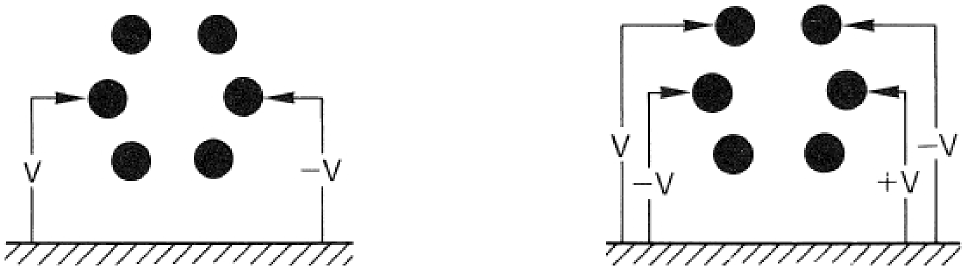


d) $a_c \approx 0$ dB e) a_c = 0,5 … 1 dB f) a_c = 0,5 … 1 dB

Double circuit lines – coupling to one circuit

g) a_c = 1 … 3,5 dB h) a_c = 0 … 0,5 dB

Double circuit lines – intercircuit coupling



i) $a_c \approx 0$ dB j) $a_c \approx 0$ dB

Figure 34 – Optimum coupling arrangements and modal conversion loss a_c

5.6.3.5 Inhomogeneous lines

Inhomogeneities such as line transpositions, tapped lines or junctions of overhead lines with power cables may cause serious problems and, therefore, have to be studied carefully when planning a PLC network.

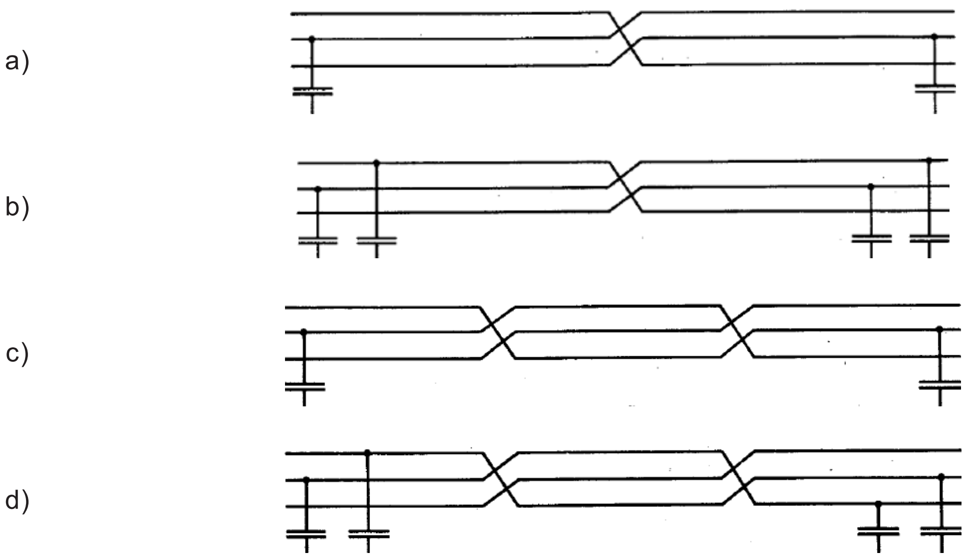


Figure 35 – Optimum phase to earth and phase to phase coupling arrangements

Line transpositions can lead to intolerably high line attenuation under certain circumstances. Their effect on carrier signal transmission depends on the line parameters, line length, coupling arrangement, type and number of transpositions, earth resistivity and carrier frequency.

- In the case of single-circuit vertical or triangular line configurations, the additional loss a_{add} is virtually independent of carrier frequency, type and number of transpositions, provided that coupling is done to electrically through-connected phase conductors. The following figures may be assumed:
  - phase-to-earth coupling: a_{add} = 6 dB to 12 dB;
  - phase-to-phase coupling: a_{add} = 4 dB to 8 dB.
- In the case of double-circuit vertical or triangular line configurations, the additional loss a_{add} depends on the number of transpositions, line parameters, ground resistivity, coupling arrangement and the product of carrier frequency and line length; figures of 2 dB to 10 dB, or even 20 dB have been measured. It is advisable, in critical cases, to calculate the overall attenuation with the aid of a modal computer programme or carry out field measurements should the line be available.
- In the case of horizontal line configuration, the choice of the correct coupling arrangement and carrier frequency range is essential. Assuming that the optimum coupling arrangements given in Figure 34 are used, the additional loss becomes:

  a) In the case of mid-point transposition:

  - phase-to-earth coupling (Figure 35 a): a_{add} = 6 dB;
  - phase-to-phase coupling (Figure 35 b): a_{add} = 8,5 dB to 12 dB.

  for the whole frequency range and any line length, since modal cancellation cannot occur.

  b) In the case of equi-spaced transpositions:

  the additional loss depends very much on the carrier frequency, line parameters and earth resistivity and there is a risk of modal cancellation.

  Therefore, the product of carrier frequency and line length $(f \cdot l)$ should not exceed 10^5 kHz · km for line voltages up to 330 kV and 0,5 · 10^5 kHz · km for higher voltages. Then for the majority of cases the additional loss will be of the order of:

- phase-to-earth coupling (Figure 35 c):

a_{add} = 1 dB to 10 dB; earth resistivity, $\rho \geq 1\,000\ \Omega\mathrm{m}$;

a_{add} = 3 dB to 8 dB; earth resistivity, $\rho = 30\ \Omega\mathrm{m}$ to $300\ \Omega\mathrm{m}$;

- phase-to-phase coupling (Figure 35 d):

a_{add} = 0 dB to 8 dB; earth resistivity, $\rho \geq 1\,000\ \Omega\mathrm{m}$;

a_{add} = 2 dB to 10 dB; earth resistivity, $\rho = 30\ \Omega\mathrm{m}$ to $300\ \Omega\mathrm{m}$;

The lower values of the ranges given are applicable for lower $f \cdot l$ products, the higher for $f \cdot l$ is given above.

The information given above for a_{add} is summarized in Table 9.

Table 9 – Additional loss a_{add} [dB] for various line configurations and optimum coupling arrangements

Line configuration and coupling Figure 34	Number of transpositions			
	0	**1**	**2**	**More than 2**
a) $\rho = 30\ \Omega\mathrm{m}$ to $300\ \Omega\mathrm{m}$	0	6	3 to 8 [a]	–
$\rho \geq 1\,000\ \Omega\mathrm{m}$	0	6	1 to 10 [a]	–
b)	0 to 3	6 to 12	6 to 12	6 to 12
c)	0 to 3	6 to 12	6 to 12	6 to 12
d) $\rho = 30\ \Omega\mathrm{m}$ to $300\ \Omega\mathrm{m}$	0 to 4,5	8,5 to 11	2 to 10 [a]	–
$\rho \geq 1\,000\ \Omega\mathrm{m}$	0 to 5,5	8,5 to 11	0 to 8 [a]	–
e)	0 to 3	4 to 8	4 to 8	4 to 8
f)	0 to 3	4 to 8	4 to 8	4 to 8
g)	2 to 10	2 to 10 [b]	2 to 10 [b]	2 to 10 [b]
h)	2 to 10	2 to 10 [b]	2 to 10 [b]	2 to 10 [b]
i)	2 to 10	2 to 10 [b]	2 to 10 [b]	2 to 10 [b]
j)	0 to 1	0 to 4	2 to 8 [b]	2 to 8 [b]

[a] $l \cdot f_{\mathrm{max}} \leq 1 \cdot 10^5$ km · kHz (≤ 330 kV);
$l \cdot f_{\mathrm{max}} \leq 0{,}5 \cdot 10^5$ km · kHz (> 330 kV).

[b] $l \cdot f_{\mathrm{max}} \leq 2 \cdot 10^5$ km · kHz.

Junctions of overhead lines with power cables result in an increased overall attenuation due to the mismatch loss at the junctions.

The PLC equipment should be matched respectively to the characteristic line impedance – or to the cable impedance. Sometimes, special measures are necessary to improve the return loss seen by the PLC transmitter coupled to the overhead line.

In the case of one junction only (Figure 36 a), the total attenuation a_{tot} (dB) can be written in the following form:

$$a_{tot} = a_{line} + a_{cable} + a_m \, . \tag{13}$$

The mismatch loss a_{m} is virtually independent of the frequency and is of the order of 5 dB to 7 dB.

In the case of two junctions (Figure 36 b), standing wave effects occur and the overall attenuation then becomes as shown in equation (14):

$$a_{tot} = a_{line\,1} + a_{cable} + a_{line\,2} + 2 \cdot a_m + a_s \, . \tag{14}$$

where

a_{s} is the additional attenuation due to standing wave effect.

Due to the frequency-dependent term a_{s}, the overall attenuation shows pronounced periodical fluctuations with frequency, particularly for small cable attenuations where a may vary between –7 dB and +5 dB. If the cable attenuation exceeds approximately 6 dB the fluctuations become less than ±1 dB and, therefore, may be neglected.

The PLC sets at both line ends should be matched to the characteristic line impedance and again it may be necessary to improve the return loss, thus reducing the risk of intermodulation in the transmitters.

In the case of a single three-phase cable, mode conversion takes place at both junctions, which is an additional loss over and above that due to the above-mentioned mismatch. The calculation of overall attenuation becomes complex and should be carried out by computer. This mode conversion does not occur with three separate single-conductor cables.

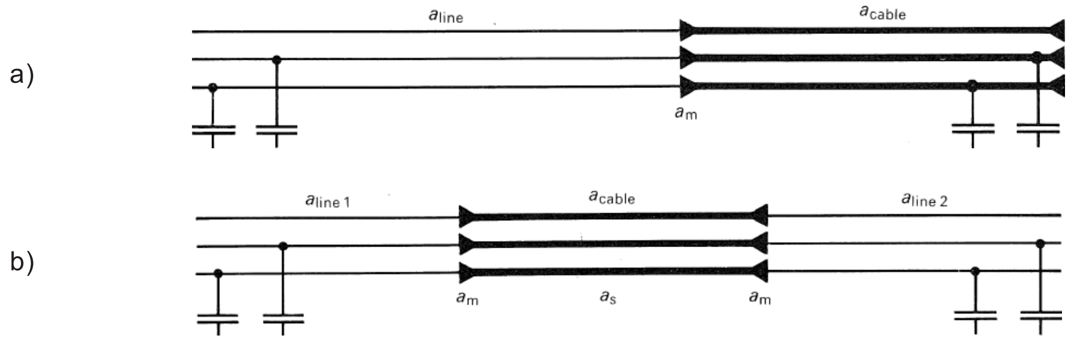


Figure 36 – Junctions of overhead lines with power cables

Tapped lines may cause serious problems due to the mismatch at the tee-point and standing wave effects on the untrapped tap-line. Without any additional means involved, the line attenuation would normally show accentuated peaks with spacing

$$\Delta f = \frac{150}{l_{\mathrm{t}}} , \tag{15}$$

where

Δf is the spacing of attenuation peaks (kHz);

l_{t} is the length of the tap (km).

The most efficient means to overcome these attenuation peaks would be to trap all three phases of the tap-line at the tee-point. Normally it is sufficient to insert a line trap into the phase conductor of the tap which carries the most signal power on the main line. It is important that the line trap be designed for a minimum resistive component R_0 over the whole frequency band used in the system, rather than for a minimum $|Z_0|$ only.

If the line trap cannot be installed at the tee-point for some reason, there is also the possibility of inserting it at the far end of the tap. In this particular case, the trapped phase conductor shall be terminated by the line impedance, thus requiring an additional coupling capacitor in the substation.

5.6.3.6 Parallel lines entering a substation

A case that frequently occurs is where an existing line is diverted into a new substation built close to the line. The new substation then has two parallel entries from the original line and the existing PLC channels shall also be diverted, either as through-circuits which by-pass the new substation or as new PLC channels operating between the original PLC terminal ends and the new substation. This new configuration may result in an increase in attenuation at certain frequencies which can be overcome by introducing a phase-shift network in the CF by-pass at the new substation.

5.6.3.7 Line losses in bad weather conditions

The propagation of carrier signals along the line is affected by rain, fog, snow and ice. In the case of rain or fog, the increase of attenuation is generally small, and can be neglected.

In certain cases (in industrial areas or near the sea shore), a rain shower may produce a lower attenuation by cleaning the insulator surface of the power line.

In the case of ice, the situation is different since increase in attenuation may assume unacceptable values for the transmission link and shall be considered by the planning engineer.

However, it should be appreciated that overhead lines are rarely affected by ice over their total length. The increase of attenuation depends on the following:

a) the configuration of the power line;
b) the thickness of the ice sheath over the conductors;
c) the ambient temperature;
d) the frequency of the carrier signal; the higher frequencies are most affected.

Hoarfrost and ice coating of the phase-conductors may, under extreme conditions, cause the fair weather attenuation constant to be increased by up to six times for the affected sections of line. In the case of a 0,5 cm thick ice coating, the attenuation constant is increased by a factor of 1,5 to 2 for frequencies above 300 kHz. Factors at the lower end of the range would apply for bundle conductors. For this reason it is recommended that for lines subject to icing the lowest carrier frequencies should be utilized.

5.6.3.8 Coupling system attenuation and losses

Losses in the coupling equipment and carrier frequency connection:

According to IEC 60481 on coupling devices for PLC system the composite loss brought about by the quadripole made up of coupling device and associated coupling capacitor(s) shall not be greater than 2 dB over the whole of the available bandwidth.

Generally the coupling loss including dielectric losses in the coupling capacitor may be expected to be less than 1,5 dB.

Typical attenuation figures for carrier frequency connecting cables are 1 dB/km to 5 dB/km in the frequency range from 30 kHz to 500 kHz.

5.6.3.9 Tapping losses

According to IEC 60353 on line traps the tapping loss should preferably not exceed 2,6 dB. This loss corresponds to a line trap impedance 1,41 times the characteristic impedance of a line.

5.6.3.10 Additional losses

Where a number of PLC sets are connected in parallel to transmit and receive via common coupling equipment, each set in subject to an additional coupling loss of 0,5 dB to 1 dB; due allowance for this should be made when carrying out the overall loss calculations on the link.

5.6.3.11 CF by-pass losses

The design of high-voltage network does not always correspond with the communications requirement of that network, in that the high-frequency channels are not always required to terminate at the sense terminal as the power termination.

In some cases the carrier channel are required to transmit over two sections of a line which may have a discontinuity due to the power system configuration.

In others cases some channels is required to terminate at the mid-point whilst others are transmitted through this point.

It is uneconomical from the point of view of cost and frequency planning to provide a full carrier termination to bring the whole circuit down to a voice frequency basis, and in these circumstances the conventional method of achieving this is to provide a high-frequency by-pass circuit.

In order to do this and to prevent dangerous voltages from the live power line section being transferred from one side of the disconnected section to other, by-pass circuits can be introduced which consist of normal coupling units built as band-pass filters and simply interconnected by a coaxial or balanced pair cable with conventional line traps arranged in the usual manner.

The pass band of this arrangement corresponds to that of the usual coupling arrangements.

The additional attenuation introduced by such a by-pass consists of the losses introduced by the coupling devices, line matching units, cable connections etc. Typical values are 4 dB to 8 dB in the case of a through-connected by-pass and 5 dB to 9 dB where there is local connection.

5.6.4 Channel frequency and impulsive response

The transfer function or the frequency response $H(f)$ completely describes how the circuit processes the input to produce the output. The transfer function reveals how the power line channel modifies the input amplitude in creating the output amplitude.

The impulse response $h(t)$ of a power line channel refers to the reaction when a brief input signal, called an impulse is applied to its input. More generally the impulse response describes and characterizes the reaction of the system as a function of time.

Thus the two functions $H(f)$ and $h(t)$ fully represents the behaviour of the power line channel but using different domains respectively frequency and time.

Figure 37 represents the EHV *H*(*f*) and *h*(*t*) typical response and Figure 38 represents the MV *H*(*f*) and the *h*(*t*) typical channel response.

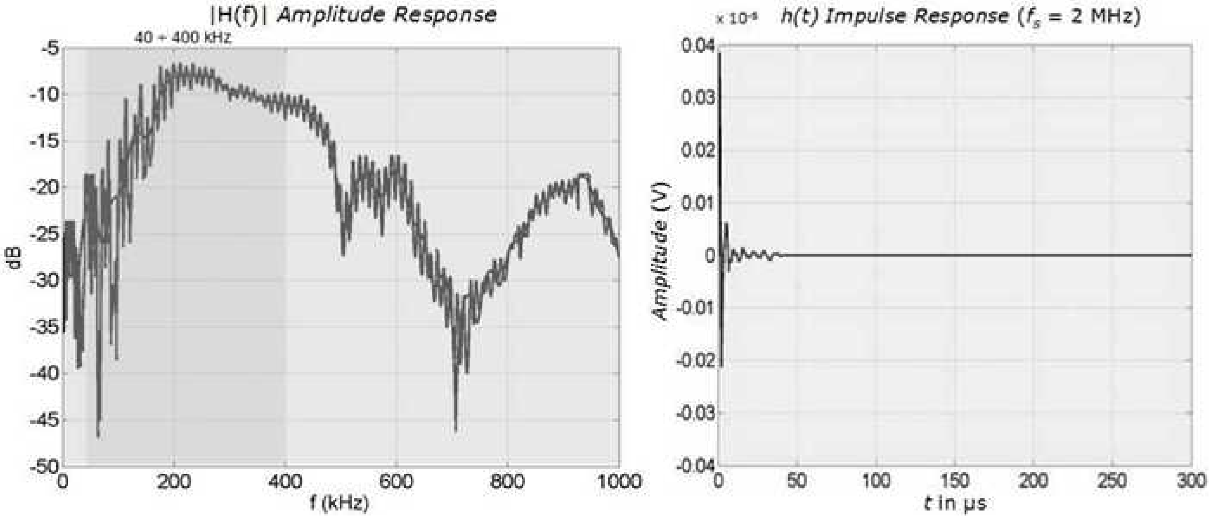


Figure 37 – EHV *H(f)* and *h(t)* typical channel response

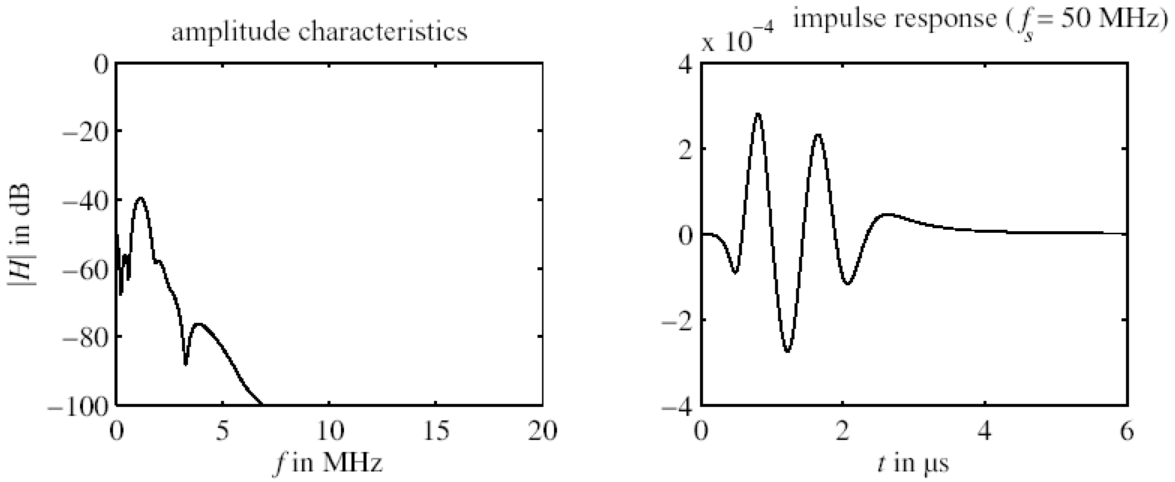


Figure 38 – MV *H(f)* and *h(t)* typical channel response

Figure 39 provides an example of the attenuation of a real HV power over the frequency range from 40 kHz to 500 kHz.

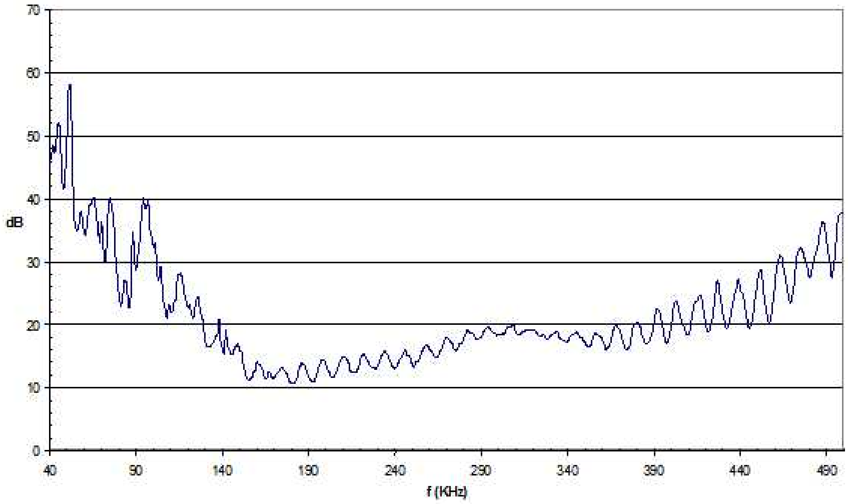


Figure 39 – Attenuation versus frequency of a real HV power line channel

5.6.5 Noise and interference

5.6.5.1 General

Noise may be defined as any unwanted signal that interferes with the communication or processing of an information-bearing signal. There may be several varieties of noise that could degrade the quality of communication, such as background noise, narrowband noise, electromagnetic radio-frequency noise, co-channel interference, impulsive noise, etc.

Special attention should be paid to all kinds of impulsive noise since digital PLC systems are very sensitive to them and this class of noise has been insufficiently considered so far. Recent approaches to apply existing concepts of data transmission from other areas of communications techniques on transmission over power line networks have proven that all requirements cannot be met without having detailed knowledge of the channel and without adapting the concepts to its properties.

For assessment of the influence of noise on digital data transmission, in the following the noise scenario is classified and shortly described.

Depending on its source for PLC considerations, it is convenient to classify a noise into a number of categories as follows:

- Background noise;
- Impulsive noise (isolated spikes, periodic, aperiodic, burst);
- Interferences.

Annex E provides information about noise measurements.

5.6.5.2 Background noise

The common sources of background noise include power lines grid corona noise, transformers, generators, switchers, breakers, insulators and for lower voltage grid also motors and motor starters, oscillators, relay.

However the main contribution on EHV and HV is due to corona noise, which is random noise caused by irregular electric discharges across insulators and conductors (corona, brush discharge).

Corona noise only approximates to “white” since its amplitude tends to decrease as frequency increases. In addition, since the noise is generated during positive half-cycles of the line voltage, it consists essentially of bursts of trains of short pulses having a fundamental burst repetition frequency of 150 Hz (for a three-phase 50 Hz system).

Background noise is partially overlaid by narrow-band noise. Narrow-band noise sometimes is considered as a part of background noise. Its intensity and frequency varies over place and time. The main sources for narrow-band noise are broadcasters in long, middle and short wave range as well as several radio services like amateur radio, so that almost the whole frequency range up to several MHz is overlaid by narrow-band noise. A part of a noise spectrum with clearly visible narrow-band noise is shown in Figure 40.

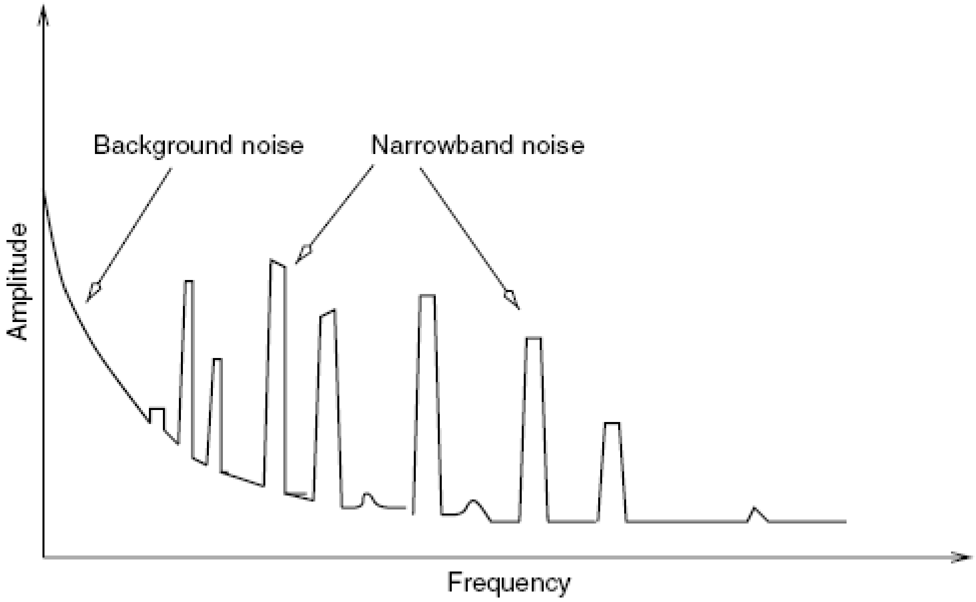


Figure 40 – Background noise

Generally, the power density of background noise decreases towards higher frequencies.

For practical purposes the noise can be considered white in the nominal carrier frequency band in the 40 kHz to 500 kHz range.

Typical overall noise power levels, referring to the coupling point of the HV line itself, are shown in Table 10. These figures are given for fair and adverse atmospheric conditions, and apply both for phase-to-earth and phase-to-phase coupling.

Table 10 – Typical power of corona noise power levels, referring to a 4 kHz bandwidth for various EHV/HV system voltages

AC Line voltage kV	Typical corona noise levels in 4 kHz on overhead high voltage lines	
	Fair weather dBm	**Adverse weather** dBm
up to 110	-50	-30
150	-45	-25
220	-40	-20
300	-35	-15
400	-30	-10
800	-20	0

NOTE Considerable variations to the above figures are possible due to differences in the design parameters of the overhead line which result in differences in the voltage gradient at the surface of the conductors for similar line voltages. Other variations are possible due to the construction, altitude and age of the line, whilst the effect of weather can also be significant, for example during mist, rain and hoarfrost.

Corrections for different bandwidths (BW) can be made by using the following equation:

$$\Delta P_{\mathrm{n}}\ [dB] = 10 \log \left(\frac{\mathrm{BW\ (kHz)}}{4\ \mathrm{(kHz)}} \right). \tag{16}$$

Figure 41 shows an example for the background noise power spectral density over frequency, while Figure 42 shows the variation of the noise spectrum over time.

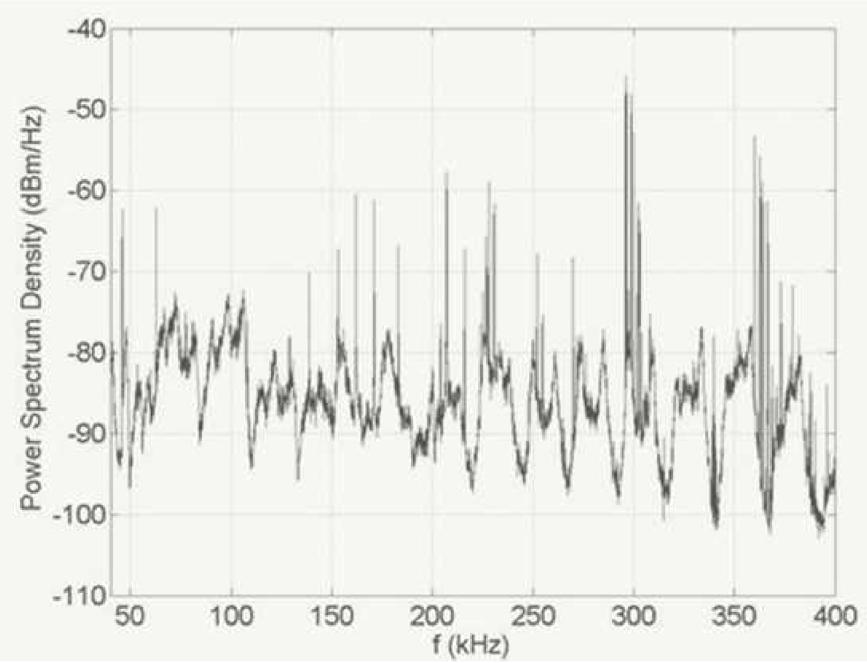


Figure 41 – Background noise over frequency

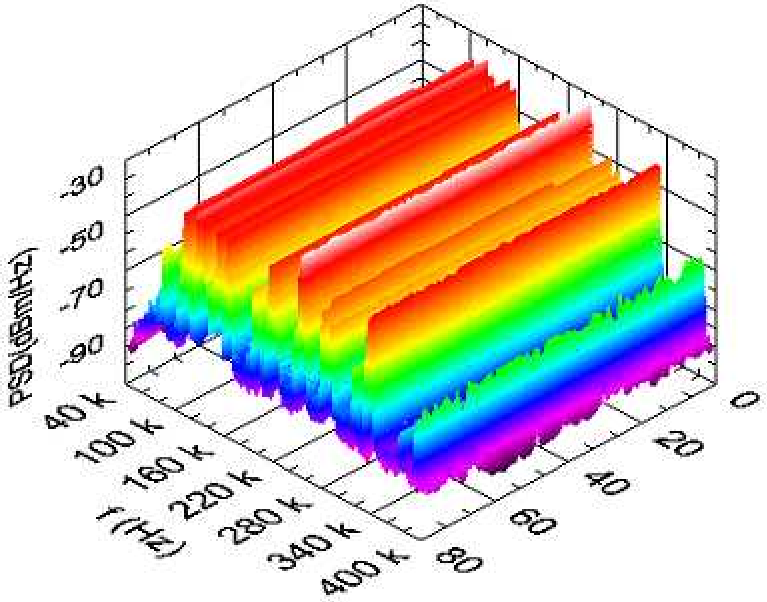


Figure 42 – Variations of the background noise spectrum over time

5.6.5.3 Impulsive noise

Impulsive noise as shown in Figures 43 and 44 consists of short-duration “on/off” noise pulses, caused by a variety of sources. The presence of short spikes and bursts of high amplitude over electricity power lines are mainly due to operation of isolators and breakers and by lightning, flashovers and the like.

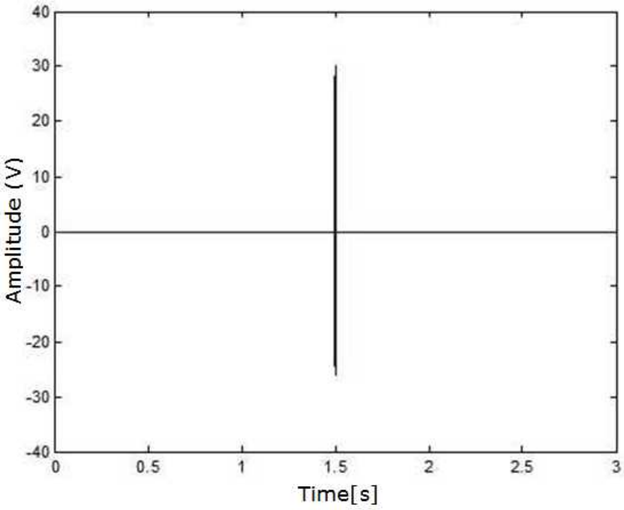


Figure 43 – Isolated pulse

Beside isolated pulses there are the so called transient noise pulses often consist of a relatively short sharp initial pulse followed by decaying low-frequency oscillations. They result from the combination of an initial pulse usually due to some external or internal impulsive interference, whereas the oscillations are often due to the resonance of the communication channel excited by the initial pulse, and may be considered as the response of the channel to the initial pulse.

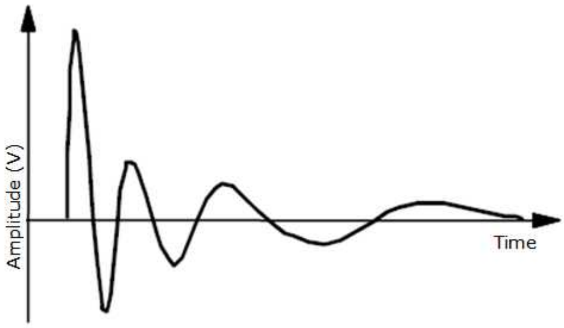


Figure 44 – Transient pulse

It is not uncommon to find over a power line a short sequence of pulses known as burst pulses. Depending on the nature of the generating source they could be periodic as shown in Figure 45 or aperiodic as shown in Figure 46.

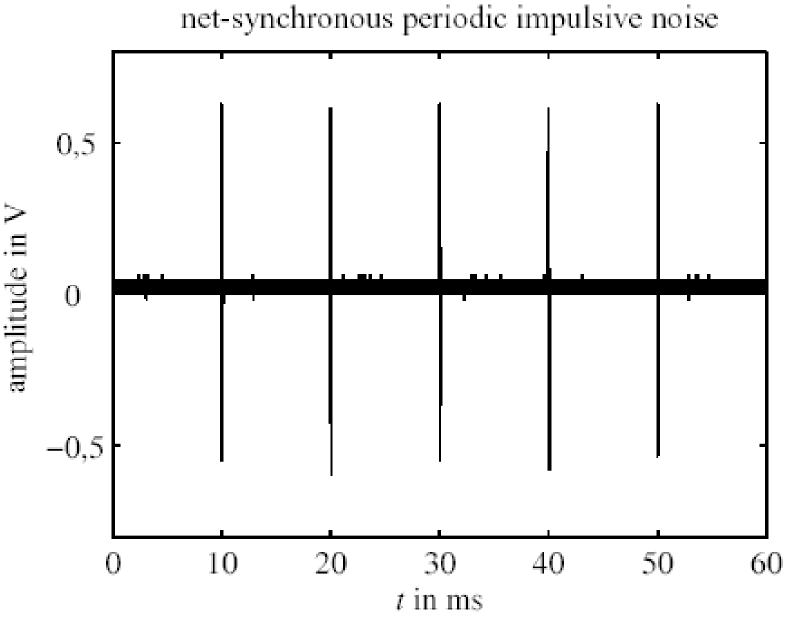


Figure 45 – Periodic pulses

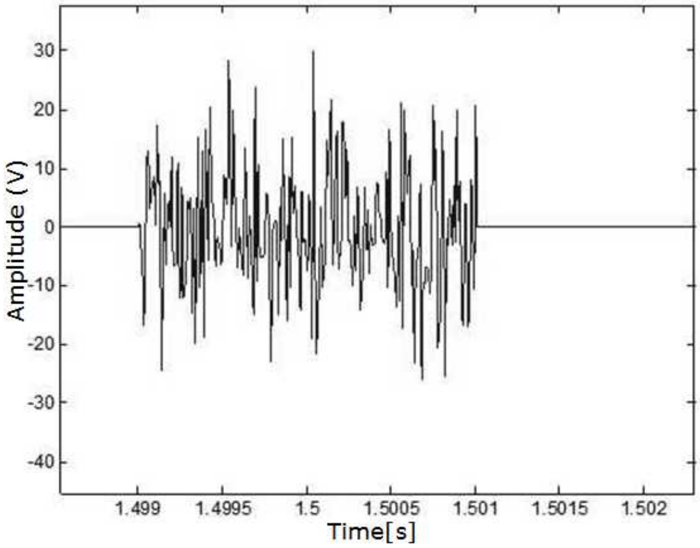


Figure 46 – Burst pulses

Impulsive noise measurements should be performed using appropriate instrumentation setup working on time domain like oscilloscope with digital advanced functionalities.

However a first basic preliminary characterization could be performed using a simple selective voltmeter like in the past.

Atmospheric discharge caused by lightning consists frequently of a number of consecutive partial discharges in irregular sequence with a spacing varying between 8 ms and 400 ms. When lightning strikes the line or near the line (tower, ground wire) the impulse-type noise voltages again have a high amplitude of the order of +20 dBV to +35 dBV.

Flashovers on a power system result in the production of broadband energy. In general, the onset of a fault is so rapid and the fault current so high that the arc path quickly becomes highly ionized. At the onset of the fault and before the arc is fully established, the noise levels on the high and extra high voltage networks are of the order of +15 dBV to +25 dBV and have a duration of about 2 ms to 10 ms. When the arc has become established, the noise falls to a lower level of about –15 dBV to –25 dBV.

The operation of circuit-breakers for energizing and de-energizing lines produces noise of magnitude varying from –10 dBV up to +25 dBV and having a duration of about 10 ms.

Normal switching operations involving slow speed isolators (“disconnect”) may occur frequently. The interference so generated is characterized by high amplitude noise of the order of +20 dBV to +35 dBV and relatively long duration, i.e. 0,5 s to 5 s, depending on the isolator design. The weak ionization of the arc results in repeated restriking (both on opening and closing) which produces high-amplitude trains of high-frequency oscillations within the area of the substation. These oscillations are coupled in the substation to HV-lines in various ways, for example, by direct coupling, by induction, by leakage or by the common earthing system.

The information given above for impulse-type noise is summarized in Table 11.

Table 11 – Typical average impulse-type noise levels, measured at the HF-cable side of the coupling across 150 Ω in a bandwidth of 4 kHz

Source	**Level** dBV	**Pulse density** Pulse/s	**Duration** ms
Lightning discharge	+25	1 to 40 average 2 to 3	Up to 1 000
Isolator switch (bus bar on or off)	+25	300 to 900	500 to 5 000
Circuit breaker (line on or off)	+20	1 000 to 2 000	5 to 20
Circuit breaker (short circuit off)	+4	1 000 to 2 000	5 to 20
Ground fault (onset of line fault)	+20	1 000 to 2 000	5 to 20
Burning arc	–20	100 to 300	–
NOTE Subtract 4 dB for 2,5 kHz bandwidth.			

5.6.5.4 Interference

Interference is caused by unwanted signals from other equipment on the same line or in the same geographical area.

The reasons for interference are:

- bad frequency planning;
- faulty existing equipment;
- external sources.

Power line carrier systems can suffer from interference, particularly from other power line carriers operating elsewhere on the power network, owing to leakage and coupling of energy past the line traps.

This effect has to be taken into account in planning any PLC installation and in recommending the choice of a particular frequency.

Depending on the particular system design, energy from external sources such as open-wire carrier systems and more particularly from MF and LF radio transmitters may be picked up and enter the carrier receivers.

The radio systems which could be involved in interference include maritime and aeronautical systems, broadcasting services and some systems operating in the MF and LF bands. One major category is that of aids to navigation such as the OMEGA, DECCA, CONSOL guidance systems and approach locators at airports.

Some services necessitate protection of very weak signals, particularly when human life is at stake. The necessary protection can be assessed by appropriate frequency and geographical separation. This can be achieved by continuous co-operation and consultation between appropriate services.

In many cases the relative signal ratios required for protection are laid down by the ITU Radio Regulations (RR) and by Annex 10, Volume V to the ICAO (International Civil Aviation Organization) Convention for protecting radio services.

Where there is a mutual conflict of interests between the authorities responsible for HV networks and aeronautical services, consultation should then take place between the authorities concerned on a national basis.

One may gain an idea of protection afforded, if one notes that, at the limit of the normal area of use of aeronautical locators (ranging generally from 15 to 100 nautical miles) the signals received from the locator is required to be greater than +37 dB in relation to 1 μV/m and that there is to be a ratio of 15 dB between the locator signal and any interfering signal at the same frequency.

6 Planning DPLC and APLC links and networks

6.1 General

Before planning a PLC system it should be clarified the needs that the user has. Today there are available different types of PLC terminals, pure analogue, pure digital and combined systems. The HF bandwidth needed for each type depends on the capacity offered by each one. So, it is important to know the present and future needs about the services to be transmitted in order to make a good choice of the equipment to be used.

Apart from the transmission capabilities, the systems usually offer additional features to be taken also into account. These features refer to facilities like management and maintenance options that today are considered essential for the exploitation of a communication system.

The starting points to be considered when planning a PLC system can be summarized as follows.

a) Type of interfaces needed:

- Analogue interfaces for analogue applications/services such as speech, analogue signals delivered by modems, typically for low data speed applications, and analogue signals coming from teleprotection terminals. The modems and teleprotection terminals mentioned can be external units or in built optional modules in the same PLC system. In these cases, the services are organized using FDM technique making blocks of 4 kHz baseband units. Depending on the total number of services needed, one or several 4 kHz channels could be needed.
- Digital interfaces for those applications/services that are already available in digital format at the user premises. In this case the number and type of interfaces should be known. Also the speed in bits per second of each service has to be taken into account. The different digital data streams are organized using TDM technique giving place to a digital frame containing the user services plus internal information for synchronism purposes among others such as redundancy for BER improvement and management facilities. Of course this digital frame has a digital speed that is higher than the addition of the individual speed of each user services.

This digital frame is processed by means of a digital modulation, such as QAM or OFDM, giving place to an analogue signal having a total bandwidth that depends on the total speed and the spectral efficiency of the digital modulation used.

When speech has to be transmitted using digital transmission, the analogue speech signal is first digitized and properly processed so that it is converted to a digital format.

When teleprotection information is transmitted using digital systems in fact the teleprotection signal is transmitted in the typical analogue concept in order to avoid the additional delay usually introduced in the coding-decoding process for the digital services. Another effect to consider is due to the very high noise level present during a line fault degrades seriously the digital transmission.

In both cases the analogue 4 kHz basebands and the analogue band containing the digital services are transposed to the desired HF location and transmitted to the power line through the coupling devices.

b) Performance of the system:

There are several considerations that play an important role on the performance of the PLC link. These items are considered in Clause 7.

Here only a brief summary is given. The key point is the signal to noise ratio at receive side that of course depends on the transmitted power, the link attenuation and the noise level.

In Clause 5, all topics related to attenuation and noise are covered.

To improve the transmission quality, some techniques of coding are used in digital systems. The main drawback of these techniques is an increase of the latency of the overall transmission.

6.2 APLC link budget

Analogue PLC transmission has been used for a long time and the type of modulation used, single side band (SSB) is mature and very well-known by PLC users. Only the technology used in the terminals is changing in order to include more facilities related to ease of commissioning and improved management facilities.

In an APLC system as shown in Figure 47, only signals in analogue format are transmitted such as speech, narrow band pass signals delivered by modems that are used for low speed data transmission and teleprotection signals. It is common practice, when needed, to use the total useful baseband only for data transmission, using a more sophisticated modem or to devote the baseband channel for teleprotection transmission purposes.

Depending on the total number of services to be transmitted, single channel or twin channel APLC terminals are in general used.

When speech is transmitted, the corresponding interface includes the facility for pulse dialling transmission. The speech signal is low pass filtered in order to fix the bandwidth used for this service and amplitude limited in order to avoid over-modulation in the power stage of the APLC terminal. Using a compandor circuit or process for the speech channel improves the signal to noise ratio for speech by about 10 dB.

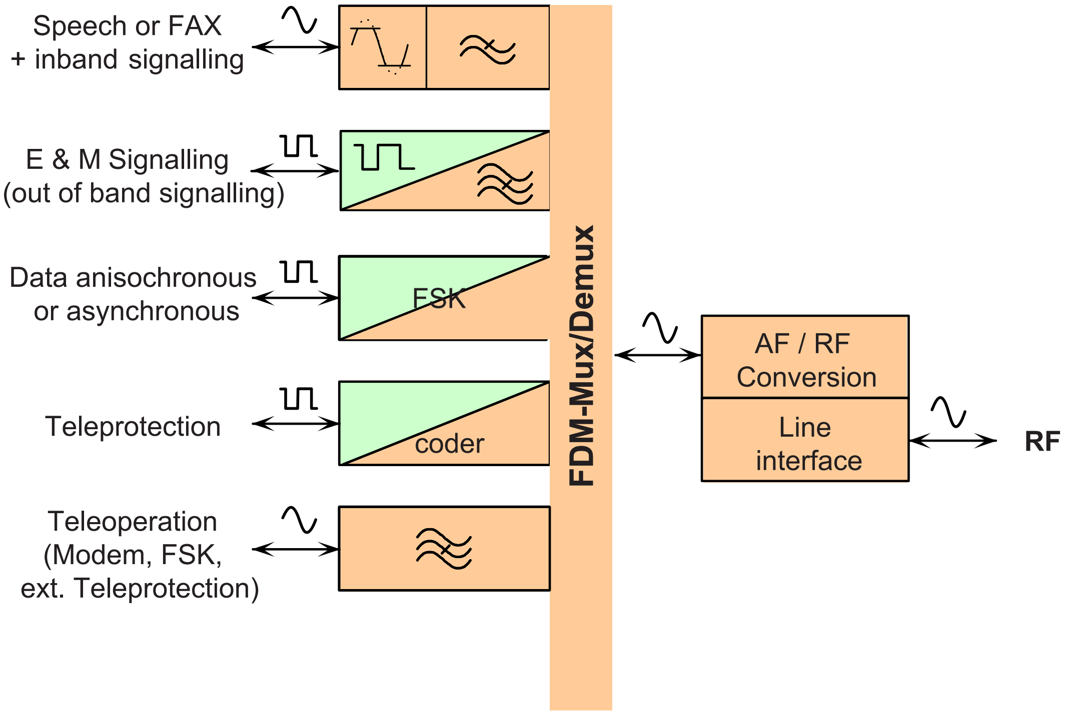


Figure 47 – APLC equipment architecture

Pilot signals, one in total or one per 4 kHz baseband channel, are also included in order to allow the automatic gain control (AGC) function to be carried out at receive side. This function has the purpose of compensating the HV line attenuation variations due to weather changes or changes of HV system topology that can cause variations in the link attenuation.

Depending on the facilities included in the specific PLC terminal, sometimes pilot signals are also used for other functions apart from the AGC process. Often these additional functions are related to management facilities.

The baseband is arranged in frequency division multiplexing (FDM) concept, in other words, each service to be transmitted, including the pilot signal, has a specified bandwidth that allows to combine all services, each one occupying a different range of frequencies, without any frequency overlapping between them.

Once the baseband is arranged as far as frequency allocation of each service is concerned, then the amplitude level of each service has to be decided. The goal is to maximise the performance of the PLC communication under white noise conditions. This is achieved by setting the individual signal levels according to the following two rules:

Rule 1: The individual signal powers shall be proportional to the product of signal to noise power ratio, peak to average power ratio, bandwidth and, if required, an additional safety margin of the individual signals.

Rule 2: The peak voltage of the sum of the individual signals shall be as high as possible, but not higher than the peak voltage that can be delivered by the power amplifier.

Annex C explains the formulas behind these rules.

The resulting set of individual signal levels for each service is the APLC link budget. Equivalently, the modulation percentages can used to specify the signal levels. Usually, the link budget is fixed by the manufacturer and the individual signal levels are given in the documentation. In case individual signal levels can be chosen by the user, it is important to understand the concept of the link budget.

As an example, assume that the following signals have to be transferred over the link:

- 1 speech channel,
- 2 data channels 200 Bd,
- 1 voice band modem,
- 2 pilot channels.

Figure 48 shows a possible arrangement of these signals in two baseband channels of 4 kHz each.

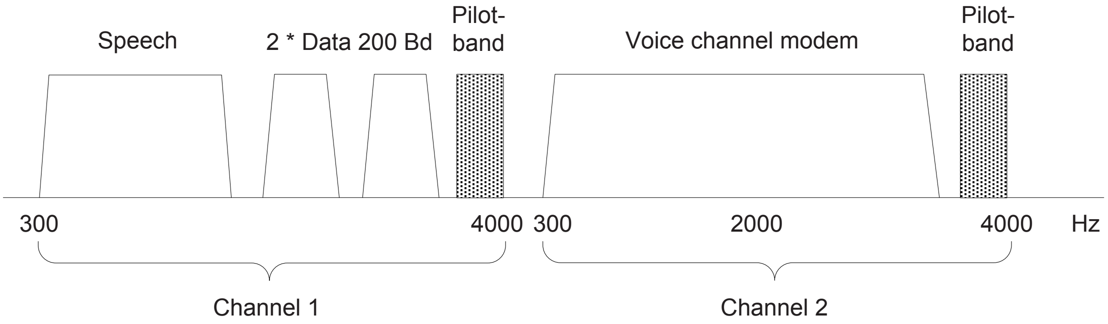


Figure 48 – Example for a signal arrangement in two baseband channels

The signals are characterized by the quantities addressed in Rule 1 as shown in Table 12.

Table 12 – Signal parameters

Type of service or signal	Number of services, each type	Peak to RMS ratio dB	Bandwidth kHz	Required SNR dB	Additional SNR safety margin dB
Speech	1	6,0	2,00	15,0	0,0
Pilot	2	3,0	0,50	15,0	6,0
FSK 200 Bd	2	5,0	0,48	15,0	0,0
Voice band modem	1	10,0	3,40	25,0	0,0

Table 13 shows the calculated link budget for an RF PEP of 46 dBm. Note that the RMS power of the RF signal is about 10 dB lower than the PEP of the RF signal. Moreover, 83,0 % of the RMS power is given to the voice band modem, which occupies the highest bandwidth, has the highest PAR and requires the highest SNR. The remaining signals get only a few percent of the total RMS power.

Table 13 – Link budget

RF PEP = 46 dBm		**At RF connector, transmitter side**			
Type of service or signal	**Number of services, each type**	**Absolute peak level, each service dBm**	**Absolute RMS level, each service dBm**	**RMS power of services, per type mW**	**Percentage of total RMS power, per service type %**
Speech	1	29,2	**23,2**	207	4,9
Pilot	2	26,1	**23,1**	413	9,7
FSK 200 Bd	2	22,0	**17,0**	100	2,3
Voice band modem	1	45,5	**35,5**	3 525	83,0
Total			**RF RMS =**	**36,3 dBm**	100 %

The levels at the receiver input can be calculated when the path attenuation – i.e. the attenuation from transmitter to receiver including the coupling losses – is known. Table 14 shows the resulting RMS levels at the receiver input assuming a path attenuation of 25 dB. In addition, the table shows the maximum allowed RMS noise levels for adequate performance of each service.

Table 14 – Signal and allowed noise levels at the receiver input

RF PEP = 46 dBm **Path attenuation = 25 dB**			**At RF connector, receiver side**	
Type of service or signal	**Number of services, each type**	**Percentage of total RMS power, per service type %**	**Absolute RMS level, each service dBm**	**Max. allowed noise level in 4kHz, each service dBm**
Speech	1	4,9	–1,8	**–13,8**
Pilot	2	9,7	–1,9	**–7,8**
FSK 200 Bd	2	2,3	–8,0	**–13,8**
Voice band modem	1	83,0	10,5	**–13,8**
Total		100,0 %		

The additional safety margin of 6 dB for the pilots as given in Table 12 is clearly visible. The conclusion is that the link shows adequate performance for noise levels of up to –13,8 dBm in 4 kHz. Taking into account coupling losses of about 4 dB, the line noise level can be up to –9,8 dBm in 4 kHz. According to Table 15, the link can be operated on AC lines with voltages up to 400 kV AC.

Table 15 – Typical corona noise levels for AC overhead lines

AC Line voltage kV	**Typical corona noise levels in 4 kHz on overhead high voltage lines**	
	Fair weather dBm	**Foul weather dBm**
up to 110	–50	–30
150	–45	–25
220	–40	–20
300	–35	–15
400	–30	–10
800	–20	0

When teleprotection service is transmitted together with other services, it is common practice to consider two different possible transmission states. One of them, usually known as quiescent conditions, is when the teleprotection signal is the one corresponding to the state when nothing abnormal happens in the protected line. This signal known as guard signal is transmitted sharing the total output power with the other services. The other possible state takes place when the teleprotection signal transmitted is the one corresponding to a command transmission that is due to some fault in the HV line. This signal sometimes is called trip signal and it is transmitted only for a short time, typically a few 100 ms. Obviously in this case the teleprotection signal transmission has priority over the other services and it is common practice to stop the transmission of all services except for the teleprotection signal so that the maximum output power can be assigned to teleprotection transmission in order to maximize the signal to noise ratio at receive side, improving the teleprotection action.

In this case, two sets of level adjustments have to be defined: One of them for quiescent conditions and the other one during trip transmission conditions. Usually, the level settings for both cases are fixed by the manufacturer and given in the documentation.

6.3 DPLC link budget

The basis for DPLC systems planning is similar to that for APLC systems the main difference being the characteristics of the digital modulation used. The functional block diagram of a digital PLC system is shown in Figure 49. The signals of the user interfaces are converted to digital format usually in accordance with well-defined standards. This means that physical connections and bit rates are known.

If the system has more than one interface, a TDM multiplexer is used to combine the user side bit streams into one single aggregate bit stream that also contains information needed for internal link operation such as synchronism between the two ends of the link plus information for management purposes. In case only one service has to be transmitted, TDM multiplexing is not required.

Additional coding techniques can be applied to the aggregate bit stream in order to improve the overall operation against noise. The aggregate bit stream is converted to a band limited signal by the DPLC modem typically using OFDM or QAM modulation. This signal is transposed to the desired frequency inside the HF PLC band and transmitted through the HV line using the same type of coupling devices as for the classical analogue terminals.

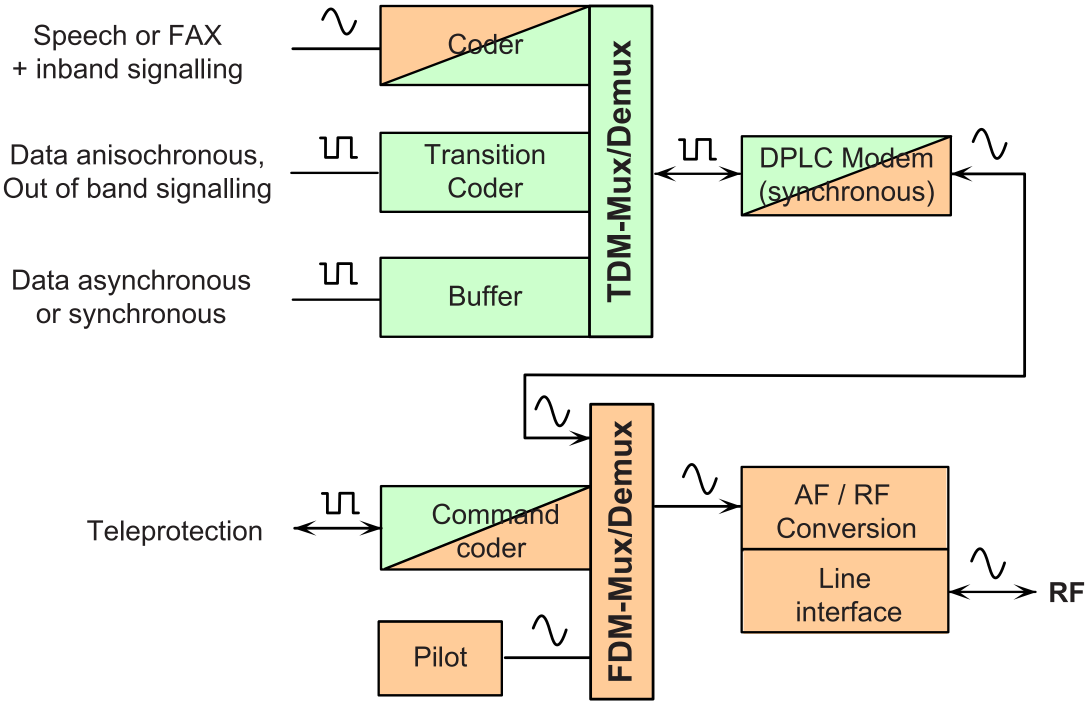


Figure 49 – DPLC equipment architecture

As shown in Figure 49, the interface signals have to be pre-processed before they can be inserted into the TDM frame:

- Synchronous or asynchronous data signals have to be buffered.
- Transferring the data transitions of anisochronous data signals with sufficient time resolution requires oversampling as e.g. described in ITU-T recommendation R.111.

  NOTE This produces several bits (typically 5 to 10) of synchronous data for every bit of anisochronous data.

- Speech is converted into digital form using a suitable coder. A possible coder is described in the standard ITU-T G.723.1.

Clearly, the gross aggregate data rate, i.e. the data rate of the aggregate bit stream including overhead to be transmitted by the DPLC modem, cannot be lower than the sum of the data rates of the individual services after pre-processing. The overhead is due to the TDM framing and is usually documented by the manufacturer.

The AGC control method is not standardized and every manufacturer is using its own method. In the case teleprotection is needed, the APLC teleprotection concept is used and there are different methods of sharing the total bandwidth between the signal containing the digital information and the teleprotection signals.

As for analogue PLC, the peak value of the combined signal i.e.: the digital modulated signal plus teleprotection guard signal (if present) plus some pilot signal (in those cases when the AGC is carried out by means of such pilot signal) should correspond to the peak value for the output PEP at HF transmission side. The percentage of the total value assigned to each service (data, teleprotection and pilot) should be in accordance with the bandwidth used for each service and affected by a factor in order to modify the signal to noise ratio at the input of the receive end once the noise level and attenuation are taken into account for a given output power.

In DPLC links, special care has to be taken because the PAR of the DPLC modem signal is quite high – typically 10 dB. In other words, the average power of that signal can be relatively low for common values of PEP. It should be noted that the SNR for the DPLC modem signal at the receive end has a direct influence on the bit error rate (BER) of the recovered data at the receiver output when data is transferred to the user (see Clause 7). In order to improve this behaviour, some techniques like additional coding can be used.

A parameter that characterizes the DPLC modulation is the digital efficiency. It is obtained by dividing the data rate of the aggregate bits stream by the bandwidth used for DPLC signal. The higher this value the better is the use of the spectrum. However, high values of spectral efficiency could make the transmission quality very sensitive to the SNR unless additional coding is used that in turn could introduce additional delay (latency).

For planning purposes, a trade-off between the digital speed, bandwidth needed, latency and quality as a function of the SNR has to be chosen depending on the application under consideration.

As an example, assume that an 19,2 kbit/s asynchronous data channel plus a number N_{SP} of speech channels, each coded into a bit stream of 5,3 kbit/s, have to be transmitted. The resulting net aggregate data rate DR_N equals $(19{,}2 + 5{,}3 \cdot N_{SP})$ kbit/s. With an overhead of 1 kbit/s for the TDM frame, 0,2 kbit/s for the anisochronous channel and 0,3 kbit/s for each speech channel, a gross aggregate data rate DR_G of $(1 + 0{,}2 + 19{,}2 + ((0{,}3 + 5{,}3) \cdot N_{SP}))$ kbit/s = $(20{,}4 + 5{,}6 \cdot N_{SP})$ kbit/s is obtained. If the channels are ordered according to priority, the diagram shown in Figure 50 can be drawn. As the 19,2 kbit/s data channel has the highest priority, a DPLC system offering a gross aggregate data rate of at least 20,4 kbit/s is required. If the DPLC system offers data rates of e.g. 32 kbit/s or 64 kbit/s, 2 or 7 speech channels can be transmitted in addition to the data channel.

Most manufacturers offer DPLC systems with several nominal bandwidths, typically 4 kHz, 8 kHz and/or 16 kHz. Moreover, some offer more than one data rate per bandwidth. In this case, a feature called “Automatic data rate adaptation” may also be available. If this feature is activated, the DPLC modem automatically switches between the available data rates – or a selection thereof – depending on the prevailing noise level.

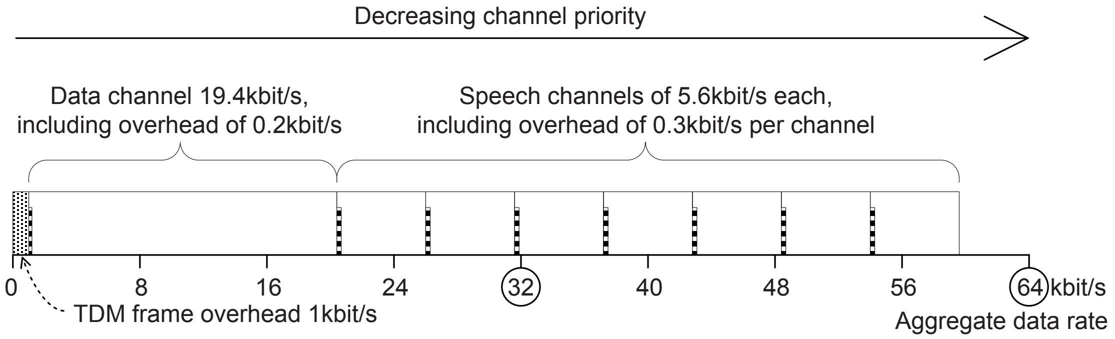


Figure 50 – Example for a DPLC channel arrangement

To decide on the required DPLC bandwidth, the efficiency curve should be consulted. Table 16 gives possible solutions based on the efficiency curve shown in Figure 51.

Table 16 – Possible solutions for the example of Figure 50

Aggregate data rate kbit/s	**Bandwidth** kHz	**SNR** [dB]
64	16	22
32	16	14
64	8	40
32	8	22
32	4	40

The maximum allowed line noise level in 4 kHz can be evaluated using

$$N_{in4kHz} = S_{RxLineEnd} - SNR_{DPLC} - 10 \times \log\left(\frac{B_{DPLC}}{4kHz}\right), \tag{17}$$

where

$S_{RxLineEnd}$ is the RMS power of DPLC signal at the receiving end of the HV line

SNR_{DPLC} is the required SNR inside the DPLC band in dB,

B_{DPLC} is the DPLC bandwidth in kHz.

The value of $S_{RxLineEnd}$ is obtained from

$$S_{RxLineEnd} = PEP_{RF} + 20 \times \log(m_{DPLC}) - PAR_{DPLC} - Att_{Line} - Att_{CplTx}, \tag{18}$$

where

PEP_{RF} is the peak envelope power of the at the transmitter output in dBm,

m_{DPLC} is the modulation factor of the DPLC signal, takes into account possible pilot and teleprotection guard signals also to be transmitted,

PAR_{DPLC} is the peak to average ratio of the DPLC signal in dB,

Att_{Line} is the line attenuation in dB,

Att_{CplTx} is the coupling losses on the transmitter side of the line

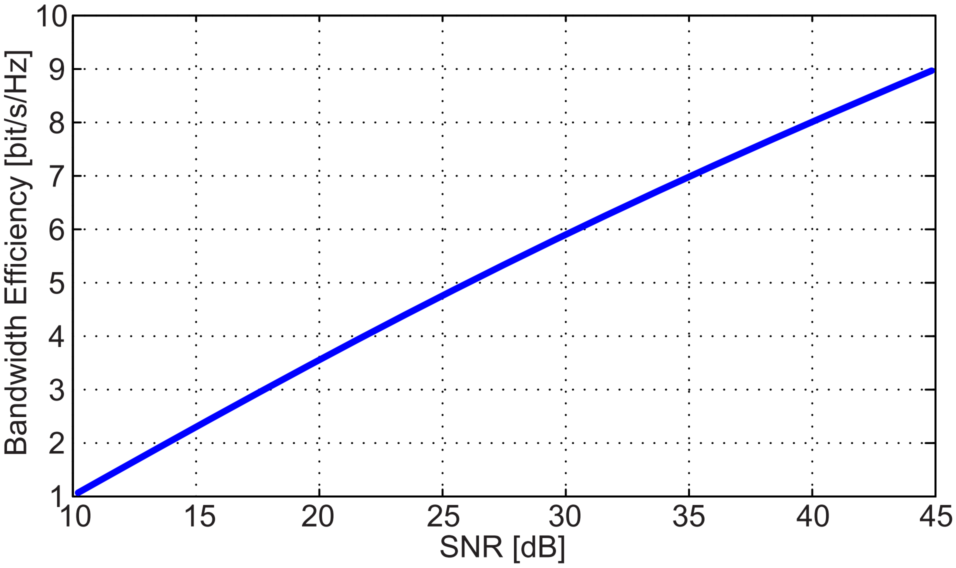


Figure 51 – Typical DPLC bandwidth efficiency for a BER of 10^{-6}

The equations (17) and (18), together with the efficiency curve of Figure 51 and the typical corona noise levels for HV overhead lines according to Table 15 relate the DPLC data rate to the voltage of the HV line suitable to operate the DPLC link. The relation is shown graphically in Figure 52 for $S_{RxLineEnd}$ = 15 dBm and for the bandwidths 4 kHz, 8 kHz and 16 kHz.

From Figure 52, the following observations can be made:

- For a bandwidth of 4 kHz, the data rate is limited to about 32 kbit/s. Under fair weather conditions, operation at 32 kbit/s is possible over HV lines of up to 400 kV, but under adverse weather conditions, only HV lines with voltages of 150 kV or lower are possible.
- With a bandwidth of 8 kHz, a data rate of 64 kbit/s is possible for HV lines up to 400 kV under fair weather conditions. However, the data rate has to be reduced to 32 kbit/s under adverse weather conditions, which requires a DPLC system supporting automatic data rate adaptation.
- If automatic data rate adaptation is not available and the link is required to operate in a bandwidth of 8 kHz over a 400 kV line under adverse weather conditions, a data rate of 32 kbit/s or lower shall be chosen.
- Increasing the bandwidth to 16 kHz does not clearly allow reaching a data rate of 64 kbit/s over 400 kV lines under adverse weather conditions. A line noise calculation or measurement could be done to clarify the situation.

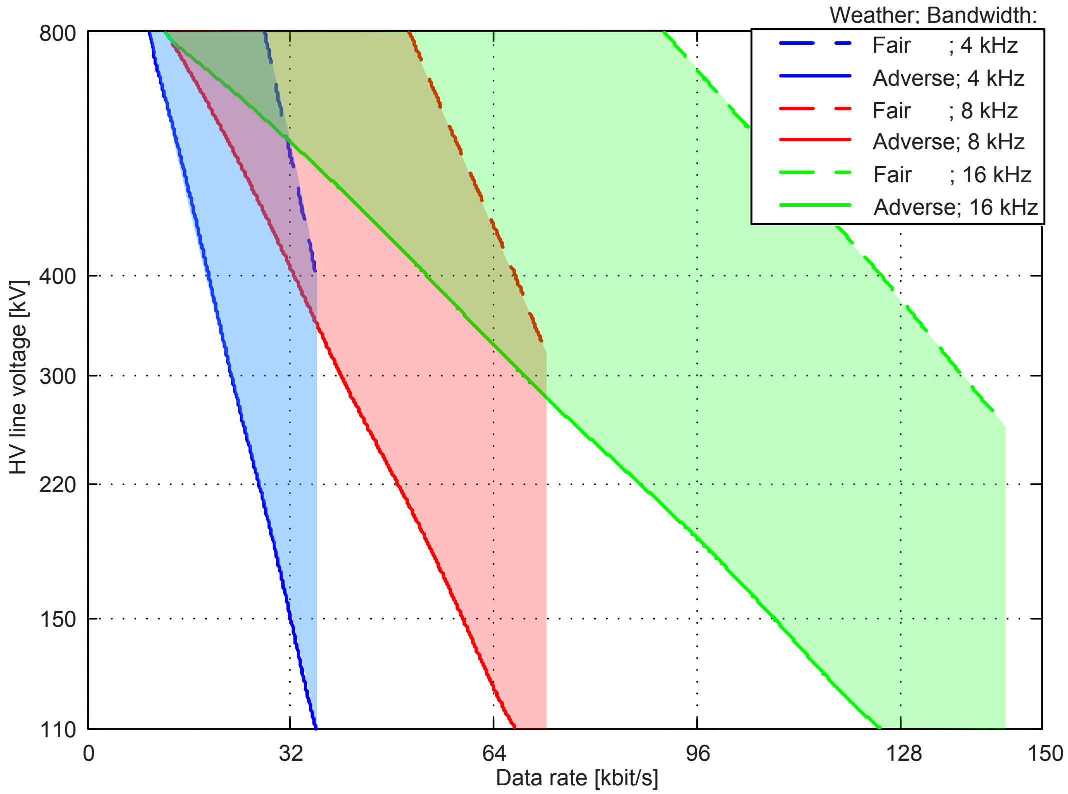


Figure 52 – HV line voltage ranges

One possibility for automatic data rate adaptation is based on switching on or off individual services. This is shown in Figure 53 for the example of Figure 50: Under adverse weather conditions at an SNR between 22 dB and 40 dB, the data channel and two speech channels can be transmitted, while under fair weather conditions at an SNR of 40 dB or higher, the link can transmit the data channel plus 7 speech channels.

A further possibility for automatic data rate adaptation is to vary the data rate of individual services. However, this is only possible if the data terminals connected to the affected interfaces support such variations.

Note that the corona noise levels for HV overhead lines given in Table 15 are typical values. The actual noise levels depend on a number of factors such as the carrier frequency, the surface quality of the conductors and geometrical line data (e.g. conductor diameter, distance between conductors, etc.). Line noise calculations based on the geometrical data of the overhead line as offered by some manufacturers help improving the planning quality.

Corona noise does not appear on links operated over HV cables. However, for links operated over a series circuit of cable and overhead line sections, corona noise has to be taken into account for PLC planning.

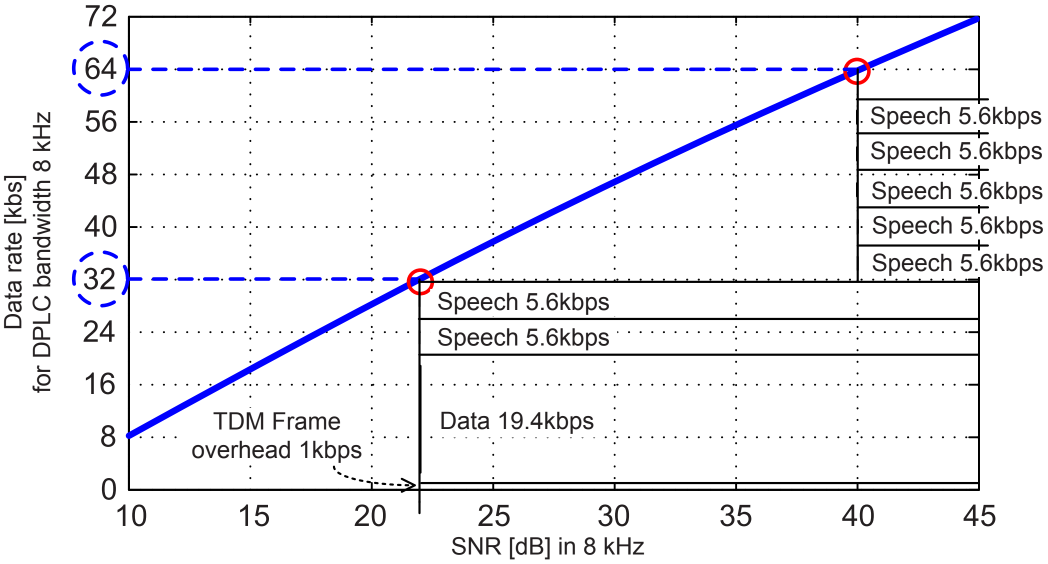


Figure 53 – Example for DPLC system with automatic data rate adaptation

6.4 Frequency plan

6.4.1 General

Analogue PLC and digital PLC terminals should be compatible as far as the simultaneous operation in the same HV line is concerned and with common coupling and blocking devices. This means that the HF connections of both types of terminals should present the same technical characteristics regardless of the type of information transmitted. The main difference between the two types of terminals is the bandwidth used because the different amount of information transmitted depending on the type of terminal.

We consider two aspects, the frequency planning for all PLC links transmitting over the same HV line between two substations sharing the same coupling devices and the frequency plan for the whole system.

A common rule to be satisfied is that the frequency bandwidth used for each individual PLC link should be in accordance with the standardized frequency range, which is to say, the total bandwidth should be a integer multiple of the elemental frequency slot (n × 4 kHz) and the frequency of the band edges should be a multiple of 4 kHz. Particular considerations existing in some countries can modify this rule.

6.4.2 Links over the same HV line between two substations

First point is to decide the type of coupling to be used, phase-to-earth or phase-phase. Also inter-circuit coupling is also possible when the HV line has two circuits in the same poles. Although it is rarely used it is also possible to establish a three phase coupling scheme. The details of type of coupling are given in Clause 5. Basically the difference between them is the attenuation and survivability in the case of inter-circuit coupling. So the length of the line and the desired availability of the link are the starting conditions for making the deception about the type of coupling to be used.

The number of line traps should be in accordance with the type of coupling and the blocking band offered by them with the total band used by all PLC links in the HV line under consideration. The blocking band and efficiency offered by line traps is closely related with the inductance of the line trap coil.

The line matching units should be suitable for the type of coupling as well and also the band pass offered by the complete coupling set (line matching units, coupling capacitors, characteristic impedance of HV line transmission) should cover the complete band used by the PLC terminals operating in the same HV line. It shall be pointed out that the value of the coupling capacitor together with the characteristic impedance of the HV line impose some restrictions on the bandwidth and the edge frequencies of the coupling band. Owing to this a joint analysis of the possible coupling band, for a given return loss, and the number of PLC terminals operating in the same HV line is advisable.

Related with the previous paragraph it is important to make a good frequency planning and wiring of the PLC terminals installed in the same substation operating over a common coupling devices.

These PLC terminals have to be connected in parallel at their HF connection using a short length cable (compared with the wave length of the signals) and only one cable has to be used as a connection from the total set of PLC terminals and the coupling network. This arrangement allows mismatching and signal reflections that could happen if the parallel connection were carried out close to the matching units using individual cables for each PLC terminals because of the possible long distance between the terminals and coupling units that will modify the impedance of each cable at the connection point.

The operating frequencies of each link have to be chosen in order to meet the tapping loss requirements. This means that the minimum distance in frequency between band edges of every two pairs of PLC terminals shall be known. The different bandwidth of PLC terminals, depending on the number of channels and the digital speed transmitted makes this point quite laborious. The out of band impedance of HF transmit and receive filters is the main factor affecting the frequency plan of all PLC terminals operating over the same line.

6.4.3 Global frequency planning

The frequency planning of all PLC links in a network shall satisfy the requirements needed in order to avoid interference between links operating in the same network and also between links operating in networks that belong to different utilities.

Also additional requirements in order to avoid possible interference with other services like beacons shall be satisfied. This last requirement gives place to the situation where some bands are forbidden for PLC operation. So, particular regulations for each country shall be taken into account. For the same reason sometimes the output power can have some restrictions on its value or in the duration of signal transmission for specific applications like teleprotection.

The interference between links using the same bands or bands with some degree of overlapping can be due to different reasons.

When we consider PLC links on the same HV line but operating in different sections, the low efficiency of blocking devices and the signal coupling through the conductors without line traps are responsible for the interference.

In this case unless the blocking efficiency can be improved, the only possibility is to avoid the use of the same frequency in contiguous HV line sections. Two or three HV line zone hops without repeating the same frequency is recommended.

Another possible interference reason is the coupling between HV lines that are close or run in parallel topology even though there are not electrical connections between them.

6.4.4 Other considerations

In general a difference has to be made between intelligible and non-intelligible interference. With the appearance of digital systems this concept is more relevant.

Nowadays analogue and digital PLC systems coexist in the same network. More research has to be done in order to determine the effect of the interference between the two types of these systems.

Analogue systems transmit the information as it is in baseband state with the only process of modulating in SSB, just a translation in frequency, and the transmitted band can be in erected or inverted position, so an interference caused by other analogue system can affect directly the services of the interfered system.

Digital systems transmit the information, which originally is in digital format, after a digital modulation; therefore the transmitted analogue signal, which is the result of the digital modulation, contains the user information but completely garbled in the total signal and not in separate bands as it is in the case of analogue systems.

This last point gives place to the need of revising the concept of interference between digital systems and between digital and analogue systems.

6.5 Network planning

6.5.1 General

PLC systems are included in the telecommunications network together with other types of systems. Therefore, the particular characteristics of those systems have to be taken into account when planning the communications network.

Of course, the main characteristic of PLC systems is that they use the power line as a physical media for transmission. This fact offers a high reliability to PLC systems but at the same time the noise characteristics are in general worse than those in other systems and also due to bandwidth characteristics the information capacity is lower.

6.5.2 Redundancy

PLC systems have been proven to be a good option as back-up systems, mainly for teleprotection applications. There are teleprotection PLC systems that are especially designed for direct HF teleprotection applications. Sometimes these systems use a narrower band than the general purpose ones.

6.5.3 Integration with other transmission technologies

As said before one of the main application of PLC systems are for teleprotection transmission, which usually is a point to point communication and it is transmitted as analogue signal over the PLC link regardless the type of PLC equipment. Nowadays another application is to establish digital links for telecontrol application that can take different topologies depending on the policy of the electrical utility. It is common to find ring topologies and also mesh topologies where the PLC links are used, together with other type of links, as an access or trunk links between nodes like switches and routers.

In general PLC links do not work as a separate system but they are integrated in a more comprehensive network. For this reason the type of interfaces, mainly for digital PLC, have to be compatible with the interfaces used in other types of systems.

Nowadays networking facilities, like bridging function, are sometimes included as an integral part of the terminal allowing the use of PLC links for LAN interconnection.

When speech transmission is used, it is possible to use analogue PLC terminals in the classical arrangement and also the digital terminals are prepared with interfaces for speech connection. In this case the speech is sampled, digitized and coded. Different types of coding are available offering a choice among quality, digital speed used and latency.

6.6 Introduction to Internet numbering

6.6.1 Internet protocol numbering

The Internet protocol (IP) address is assigned to the range of devices used in the communications network infrastructure. Principally, it has two address functions: host or network interface identification and location addressing. The first IP addressing used a 32 bit number known as Internet protocol version 4 (IPv4) However, due to the usage of these addresses, there is now the IPv6 with similar notation in numbering. The adoption of a particular IP version will be determined by the company and communications network they employ.

A host connected to an Ethernet LAN/IP network, for example a PLC terminal connected to the management network, has two addresses:

– A MAC address, used within the LAN environment. This is a globally unique address and it is written in hardware so that it cannot be changed. This address is essential so that the LAN technology can transmit and receive data regardless of the upper-layer protocols. Ethernet, for example, uses 48-bit addresses. Each Ethernet frame incorporates both the source and destination Ethernet address.

– An IP address. IP is a network protocol whose duty is to discover the network topology (supported by other specific protocols like RIP and OSPF) and make packets travel over the different links and reach their final destination by choosing the best route and regardless of the physical network technology being used in each hop. Each host in a network shall have an IP address, which is software-assigned and is usually assigned during commissioning.

IP and Ethernet usually work together. IP builds packets, which are delivered by the link layer. When this technology is Ethernet, an Ethernet frame is built by adding an Ethernet header and an Ethernet trailer to the IP packet. When the frame arrives at an intermediate switch the switch decides the output port by matching the destination Ethernet address to an internal look-up table that maps all possible destination addresses into output ports.

Nowadays two different versions of IP coexist: IPv4 (the most widely used) and IPv6.

6.6.2 IP addresses

IPv4 addresses have the following structure:

- 32 bits, commonly grouped in 4 octets. For the sake of clarity each of these octets is usually translated into decimal and the following structure is obtained:

  {0...255}.{0...255}.{0...255}.{0...255}

- Part of the address is a network identifier
- Part of the address is a host identifier within a given network

There are five types of IPv4 addresses:

Class A:

0	netid(7)	hostid(24)

Class B:

1	0	netid(14)	hostid(16)

Class C:

1	1	0	netid(21)	hostid(8)

Class D:

1	1	1	0	multicast group id

Class E:

1	1	1	1	0	reserved

Table 17 shows the definition of each IP address.

Table 17 – IP address definitions

Address class	First bits	Network identifier	Host identifier	Range	Application
A	0	7 bits	24 bits	0.0.0.0 … 127.255.255.255	A few networks (128 maximum) with a high number of hosts (up to 16 777 216 hosts per network)
B	10	14 bits	16 bits	128.0.0.0 … 191.255.255.255	Up to 16 384 networks with up to 1 048 576 hosts per network
C	110	21 bits	8 bits	192.0.0.0 … 223.255.255.255	A high number of networks (up to 2 097 152) with few hosts per network (256 maximum)
D	1110			224.0.0.0 … 239.255.255.255	Multicast addressing
E	11110			240.0.0.0 … 247.255.255.255	Reserved for the future

Some examples of IP addresses are:

Class A:	26.104.0.19 →	26 = 00011010 (0 + 7 bits network, 24 bits host)	Host number 104.0.19 in LAN number 26
Class B:	128.66.12.1 →	128 = 10000000 66 = 0100010 (10 + 14 bits network, 16 bits host)	Host number 12.1 in LAN number 128.66
Class C:	192.178.16.1 →	192 = 11000000 178 = 10110010 16 = 00010000 (110 + 21 bits network, 8 bits host)	Host number 1 in LAN number 192.178.16.0

Please note that some combinations have special meanings regardless of the IP address class:

- Network ID set to all 0: It means “this LAN”, with no special reference to any specific host;
- Host ID set to all 0: It means “this host”;
- Host ID set to all 1: It means “broadcast to all hosts in this LAN”;
- IP address 127.0.0.1: It means “loopback to this same host”. It is used to test TCP/IP applications, with no information sent to the LAN.

IP addresses are managed by the Network Information Centre (NIC) to ensure that all addresses are globally unique.

6.6.3 Private IP addresses

There are certain addresses in each class of IP address that are not assigned. These addresses are called private addresses. Private addresses might be used by hosts that use network address translation (NAT), or a proxy server, to connect to a public network; or by hosts that are not connected to the public Internet.

Many applications require connectivity within only one network and do not need external connectivity. In large networks, TCP/IP is often used, even when network layer connectivity outside the network is not needed. A good example is the management network of an electricity utility, which may use TCP/IP and SNMP with no connection to the public Internet at all, so private addresses are the natural choice. Private addresses can also be used on a network where there are not enough public addresses available.

The private addresses can be used together with a network address translation (NAT) server or a proxy server to provide connectivity to all hosts in a network that has relatively few public addresses available. Packets with a destination address within one of the private address ranges will not be routed on the Internet.

The following ranges are available for private addressing:

Class A	10.0.0.0	10.255.255.255
Class B	172.16.0.0	172.31.255.255
Class C	192.168.0.0	192.168.255.255

6.6.4 Subnetting

The structure given to the IP addresses greatly simplifies the computational burden in the routers. Instead of storing one entry per destination host only one entry per destination LAN is stored. The routing process uses the network ID only, thus reducing the size of the look-up tables and the computational burden.

However this structure can lead to strong inefficiencies. Let us imagine an electricity utility that has 257 hosts to be connected to a LAN. This LAN cannot be assigned a class C address, because 257 exceeds the maximum number of hosts in a class C network (256). In principle this LAN should be assigned a class B address, which can have up to 65536 hosts. And from the definition of an IP address we conclude that no other LAN can use this network identifier, so the conclusion is that 65536 addresses will be reserved for the exclusive use of 257 hosts. This inefficiency is one of the major drawbacks of the IP addressing system. In fact the NIC is running short of class B addresses.

Two solutions have proposed for this problem. One of them is to expand the range of addresses, and in fact IPv6 uses 128 bit addresses. The problem with introducing IPv6 is the compatibility with the software already installed in most hosts around the world.

Another possibility, more flexible in the short term, is the use of subnetting. The concept is very simple: the network identifiers are shared among more than one network. For example, if we have two LANs with 257 hosts each LAN, instead of wasting two class B addresses we can design a new addressing system where both LANs can share the same network identifier.

The easiest way to understand subnetting is to imagine that a given network has a single IP address (class B for example), but two or more physical networks. The rest of the Internet will think that there is only one network, and only the local routers know that in fact there is more than one physical network. For example:

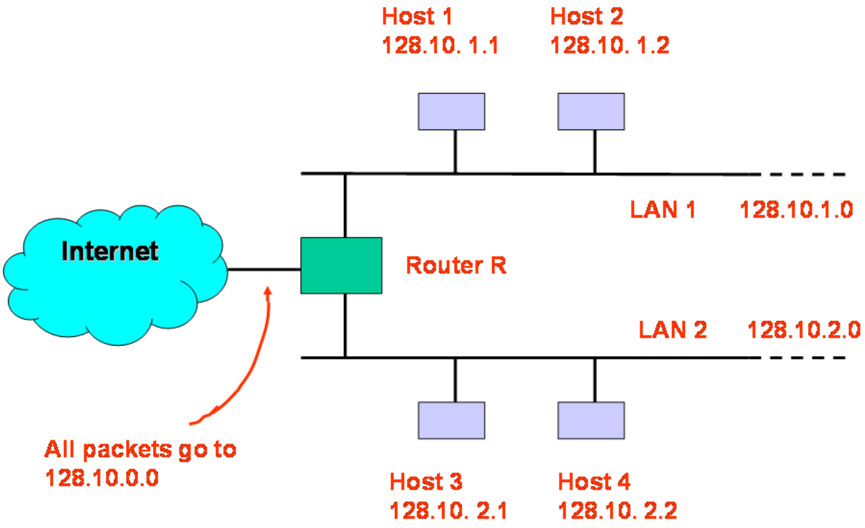


Figure 54 – Example of subnetting

In the example of Figure 54, a class B address is used for both networks (128.10.0.0), All routers in the outside Internet (except R) will route all packets to 128.10.0.0, as if only one physical network existed.

Router R will deliver the IP packets to the corresponding physical network. To accomplish this task the third octet in the IP address is used: the hosts in LAN 1 are identified as 128.10.1.x and the hosts in LAN 2 are identified as 128.10.2.x, where x is the number of hosts within a given LAN. Those packets whose third octet in the destination IP address is 1 will be delivered to LAN 1, and those with a 2 will be delivered to LAN 2. Even if we have two physical LANs with 257 hosts each only one class B address is used, saving one class B address.

When subnetting is used a new interpretation of the IP addresses is useful; the terminology “network ID-host ID” is replaced with the new terminology “Internet part-local part”, where the local part is divided into “physical part-host”:

<table>
<tr><td colspan="3">IP address with subnetting</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Internet part</td><td colspan="2">Local part</td></tr>
<tr><td></td><td colspan="2"></td></tr>
<tr><td>Internet part</td><td>Physical part</td><td>Host</td></tr>
</table>

The question now is how to divide the local part into “physical part” and “host”. The TCP/IP standard for subnetting allows flexibility, and it is up to the network manager to decide how many bits to assign to the physical part and the host part. Following with our example, the 16 bits in the class B address with were originally intended for the host ID could be divided in a number of different arrangements. For example:

– 8 bits for the physical part and 8 bits for the host (256 networks with up to 256 host per network);

– 3 bits for the physical part and 13 bits for the host (up to 8 networks with up to 8192 hosts per network);

– Any other possibility.

The nice feature about subnetting is that, from the point of view of the Internet, only one class B address is used (in all cases).

Subnetting is usually implemented with the use of subnet masks. A subnet mask is a 32 bit binary number where a bit set to 1 means that the corresponding bit in the IP address belongs to the Internet part or the physical part, and if set to 0 it means that the corresponding bit in the IP address corresponds to the host. For example:

11111111 11111111 11111111 00000000

means that the first three octets in the IP address correspond to the Internet part and the physical part, and the fourth octet corresponds to the host. Another example is:

IP address:

10000000.00000011.01001000.00110110 (can be expressed as 128.3.72.54)

Subnet mask:

11111111.11111111.11100000.00000000 (expressed as /19, 19 bits set to 1)

The interpretation of this IP address is as follows:

– The first byte of the IP address is 128, so it is a class B address, with the network ID = 128.3. This class B address is reserved for our use and it is globally unique. By the way, this forces the first 16 bits of the subnet mask to be “all 1”.

– The third octet of the subnet mask is 11100000. This means that the first three bits in the IP address correspond to the physical part of our network and the other 13 bits correspond to the host. Our network will have up to 8 subnetworks with up to 8196 hosts each.

– The destination host is located in subnetwork 010 and is host number 01000.00110110.

6.7 Security

The security developed for the power line carrier system will depend on a number of key points. This will include the functions performed by the system, the data rate of the system, together with the complexity of the power line communications system, which may vary from a basic system for the transmission and reception of voice band signals to a more complex system which offers voice communications, data transmission system together with more complex communications data transfer within a WAN communications system. Therefore, the security may address local data transfer to alarms for establishing specific functions. Also the system will integrate with parts of the communications network for transmission and distribution system. In this case, where there is full integration into the power network consultation with IEC 62351, dealing specifically with these issues is strongly advised.

When planning, a PLC link security can be looked at from different points of view:

- From a network point of view, the fact that the information to be transmitted uses cryptography is transparent to the PLC link except for the additional overheads, which will mean an additional delay or the need for more transmission capacity.
- From the management point of view, many systems today make use of the SNMP management protocol. If public networks are used to access the management port of the PLC link it is recommended that SNMP v3 be used, since it incorporates authentication, privacy and access control. If only private networks are used to access the management port of the PLC link SNMP v2c may be enough.
- The local management application may be password protected to prevent unauthorised access. There are usually different password levels with different access rights, like user (read configuration only), administrator (read or write configurations) or factory (read, write and download firmware).

6.8 Management system

Modern systems usually are designed in such a way that almost all parameters are set and monitored using a common computer or a special data terminal. The computer or data terminal is directly connected to the terminal or using an IP network. For this last reason PLC terminal are provided with an IP address. Typical parameters to be programmed are signal levels, modulation percentages, frequency allocation and bandwidth used, mainly in digital terminals where also the bit speed is also programmable. By means of the same system the terminal or even the whole network can be managed.

For this reason, management facilities like SNMP are included already in the basic configuration of present terminals.

7 Performance of PLC systems

7.1 System performance

Performance of any telecommunication system should be assessed according to some key parameters properly identified for each layer of the ISO-OSI stack.

The ISO-OSI seven layer reference model shown in Figure 55 presents a means of describing the functions of the various sections, or layers, of a data communication system.

Layers 1 to 3: Media or communication layers
Layer 1: Physical
Layer 2: Link
Layer 3: Network
Layers 4 to 7: Upper or host layers

which include among others transport and application layers.

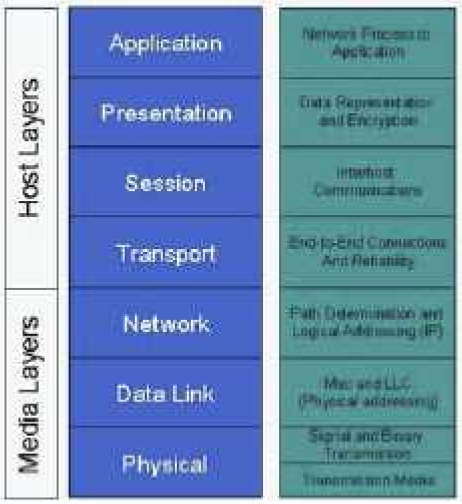


Figure 55 – ISO/OSI reference model

Parameters unambiguously defined help to assess the conformity of PLC link to each related performance criterion.

Currently APLC and DPLC implement media layers physical, link and in some cases network.

The purpose of layer 2 is to ensure data is transferred over a link in a communications network, while the layer 3 protocol has the job of ensuring the data is transferred over the whole network, from the original source to the ultimate destination. Network may use any number of separate links.

The higher layer protocols, layers 4 and above, have the task of ensuring the integrity of transmitted data and presenting the data to the user or application. The function of these higher layer protocols is out of the scope of this standard and will be addressed only to emphasize the impact due to a low quality PLC channel on the transported applications.

The aim of performance measurements is to provide to end users with information referred on a set of key parameters and objectives to be used to “certify” the compliance of PLC with carried applications and in particular their requirements which are focused and detailed in Clause 8.

7.2 APLC link layer performance

The performance evaluation at Link Layer for an analogue PLC system results mainly from the analysis of several channel aspects. In the following are reported the most used parameters; further detailed information in particular for baseband definitions can be found into recommendation ITU-T M1020.

Among others the following aspects will have a strong impact on the performance of the PLC link:

- Channel attenuation:

  The attenuation of the HV line varies in time due to changes of the weather conditions and configurations of the HV network (switching activities). The receiver of the PLC System has to be able to handle these changes.

- Channel frequency response:

  Channel frequency response within the used bandwidth cannot be expected to be flat. Especially at short HV lines remarkable peaks of the frequency response will be the reality. Special algorithms in the receiver of the PLC Systems may be used to flatten the frequency response and to ensure the performance of the link.

- Corona noise:

  Corona noise is typical for all EHV/HV lines. The noise level depends on the voltage of the EHV/HV power line and varies over time according the weather conditions. High humidity will lead to a considerable increase of the noise level.
- Noise bursts / impulsive noise:

  The main reason for noise bursts and impulsive noise are switching activities in the HV network and lightning (see also 5.6.5). The APLC link will be interrupted during the time of disturbance, but will be available directly after.
- Narrow band interference:

  Other radio services and/or PLC links operating in the same HF spectrum are the main sources of narrowband interference. In many practical cases their effect can be mitigated through an accurate frequency planning. While narrow band interference will “only” degrade the quality of analogue voice channels, it will have more serious influence to analogue data channels.

To ensure the performance of an analogue PLC link both high frequency as well as baseband parameters are worth considering.

High frequency parameters:

- Power spectrum shape,
- Transmitted power,
- Received power,
- Signal to noise ratio (SNR),
- Link margin and availability.

According to the ITU-T recommendation M.1020 and others related, which may be used as a guideline, quality evaluation of baseband parameters have to address the following aspects:

- Limit of the overall equivalent,
- Group delay,
- Amplitude hits (measured according to ITU-T recommendation O.95),
- Phase jitter,
- Impulsive (measured according to ITU-T recommendation O.71) & background noise (measured according to ITU-T recommendation O.41),
- Total distortion (harmonic and intermodulation),
- Crosstalk,
- SNR,
- Transit delay.

The figures provided in M.1020 are given for a baseband from 300 Hz to 3 400 Hz, whereas the used baseband in power line carrier systems may be different.

Examples excerpt from M.1020 for base band parameters:

- Loss/frequency distortion as shown in Figure 56;
- Group delay as shown in Figure 57.

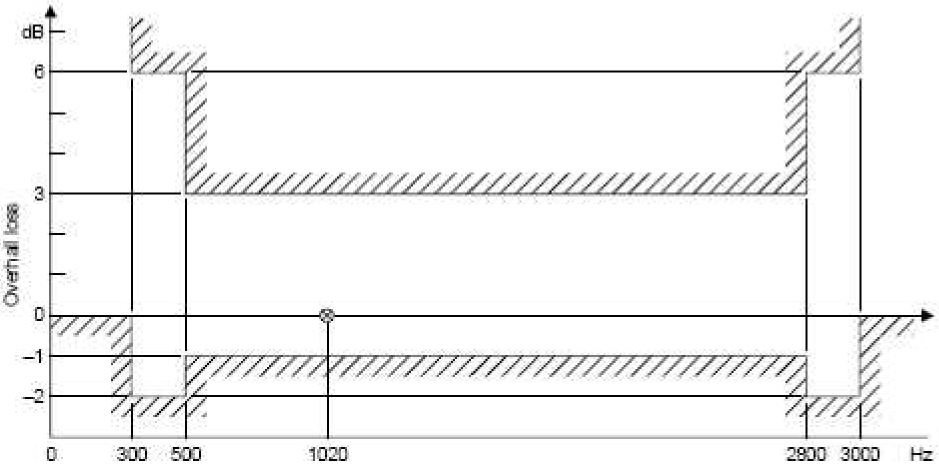


Figure 56 – Limits for overall loss of the circuit relative to that at 1 020 Hz (ITU-T M.1020)

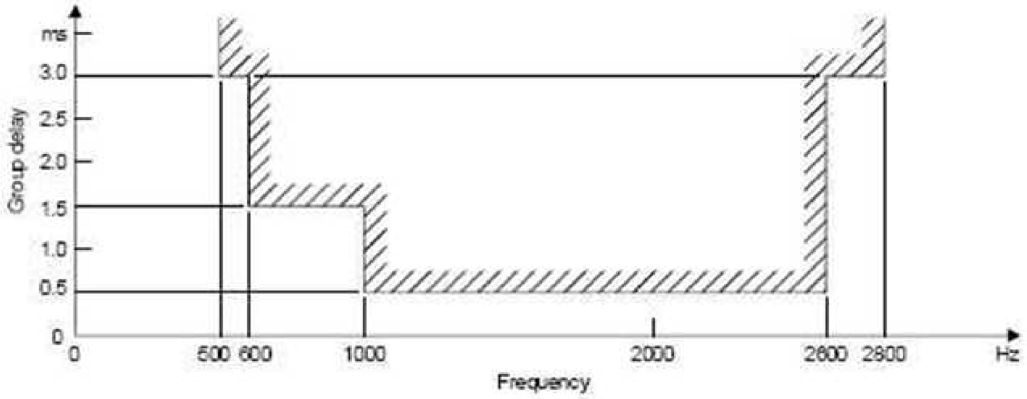


Figure 57 – Limits for group delay relative to the minimum measured group delay in the 500 Hz – 2 800 Hz band (ITU-T M.1020)

7.3 DPLC link layer performance

The link performance of a DPLC connection results from the analysis of several parameters.

Currently no standard for assessing the link performance of DPLC is available.

However, some assumptions, parameters and approach defined within some well accepted ITU standards like ITU-T G.821, G.826, G.823 and related methods based on them will be used in this standard in order to define a method for link performance assessment:

- Bit error ratio (BER),
- Transmission capacity,
- Slip,
- Phase jitter,
- Sync loss and recovery time,
- Latency,
- ETH frame loss,

- Overall quality link mask.

7.4 Bit error ratio (BER)

The BER is one of the most common parameter to be considered to evaluate the quality of digital transmission as shown in Figure 58.

The bit error ratio or BER represents the percentage of bits with errors relative to the total number of bits received in a transmission, usually expressed as ten to a negative power.

A transmission with BER ≤ 10^{-6}, meaning that, out of 1 000 000 bits transmitted, in the worst case one bit was in error.

The behaviour of a digital transmission can be easily described considering the BER curves related to each specific digital transmission modulation (QAM, PSK, etc.) mathematically simulated over an ideal channel called Additive White Noise Gaussian (AWGN).

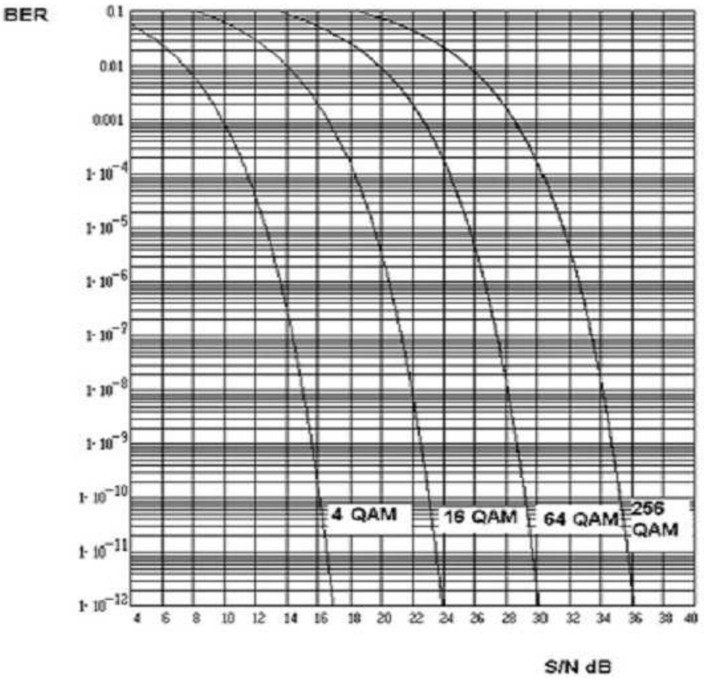


Figure 58 – Some theoretical BER curves

However a BER ≤ 10^{-6} is considered to be sufficient for the applications transmitted via PLC systems and corresponding frame loss for Ethernet link can be negligible.

7.5 Transmission capacity

The transmission capacity of a DPLC channel is limited by the bandwidth and the required SNR. The bandwidth efficiency or “C/SNR” characteristic (bit rate per bandwidth versus SNR) of a DPLC channel is an essential parameter. An example is shown in Figure 59.

The “C/SNR” characteristic is always given for a certain value of BER, usually for the value 10^{-6}. The transmission capacity C is indicated as bits/s/Hz (bit per second per Hertz).

Measurement of a DPLC channel “C/SNR” characteristic is carried out, while Additive White Gaussian Noise (AWGN) is used as a disturbing signal, and the channel frequency response is assumed to be free of amplitude and group delay distortion.

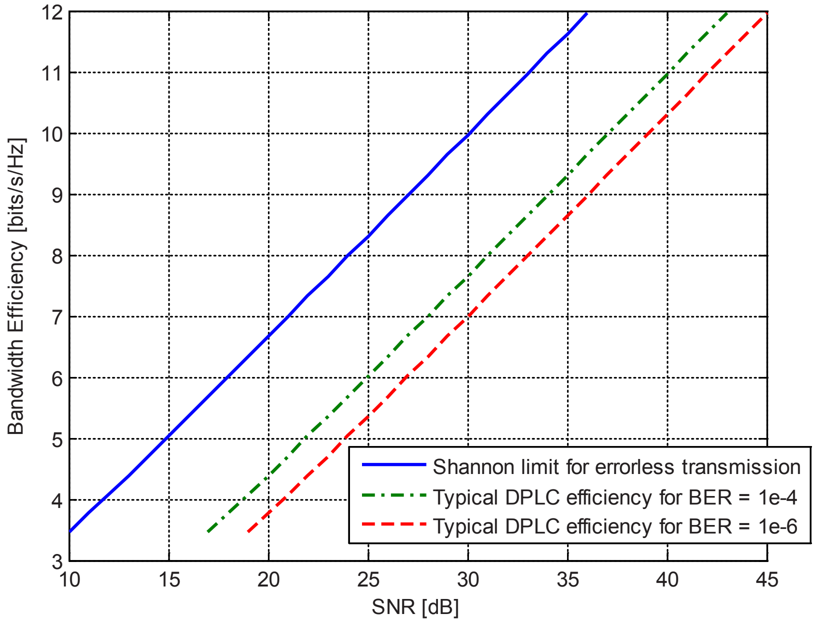


Figure 59 – DPLC “C/SNR” characteristic in comparison to the Shannon limit efficiency for BER = 1E-4 and 1E-6 and Shannon limit

The bandwidth efficiency of practical DPLC systems will be a bit lower than shown in Figure 59 due to implementation losses and shall be stated by the manufacturer. For more details about bandwidth efficiency refer to Annex D.

7.6 Slip

The process of deletion or insertion of bits (or a group of bits) within a digital stream due to timing inequalities, timing imperfections or memory interface saturations is known as slip. The main source of timing inaccuracies are imperfect clocks. Jitter and transmission delay variations may cause slips as well, but are usually filtered out at the timing recovery circuits.

The occurrence of slips has to be considered as an anomaly event, changing the path performance and increasing the unavailable time. They will cause transmission errors and lead to retransmission of the information at higher level protocols.

Performance categories for slips in digital links are stated in ITU-T recommendation G.822.

7.7 Phase jitter

Jitter is defined as the misalignment of the significant edges of a digital signal from their ideal positions in time. Such misalignment, if uncontrolled, can lead to errors in digital transmission. Jitter can also be thought of as an unwanted phase modulation of a digital signal.

The term jitter is applied where the frequency band of the unwanted phase modulation is above 10 Hz. Where the frequency band is less than 10 Hz, the modulation is referred to as wander.

Intrinsic jitter refers to the jitter present on the output of a single device. It is specified in unit intervals and the result as an RMS or peak-to-peak value.

In order to ensure that your devices can operate error free in the presence of the worst-case jitter from preceding sections in the network, you need to measure jitter tolerance.

Jitter becomes an important parameter when DPLC channel is used as an integral part of a digital telecommunication transmission network. The DPLC channel may be used as an access link to serve as telecommunication connection between power system site and backbone of digital transmission network or as redundant digital channel in other parts of the digital transmission network.

Jitter, as parameter of a DPLC channel, has to be observed from two points of view:

- DPLC channel as generator of jitter (how much jitter a DPLC channel generates)
- DPLC channel as receiver of jitter-corrupted digital signal (how resistant is a DPLC channel to jitter)

Jitter requirements for digital links are stated in ITU-T recommendations G.823, G.824 and G.825.

7.8 Sync loss and recovery time

Increasing attenuation or corona noise are the main reasons for long term sync loss of a DPLC-link. Sync loss of a DPLC-link may occur due to noise bursts caused by switching activities in the HV network or by other short term influences (like lightning). Noise bursts usually result in a sync loss of less than 10 s and are not counted as UT (unavailable time).

Sync losses have to be considered as anomalies and added to the overall unavailable time.

Interruptions of the communication link during or short after switching activities in the HV network are critical because it affects the control of the power grid.

In DPLC systems the synchronisation between transmitter and receiver is mandatory and (usually) includes an adaptation to the characteristics of the transmission path. To achieve a high transmission quality an accurate measurement of the transmissions parameters is necessary. Depending on the modulation scheme and the expected result (amount of adaptation to the transmission path) the synchronisation phase may take some time. Compared to APLC systems (where no synchronisation is needed), the new synchronisation of the digital link has to be taken into account (recovery time).

It is up to the design of the modulation scheme of the DPLC system to minimise the downtime of the link. This may be done by not losing synchronisation in case of short interruptions and by balancing the requirements according recovery time and transmission quality.

7.9 Link latency

Depending on the modulation scheme the delay of a DPLC-link may be higher than the typical delay of APLC-links.

For the measurement of the delay of the DPLC-link a direct access of the data tester to the higher data rate stream of the DPLC system is essential to get a result identifying correctly delay caused by internal/external multiplexing or by upper layers.

7.10 IETF-RFC2544 Ethernet performance parameters

IETF-RFC2544 is a mature standard that can be used as guideline for benchmarking Ethernet based networks. It defines the parameters, their meaning and includes the list of tests to be performed on transmitted Ethernet frames.

It calls for different frame sizes i.e. 64,128, 256, 512, 1 024, 1 280 and 1 518 bytes. Test time for each test iteration should be at least 120 s.

- Data throughput:

It simply refers to the maximum amount of data that can be transported from source to destination. It should be measured with no errors or loss of frames.

- Frame loss:

  It represents the number of frames that were transmitted successfully from the source but were never received at the destination. It is usually referred to as frame loss rate and is expressed as a percentage of the total frames transmitted. According to RFC 2544 indication any frame received more than 2 s after it is transmitted would be counted as lost. Most layer 2 devices will drop a frame with an incorrect FCS. This means that a single bit error in transmission will result in the entire frame being dropped. For this reason BER, the most fundamental measure for bit oriented transmission, has no meaning in Ethernet based PLC since the ratio of good to errored bits cannot be ascertained.

- Latency (Ethernet):

  Ethernet latency refers to the total time taken for a frame to travel from source to destination. This total time is the sum of both the processing delays in the network elements and the propagation delay along the transmission medium. In order to measure latency a test frame containing a timestamp is transmitted through the network. The timestamp is then checked when the frame is received. In order for this to happen the test frame needs to return to the original test set by means of a loopback (round-trip delay).

- Burstability or back to back:

  The back-to-back value is the number of frames in the longest burst that the link under test will handle without the loss of any frames.

7.11 Bit error testing setup

To perform a bit error test over APLC/DPLC links, synchronous serial or Ethernet ports could be used.

Long term tests will be performed to validate integrity of both serial as well as Ethernet links (one month).

Furthermore measurements on the real HV line are influenced by external disturbances like lightning and switching activities in the HV network, and so this has to be taken into account when evaluating the results.

7.12 Serial synchronous interface

BER figures are determined using a data tester which generates a predefined pattern and check at receiving side for sync loss, slips, anomalies and BER figures.

The measurement of the bit error rate is done by means of pseudo-random bit sequence of length 2^{n-1}; n = 6, 9, 11, 12 or 15.

It is worth here to note that a BER $\leq 10^{-6}$ is considered to be sufficient for the applications transmitted via PLC systems.

7.13 Ethernet interface

A different approach should be used when test is performed on PLC links including Ethernet interfaces. In this case, occurring errors affect not the single bit but the transmitted frames.

Ethernet is an asynchronous, frame-based protocol originally intended to provide a means of communication between more than two data devices, using shared media.

Ethernet is an IEEE 802.3 standard which allows amongst others the use of full-duplex transmission, rather than shared media. This make it interesting when applied to PLC.

Even used over different media at different speed all Ethernet implementation keep the same frame structure, access/control method (MAC – media access control) and, for systems using shared media, the same collision detection scheme (CSMA/CD – carrier sense multiple access / collision detect).An example is shown in Figure 60.

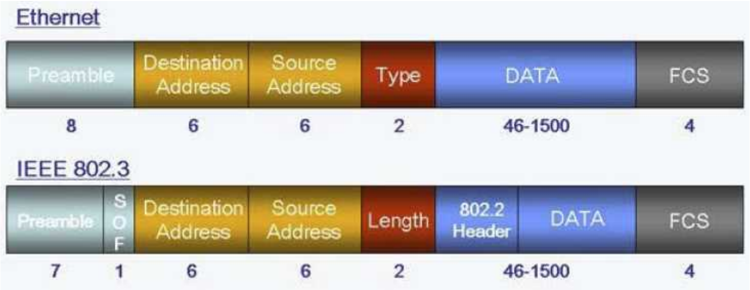


Figure 60 – Ethernet standard structure of frame format

Indeed on frame oriented transmission systems for each error occurring a frame is discarded (bad CRC) and it is not possible to distinguish if it was due to one bit or burst error. For this reason it is not possible define the corresponding BER figures.

However a BER $\leq 10^{-6}$ is considered to be sufficient for the applications transmitted via PLC systems and corresponding frame loss for Ethernet link can be negligible.

Assessment of Ethernet link requires the assessment of specific parameters as defined into IETF-RFC2544:

- Data throughput
- Frame loss
- Latency
- Burstability or back to back

IETF-RFC2544 is used to benchmark Ethernet based networks. It calls for different frame sizes i.e. 64, 128, 256, 512, 1024, 1280 and 1518 bytes. Test time for each test iteration should be at least 120 s.

As for serial links, long term tests will be performed to validate integrity of Ethernet links (one month).

7.14 Overall quality link performance

At the moment, no IEC, ITU-T or IETF standards are available covering link performance of DPLC for layer 2.

Key parameters to consider and criteria for the allocations of end-to-end performance over constant bit rates paths can be derived using the rules laid out in the ITU-T recommendations G.821, G.826 and G.823 in order to estimate the overall quality of digital PLC link.

In the following the main error performance parameters to be used include the following:

- Error free seconds (EFS): Seconds with no bit error.
- Errored seconds (ES): One second intervals with any error.
- Errored second ratio (ESR): The ratio of ES to total seconds in available time during a fixed measurement interval.
- Severely errored seconds (SES): One second intervals with a bit error rate $> 10^{-3}$.

- Severely errored seconds ratio (SESR): The ratio of SES to total seconds in available time during a fixed measurement interval.
- Total time
- Available time (AT) or equally unavailable time UAT): A period of unavailable time begins when BER in each second is worse than 10^{-3} for a period 10 consecutive seconds and terminates when the BER in each second is better than 10^{-3} for 10 consecutive seconds.
- % of the overall time with ANOMALIES & Defects (slip, AIS, sync loss, etc.)
- Link availability
- BER performance time (BPT): It is the period of the measurement time where link presents a BER better than 10^{-3}.

In Figure 61, the application of the above parameters for the unavailability determination of a bidirectional digital link is shown.

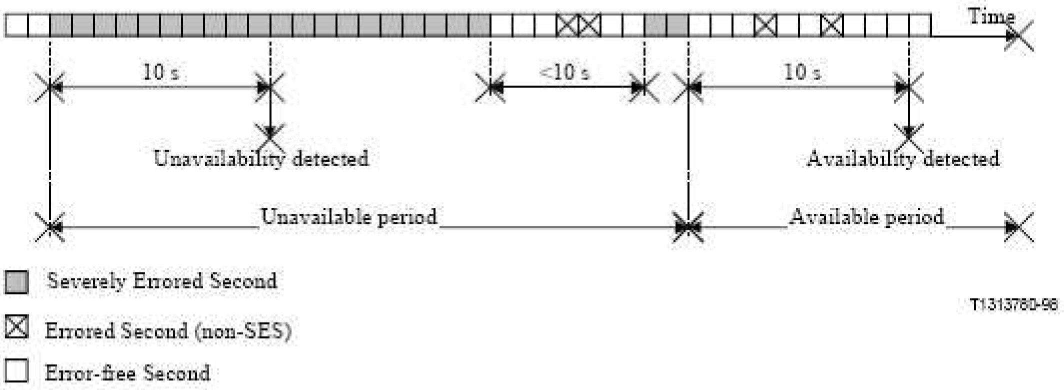


Figure 61 – Example of unavailability determination (ITU-T G.826)

From a service point of view, the different unavailability periods could occur independently in each direction. They have to be cumulated as shown in Figure 62.

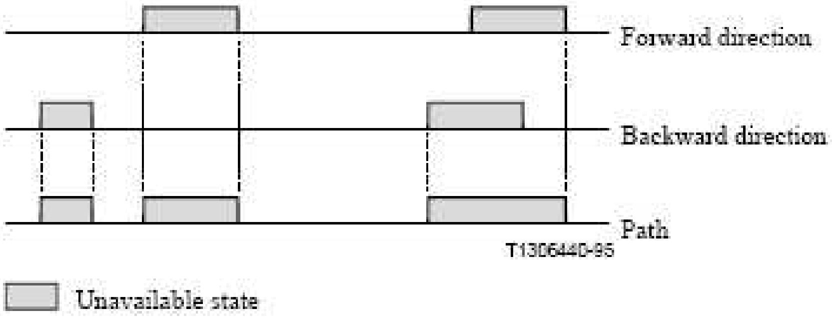


Figure 62 – Example of the unavailable state of a bidirectional path (ITU-T G.826)

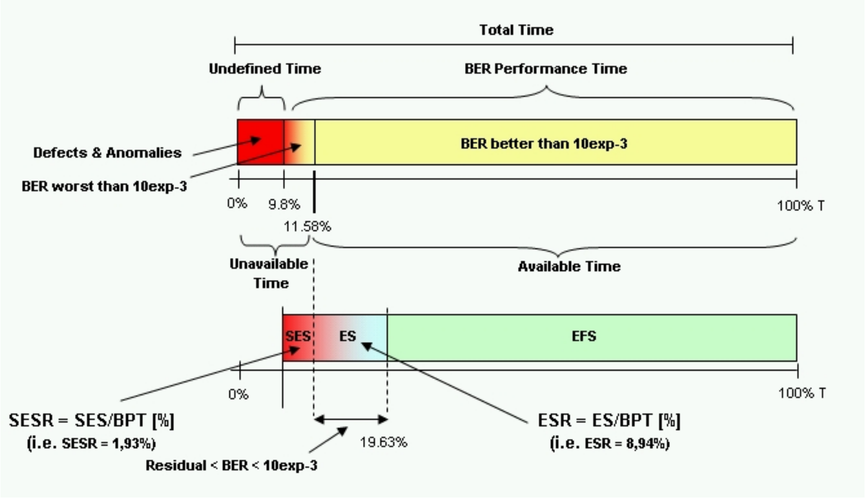


Figure 63 – Quality performance estimation based on ITU-T G.821 and G.826

Once the overall quality link has been assessed, it is possible to check its conformity with the quality mask objectives. Generally they are defined in the service level agreement and are specific for each family of services. An example is shown in Table 18.

Table 18 – Quality mask objectives (sample)

A ≥ 99,95 % & ESR ≤ 0,08 & SESR ≤ 0,002 & #SLIP/Month ≤ 0,06 % & MAX #SLIP/Day <10	**X**	**Good**
98 % ≤ A ≤ 99,95 % & ESR ≤ 0,08 & #SLIP/Month ≤ 0,06 %		**Poor**
A < 98 %		**Not compliant**

If the error performance parameters are compliant with the target objectives, the PLC link is expected to be able to adequately support the requested service.

8 Applications carried over PLC systems

8.1 General

This subclause describes the main features and requirements for both typical as well as innovative applications that can be carried by PLC systems and telecommunication networks which may include PLC segments.

A very rough classification of the applications could be:

- Telephony (analogue and digital),
- Data transmission bit, byte, packet and message oriented.

However, one should bear in mind there are further aspects to be considered (i.e. real time, no real time, off line) to identify the requirements of the currently most used applications like email, ftp, HTTP, SNMP, VoIP and in general the requirements of any specific application protocol transported by the telecommunication system.

8.2 Telephony

Along with low data rate telegraphic transmission, telephony has been for a long time the most relevant application carried out by PLC systems.

Indeed the telephony channel metric or 4 kHz band was adopted at the beginning by all transmission systems including the PLC. To reduce the necessary bandwidth in some cases is possible to limit the telephony channel at 2,5 kHz.

With the aim of increasing the number of signals to be carried within a standard telephone channel compressed voice channels and suitable vocoders for analogue and digital channels were introduced.

These bandwidth reduced voice channels are influenced by a lot of parameters, the most important are:

- speech quality,
- intelligibility (clarity),
- time delay,
- echo cancellation,
- bit rate,
- reduction of quality by multiple compression,
- sensitivity to bit errors.

8.3 Speech quality

8.3.1 General

For voice telecommunications speech quality is one of the most important aspects for assessing the overall quality of service (QoS). While there are many factors that affect voice quality, there are three key parameters that characterise it:

- intelligibility (clarity),
- delay,
- echo.

The relationship between clarity, delay, and echo can be quite complex as shown in the three-dimensional Figure 64.

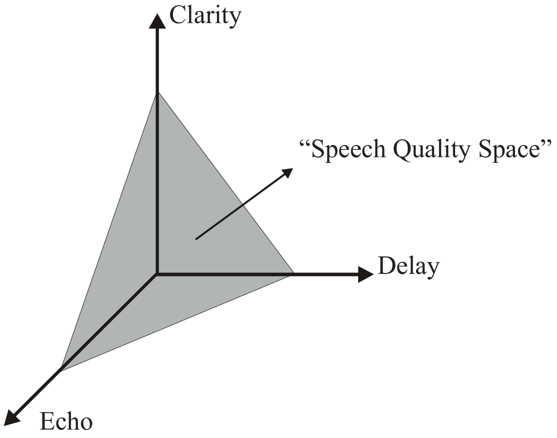


Figure 64 – Relationship between clarity, delay, and echo with regards to speech quality

Intelligibility (clarity) refers to the clearness or fidelity of voice as it is reproduced by a network and perceived by a listener. Clarity is independent of delay. Clarity is also independent of echo since echo is perceived by the speaker and clarity is perceived by the listener.

Delay is the time it takes a voice signal to travel end-to-end between talker and listener and often manifests itself as an apparent time lag between when the talker speaks and when the listener responds. When a perceptible delay is present, conversations can seem uncomfortable. When too much delay is present, voice conversation can become impossible.

Echo in a telephony environment is usually caused by hybrid wire junctions in a network in which a portion of the energy from a person’s speech signal is reflected back to the same line.

8.3.2 Measuring intelligibility (clarity)

The first significant technique used to measure speech clarity was to actually use large numbers of human listeners to produce statistically valid subjective clarity scores. This technique is known as mean opinion scoring (MOS) where value of large numbers of human opinion score is calculated. The technique for performing MOS testing on networks is generally described in ITU-T P.800, while ITU-T P.830 provides more specific methods for subjective testing on speech codec’s. Both of these ITU-T recommendations describe methods for testing, method for subjective scoring, value of scores, characteristics of speech samples to be used, and other conditions under which testing is to be performed.

MOS testing can be based on two-way conversational tests or on one-way listening tests. In MOS subjective testing of the quality value of speech is from 1 to 5.

Obviously, MOS testing has several drawbacks:

- it is subjective because results depend on many uncontrollable attributes of the test subjects including mood, attitude, and culture. Practically speaking, MOS testing is not a repeatable or consistent method for testing;
- it is expensive because it requires a large number of people and elaborate testing setups;
- it is inefficient and impractical to use to perform frequent testing such as that needed for network design and configuration changes and for routine network monitoring.

MOS testing drawbacks suggest that objective, automated, and repeatable testing methods are needed for measuring subjective speech clarity.

To answer the need for an objective, automated, and repeatable speech clarity testing method that takes into account the subjective nature and perception of clarity, one technique was developed and standardised by ITU-T:

- PESQ (Perceptual Evaluation of Speech Quality) method standardised by ITU-T P.862.

There are developed instruments that perform measurements in accordance with ITU-T P.862, and measurements of delay and echo.

8.4 Analogue telephony

For speech transmission, a signal-to-noise ratio of 25 dB, psophometrically measured, under adverse weather conditions is considered to be acceptable. This will result in a SNR of 30 dB to 40 dB at the receiver input for the majority of time under normal operating conditions.

An improvement of the SNR of approximately 15 dB can be achieved by the use of compandors.

8.5 Digital telephony

Digital technology has made a significant effect on the transmission and reception of a range of data formats including, speech, instrumentation signals and generally data transmission for electricity supply switching. The data networks normally extend to high data rates with minimal interference but where this does happen there are excellent computer software systems to perform error correction. These systems are software controlled thereby providing fast and efficient seamless communication of a range of services.

8.6 VoIP applications

There are many applications of VoIP covering standard voice communications, data communications and internal communications, to the communications for monitoring the functionality and reliability of the system. This enables fast and efficient communications with minimal errors in the communications system.

8.7 Data transmission

For the frequency shift keyed (FSK) data channels up to 2 400 Baud a signal-to-noise ratio of 15 dB under adverse weather conditions is considered to be acceptable. The development of digital communications systems and associated software control systems will enable higher data rates to be communicated with minimal distortion.

8.8 Internetworking

The power line carrier communication systems development over the last two decades, coupled with the increase in reliability through the development of software systems. This has allowed the integration of many telephony, SCADA other electric power communications systems to interface and provide reliable communications for the complete power distribution network and other general communications.

8.9 Telecontrol

8.9.1 IEC 60870-5-101 SCADA-RTU communication

SCADA-RTU applications may use a serial protocol according IEC 60870-5-101 for the communication between control centre and the remote controlled RTUs.

According to the definitions of this standard there are no byte-gaps allowed within one telegram. This definition results in a requirement that is usually not covered by the communication equipment.

Because byte-gaps are not detected as an error by “normal” data tester, a protocol tester is needed to check the compatibility of the DPLC system with IEC 60870-5-101.

8.9.2 IEC 60870-5-104 SCADA-RTU communication

In some cases it is required to send the application messages between SCADA and RTU using a data network containing relay stations, e.g. routers for LAN/WAN/LAN extensions, and provide only for a virtual circuit between the interested telecontrol stations.

IEC 60870-5-104 standard defines the use of an open TCP/IP interface to a network containing a LAN/WAN/LAN connectivity supporting communication between telecontrol equipment, which transports IEC 60870-5-101 messages units.

DPLC which may implement the interface to the LAN/WAN segments have to keep transit delay and packet loss very low to ensure a quality compatible with the typical requirements of telecontrol service.

8.9.3 Teleprotection

The transmission of teleprotection signals is one of the most important functions performed by a PLC system and a secure transmission of trip commands with high reliability and low latency has to be ensured.

More information about performance guidance figures for teleprotection schemes and testing of teleprotection command systems are given in IEC 60834-1.

8.9.4 Teleprotection signal

It is advisable to keep the teleprotection as an analogue system. The reason is that if we would transmit digital teleprotection over a digital PLC then the teleprotection system would be operative only as long as the digital PLC is able to recover the received data and deliver them to the teleprotection receiver. This involves detecting the received signal, estimating the transmitted bits and delivering them over a certain data interface. However, this process has some limitations that are critical for teleprotection operation:

- There is a minimum signal-to-noise ratio (SNR) for proper operation (proper demodulation and detection of data), below which the digital PLC receiver performance degrades considerably. The value of this threshold SNR will depend on the specific implementation, but it will be higher than the SNR usually required for analogue teleprotection systems. If the teleprotection were a digital system this would impose a severe risk. This is mostly true under faulty line conditions, when the minimum SNR as required by a digital PLC receiver cannot be guaranteed.
- Under fault conditions, the channel will suffer from severe spectral distortion, both amplitude and group delay distortion, preventing the digital PLC from recovering the received data.
- The coding and decoding process both introduces a certain time delay. Again the specific value of this delay depends on the implementation, but this value will add to the nominal transmission of the teleprotection itself. This could degrade the performance of the teleprotection unacceptably (e.g. maximum actual transmission time for a given dependability).

Annex A
(informative)

Environmental conditions

The following conditions should be observed when operating equipment:

– Temperature and humidity

The equipment, including its protection shall meet the requirements of this standard while operating under the conditions specified in IEC 60721-3-3 and classified as follows:

– High temperature

The equipment shall operate without damage at temperatures up to +55 °C for a period of not more than 24 h per month. In these conditions a temporary degradation in performance may be accepted.

– Low temperature

The lower temperature limit of operation shall be 0 °C.

– Condensation: Formation of ice

In normal operation, the formation of ice shall not occur.

Annex B
(informative)

Electromagnetic compatibility (EMC)

From the EMC standards available from the International Electrotechnical Commission (IEC), the most applicable is CISPR 22 (2008). This standard is entitled ‘Information technology equipment – Radio disturbance characteristics – Limits and methods of measurement’.

According to the IEC, the object of this standard is to ‘establish uniform requirements for the radio disturbance level of the equipment contained in the scope, to fix limits of disturbance, to describe methods of measurement and to standardise operating conditions and interpretation of results’.

It is clear from the definition of information technology equipment (ITE) within CISPR 22 that telecommunications equipment falls within the scope of this standard. PLC systems are neither specifically excluded nor included but according to a strict interpretation of the ITE definition, would also fall within the scope of CISPR 22.

CISPR 22 classifies ITE equipment into two categories, according to its intended environment. Class B equipment is intended for a domestic environment, defined simply as an environment in which radio / television receivers are likely to be used within 10 m of the device or system in question.This would appear to be the most appropriate classification for any PLC system transmitting and/or receiving signals via the internal mains wiring of a residential or commercial building.

Class A devices are permitted significantly higher limits for conducted and radiated emissions but shall display the following warning:

‘This is a class A product. In a domestic environment this product may cause radio interference in which case the user may be required to take adequate measures.’

For PLC systems operating over LV distribution networks, it may be felt acceptable to test to class A standard. In such cases, equipment installation could be strictly controlled.In addition, with this type of PLC system, signal penetration onto the building wiring may be limited – either through the application of filters, or due to the inherent attenuation caused by the electricity meter.

Class A and B limits for conducted and radiated emissions, in a measurement bandwidth of 9 kHz, are shown in Table B.1 and Table B.2, respectively.

Table B.1 – Permitted conducted emissions on the mains port of class A equipment

Frequency range MHz	**Limits** dBµV	
	Quasi-peak	**Average**
0,15 to 0,5	79	66
0,5 to 30	73	60

Table B.2 – Permitted conducted emissions on the mains port of class B equipment

Frequency range MHz	**Limits** dBμV	
	Quasi-peak	**Average**
0,15 to 0,5	66 to 56 *	56 to 46 *
0,5 to 5	56	46
5 to 30	60	50
* Limit to decrease linearly with the logarithm of frequency.		

Temporary condensation may occur during maintenance when spare parts are introduced which have been stored at a lower temperature than that prevailing in the telecommunications equipment environment.

Annex C
(informative)

HF modulated power signal

C.1 General

The purpose of this annex is to understand the concepts related with power for each service and total power transmitted by the system. Also the signal to noise ratio for each service is considered.

The concepts covered are:

- Average power,
- Peak power,
- Peak envelope power (PEP),
- Peak to average power ratio (PAPR).

In the following explanations it is considered, unless otherwise indicated, that the frequency spectrum of each service is flat in the corresponding bandwidth, where the bandwidth is the equivalent noise bandwidth.

Also it is assumed that a good estimation of the peak voltage of each service is known.

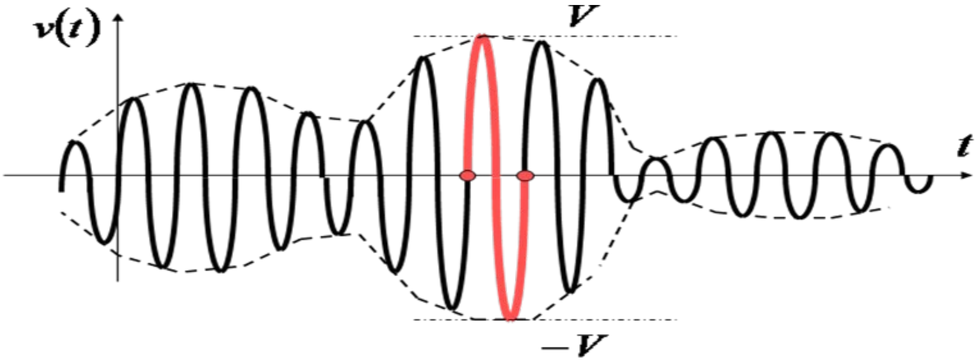


Figure C.1 – Power concepts

In Figure C.1 a summary of the involved power concepts is shown. A possible wave shape of a voltage $v(t)$ is depicted. This signal can be considered as the signal corresponding to one single service or the combination (addition) of all signals transmitted by a PLC terminal.

The average power of that signal, in a time window T, is the power over a reference resistor R of the average of the squared instantaneous values of the voltage $v(t)$:

$$P_{av} = \frac{1}{R}\left[\frac{1}{T}\int_{T}[v(t)]^2\,dt\right]. \tag{C.1}$$

If the measurement or calculation could be done for $T \to \infty$ the result is the actual average value of the power of $v(t)$ over a resistor R.

Assuming that the maximum instantaneous voltage V (peak voltage) is known, then the peak power value is

$$\frac{V^2}{R} \text{ (note that this is an instantaneous value).} \tag{C.2}$$

Around the time when the peak voltage takes place we can consider a piece of signal the shape of which corresponds to a one period of a sinus wave. The average power of the signal in this period is called the peak envelope power (the average power of the signal in one period when the envelope reaches the maximum value)

Applying (C.1) for a sinus signal, we obtain:

$$\text{Peak envelope power (PEP)} = \frac{\left(\frac{V}{\sqrt{2}}\right)^2}{R} = \frac{1}{2}\frac{V^2}{R}. \tag{C.3}$$

Comparing (C.2) and (C.3), we find that the peak envelope power (PEP) is one half of the peak power.

Finally, if the peak power value and the average power value are known (or estimated), the ratio between the two mentioned values (in logarithm representation) is known as the peak to average power ratio (PAPR):

$$PAPR = \frac{peakpower}{averagepower}. \tag{C.4}$$

Using these definitions, it is possible to make the following considerations:

- If the peak voltage value V_i for all services (i = 1, 2,....,n) is known, then it is possible to calculate the individual PEP power for each service (signal) and the total PEP power for the addition of all signals:

  Individual peak power for the i-th service = $\frac{V_i^2}{R}$ as indicated by (C.2).

  Total peak power for the addition of all signals:

$$\frac{1}{R}\left(\sum_{i=1}^{i=n} V_i\right)^2 = \frac{1}{R}V_{tot}^2. \tag{C.5}$$

- In other words, the maximum peak of the composite signal is the addition of the maximum peak of individual signals. This is an important point when planning the system because the maximum peak V_{tot} of the composite signal could be limited by the output amplifier and therefore this value has to be split in several smaller parts V_i , each one for the different services to be transmitted.
- However, when considering the signal to noise ratio for each service at receive end, the average power value should be used for that purpose. From this consideration we see that the PAPR factor has a big relevance.

In Figure C.2 we see example 1, where a single tone (constant envelope) of peak voltage value V is considered and the corresponding peak power, average power, PEP power and PAPR are calculated according to the definitions given before. In this case we see that the average power coincides with the PEP power that satisfies the definition of PEP power. We can also see that in this very simple case the PAPR value is only 3 dB.

Figure C.3, example 2, is the case of two tones with different frequencies but with the same amplitude V/2. The same parameters and relations as in example 1 have been calculated and they are given in the same picture

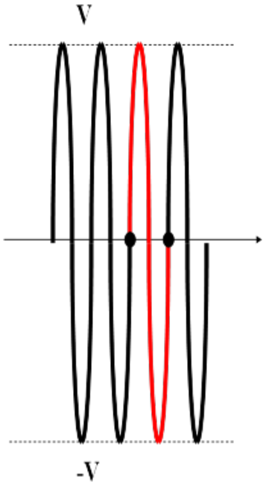


Figure C.2 – Single tone

In Figure C.2, example 1, a single tone (constant envelope) of peak voltage value V is considered. According to the definitions given before we find that:

$$\text{Peak power } = \frac{V^2}{R}. \tag{C.6}$$

The average power, which is the same for every period is:

$$\text{Average power} = \frac{\left(\frac{V}{\sqrt{2}}\right)^2}{R} = \frac{V^2}{2R}. \tag{C.7}$$

The PEP power in this case coincides with the average power:

$$\text{PEP power} = \frac{\left(\frac{V}{\sqrt{2}}\right)^2}{R} = \frac{V^2}{2R}. \tag{C.8}$$

and the resulting PAPR is:

$$\text{PAPR}= 10\log\frac{peakpower}{averagepower} = 10\log\frac{V^2/R}{V^2/2R} = 10\log 2 = 3\ dB. \tag{C.9}$$

In Figure C.3, example 2, the case of the addition of two tones $v_1(t)$ and $v_2(t)$ having different frequencies but equal amplitudes V/2 is shown. The PAPR for $v_3(t) = v_1(t) + v_2(t)$ can be derived as follows:

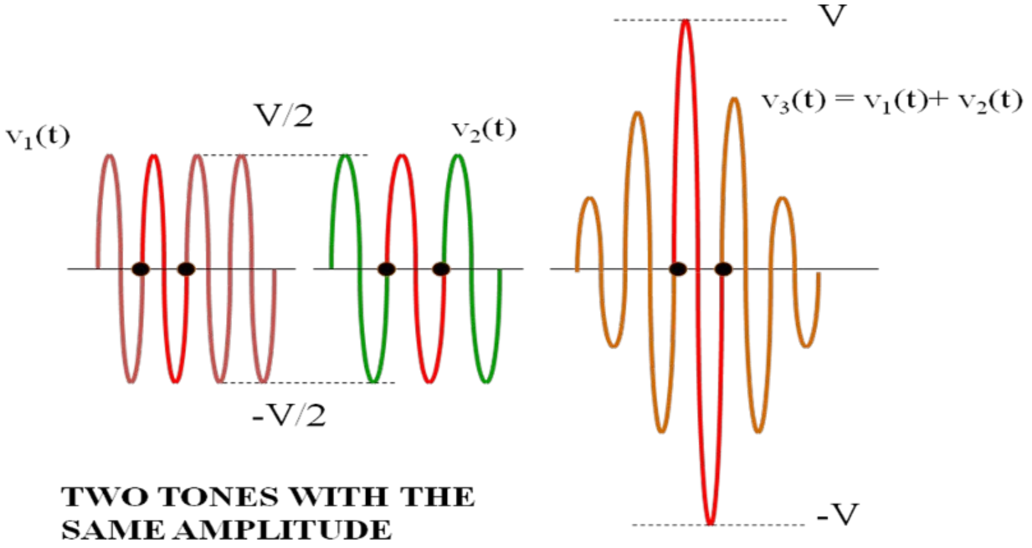


Figure C.3 – Two tones

$$\text{Peak power for } v_3(t) = \frac{V^2}{R}; \tag{C.10}$$

$$v_1(t) = \frac{V}{2}\cos\omega_1 t \Rightarrow \text{average power } P_1 = PEP_1 = \frac{\left(\frac{V/2}{\sqrt{2}}\right)^2}{R} = \frac{V^2}{8R}; \tag{C.11}$$

$$v_2(t) = \frac{V}{2}\cos\omega_2 t \Rightarrow \text{average power } P_2 = PEP_2 = \frac{\left(\frac{V/2}{\sqrt{2}}\right)^2}{R} = \frac{V^2}{8R}; \tag{C.12}$$

$$v_3(t) = v_1(t) + v_2(t) \Rightarrow PEP_3 = \frac{\left(\frac{V}{\sqrt{2}}\right)^2}{R} = \frac{V^2}{2R}; \tag{C.13}$$

$$\text{average power } P_3 = P_1 + P_2 = \frac{V^2}{4R} = \frac{1}{2}PEP_3; \tag{C.14}$$

ratio between PEP and average power for $v_3(t) = \dfrac{V^2/2R}{V^2/4R} = 2 \Rightarrow 3\ dB$; (C.15)

$$PAPR(v_3) = 10\log\frac{V^2/2R}{V^2/4R} = 10\log 4 = 6dB. \tag{C.16}$$

C.2 HF modulated bandwidth and power signal

The goal of this clause is to clarify subclause 4.5.3 of IEC 60663 published in 1980, where the power for each service is related to its noise equivalent bandwidth together with the PEP power of the terminal using an arbitrary reference channel.

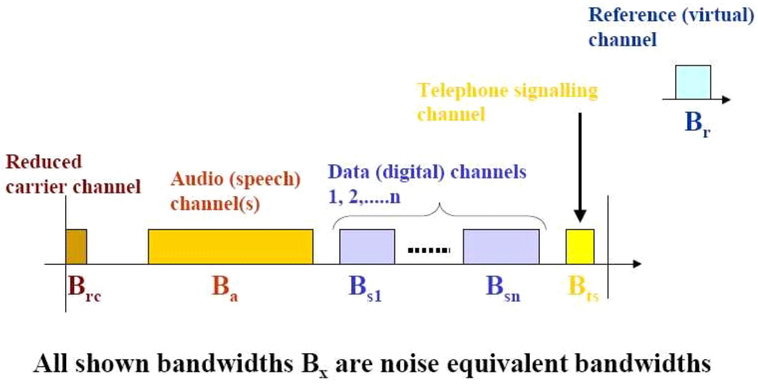


Figure C.4 – Example of noise equivalent bands for different services

Figure C.4 shows an example of the noise equivalent bandwidths for different services such as residual carrier B_{rc}, audio (speech) B_a, several data channels (low speed or high speed) B_{s1} ,....., B_{sn}, telephone signalling B_{ts}.

These services have to be taken as arbitrary services that can be transmitted by a general purpose (analog and/or digital) PLC terminal.

Additionally we consider a reference (virtual) channel having an arbitrary equivalent noise bandwidth B_r that it is used only for calculation purposes.

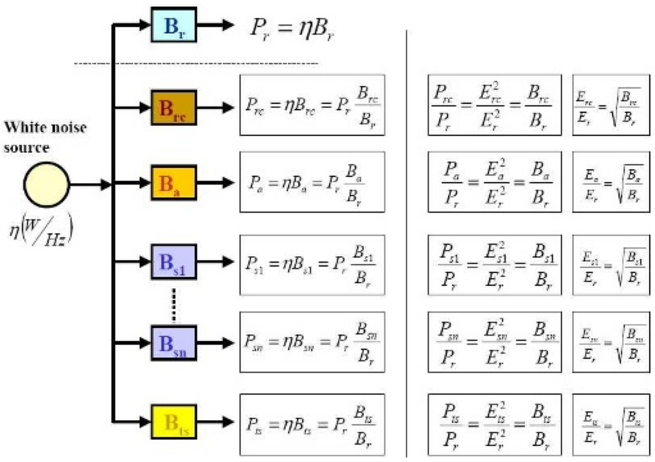


Figure C.5 – Noise equivalent band for different services

Consider, as shown in Figure C.5, a bank of filters, each one having the mentioned bandwidths, and all of them fed by a white noise source with spectral power density $\eta(W/Hz)$.

Obviously the mean power at the output of each filter is proportional to its bandwidth:

$$P_i = \eta B_i \,, \tag{C.17}$$

and if we consider the output power of the reference channel

$$P_r = \eta B_r \,, \tag{C.18}$$

we can write $P_i = P_r \dfrac{B_i}{B_r}$. (C.19)

So, the power corresponding to each service can be related to the power of the reference channel and the ratio of the corresponding bandwidths.

If the PAPR of each service are similar, the PEP and peak power of each service will be proportional to the mean power and at the same time proportional to E_i^2, where E_i is the peak value of each service:

$$\frac{P_i}{P_r} = \frac{B_i}{B_r} = \frac{E_i^2}{E_r^2} \,. \tag{C.20}$$

From this last formula we can write:

$$\frac{E_i}{E_r} = \sqrt{\frac{B_i}{B_r}} \,. \tag{C.21}$$

Following the situation given in Figure C.3, we can write the peak value of the combined signal (all services together) as the addition of all peak values and develop the expression in the following way:

$$\begin{gathered}E_{PEP}=E_{rc}+E_a+\left(\sum_{i=1}^{n}E_{si}\right)+E_{ts}\\ \frac{E_{PEP}}{E_r}=\frac{E_{rc}}{E_r}+\frac{E_a}{E_r}+\left(\sum_{i=1}^{n}\frac{E_{si}}{E_r}\right)+\frac{E_{ts}}{E_r}=\sqrt{\frac{B_{rc}}{B_r}}+\sqrt{\frac{B_a}{B_r}}+\left(\sum_{i=1}^{n}\sqrt{\frac{B_{si}}{B_r}}\right)+\sqrt{\frac{B_{ts}}{B_r}},\end{gathered} \tag{C.22}$$

$$\begin{gathered}E_{PEP}=E_{rc}+E_a+\left(\sum_{i=1}^{n}E_{si}\right)+E_{ts}\\ \frac{E_{PEP}}{E_r}=\frac{E_{rc}}{E_r}+\frac{E_a}{E_r}+\left(\sum_{i=1}^{n}\frac{E_{si}}{E_r}\right)+\frac{E_{ts}}{E_r}=\sqrt{\frac{B_{rc}}{B_r}}+\sqrt{\frac{B_a}{B_r}}+\left(\sum_{i=1}^{n}\sqrt{\frac{B_{si}}{B_r}}\right)+\sqrt{\frac{B_{ts}}{B_r}},\end{gathered} \tag{C.23}$$

and introducing PEP concepts for the reference channel and for the total signal

$$\begin{gathered}\frac{P_{PEP}}{P_r}=\left(\frac{E_{PEP}}{E_r}\right)^2=\left[\sqrt{\frac{B_{rc}}{B_r}}+\sqrt{\frac{B_a}{B_r}}+\left(\sum_{i=1}^{n}\sqrt{\frac{B_{si}}{B_r}}\right)+\sqrt{\frac{B_{ts}}{B_r}}\right]^2\\ 10\log\left(\frac{P_{PEP}}{P_r}\right)=10\log P_{PEP}-10\log P_r=10\log\left[\sqrt{\frac{B_{rc}}{B_r}}+\sqrt{\frac{B_a}{B_r}}+\left(\sum_{i=1}^{n}\sqrt{\frac{B_{si}}{B_r}}\right)+\sqrt{\frac{B_{ts}}{B_r}}\right]^2.\end{gathered} \tag{C.24}$$

If in this formula we express P_{PEP} and P_{r} in mW, we can write

$$P_r(dBm)=P_{PEP}(dBm)-10\log\left[\sqrt{\frac{B_{rc}}{B_r}}+\sqrt{\frac{B_a}{B_r}}+\left(\sum_{i=1}^{n}\sqrt{\frac{B_{si}}{B_r}}\right)+\sqrt{\frac{B_{ts}}{B_r}}\right]^2, \tag{C.25}$$

where now the P_{PEP} of the transmitter and P_{r} of the reference channel are expressed in dBm as indicated in the formula itself.

So, from formula (C.25) we see that if we know the P_{PEP} of the transmitter and the bandwidth of each service we can calculate the power P_{r} of the reference channel once its bandwidth B_{r} has been decided and now from (C.19) we can calculate the power assigned to service, that is

$$P_x(mW)=\frac{B_x}{B_r}P_r(mW), \tag{C.26}$$

or

$$P_x(dBm)=P_r(dBm)+10\log\frac{B_x}{B_r}. \tag{C.27}$$

The theory described so far assumes a fair treatment to every service, that is to say, average signal power proportional to the noise equivalent bandwidth for each service. The subjective effect of the compandor process for the analogue speech transmission has not been taken into account. Moreover, it was assumed that the PAPR of all services are equal.

Annex D
(informative)

Bandwidth efficiency

The bandwidth efficiency of a DPLC link is the achievable data rate divided by the transmission bandwidth for a given signal to noise ratio (SNR) and bit error rate BER.

Most DPLC modems use quadrature amplitude modulation (QAM), either with a single carrier or with multiple carriers. Both modulation types yield essentially the same bandwidth efficiency.

QAM can be considered as the superposition of two pulse amplitude modulated (PAM) signals X_i and X_q modulated on two carriers of the same frequency but with 90 degrees phase difference. When both PAM signals X_i and X_q have bandwidth B, the modulated QAM signal has bandwidth 2B. The QAM data rate is twice the PAM data rate of X_i or X_q alone. However, when transmitting only one PAM signal, single sideband modulation can be used, so that the modulated PAM signal has the same bandwidth B as the unmodulated signal, thus occupying only half of the bandwidth of the modulated QAM signal. As a consequence, QAM and PAM have the same bandwidth efficiency. In the sequel, the efficiency of PAM is evaluated since it is simpler to calculate than that of QAM.

Figure D.1 shows the signal constellation for PAM with 8 amplitude steps (8-PAM) at the decoder input in the receiver. In the bandwidth B, this PAM system can transmit $\log_2(8) = 3$ bits in each time interval $T = 1/(2B)$. The resulting efficiency is 3 bits/(BT) = 6 bits/s/Hz.

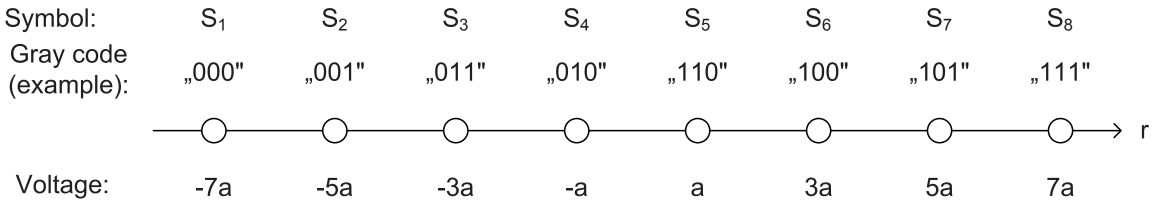


Figure D.1 – 8-PAM signal constellation

The efficiency of an M-PAM transmission is given by

$$E = 2B * \log_2(M)/B = 2 * \log_2(M) = \log_2(M^2). \qquad \text{(D.1)}$$

For random data, the M amplitude levels are equally likely to occur. Using the relationship

$$\sum_{i=1}^{M/2} (2i-1)^2 = \tfrac{1}{6} M * (M^2 - 1), \qquad \text{(D.2)}$$

the average power of the M-PAM signal is

$$S = \frac{1}{M} \sum_{i=-M/2}^{M/2} a^2 (2i-1)^2 = \frac{2}{M} a^2 \sum_{i=1}^{M/2} (2i-1)^2 = \tfrac{1}{3} a^2 (M^2 - 1). \qquad \text{(D.3)}$$

NOTE For M >> 1, a peak to average ratio (PAR) of 20*log(3) = 9,5 dB results. The PAR of practical DPLC modems will be a few dB higher.

Solving formula (D.3) for M^2 and inserting the result in formula (D.1) yields

$$E = \log_2\left(1 + \frac{3S}{a^2}\right). \qquad \text{(D.4)}$$

In the presence of noise, symbol errors will occur whenever the absolute value of the noise voltage n at the decoder input exceeds a. For Gaussian noise of mean power N at the decoder input, the probability density function (pdf) is

$$pdf(n) = \frac{1}{\sqrt{2\pi N}} \exp\left(\frac{-n^2}{2N}\right). \qquad \text{(D.5)}$$

.

The symbol error probability or symbol error rate (SER) for all symbols except the first and the last symbol S_1 and S_M is given by

$$SER = \Pr(n > a) + \Pr(n < -a) = 2\int_a^\infty pdf(n)dn = erfc\left(\frac{a}{\sqrt{2N}}\right). \qquad \text{(D.6)}$$

where $erfc(\ )$ is the complementary error function

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp\left(-x^2\right)dx\,. \qquad \text{(D.7)}$$

.

Assuming that $M >> 1$, the fact that the symbol error probability for the 1st and the M^{th} symbol is half of the value given by (D.6) can be ignored, so that (D.6) is a good approximation for the symbol error rate.

Solving formula (D.6) for a yields

$$a = \sqrt{2N} * erfcinv(SER), \qquad \text{(D.8)}$$

where $erfcinv(\ )$ is the inverse complementary error function. Inserting this result in (D.4) yields

$$E = \log_2\left(1 + \frac{3}{2 * erfcinv^2(SER)} * SNR\right), \qquad \text{(D.9)}$$

where $SNR = S/N$ is the signal to noise ratio.

By using a Gray code for the mapping of bits to symbols as shown in the example adjacent symbols will differ just by one bit. If the r.m.s. noise voltage is small compared to a, most symbol errors will consist of picking a symbol adjacent to the correct one, thus producing just one bit error per symbol error. Under these conditions, the symbol error rate SER will be almost equal to the bit error rate (BER). Replacing SER by BER in (D.9), the final result for the bandwidth efficiency of a DPLC link is

$$E = \log_2\left(1 + \frac{3}{2 * erfcinv^2(BER)} * SNR\right), \tag{D.10}$$

It is interesting to compare this result to the maximum efficiency of a band limited channel for errorless transmission due to Shannon [1]:

$$E_{Shannon} = \log_2(1 + SNR). \tag{D.11}$$

Obviously, there is an SNR gap between E and E_{Shannon} given by

$$SNR\ gap = 10 * \log\left[\frac{2 * erfcinv^2(BER)}{3}\right] dB\ . \tag{D.12}$$

This is shown in Figure D.2 as a function of the BER.

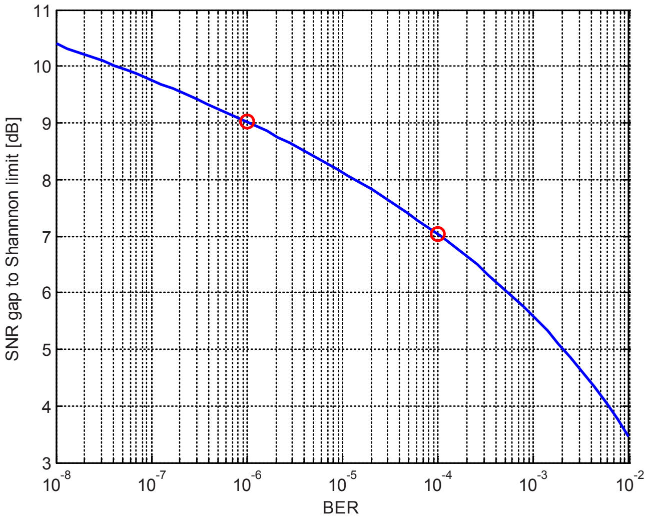


Figure D.2 – SNR gap of DPLC efficiency to Shannon limit

For the BER values of 10^{-4} and 10^{-6}, the gaps are 7,0 dB and 9,0 dB, respectively. The efficiency curves for these BER values are shown in Figure D.3 together with the Shannon limit.

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[1] C.E. Shannon, Communication in the Presence of Noise, Proc. IRE, vol. 37, pp.10-21, 1949.

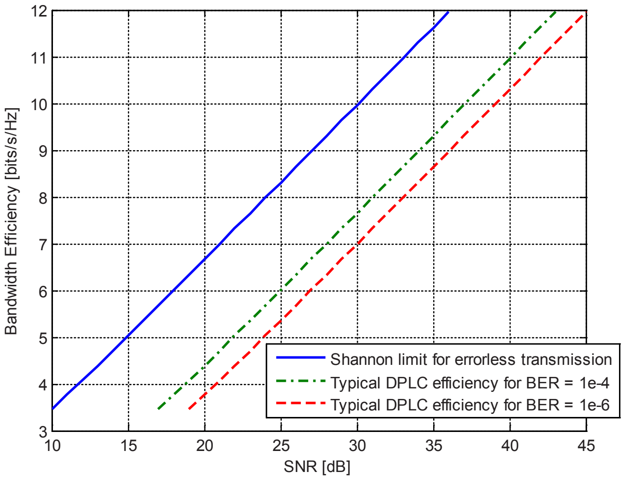

Figure D.3 – DPLC efficiency for BER = 10^{-4} and 10^{-6} and Shannon limit

Annex E
(informative)

Noise measurements

Noise measurements have been classified according to the responses of various measuring instrument detectors to different noise characteristics. These distinctions are useful because of their different effects on various kinds of carrier receivers.

The peak value of power-line noise is the maximum voltage amplitude of recurring impulses. It is these impulses, for example, that effect trigger circuits such as are found in electronic switching devices.

Peak values of noise may be measured by certain peak-reading voltmeters.

The quasi-peak value of noise is a reference level related to peak amplitude and to impulse repetition rate. It is measured by a detector circuit with a fast charging time and a relatively slow discharge time (typically 1 ms and 600 ms, respectively).

For pulses occurring at high repetition rates, the quasi-peak value approaches the peak value. Quasi-peak noise is a measure of the masking effect of noise as a background for speech.

Quasi-peak values may be measured only by noise meters that have appropriate detector characteristics. Although used extensively for measurements of noise affecting radio broadcast, quasi-peak measurements have not been used to any great extent in carrier applications.

The average value of noise is its average voltage over a finite period of time.

It is defined as the area under the amplitude-time curve divided by the base length (time period).

Average noise affects receiver-detector d.c. output for telegraph functions, for continuous wave relaying, or for ON–OFF pulse functions.

Average values of noise may be measured by selective carrier-frequency voltmeters of known bandwidth. Also, average noise can be derived from audio noise measurements made at the output of a single-sideband carrier receiver. Because noise energy is distributed throughout the frequency spectrum, measured values will be a function of the bandwidth of the measuring instrument.

The RMS value of noise is the effective voltage of a reference sine wave that would have the same average power level as the noise being measured.

RMS noise is of secondary importance in carrier equipment.

The measured values of average and RMS noise would be lowered by 3 dB if the bandwidth was reduced by 2:1.

The noise level on a power line is determined by both generation and propagation of noise energy.

Propagation phenomena, such as attenuation, reflections, and absorptions, affect noise voltages in the same way they affect desired carrier signals.

The amplitude of power-line noise decreases with increasing frequency.

A rule of thumb is that the noise amplitude varies inversely as the frequency.

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Annex 10 to the Convention of International Civil Aviation Organization ICAO, Aeronautical Telecommunications, Volume V, Aeronautical Radio Frequency Spectrum Utilization

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