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Technical Specification

Power Line Telecommunications (PLT)
Narrow band transceivers in the range 9 kHz to 500 kHz
Power Line Performance Test Method Guide

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Foreword

This Technical Specification (TS) has been produced by ETSI Technical Committee Powerline Telecommunications (PLT).

Introduction

Customers need not only a standards based power line communications (PLC) technology, but also that one that is able to meet their business requirements. A standardized PLC technology that does not fully meet the customer's requirements can undermine the general acceptance of PLC as a technology. Therefore, it is important to verify that a proposed technology can meet these requirements under realistic channel conditions. A link budget and data rate test measurement method can be used for this purpose.

A potential PLC modem customer can also use field trials to evaluate the suitability of a particular product for their application, but field trials cannot easily expose the technology to all possible types of impairments, thus limiting the effectiveness of the trials. However, a properly designed test method can easily expose the technology to all possible types of impairments; the link budget and data rate test method can then be correlated with field studies. After this correlation is established, it is possible to reduce field trial requirements significantly and accelerate technology deployments.

One purpose of a standardized test method is to include real world noise characteristics that represent something more challenging than the typical case likely found in a field trial. A test method can emulate the 95th to 99th percentile level of each type of noise that occurs on the power line. A field trial that could replicate this level of real world challenge would require a very large sample size to find the hardest 1 % to 5 % of cases. A standardized test method addresses this limitation of field trials.

Clear results from a standardized test method provide a way to communicate quantitative information to a customer, including suitability of the technology for their requirements at an early stage of their product evaluation, development, and deployment.

The test measurements can be made by an independent test house. Independent testing provides credibility to enable faster mass market penetration of the technology. The test results enable the customer to know beforehand the suitability of the technology they buy, without the need to go through time-consuming pilot phases.

1 Scope

The present document describes test techniques that can be used to determine the performance of narrow band power line communications technologies using any modulation technique in the frequency range 9 kHz to 500 kHz.

2 References

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

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NOTE: While any hyperlinks included in this clause were valid at the time of publication ETSI cannot guarantee their long term validity.

2.1 Normative references

The following referenced documents are necessary for the application of the present document.

[1] CISPR 11:2009+A1:2010: "Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement".

[2] CISPR 15:2009: "Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment".

[3] CISPR 16-1-1:2010: "Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-1: Radio disturbance and immunity measuring apparatus - Measuring apparatus".

[4] CISPR 22:2008: "Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement".

[5] CENELEC EN 50065-1:2011: "Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz - Part 1: General requirements, frequency bands and electromagnetic disturbances".

[6] Title 47 of the Code of Federal Regulations (CFR) Part 15, Radio Frequency Devices.

NOTE: Available at www.fcc.gov/oet/info/rules/.

[7] ISO/IEC 14908-3:2012: "Information technology -- Control network protocol -- Part 3: Power line channel specification".

2.2 Informative references

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] TS 103 908 (V1.1.1): "PowerLine Telecommunications (PLT); BPSK Narrow Band Power Line Channel for Smart Metering Applications [CEN EN 14908-3:2006, modified]".

[i.2] IEEE P1901.2: "Standard for Low Frequency (less than 500 kHz) Narrow Band Power Line Communications for Smart Grid Applications".

3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

AC	Alternating Current
ADC	Amperes Direct Current
BPSK	Binary Phase Shift Keying
CISPR	Committee International Special Radio Perturbation
CRC	Cyclic Redundancy Rate
DBPSK	Differential Binary Phase Shift Keying
DCR	Direct Current Resistance
DQPSK	Differential Quadrature Phase Shift Keying
DR_{LINK}	Data Rate Link Layer
DR_{PKT}	Data Rate Packet Level
EN	European Norm
FCC	Federal Communications Commission
FM	Frequency Modulation
IEEE	Institute of Electrical and Electronics Engineers
LB_{LINK}	Link Budget Link Layer
LB_{PHY}	Link Budget Physical Layer
LED	Light Emitting Diode
MAC	Medium Access Control layer
MER	Message Error Rate
OSI	Open Systems Interconnect
PHY	Physical Layer (protocol layer)
PL	Power Line
PLC	Power Line Carrier
PRIME	Powerline Related Intelligent Metering Evolution
RMS	Root Mean of Squares
US	United States
UUT	Unit Under Test
VAC	Voltage Alternating Current
VDC	Voltage Direct Current

4 Overview

4.1 Overview

The present document defines a set of standardized test methods for characterizing power line communications (PLC) technologies, particularly within the frequency range of 9 kHz to 500 kHz.

In a typical power line environment, many devices are connected to the AC mains. An examination of real-world AC mains environments reveals that these various devices generate a wide variety of noise, which can be classified into four categories:

- Tonal noise.
- Periodic impulse noise.
- Random impulse noise.
- Intentional communicator noise.

The present document describes tests for these four noise types, and includes a test for a noiseless environment. These test types are described in the following clauses.

These tests are based on real world noise characteristics, and represent the 95th to 99th percentile of noise levels that would be found in full-scale, real-world deployments. This 95th to 99th percentile level is more challenging than what would commonly be found in a field trial, but represents what would be encountered in a full deployment. The test measurements are designed so that they can be made by an independent testing house.

The test metrics defined for these tests measure the link budget and effective data rate for communications performance of a power line device at the physical layer (PHY layer) and at the data-link layer, as described in clause 4.2. The test setup is described in this clause, whereas clause 5 describes the waveforms for each type of noise. Clause 6 provides more information about the selection of the test parameters.

4.1.1 Unimpaired Testing

Power line communications environments with no noise impairments represent baseline conditions for defining PLC testing specifications. It is important to measure a power line device in an unimpaired environment to provide comparison measurements to help understand how noise sources impair communications.

4.1.2 Tonal Noise Testing

Tonal noise sources are extremely common on the AC mains. They are most frequently found in the form of off-line AC switch-mode power converters. The vast majority of modern electronic products use this type of power converter. Examples include personal computers, portable electronic device chargers, energy-efficient lighting devices (such as compact florescent lamps and LED lamps), consumer appliances, and solar-panel inverters. Energy at the power converter's fundamental switching frequency and its harmonics appear as conducted emissions on the AC mains.

The fundamental switching frequency for off-line switch-mode power converters is most commonly in the range of 25 kHz to 150 kHz, thus the test suite includes tonal noise tests with fundamental frequencies in this range, along with harmonic content that extends out to 500 kHz.

4.1.3 Periodic Impulse Noise Testing

Periodic impulse noise is very common on the AC mains. It can be caused by a number of devices, but one of the most common sources is a triac-controlled lamp dimmer. This type of device leaves its load disconnected from the AC mains for some fraction of each half AC cycle, and then connects the load to the mains for the remainder of that half cycle. In the case of a lamp dimmer, the in-rush of current associated with connection of the load part way through the AC cycle produces a large voltage spike on the mains at the point in time when the load is connected. This chopping of the waveform results in voltage spikes on the mains with a repetition rate of twice the AC mains power frequency.

4.1.4 Random Impulse Noise Testing

Random impulse noise is introduced onto the AC mains from a variety of sources. Series-wound AC motors are a very common source of this type of noise. These motors have brushes that arc when passing between commutator segments. The arcing produces impulses on the AC mains that are much smaller in amplitude than can be produced by periodic-impulse noise sources, but much greater in frequency.

A typical waveform for this type of noise is produced when an up-right vacuum cleaner is connected to the mains.

4.1.5 Intentional Communicator Noise Testing

In addition to noise on the AC mains from unintentional sources, there is a significant population of intentional communicators on the mains. A very common example of these types of devices is power line intercoms, or baby monitors. In large parts of the world, these devices use carrier frequencies in the range of 160 kHz to 400 kHz. Sampling a number of these devices, it is observed that they use analog frequency modulation (FM) of the carrier with modest frequency deviations.

For a power line device to operate reliably in North America (as well as a number of other countries), it is essential that the device be able to function when power line intercoms and baby monitors are active on the AC mains (note that most of these devices include a transmit-lock feature to support continuous communication between units).

Another type of intentional power line communications devices are those that comply with EN 50065-1 [5] requirements for operation in the European consumer use "C-band", they are found in both CENELEC and non-CENELEC countries.

4.2 Defining the Test Metrics

The testing methodology described in the present document defines test metrics at two layers of the seven-layer OSI computer networking model:

- Link budget and effective data rate for the physical layer (PHY layer) - called the LB_{PHY} and DR_{PKT}.
- Link budget and effective data rate for the data-link layer - called the LB_{LINK} and DR_{LINK}.

For both of these layers, the link budget test methodology defines test metrics for each of the four noise tests and the unimpaired test to measure communications performance of a power line device.

Because testing for the PHY layer and data-link layer can be performed independently, the tests results shall be reported independently:

- The LB_{PHY} metric tests the PHY layer performance. For any PLC device, it is critical that its PHY layer is designed robustly so that it can successfully pass data to data-link layer for further processing. Because the chosen physical layer and message preamble parameters affect the rate at which messages can be sent and received, an effective data rate at the individual packet level (DR_{PKT}) is defined and associated with each set of LB_{PHY} results.
- The LB_{LINK} metric tests the combination of PHY layer performance and data-link layer algorithms, which together provide power line communications. Because the chosen data-link layer algorithm impacts the rate at which messages can be sent and received successfully by the device, the DR_{LINK} result (effective data-link layer rate, specified in kbps) shall be associated with each individual LB_{LINK} result.

The primary purpose of defining standard test metrics is to allow potential end users evaluate whether a PLC device can meet their application requirements. A correlation can then be established between a test evaluation and field deployment experience, so long as the test conditions resemble realistic power mains environments.

For link-budget and data rate measurements to be useful, the test conditions shall be specified such that results are repeatable and can be verified by multiple parties. To provide for both repeatability and portability, equipment with defined calibration procedures shall be employed.

For the results to be of value to potential end users, a test suite should include realistic representations of each general type of noise that is commonly found on the AC mains. Examination of the AC mains environment reveals that the wide variety of noise sources found on the mains can be classified into four categories: tonal noise, periodic impulse noise, random impulse noise, and intentional communicators.

4.2.1 Defining the Link Budget

The link budget is a measure of how much signal attenuation (in dB) can be present between a transmitter and receiver such that a specified level of successful message delivery is achieved.

The link-budget test suite specified in the present document includes each interference category. It is the goal of this test suite to specify interference levels for each category that represent the 95th to 99th percentile level for that type. Background information for the selection of each interference source and its specified level is provided in clause 6.

The link budget for a device is first measured without any interference, and is measured again separately with each of the four classes of interference.

The link budget for each impairment is determined by measuring the message error rate (MER) between the transmitter and the receiver with various levels of attenuation between them. Message error rate is defined by the following formula:

$$MER(\%) = 100 \times \left(1 - \frac{M_r}{M_s}\right)\%$$

where: M_r = the number of messages received without error (indicated by reception of a correct CRC value)

M_s = the number of messages sent

The size of the message used for testing is specified to be 128 bytes delivered to the data-link layer of the protocol (that is, 128 bytes excluding preamble, frame control header, and error correction redundancy overhead, but including a 16-bit [or longer] CRC). The number of messages sent shall be at least 500 for each measurement of message error rate.

The resulting link budget is the greatest level of attenuation that yields ≤ 5 % MER. The link budget is measured and reported using 1 dB steps. The link budget is reported for both the PHY layer (LB_{PHY}) and data-link layer (LB_{LINK}). Physical layer link budget tests are performed without any message repeats or retries (note that in this case, the message error rate becomes a measure of packet error rate). If the unit under test supports multiple physical layer options, then the LB_{PHY} test can be performed with a variety of these options; the options used shall be documented with the DR_{PKT} associated with each set of LB_{PHY} results.

Data-link layer link budget tests (LB_{LINK}) are performed initially without any adaptation of PHY layer or MAC sub-layer parameters, but with MAC sub-layer retries enabled.

Note that for data-link layer testing, the test operator shall ensure that a correctly received unique message is counted just once. Ensuring message uniqueness is especially important to validate for protocols that, in some instances, repeat messages that might have already been correctly received as an earlier instance of the same message.

If the units under test support adaptation of PHY layer or MAC sub-layer parameters, optionally the LB_{LINK} test can be repeated allowing adaptation of these parameters. The time constants used to adapt PHY layer and MAC sub-layer parameters are typically quite long, and would therefore result in inordinately long test times if time were allowed for them to settle for each error rate measurement. While long time constants can be appropriate for field environments, to facilitate reasonable test times, devices that are tested using the present document shall provide a means for the test operator to force an update to adapt PHY layer and MAC sub-layer parameters. After the test operator initiates the adaptation update, the adaptation process shall take no longer than 10 s. The test operator shall then invoke the PHY/MAC adaptation process prior to each subsequent error rate measurement.

4.2.2 Defining the Data Rate

In general, a data rate is a measure of a number of bits received within a specified time interval. Because there is a tendency for higher data rates to provide lesser link budget performance (and for larger link budgets to provide lower data rates), each measure of link budget shall be associated with a relevant data rate value. The two values together allow a potential user to evaluate device suitability based on their own data rate and link budget requirements.

Standardized methods for reporting the effective data rate are defined in this clause for use with both LB_{PHY} and LB_{LINK} results. For use with LB_{PHY} results, the effective rate of data delivered to the data-link layer is used. This data rate is defined to be the number of bits delivered to the data-link layer of the protocol divided by a full formatted packet cycle time (including preamble, frame control header, and average inter-packet gap). This data rate is designated as the packet level data rate (DR_{PKT}). A single value for DR_{PKT} is reported for each set of physical layer parameters for which LB_{PHY} values are reported. The DR_{PKT} value can be measured or calculated, so long as all of the elements of a full formatted packet cycle are included.

A standardized method of measuring and reporting the data rate associated with LB_{LINK} results is also defined (DR_{LINK}). DR_{LINK} is defined to be the number messages (where all bytes delivered to the link layer are correct), multiplied by the number of bits delivered to the link layer for each correct message, divided by the time it takes for a 500-message test to be completed. This data rate test is performed first for the unimpaired case, and then performed again with each of the same impairments specified for link-budget testing. A data rate measurement shall be performed at the maximum attenuation (using 1 dB steps) that results in ≤ 5 % MER for each particular impairment.

Initially, tests should be performed without any adaptation of either PHY layer or MAC sub-layer parameters, although message retries at the MAC sub-layer are allowed.

If the units under test support adaptation of PHY layer or MAC sub-layer parameters, then optionally the test can be repeated using PHY/MAC adaptation. Adaptation time constants are generally quite long, and would result in inordinately long test times if time were allowed for adaptation with each error rate measurement. While longer adaptation time constants are generally appropriate for field environments, in order to facilitate timely testing of devices tested under the present document, a means for the test operator to force an adaptation update shall be provided. The adaptation process shall take no longer than 10 s once initiated. The test operator shall then invoke the adaptation process prior to each data rate measurement.

The size of the message used for testing is specified to be 128 bytes delivered to the link layer of the protocol (that is, 128 bytes excluding preamble, frame control header, and error correction redundancy overhead, but including a 16-bit [or longer] CRC). The number of messages sent shall be 500 for each measurement of the data rate.

The resulting data link-layer data rate is:

$$DR_{LINK} = \frac{M_r \times 128 \times 8}{t_{500}}$$

where: M_r = the number of messages received without error (indicated by reception of a correct CRC value).

128 = number of bytes delivered to the link layer of the protocol.

8 = number of bits per byte.

t_{500} = time required to send all 500 messages, in seconds.

It shall be ensured that a correctly received unique message is counted just once in the numerator. Ensuring message uniqueness is especially important to validate for protocols that, in some instances, repeat messages that might have already been correctly received as an earlier instance of the same message.

4.2.3 Reporting Test Results

For production devices, link-budget and data rate test results are only meaningful if the units being tested comply with relevant regional emissions regulations. Thus, conducted emissions testing shall be performed on all devices under test in accordance with the appropriate standards, and the results shall be documented together with the link-budget and data rate performance results.

Because support for multiple PHY/MAC solutions is envisioned along with their associated profiles (such as IEEE P1901.2 [i.2] FCC, G3 CENELEC A, PRIME CENELEC A, ETSI TS 103 908 [i.1] and ISO/IEC 14908-3 [7]), with a variety of modulation and error correction options (for example, differential quadrature phase shift keying [DQPSK] modulation, differential binary phase shift keying [DBPSK] modulation, Robo modulation, and so on), it is necessary that a link budget report include the profile and options that were used for testing. The associated data rates (as defined in clauses 4.2.1 and 4.2.2) shall also be documented.

Tables 1 and 2 show how the test results shall be reported. The information for every row shall be listed when reporting results (that is, it is not acceptable to omit the information from any row when reporting results). For this example table, "*Test Result*" is a placeholder for the actual results. Various profiles can be tested and reported, based on the target application, by adding or deleting "Result" columns. If the data rate tests include adaptation, the results shall report separately, as shown in table 4.

Table 1: Example Test Results for the PHY Layer

Parameter	Result 1	Result 2	Result 3	Units
Profile	FCC	G3-A	G3-A	-
Conducted emission verification	FCC	EN50065	EN50065	-
Physical layer mode	*DBPSK*	*DBPSK*	*Robo*	-
Packet level data rate (DR_{PKT})	*Test Result*	*Test Result*	*Test Result*	kbps
Unimpaired link budget	*Test Result*	*Test Result*	*Test Result*	dB
Tonal noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Periodic impulse noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Random impulse noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Intentional communicator link budget	*Test Result*	*Test Result*	*Test Result*	dB
Composite Link Budget (LB_{PHY})	*Test Result*	*Test Result*	*Test Result*	dB

Table 2: Example Test Results for the Data-Link Layer (without Adaptation)

Parameter	Result 1	Result 2	Result 3	Units
Profile	FCC	G3-A	G3-A	-
PHY/MAC adaptation	No	No	No	-
Conducted emission verification	FCC	EN50065	EN50065	-
Physical layer mode	*DBPSK*	*DBPSK*	*Robo*	-
LINK BUDGET TESTING				
Unimpaired link budget	*Test Result*	*Test Result*	*Test Result*	dB
Tonal noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Periodic impulse noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Random impulse noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Intentional communicator link budget	*Test Result*	*Test Result*	*Test Result*	dB
Composite Link Budget (LB_{LINK})	*Test Result*	*Test Result*	*Test Result*	dB
DATA RATE TESTING				
Unimpaired data rate	*Test Result*	*Test Result*	*Test Result*	bps
Tonal noise data rate	*Test Result*	*Test Result*	*Test Result*	bps
Periodic impulse noise data rate	*Test Result*	*Test Result*	*Test Result*	bps
Random impulse noise data rate	*Test Result*	*Test Result*	*Test Result*	bps
Intentional communicator data rate	*Test Result*	*Test Result*	*Test Result*	bps
Composite Data Rate (DR_{LINK})	*Test Result*	*Test Result*	*Test Result*	bps

Table 3: Example Test Results for the Data-Link Layer (with Adaptation)

Parameter	Result 1	Result 2	Result 3	Units
Profile	FCC	G3-A	G3-A	-
PHY/MAC adaptation	Yes	Yes	Yes	-
Conducted emission verification	FCC	EN50065	EN50065	-
Physical layer mode	*DBPSK*	*DBPSK*	*Robo*	-
LINK BUDGET TESTING				
Unimpaired link budget	*Test Result*	*Test Result*	*Test Result*	dB
Tonal noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Periodic impulse noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Random impulse noise link budget	*Test Result*	*Test Result*	*Test Result*	dB
Intentional communicator link budget	*Test Result*	*Test Result*	*Test Result*	dB
Composite Link Budget (LB_{LINK})	*Test Result*	*Test Result*	*Test Result*	dB
DATA RATE TESTING				
Unimpaired data rate	*Test Result*	*Test Result*	*Test Result*	bps
Tonal noise data rate	*Test Result*	*Test Result*	*Test Result*	bps
Periodic impulse noise data rate	*Test Result*	*Test Result*	*Test Result*	bps
Random impulse noise data rate	*Test Result*	*Test Result*	*Test Result*	bps
Intentional communicator data rate	*Test Result*	*Test Result*	*Test Result*	bps
Composite Data Rate (DR_{LINK})	*Test Result*	*Test Result*	*Test Result*	bps

4.3 Test Setup

The test setup for measuring the power line communications link budget and data rate is shown in figure 1. The test setup uses industry-standard equipment that is widely available, can be easily maintained, and easily calibrated. Table 4 lists the components for the test setup shown in figure 1.

Note that an additional filter stage (L2, L3, C5, and C6) has been added in front of each V-Network; see figure 2 for a detailed view of the filter circuit. This filter:

- Ensures that noise from the AC mains is sufficiently attenuated so that it does not degrade the measurement environment.
- Ensures that there is sufficient signal attenuation (from the transmitter, through the V-Network, through the other V-Network, to the Receiver Under Test) so that the attenuation between the Transmitter and Receiver is determined solely by VR1.

See figure 3 for a detailed view of the 450 Ω adaptor. See figure 4 for a detailed view of the specified V-Network.

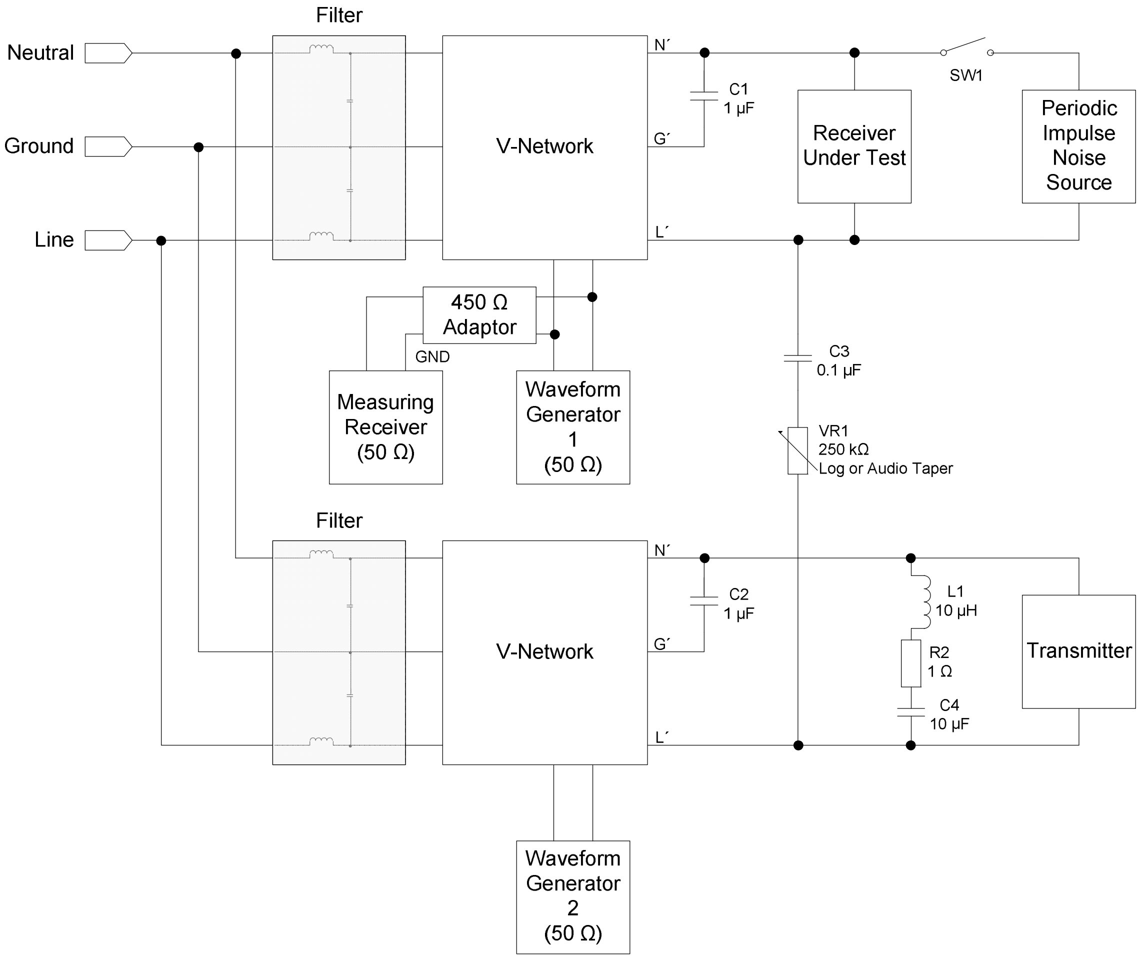

Figure 1: Test Setup for Measuring PLC Link Budget and Data Rate

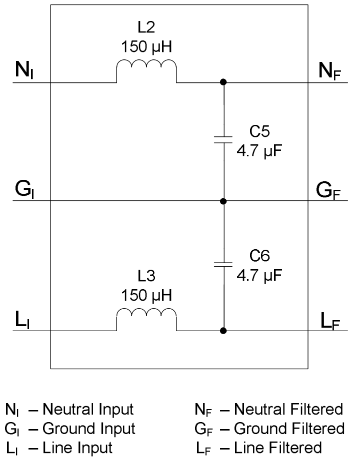

Figure 2: Filter Circuit

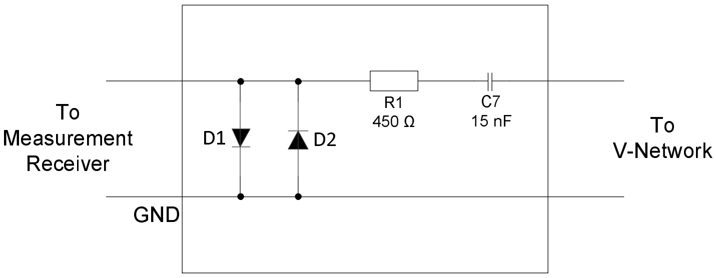

Figure 3: 450 Ω Adaptor Circuit

Table 4: Component Specifications for Test Setup

Component	Specification
V-Network	50 Ω || (50 µH + 5 Ω) network See CISPR 16-1-1 [3] for complete specification
Waveform Generator 1	Arbitrary waveform generator Output impedance 50 Ω, maximum output 10 V_{p-p} into 50 Ω, vertical resolution ≥ 14 bits, memory depth ≥ 65 536 points, output sample rate ≥ 10 MHz and support for frequency modulation See also figure 5 for waveform purity requirements
Waveform Generator 2	Function generator Output impedance 50 Ω, maximum output 10 V_{p-p} into 50 Ω. Capable of being locked to an external frequency reference
Measuring Receiver	Spectrum analyzer Minimum frequency ≤ 25 kHz, maximum frequency ≥ 500 kHz, input impedance 50 Ω, minimum resolution bandwidth ≤ 3 Hz. Capable of being locked to an external frequency reference
VR1	250 kΩ, logarithmic (or audio) taper, ≥ 1 W power rating, < 3 pF shunt capacitance You can substitute alternate variable resistor values to provide either finer resolution at low attenuations or greater overall attenuation
R1	450 Ω, 2 % tolerance
R2	1 Ω, 1 % tolerance, ≥ 3 W power rating
C1, C2	1 µF, ≤ 20 % tolerance, X2 rated for ≥ 250 VAC
C3	0,1 µF, ≤ 20 % tolerance, X2 rated for ≥ 250 VAC
C4	10 µF, ≤ 20 % tolerance, X2 rated for ≥ 250 VAC
C5, C6	4,7 µF, ≤ 20 % tolerance, X2 rated for ≥ 250 VAC
C7	15 nF, ≤ 10 % tolerance, ≥ 50 VDC
D1, D2	1N4148
L1	10 µH, ≤ 10 % tolerance with up to 1 ADC, DCR ≤ 0,05 Ω
L2, L3	150 µH nominal (between 100 µH and 200 µH with 0 to 5 ADC), DCR ≤ 0,1 Ω

The test setup establishes a controlled AC mains environment by using a pair of standardized artificial mains V-Networks, as defined in international standard CISPR 16-1-1 [3]. Between the AC mains and the V-Networks, the test setup includes additional filters which, in conjunction with the V-Networks, provide two isolated mains branches:

- one for a transmitter; and
- one for a receiver under test.

A variable resistor and series capacitor coupled between the transmitter and receiver under test provides a controlled value of attenuation between the transmitting and receiving branches.

The 1 µF capacitors added between the neutral and ground terminals of each of the two V-Networks facilitate the use of single-ended instruments and single-ended attenuation coupling between branches.

Injection of controlled interference is provided by loading impairment waveforms into the 50 Ω waveform generator 1. A 50 Ω measuring receiver is also connected to this port through a 450 Ω adaptor. This combination provides measurement access, while substantially preserving the 50 Ω termination impedance at this port. Note that the 450 Ω adaptor, in conjunction with the 50 Ω input impedance of the measuring receiver, introduces a 10:1 divider relative to the voltage on the V-Network port. This 10:1 voltage division (20 dB of attenuation) shall be compensated for when reporting results observed using the measuring receiver.

Because the amplitude of periodic impulse noise on the AC mains frequently exceeds that which can be provided by standard waveform generators, a separate circuit is included to provide for this type of impairment. Specifications for this source are described in clause 5.1. Switch SW1 (in figure 1) is set to the closed position only when performing tests with the periodic impulse noise source.

Important: Each of the artificial mains networks shall comply with the specifications for a 50 Ω || (50 µH + 5 Ω) network, as specified in CISPR 16-1-1 [3]. Figure 4 shows a more detailed view for the specified V-Network.

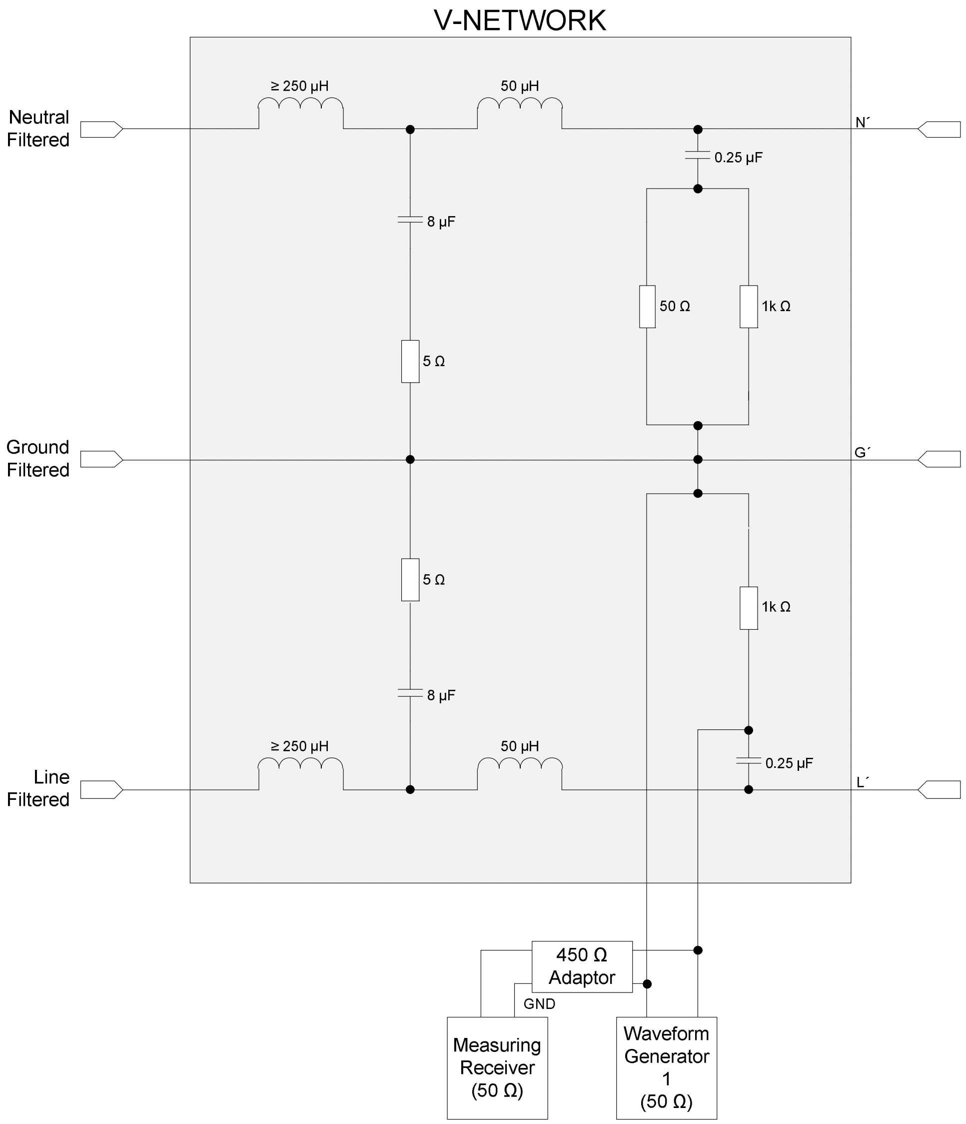

Figure 4: The V-Network

See clause 7 for a procedure that shall be used to verify that the test setup has appropriate attenuation characteristics.

From a statistical perspective, a 50 Ω || (50 µH + 5 Ω) impedance is on the higher end of the distribution curve for impedances typically found on the AC mains. Using the higher end of the distribution is appropriate when evaluating noise levels, but it is more appropriate to look to the lower end of the statistical distribution when selecting an impedance that a transmitting device shall drive. It is the goal of this test method to set the impedance that the transmitter shall drive to a value that represents the 5th percentile of impedance values encountered on the AC mains. Initial data suggests that lowering the impedance of the transmit branch mains by a factor of 5 accomplishes this goal. The impedance of the transmit branch is lowered by the addition of a series-connected inductor, capacitor, and resistor between line and neutral terminals of the transmit branch V-Network's output port, as indicated in figure 1.

4.4 Calibrating the Attenuation

To overcome issues with measuring high levels of attenuation when using a modulated power line signaling waveform, the test setup uses a second waveform source, waveform generator 2, for attenuation measurement. The value of attenuation can be calibrated by setting 20 dB of attenuation using a transmitted waveform from the transmitter, and then measuring the attenuation indicated between waveform generator 2 and the measuring receiver. Subsequent attenuation measurements shall be made using waveform generator 2, the measuring receiver, and the calibration value. To determine the calibration value, perform the following tasks:

1) Set the coupling resistor VR1 to its maximum value and substitute an oscilloscope with a 50 Ω input termination in place of the waveform generator 2. Using the oscilloscope, measure the RMS voltage of a message produced by the transmitter over the full duration of the message.

2) Move the oscilloscope with 50 ohm input termination, substituting it in place of the measuring receiver. Restore waveform generator 2 to its original location, as shown in figure 1. Adjust the variable resistor **VR1** until the RMS voltage measured on the oscilloscope (over a complete message identical to that from step 1) is one one-hundredth of the value measured in step 1. Note that waveform generators 1 and 2 shall be in benign states that preserve their 50 Ω input impedances (such as, set to produce 100 Hz $\leq$ 50 mV_{PP} sine waves).

3) Halt transmissions from the transmitter and restore the test setup to that shown in figure 1 (with the oscilloscope removed and measuring receiver connected as shown in the figure). Set waveform generator 2 to produce a continuous 88,5 kHz, 10 V peak-to-peak sine wave - if it were driving a 50 Ω resistive load. The level of the 88,5 kHz sine wave observed on the measuring receiver (in dBV) is the calibration value corresponding to 20 dB of attenuation between the transmitter and receiver under test.

This calibration value is designated as V_{20dB}, and other values of attenuation are determined from this reference point. The resolution bandwidth of the measuring receiver shall be $\leq$ 3 Hz, and shall be the same value for both this measurement and for all subsequent attenuation measurements. If a spectrum analyzer is used as the measuring receiver, then a center frequency of 88,5 kHz and zero frequency span can be selected to avoid waiting for long sweep times.

Waveform generator 2 and the measuring receiver shall be locked to a common reference frequency to guarantee that the tone from waveform generator 2 is within the narrow bandwidth of the measuring receiver (many waveform generators and measuring receivers support the use of external frequency references).

4.5 Measuring the Attenuation

To measure attenuation between the transmitter and receiver under test:

- Inject a tone with waveform generator 2.
- Measure the level of the tone at the measuring receiver.
- Adjust for the calibration value determined in clause 4.4. The transmitter shall not be transmitting while measuring attenuation.

With waveform generator 2 set to produce an 88,5 kHz sine wave and with its amplitude set to 10 V peak-to-peak, record the level of that sine wave at the measuring receiver. This value is designated V_{MdB}. The attenuation between the transmitter and receiver is then given by the following formula:

$$\text{Attenuation (dB)} = 20 - (V_{MdB} - V_{20dB})$$

You can then adjust the variable resistor connected between the two branches until a desired level of attenuation is achieved.

4.6 Measuring Link Budgets and Data Rates

The following clauses define PLC link budgets and data rates in the presence of various noise sources. Clause 5 describes the specifications for each of the noise source types. Clause 6 describes the background for defining each of the noise waveform specifications.

4.6.1 Unimpaired Measurement

The unimpaired link budget or data rate between a transmitter and receiver shall be measured using the test setup of figure 1, with no impairment present. For this test, set waveform generator 1 such that its 50 Ω source impedance is still present but such that it otherwise introduces no impairment to communication. Set waveform generator 1 to produce a sine wave:

$$100 \text{ Hz} \leq 50 \text{ mV}_{pp}.$$

Measure the message error rate with the variable resistor set to zero ohms. Then measure the highest level of attenuation that results in ≤ 5 % MER, when measured in 1 dB steps.

The unimpaired link budget is defined as the greatest level of attenuation that results in ≤ 5 % MER when measured with 1 dB steps - unless the measured MER with the variable resistor set to zero ohms results in > 5 % MER, in which case the unimpaired link budget is defined to be 0 dB.

The unimpaired data-link layer data rate is defined as DR_{LINK} at the maximum attenuation (using 1 dB steps) that results in ≤ 5 % MER.

4.6.2 Tonal Noise Measurement

To establish the link budget or data rate between a transmitter and receiver in the presence of tonal noise, the link budget or data rate with each of 25 specified tonal noise waveforms that span a range of interfering fundamental frequencies with harmonics included shall be measured. The final tonal-noise link budget or data rate is then defined to be a statistical combination of the 25 individual measurements.

The individual link budget or data rate values with the test setup of figure 1 shall be measured, using each of the 25 tonal waveforms specified in clause 5.1 in turn. For each test, one of the 25 waveforms is reproduced by waveform generator 1 (see clause 5.1).

The individual tonal link budget values are defined to be the greatest level of attenuation that results in ≤ 5 % MER, measured and reported using 1 dB steps for each of the 25 specified tone waveforms.

The tonal noise data link-layer data rate is defined as DR_{LINK} at the maximum attenuation (using 1 dB steps) that results in ≤ 5 % MER, measured and reported for each of the 25 specified tone waveforms.

To determine a composite tonal noise result, calculate the average of the 25 individually measured link budget or data rates values. To provide added statistical weight to the most challenged result, while also considering the average, the overall tonal noise link budget or data rate is specified to be the lowest of the 25 individually measured link budget or data rate values, averaged with the previously calculated overall average, giving equal weight to those two figures.

4.6.3 Periodic Impulse Noise Measurement

The periodic impulse noise link budget or data rate between a transmitter and receiver shall be measured with switch SW1 of figure 1 closed and with no impairment from waveform generator 1. For waveform generator 1 to preserve its 50 Ω terminal impedance without adding any impairment to the receive branch, set it to produce a 100 Hz sine wave of $\leq 50 \text{ mV}_{pp}$. See clause 5.2 for detailed specifications for the impairment waveform produced by the periodic impulse noise source.

The periodic impulse noise link budget is defined as the greatest level of attenuation that results in ≤ 5 % MER measured and reported using 1 dB steps.

The periodic impulse noise data-link layer data rate is defined as DR_{LINK} at the maximum attenuation (using 1 dB steps) that results in ≤ 5 % MER.

4.6.4 Random Impulse Noise Measurement

The link budget or data rate between a transmitter and receiver shall be measured using the test setup of figure 1 while waveform generator 1 produces the random impulse noise waveform specified in clause 5.3.

The random impulse noise link budget is defined as the greatest level of attenuation that results in ≤ 5 % MER measured and reported using 1 dB steps.

The random impulse noise data-link layer data rate is defined as DR_{LINK} at the maximum attenuation (using 1 dB steps) that results in ≤ 5 % MER.

4.6.5 Intentional Communicator Measurement

The intentional communicator link budgets or data rates between a transmitter and receiver shall be measured using the test setup of figure 1. This test is performed with several different impairment waveforms loaded into waveform generator 1, as specified in clause 5.4.

The individual intentional communicator link budget values are the greatest level of attenuation that results in ≤ 5 % MER measured and reported using 1 dB steps for each of the waveforms that are specified.

The intentional communicator data-link layer data rate is defined as DR_{LINK} in the presence of ≤ 5 % MER, measured and reported for each of the waveforms that are specified.

For modes of devices under test that use frequencies outside the range from 125 through 140 kHz for communications, the overall intentional communicator link budget or data rate is defined to be the smallest of the four individual intentional link budget values.

For modes of devices under test that use frequencies within the range from 125 through 140 kHz for communications, the overall intentional communicator link budget or data rate is defined to be the smallest of the three individual intentional communicator link budget or data rate values, without including the ISO/IEC 14908-3 [7] result. The reason that the ISO/IEC 14908-3 [7] waveform is not included when evaluating a device that uses the 125 through 140 kHz range for communication is that separate coexistence tests are defined in other standards (for example, EN 50065-1 [5] and other pending coexistence standards) to address operation in this case.

4.7 Composite Measurement Values

The composite link-budget or data-rate measurement for a unit under test (UUT) is defined to be the average of the five individual measurement values:

- Unimpaired measurement.
- Tonal noise measurement.
- Periodic impulse noise measurement.
- Random impulse noise measurement.
- Intentional communicator measurement.

Because the noise present at a receiver on an AC mains connection is commonly dominated by the noise source that is closest to that receiver, the composite measurement averages the measurement results from each of the noise classes. For instances on the AC mains where a particular noise source is not close to a receiving device, a background noise floor is set by the totality of more distant noise sources. This background noise sets a limit on the practical usefulness of very high unimpaired measurement figures. To avoid unrealistically skewing the composite measurement in the case where a UUT provides an exceptionally high unimpaired link budget value, the unimpaired link budget is capped at 80 dB for the purpose of determining the composite link budge. In other words, if a device exhibits an unimpaired link budget of 84 dB, then a value of 80 dB (rather than 84 dB) would be averaged with the other four test results to determine the composite link budget value.

For a device to function in the field, it shall at least be able to communicate with a neighboring device so that its signal can be repeated until the target device receives the message. The median attenuation per 100 meters of AC mains distribution wiring has been measured to be approximately 40 dB, when including both overhead and underground distribution wiring. The corresponding the 95th percentile value has been found to be approximately 65 dB.

4.7.1 Composite Link Budget

A device should have a composite link budget high enough to ensure reliable power line communications (in at least one of its operating modes).

Higher values of composite link budget might be of value to an end user to the extent that they lower the cost of installation and operation (for example, requiring fewer service visits to the field to analyze and resolve communication issues).

4.7.2 Composite Data Rate

A device should have a data rate that matches the users' data communications requirements. Unlike the composite link-budget value, which measures communication reliability between devices, a data-link layer data rate value represents the link-layer throughput that the units under test can support.

5 Noise Waveform Specifications

This clause describes the waveform specifications for the tonal, periodic impulse, random impulse, and intentional communicator waveforms.

5.1 Tonal Noise Waveform Specifications

This clause describes the specifications for the frequency and amplitude each of the 25 tonal noise waveforms. See clause 6.1 for background information about the selection of these particular waveforms.

For each waveform, table 5 lists the frequency, amplitude, and modulation settings for waveform generator. The values for the amplitude setting in the table are the peak-to-peak amplitudes that the generator would produce if it were driving a 50 Ω load (the fact that the V-Network load that it is driving is not 50 Ωs has already been compensated for when developing the specifications for each waveform).

See annex A, for a list of the samples for one full cycle of each waveform. Note that the number of samples provided in annex A for each waveform has been selected such that the sample rate falls between 5 MHz and 10 MHz (that is, the sample rate is at least 10 times greater than the highest harmonic component of each waveform).

The values listed in annex A are normalized to a maximum value of +1,0 and a minimum value of -1,0. This common format is accepted by a number of arbitrary waveform generators. If the generator in use does not accept this normalized format, you may have to convert the listed values to a different format (see the operator's manual for the particular generator). To check that the waveform is properly loaded into the generator, and that the amplitude is properly set, measure that the peak-to-peak amplitude when the generator is driving a 50 Ω resistive load, and verify that it matches the peak-to-peak voltages listed in table 5.

Table 5: Amplitude Settings for Each Frequency Setting

Frequency Setting (kHz)	Amplitude Setting (mVp-p)	FM Peak Deviation (kHz)	FM Rate (Hz)
26	710	1	100
31	506	1	100
36	378	1	100
41	297	1	100
46	238	1	100
51	195	1	100
56	164	1	100
61	142	1	100
66	121	1	100
71	107	1	100
76	94,4	1	100
81	84,9	1	100
86	74,2	1	100
91	68,0	1	100
96	62,4	1	100
101	56,0	1	100
106	51,9	1	100
111	48,3	1	100
116	45,2	1	100
121	42,4	1	100
126	37,5	1	100
131	35,3	1	100
136	33,4	1	100
141	31,6	1	100
146	30,1	1	100

5.2 Periodic Impulse Noise Waveform Specifications

The waveform specified for this test is defined by:

$$V_{impulse} = A\sin(2\pi ft)e^{-bt} \qquad \text{for } t \geq 0$$

$$V_{impulse} = 0 \qquad \text{for } t < 0$$

where: $A = 42$ V

$f = 190$ kHz

$b = 3{,}3 \times 10^5$

This waveform is specified to occur once each half cycle of the AC mains power frequency, with an arbitrary phase offset from the zero crossing point. The polarity of this waveform is inverted for each successive occurrence. The waveform can be generated with a commercially available triac-controlled lamp dimmer set to an appropriate phase and driving a 100 Watt incandescent lamp. See clause 6.2 for background information about the selection of this waveform.

Compliance to the defined waveform requires that the following values measured by connecting an oscilloscope with a 50 Ω input impedance in place of waveform generator 1 in figure 1.

The amplitude of the initial peak shall be within 10 % of the defined waveform. The difference in amplitude between the first and second peaks of the measured waveform shall be within 20 % of the defined waveform. The difference in amplitude between the second and third peaks of the measured waveform shall also be within 20 % of the defined waveform. The time from the first peak to the third peak shall be within 25 % of the defined waveform.

For convenience, these specifications are listed in table 6.

Table 6: Amplitude Measurements for Each Peak

Measurement	Minimum	Nominal	Maximum
Peak #1	25,4 V	28,2 V	31,0 V
Delta peak #1 to peak #2	32,1 V	40,1 V	48,1 V
Delta peak #2 to peak #3	13,4 V	16,8 V	20,2 V
Time from peak #1 to peak #3	4,0 µs	5,3 µs	6,6 µs

If a particular selected triac controlled lamp dimmer does not meet these specifications, either select a different dimmer or adjust the value of the capacitor that forms the L-C filter in the dimmer to bring the waveform into compliance.

5.3 Random Impulse Noise Waveform Specifications

This clause describes the specifications for the random impulse noise waveform. See clause 6.3 for background information about the selection of this waveform.

For this waveform, set the frequency of the waveform generator to 120 Hz, and set the amplitude for the generator to 4,4 V_{p-p}.

See annex B for a list of samples points for one half AC mains cycle of the waveform, normalized to a maximum value of +1,0 and a minimum value of -1,0. If your generator does not accept this normalized format, you might have to convert the listed values to a different format (see the operator's manual for the particular generator).

To check that the amplitude is properly set, measure the peak-to-peak amplitude when the generator is driving a 50 Ω resistive load and check that it is 4,4 V_{p-p}.

The sample rate used for this waveform is 1 MHz. This rate results in the 8 333 specified samples covering the duration of one half of a 60 Hz AC cycle. When playing this waveform back, it shall be played twice through for each AC mains cycle (that is, at a frequency of 120 Hz). Note also that there is no significant difference in what would appear on the AC mains between using this waveform played at a 120 Hz rate compared with playing 10 000 samples at a 100 Hz rate. Thus. playing the specified waveform at 120 Hz is an equally valid test of random impulse noise for both 50 Hz and 60 Hz mains environments.

5.4 Intentional Communicator Waveform Specifications

Three power line intercom/baby monitor waveforms and a standards-based intentional communicator are specified as impairments for intentional communicators. The three intercom/baby monitor waveforms represent the range of carrier frequencies used for these types of devices. See clause 6.4 for background information about the selection of these waveforms.

For the first intercom/baby monitor waveform, set the frequency of waveform generator 1 kHz to 160 kHz and set the amplitude of the generator to 3,7 V_{p-p}.

For the second waveform, set the frequency of waveform generator 1 kHz to 250 kHz and set the amplitude of the generator to 3,1 V_{p-p}.

For the third waveform, set the frequency of waveform generator 1 kHz to 400 kHz and set the amplitude of the generator to 2,8 V_{p-p}.

The generator amplitude settings specified are the peak-to-peak amplitudes that the generator would produce if it were driving a 50 Ω load (the fact that the V-Network load is not 50 Ωs has already been compensated for when developing the specifications for each waveform). For all three of these waveforms, the waveform generator shall have FM modulation activated at a rate of 1 kHz with a peak frequency deviation of 5 kHz.

The specified waveform for an international-standards-based intentional communicator represents a complete ISO/IEC 14908-3 [7] packet and inter-packet gap totalling 52,4 ms in duration. The sample rate for this waveform is 1,25 MHz, resulting in 65 536 samples for the full 52,4 ms record. Due to the size of this file, it is provided as a separate text file (14908-3_pkt_R1.txt) contained in archive ts_103909v010101p0.zip which accompanies the present document rather than being included in the present document. To play this waveform at the proper rate, set waveform generator 1 to a frequency of 19,07348 Hz and set the amplitude for waveform generator 1 while playing this waveform to 5,5 V_{p-p}.

So that the ISO/IEC 14908-3 [7] link budget or data rate test result is not constrained by the noise floor of the waveform generator, the spurious responses and noise floor of the generator shall be verified to meet both of the following criteria:

- At least 65 dB below the ISO/IEC 14908-3 [7] carrier from 30 kHz to 95 kHz.
- At least 60 dB below the ISO/IEC 14908-3 [7] carrier from 150 kHz to 500 kHz.

Figure 5 shows a spectral plot of the specified ISO/IEC 14908-3 [7] waveform when played from a 14-bit arbitrary waveform generator of a major test equipment supplier that meets this requirement.

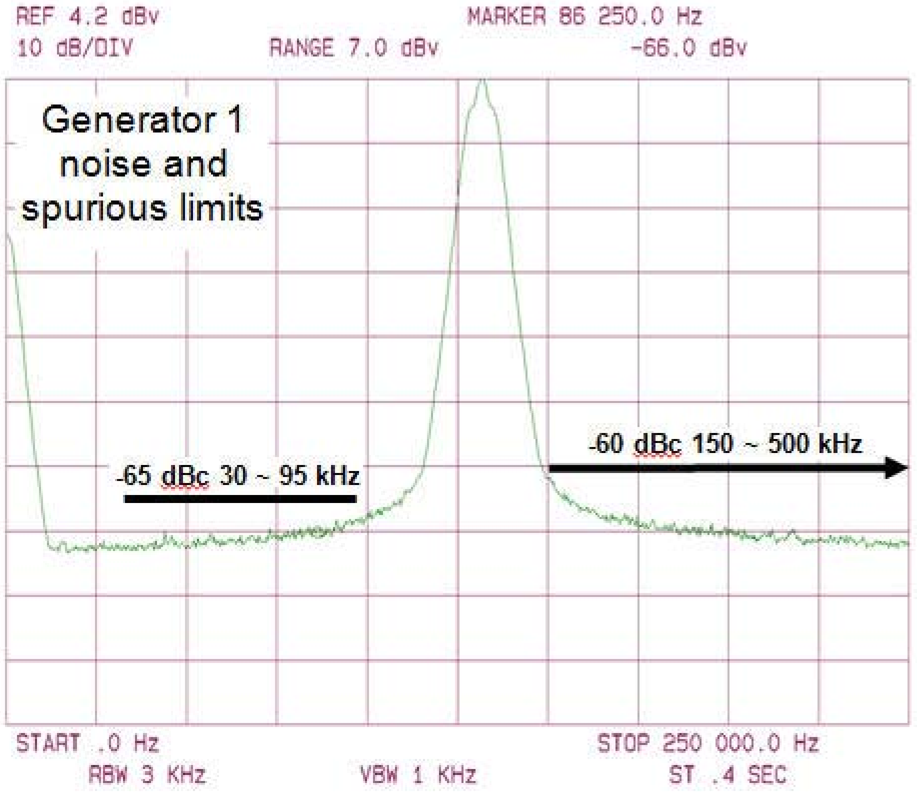

Figure 5: Spectral Plot for Waveform Generator Measurement

6 Defining the Test Parameters

This clause describes the test parameters for the tonal, periodic impulse, random impulse, and intentional communicator waveforms. This clause provides background information to explain how the waveform specifications described in clause 5 were derived.

6.1 Defining Tonal Noise

Tonal noise sources are extremely common on the AC mains. They are most frequently found in the form of off-line AC switch-mode power converters. The vast majority of modern electronic products use this type of power converter. Examples include personal computers, portable electronic device chargers, energy-efficient lighting devices (such as compact florescent lamps and LED lamps), consumer appliances, and solar-panel inverters. Energy at the power converter's fundamental switching frequency and its harmonics appear as conducted emissions on the AC mains.

The fundamental switching frequency for off-line switch-mode power converters is most commonly in the range of 25 kHz to 150 kHz. Higher switching frequencies are generally avoided in off-line converters because the high voltages associated with off-line conversion tend to result in excessive switching losses at higher frequencies. Lower frequencies are generally avoided because magnetic elements within the converter tend to be larger in size and have higher magnetic power loss at lower frequencies. For these reasons, a measure of a communication link budget or data rate with tonal noise includes a variety of tonal noise sources with fundamental frequencies in the range from 25 kHz to 150 kHz.

Conducted emissions from off-line power converters are commonly rich in both even and odd harmonics of the fundamental; however, on average, the amplitude of the harmonics tends to fall with increasing frequency. Due to the rich harmonic content of these impairments, a measurement of communication link budget or data rate with tonal noise should include all odd and even harmonics up to 500 kHz. This range encompasses the bandwidth of all devices for which the test methodology described in the present document applies.

Considering the need to have enough test waveforms that represent the range of common tonal noise, while also considering the practicality of performing these tests, 25 waveforms (in 5 kHz increments) with fundamental frequencies from 26 kHz through 146 kHz were selected. Starting with a fundamental frequency that is not on an integer multiple of 5 kHz increases the overall frequency coverage when harmonics are also considered.

It is the goal of this test to select tonal interference amplitudes that correspond to the 95th to 99th percentile range of noise that will be encountered on the AC mains. Most countries currently have regulations in place that set legal limits on emissions above 150 kHz while allowing higher levels of emissions below 150 kHz.

In most countries, emission limits in place above 150 kHz coincide with the limits stated in the international standard CISPR 22 [4]. This CISPR standard includes two classes of limits:

- Class B limits apply to equipment that is intended for use in domestic environments.
- Class A limits apply to other equipment that is not restricted in its sale, but includes a warning that in a domestic environment it may cause radio interference.

Figure 6 shows those limits, up to the relevant frequency range for PL performance testing.

It is worth noting that while CISPR 22 [4] applies to Information Technology Equipment, the limits established in CISPR 15 [2] above 150 kHz for Electrical Lighting Equipment match the CISPR 22 [4] Class B limits. Similarly, the limits established for Industrial Scientific and Medical Equipment in CISPR 11 [1] match those of CISPR 22 [4] for both Class A and class B devices.

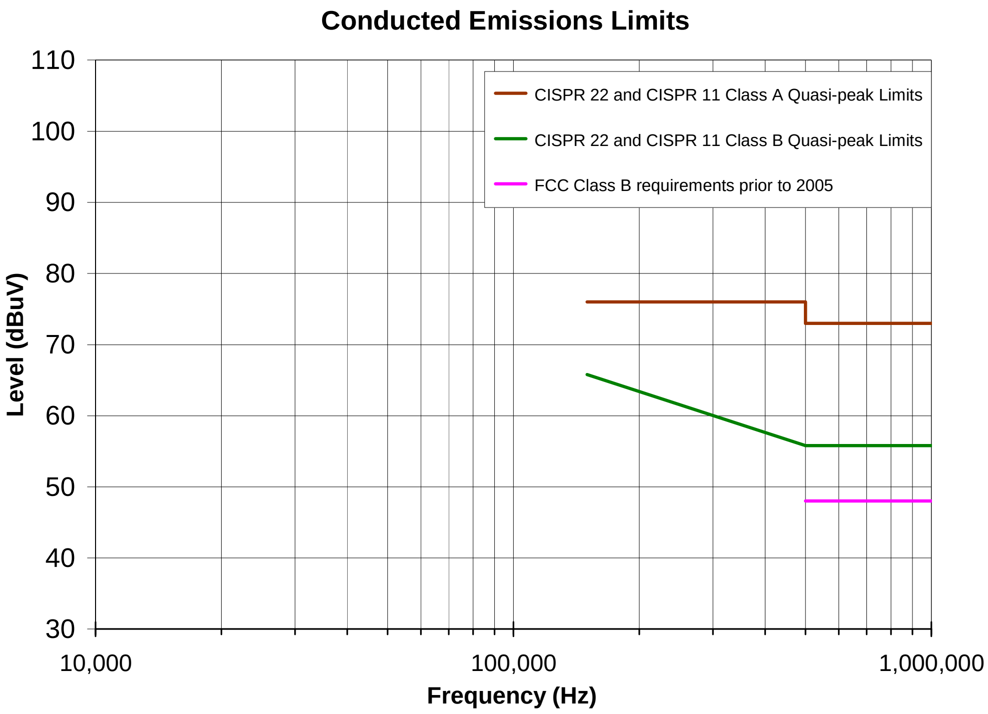

Figure 6: Conducted Emissions Limits

Unfortunately, the presence of devices on the mains that exceed the CISPR 22 [4] Class B limits are commonly observed on residential mains. In some cases, these higher levels are the result of older devices that were sold prior to the limits being established below 450 kHz. For example, prior to 11 July 2005, devices marketed and sold in the United States did not have a required limit below 450 kHz (FCC Part 15.107 [6] was amended 10 July 2002 to adopt CISPR 22 [4] limits, but that rule change allowed devices to be sold under the old rules through 10 July 2005). Considering that there were several hundred million devices sold prior to 2005 that employ off-line switch-mode power supplies, it is not surprising that it is common to encounter higher emissions below 450 kHz. The conducted emissions requirements in the United States prior to 2005 are shown in figure 6 for reference.

Another reason for higher than expected noise levels encountered on US domestic mains is the presence of Class A devices. These higher noise levels can be due to commercial devices installed outside residences (for example, well or sewage pump motors), or due to Class A devices that that have been brought into the home. It also shall be acknowledged that some devices being sold do not meet current emissions regulations. The existence of some percentage of non-compliant devices is a reality that shall be accounted for when determining a 95th to 99th percentile noise level.

The discussion has so far focused on regulatory limits for conducted emissions above 150 kHz. At frequencies below 150 kHz, CISPR 22 [4] and CISPR 11 [1] have no specified emissions limits. The lighting equipment standard, CISPR 15 [2], specifies a limit on conducted emissions in the range of 50 kHz to 150 kHz which follows the same slope as the CISPR 22 [4] higher frequency limit, but with a 14 dB offset. This CISPR 15 [2] limit has been added to figure 7.

Combining the above information with the observation that tonal interference decreases with increasing frequency, the amplitude of 95th to 99th percentile tonal noise can be estimated. This estimated 95th to 99th percentile noise level is shown in figure 7 with a red line. The levels for the fundamental and harmonic frequencies specified in the tonal noise tests of the present document correspond to the red estimated 95th to 99th percentile line of the figure.

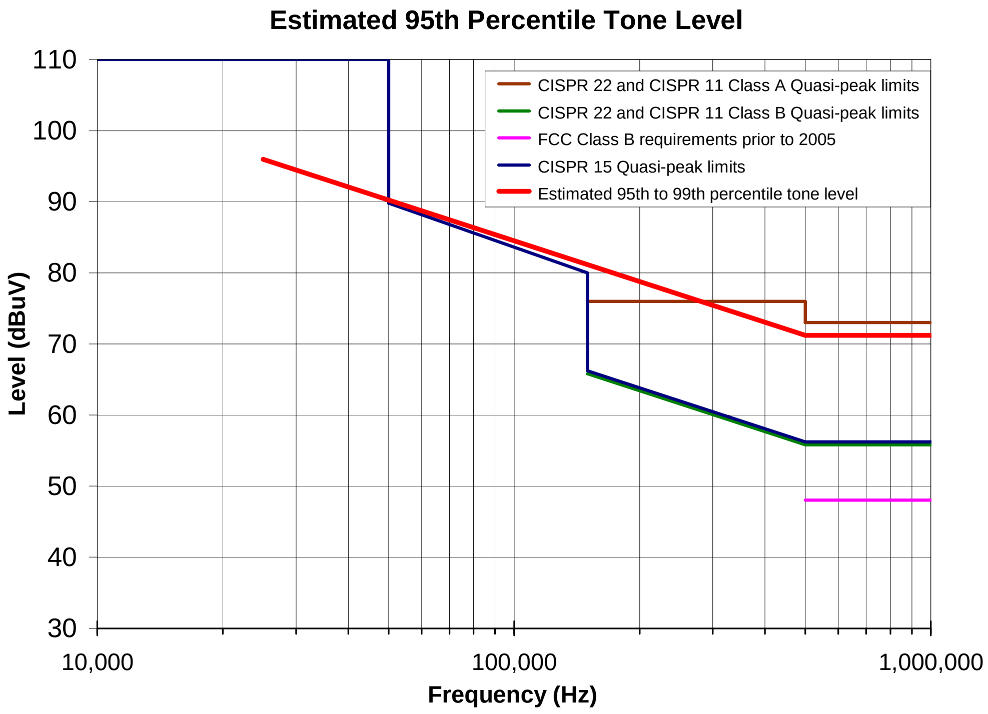

Figure 7: Estimated 95th to 99th Percentile Tone Level for Conducted Emissions Limits

The shape of the conducted emissions time domain waveform from off-line power converters is typically asymmetrical. An idealized signal that mimics this asymmetry is a saw-tooth waveform. Measured emissions from two different power converters, shown in figure 8, are examples of this of this kind of asymmetry. For illustrative purposes, idealized saw-tooth waveforms are overlaid (red dashed line) with the first two complete cycles of each measured result.

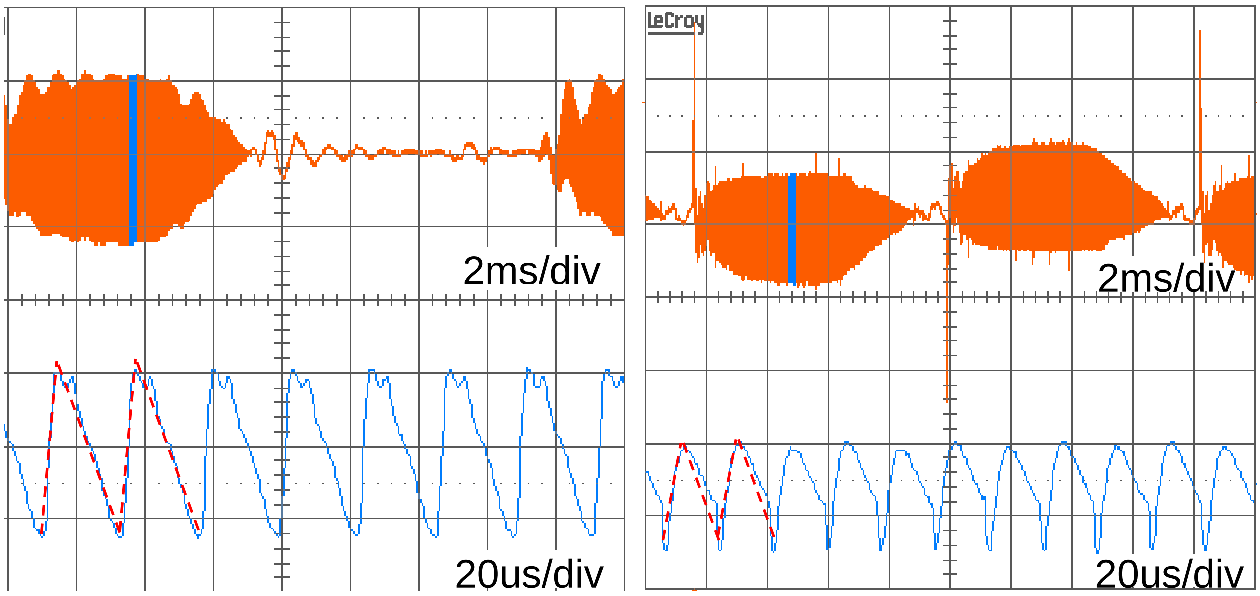

Figure 8: Time-Domain Waveforms for Offline Power Converters

The duty cycle of the emissions from off-line power converters varies greatly, as can be seen in the upper sweep for each of the two measured results in figure 8. The growing use of switch-mode power factor correction in front of off-line power converters tends to cause the duty cycle of the emissions waveform to approach 100 %. The goal of power factor correction is to draw current throughout the mains power cycle rather than only near the peaks of the mains waveform. Because increasingly stringent efficiency standards tend to dictate use of power factor correction, a 100 % duty cycle for the envelope for the tonal noise waveforms is specified.

One complication, that shall be accounted for when developing the tonal waveforms that will be played from waveform generator 1, is that the magnitude and phase response of the transfer function from waveform generator 1 through the V-network to the AC mains is not flat in the frequency range of interest. This variation occurs because the load impedance presented by the V-Network to waveform generator 1 is not resistive. An equivalent circuit and its transfer function are shown in figure 9. It is a straightforward process to apply the inverse of this transfer function to the waveforms loaded into waveform generator 1 and still achieve the desired band-limited saw-tooth waveforms on the AC mains. All waveforms specified in the present document have had this inverse transfer function applied such that the intended waveform appears at the mains terminals at the receiver under test.

Note that the most common value of AC coupling capacitor used for V-networks is 0,25 µF, and that value is used as the baseline when determining the inverse transfer function that needs to be applied to the tonal waveforms that will be played from waveform generator 1. If the V-network that is used for testing uses a larger value AC coupling capacitor, add an additional capacitor in series between waveform generator 1 and the port of the V-network such that the series combination of the two capacitors is 0,25 µF.

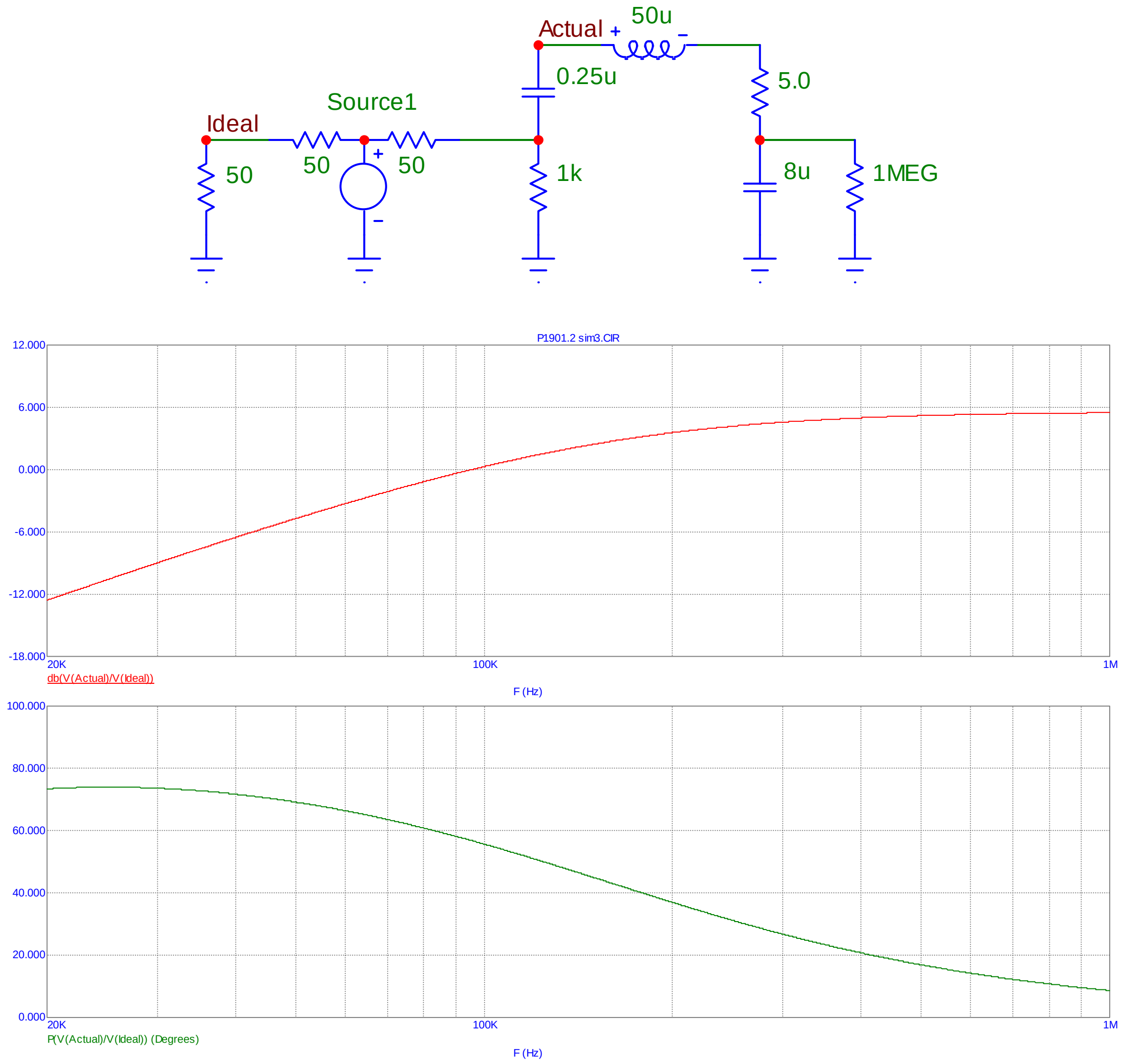

Figure 9: V-Network Equivalent Circuit Transfer Function

Figures 10, 11 and 12 show sample plots with the pre-distorted waveform from waveform generator 1 (upper trace) and the corresponding waveform shape on the AC mains (lower trace):

- Results for the lowest-frequency test tone of 26 kHz are shown in figure 10.
- Results for a mid-frequency test tone of 76 kHz are shown in figure 11.
- Results for the highest-frequency test tone of 146 kHz are shown in figure 12.

In each case, the resulting waveforms on the AC mains are the desired band-limited saw-tooth waveforms.

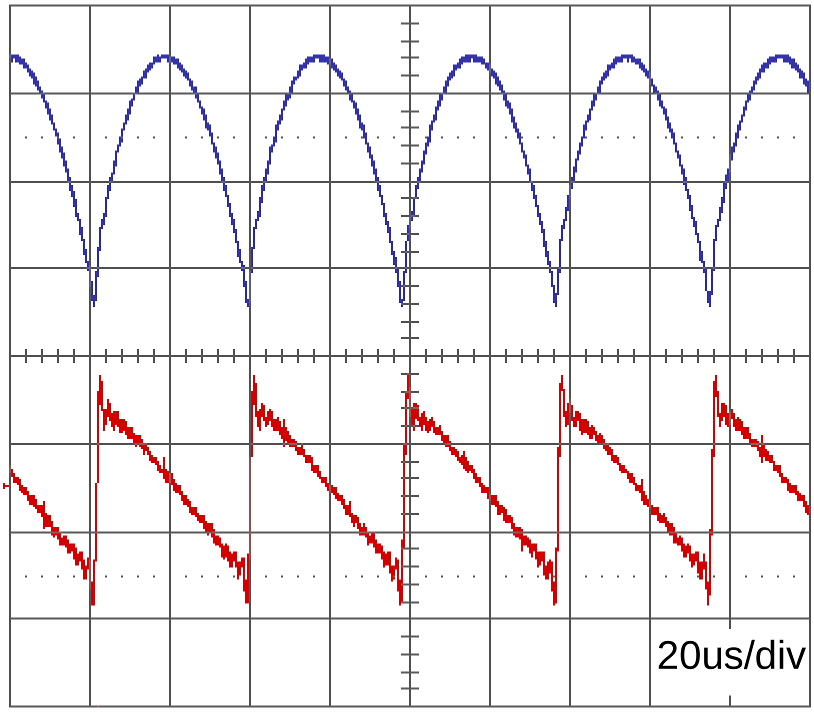

Figure 10: 26 kHz Waveforms

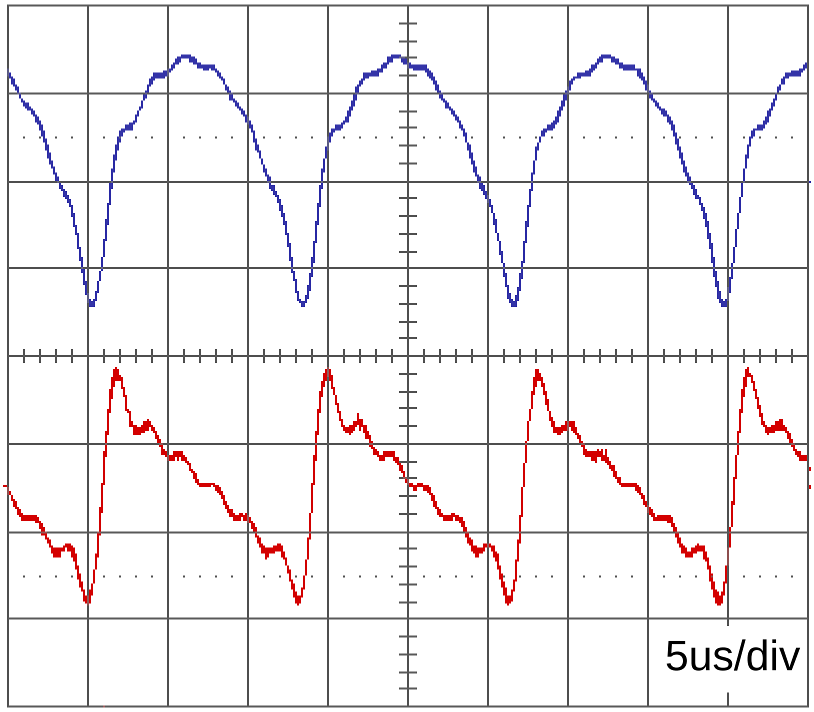

Figure 11: 76 kHz Waveforms

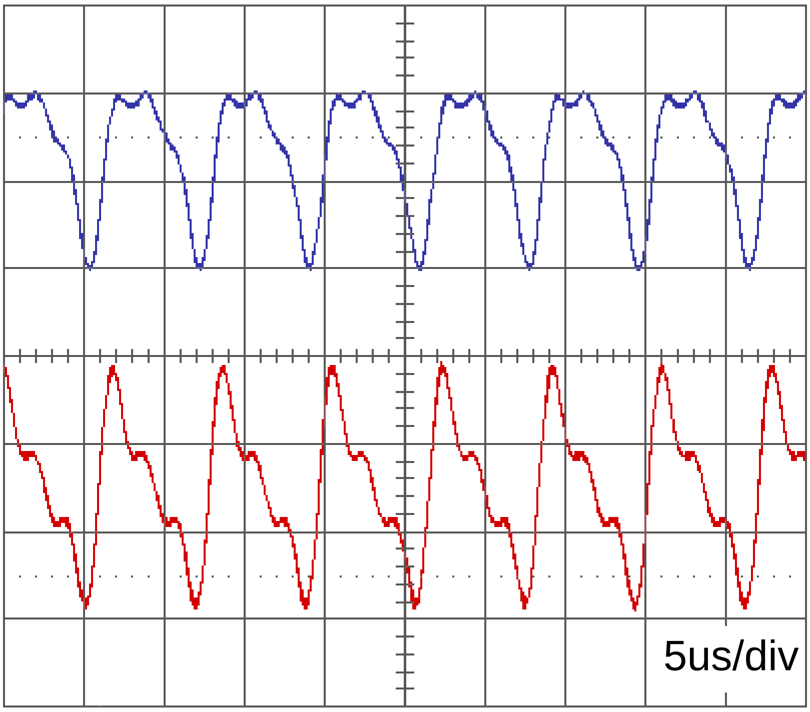

Figure 12: 146 kHz Waveforms

In practice, the majority of switch mode power supplies do not use crystal controlled oscillators to control their switching functions. For some devices, this variation is allowed to save cost, while for other devices, the frequency is purposely dithered so that it can more easily meet conducted emission requirements. A sampling of available devices indicates that frequency modulation with a peak deviation of about 1 kHz at a rate of 100 Hz is common. Clause 5.1 includes this important feature of mains-based noise by specifying the addition of frequency modulation to the tonal noise waveforms (most modern arbitrary waveform generators support frequency modulation of stored arbitrary waveforms).

Validation that each of the 25 tonal noise waveforms produces the desired fundamental and harmonic amplitudes was accomplished by loading the specified waveforms into waveform generator 1, playing them back through the test setup of figure 1 and plotting the spectrum of the resulting signal on the AC mains. Note that for this validation step, the AC mains power was not activated and the 50 Ω measuring receiver (along with its associated 450 Ω series adaptor) was connected directly across the AC mains. The 10:1 division from the 450 Ω to 50 Ω divider was compensated for prior to plotting the measured results. In addition, for this amplitude validation step, the specified frequency modulation was disabled to facilitate checking that the amplitude of each harmonic matched the target level.

Figures 13, 14 and 15 show sample plots for the lowest frequency (26 kHz), a mid-frequency (76 kHz), and the highest frequency (146 kHz) tonal noise waveforms, respectively. The estimated 95th to 99th percentile line is also shown on each of these plots. These plots show that the tonal noise waveforms specified in annex A achieve the desired result of producing tonal noise on the AC mains with fundamentals and harmonics that follow estimated 95th to 99th percentile line.

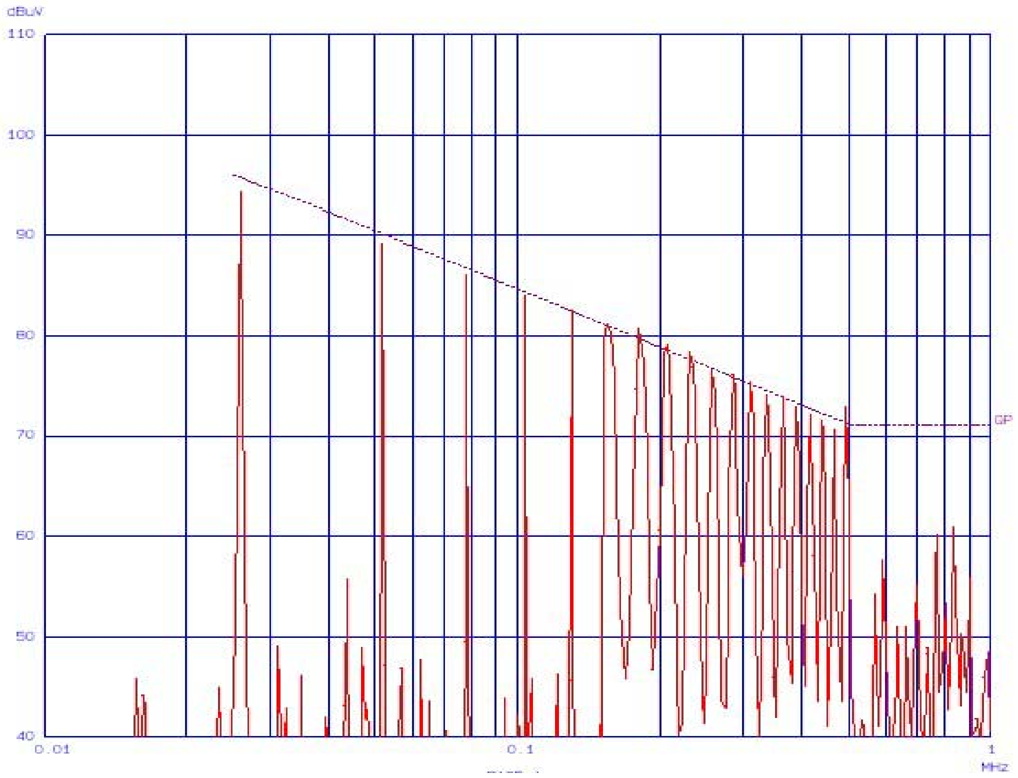

Figure 13: 26 kHz Spectral Plot

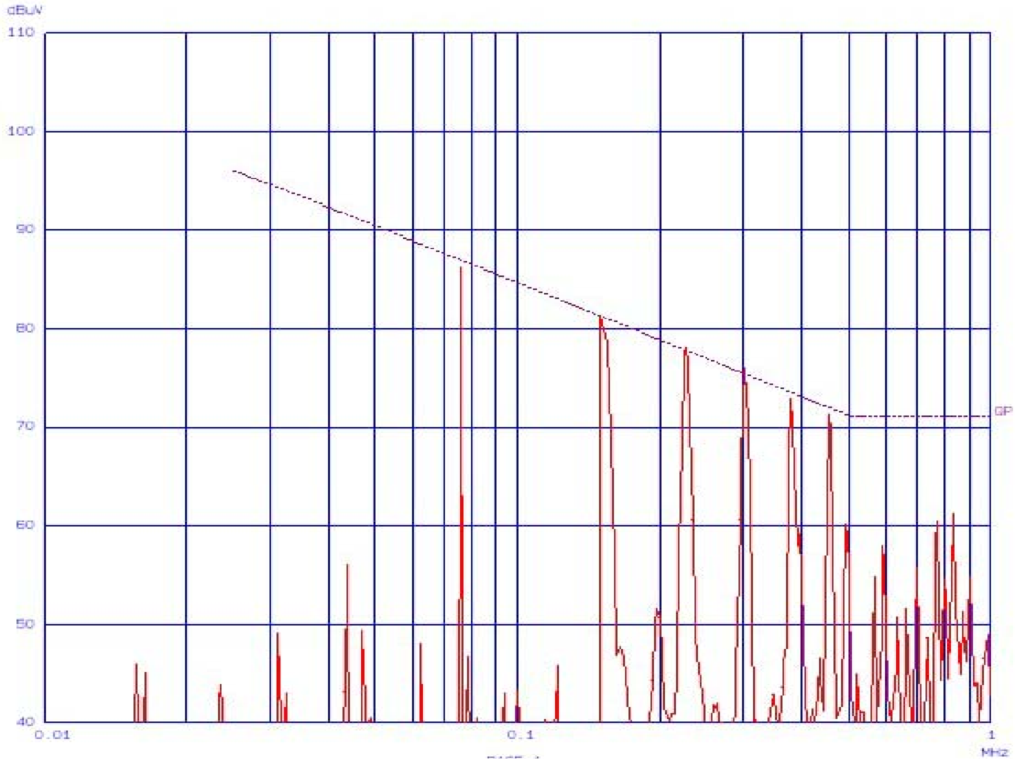

Figure 14: 76 kHz Spectral Plot

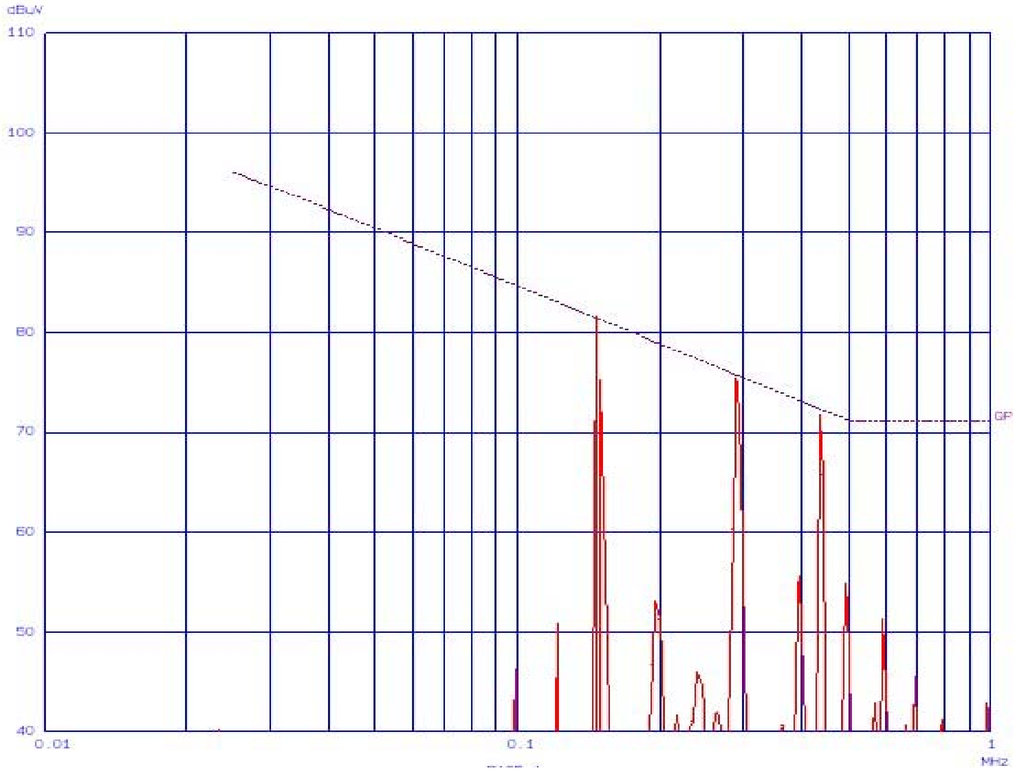

Figure 15: 146 kHz Spectral Plot

6.2 Defining Periodic Impulse Noise

Periodic impulse noise is very common on the AC mains. It can be caused by a number of devices, but one of the most common sources is a triac-controlled lamp dimmer. This type of device leaves its load disconnected from the AC mains for some fraction of each half AC cycle, and then connects the load to the mains for the remainder of that half cycle. In the case of a lamp dimmer, the in-rush of current associated with connection of the load part way through the AC cycle produces a large voltage spike on the mains at the point in time when the load is connected. This chopping of the waveform results in voltage spikes on the mains with a repetition rate of twice the AC mains power frequency. Because these triac-based controllers provide variable power to the load by varying the phase of when they connect the load, impulse noise can occur at nearly any phase relative to the zero crossing of the AC mains waveform.

The amplitude of these impulses is frequently tens of volts. This amplitude is larger than can be generated with commonly available waveform generators, yet this impairment can be produced using a commercially available triac-controlled lamp dimmer. Most of these dimmers include an L-C filter to limit the high-frequency emissions. This filter causes the impulse to have an exponentially decaying tail at the resonant frequency of the L-C circuit. The waveform specified in clause 5.2 includes these features. It can be generated with a commercially available triac-controlled dimmer set to the appropriate phase and driving a 100 Watt incandescent lamp.

An example waveform measured by connecting an oscilloscope with a 50 Ω input impedance in place of waveform generator 1 is shown in figure 16.

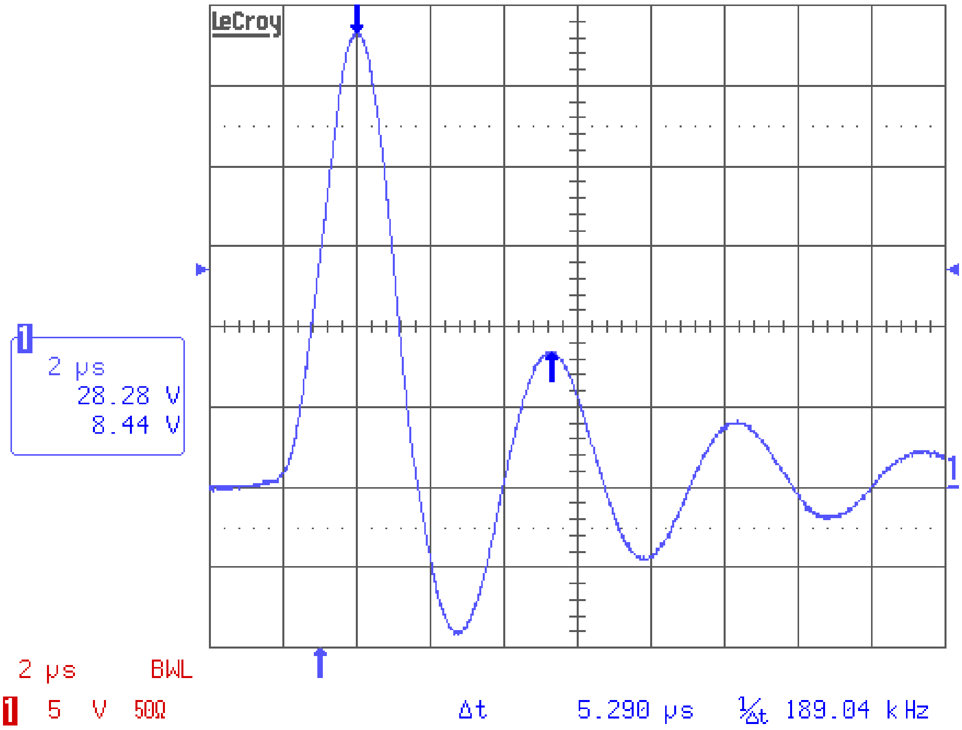

Figure 16: Example Waveform for Triac Impulse Noise at Receiver

6.3 Defining Random Impulse Noise

Random impulse noise is introduced onto the AC mains from a wide variety of sources. Series-wound AC motors are a very common source of this type of noise. These motors have brushes that arc when passing between commutator segments. The arcing produces impulses on the AC mains that are much smaller in amplitude than can be produced by periodic-impulse noise sources, but much greater in frequency.

A typical waveform for this type of noise is produced when an up-right vacuum cleaner is connected to the mains. Figure 17 shows an oscilloscope plot of this noise, with a common vacuum cleaner connected at the receiver location of figure 1. Figure 18 shows a spectrum analyzer plot of the same noise source. Note that in order to provide sufficient rejection of the mains frequency (so that higher frequency noise can be viewed), these two plots were filtered through a 2nd order high-pass Butterworth filter with a 3 dB corner of 20 kHz.

The waveform that is provided in annex B for random impulse noise testing is a digitized version of vacuum cleaner noise. Note that the waveform in annex B had to have the inverse of the transfer function of figure 9 applied so that the noise at the receiver under test would match that of the actual vacuum cleaner at that location (the same way that the tonal noise waveforms required compensation). When the amplitude of waveform generator 1 is set to the value specified in clause 5.3 the time domain characteristics and power spectral density of the random impulse noise that occurs at the mains terminals of the receiver match those produced by the vacuum cleaner.

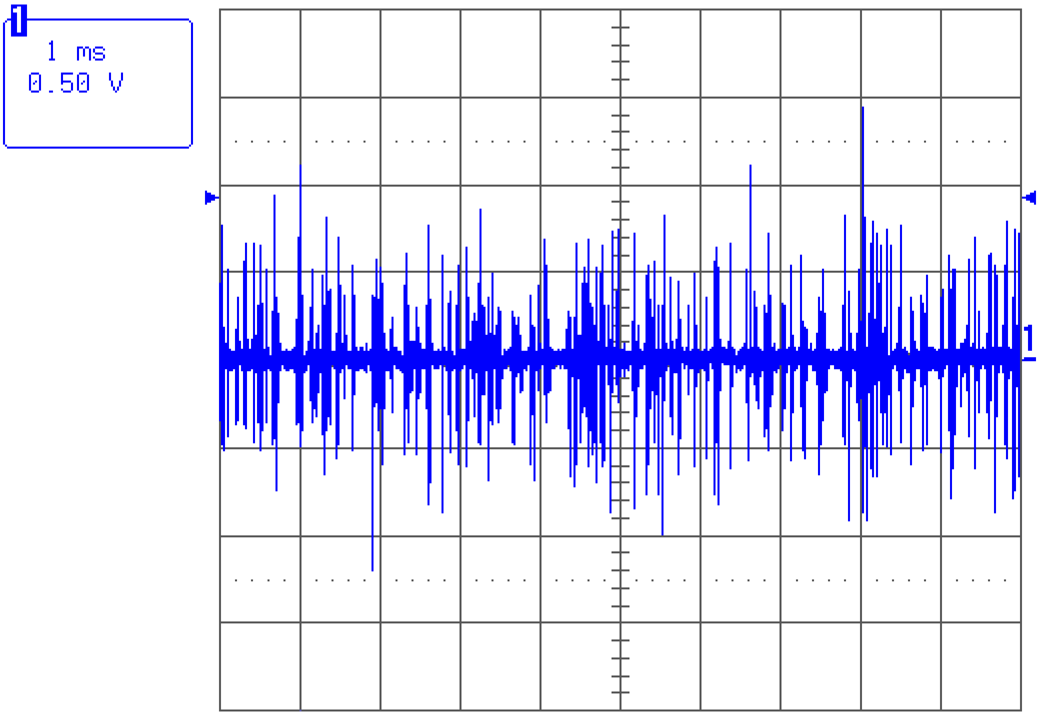

Figure 17: Sample Waveform for Random Impulse Noise

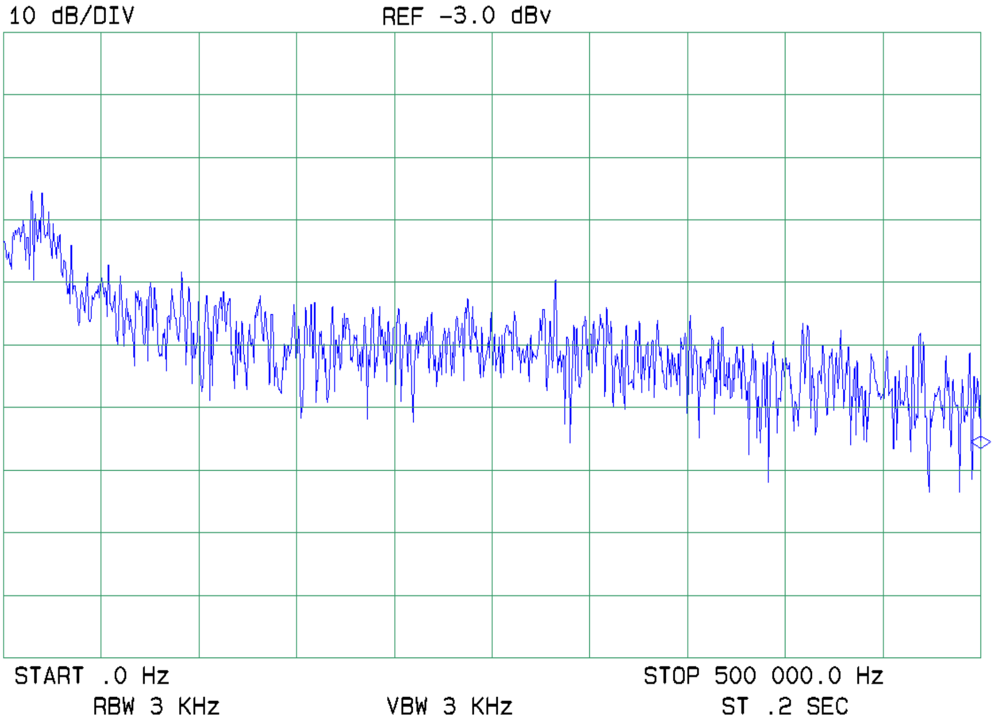

Figure 18: Spectral Plot for Random Impulse Noise

6.4 Defining Intentional Communicator Noise

In addition to noise on the AC mains from unintentional sources, there is a significant population of intentional communicators on the mains. A very common example of these types of devices is power line intercoms, or baby monitors. In large parts of the world, these devices use carrier frequencies in the range of 160 kHz to 400 kHz. Sampling a number of these devices, it is observed that they use analog FM modulation of the carrier with modest frequency deviations. The amplitude of the signals that these devices impose on the AC mains is approximately 5 V_{p-p}. The amplitude settings specified for these waveforms in clause 5.4 result in 5 V_{p-p} waveforms on the receive branch AC mains (that is, the values specified in that clause have been compensated for the transfer function from waveform generator 1 to the AC mains).

For a UUT to operate reliably in North America (as well as a number of other countries), it is essential that the device be able to function when power line intercoms and baby monitors are active on the AC mains (note that most of these devices include a transmit-lock feature to support continuous communication between units).

Clause 5.4 specifies the settings for waveform generator 1 that allow it to emulate FM based power line intercoms and baby monitors.

Another type of intentional power line communications devices are those that comply with the ISO/IEC 14908-3 [7] standard. These devices use binary phase-shift keying (BPSK) modulation of a 131,57 kHz carrier frequency. Because these devices comply with worldwide emission regulations, they have been deployed on the power mains around the globe. Because they also satisfy EN 50065-1 [5] requirements for operation in the European consumer use "C-band", they are found in both CENELEC and non-CENELEC countries.

7 Verifying Test Setup Isolation between the Transmit and Receive Locations

This clause describes how to verify that the test setup has sufficient isolation between the transmit and receive locations.

7.1 Verifying Test Setup Isolation

Any instantiation of the test setup shown in figure 1 shall be verified to have sufficient signal attenuation from the transmitter location, through the V-Network to the AC mains, through the other V-Network, to the receiver location. This verification is necessary to ensure that the attenuation between the transmitter and receiver is determined solely by VR1 at higher attenuation settings. Figure 19 shows a plot of the simulated attenuation between the transmitter and receiver with VR1 removed and the mains supply is disconnected. This plot indicates ≥ 96 dB of attenuation between the two locations from 35 kHz to 500 kHz.

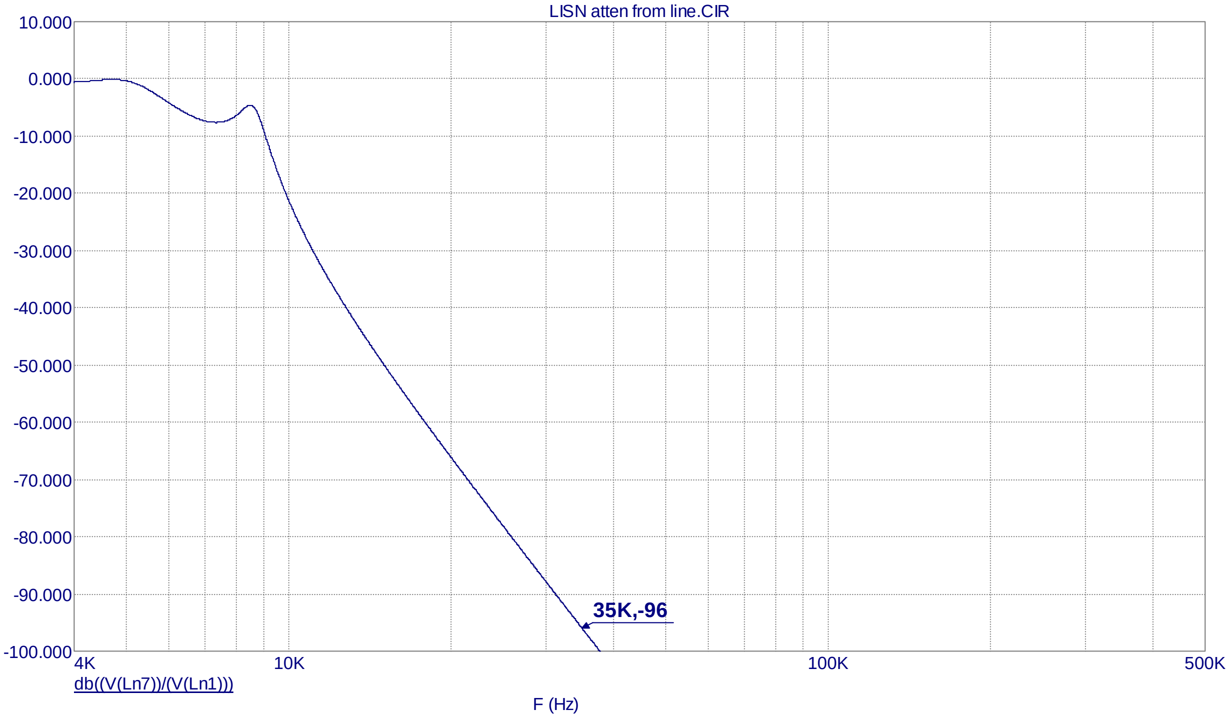

Figure 19: Simulated Attenuation between Transmitter and Receiver without VR1 and Mains Power

All instances of figure 1 test setup shall be verified to have at least 90 dB of attenuation between the transmit and receive locations using a network analyzer connected, as shown in figure 20. This measurement setup is based on the test setup of figure 1, but with the transmitter and receiver under test removed, the AC mains supply removed, and the variable resistor VR1 removed. This measurement setup verifies that the signal attenuation through the combination of V-Networks and filters is > 90 dB from 35 kHz to 500 kHz.

In figure 20, to prevent ground loops from limiting measurement results, the coaxial cable connected to the "Test" input of the network analyzer is wound through a toroidal ferrite core using multiple turns to provide > 800 µH of common mode inductance in that path. Although the figure shows only a few windings around the toroid, it is likely additional windings will be needed to achieve the required common mode inductance.

NOTE: Keep the unshielded wires that connect the coaxial cables to the V-Network as short as possible.

Preserving ≥ 90 dB of attenuation through the V-Networks and filters requires careful physical layout of the V-Networks, filter components, and interconnects.

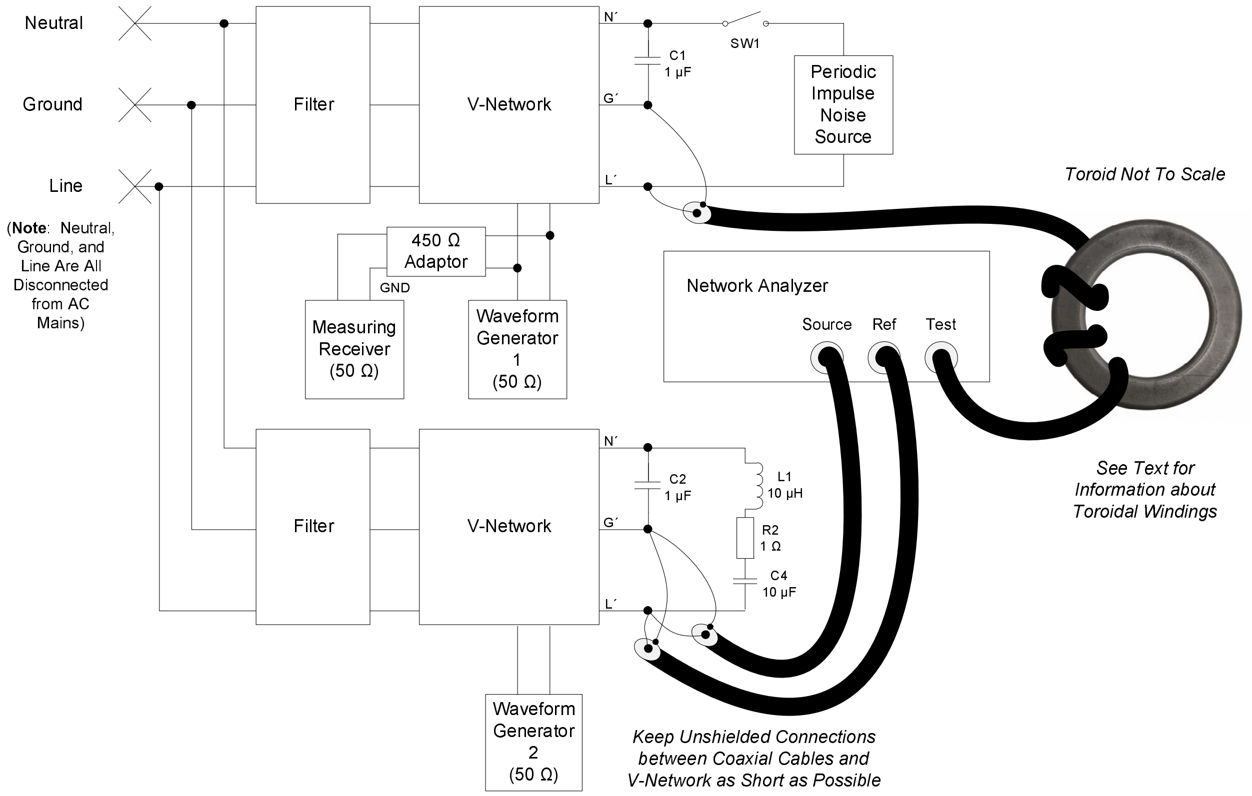

Figure 20: Measurement Setup to Verify Attenuation

Figure 21 is a plot of the measured result for one instance of the test setup of figure 1, when measured using the measurement setup shown in figure 20.

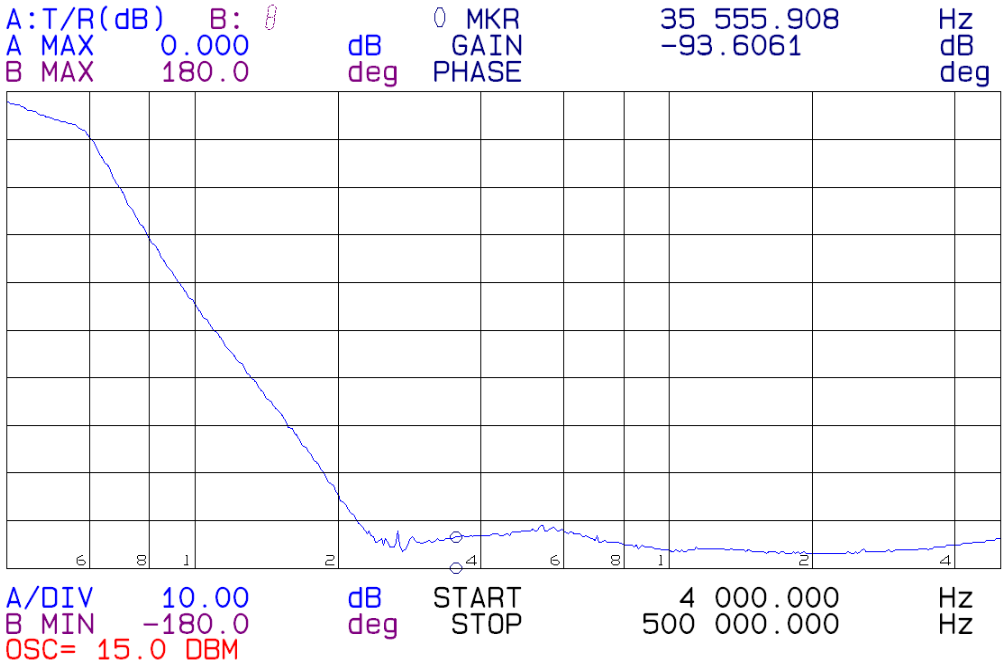

Figure 21: Example Measured Attenuation Result

Annex A (normative): Tonal Noise Waveform Sample Points

This annex lists data points for tonal noise that you can load into a waveform generator.

A.1 Tonal Noise Waveform Sample Points

This appendix provides sample data points for each of the 25 tonal noise waveforms described in clause 5.1. You can copy the values directly from the present document and paste them into a text file for loading into waveform generator 1. If your generator does not accept this normalized format, convert the values to a format that is compatible with your generator; see your generator's operator's manual.

Each waveform includes the following information:

- The frequency to which you shall set the waveform generator.
- The amplitude to which you shall set the waveform generator.

A list of the samples for one full cycle of the waveform, normalized to a maximum value of +1,0 and a minimum value of -1,0.

A.1.1 26 kHz Tone

Frequency for waveform generator: 26 kHz

Amplitude for waveform generator: 710 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.847	-0.755	-0.659	-0.570	-0.497	-0.441	-0.403	-0.378	-0.360	-0.341	-0.316	-0.284
-0.245	-0.201	-0.158	-0.118	-0.085	-0.057	-0.033	-0.011	0.013	0.041	0.071	0.105
0.139	0.172	0.201	0.226	0.248	0.268	0.289	0.311	0.336	0.363	0.391	0.417
0.442	0.463	0.482	0.499	0.516	0.534	0.553	0.574	0.596	0.618	0.638	0.656
0.671	0.684	0.697	0.710	0.725	0.741	0.758	0.775	0.791	0.804	0.816	0.826
0.834	0.843	0.853	0.865	0.877	0.889	0.901	0.910	0.918	0.924	0.929	0.934
0.939	0.946	0.954	0.962	0.969	0.975	0.979	0.981	0.982	0.983	0.985	0.987
0.990	0.994	0.997	0.999	1.000	0.999	0.996	0.993	0.990	0.988	0.988	0.987
0.987	0.986	0.983	0.978	0.972	0.965	0.959	0.953	0.948	0.944	0.940	0.935
0.929	0.921	0.912	0.901	0.891	0.881	0.872	0.864	0.857	0.849	0.839	0.829
0.816	0.802	0.788	0.774	0.762	0.750	0.740	0.729	0.716	0.703	0.687	0.670
0.652	0.635	0.619	0.604	0.590	0.576	0.561	0.545	0.526	0.506	0.485	0.464
0.444	0.426	0.409	0.392	0.375	0.356	0.335	0.311	0.287	0.262	0.239	0.217
0.197	0.178	0.158	0.137	0.113	0.087	0.059	0.030	0.003	-0.022	-0.045	-0.067
-0.088	-0.111	-0.137	-0.166	-0.198	-0.231	-0.263	-0.292	-0.318	-0.341	-0.363	-0.387
-0.415	-0.447	-0.484	-0.523	-0.562	-0.596	-0.625	-0.648	-0.669	-0.690	-0.717	-0.754
-0.801	-0.856	-0.913	-0.962	-0.994	-1.000	-0.977	-0.924				

A.1.2 31 kHz Tone

Frequency for waveform generator: 31 kHz

Amplitude for waveform generator: 506 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.822 -0.732 -0.638 -0.548 -0.467 -0.401 -0.350 -0.315 -0.291 -0.273 -0.257 -0.239
-0.214 -0.184 -0.147 -0.107 -0.065 -0.026 0.010 0.040 0.065 0.087 0.106 0.126
0.149 0.174 0.202 0.233 0.264 0.295 0.323 0.348 0.369 0.388 0.405 0.422
0.440 0.460 0.482 0.506 0.530 0.554 0.576 0.595 0.612 0.627 0.640 0.653
0.667 0.682 0.698 0.716 0.734 0.752 0.768 0.783 0.795 0.806 0.815 0.823
0.832 0.842 0.853 0.865 0.878 0.890 0.902 0.912 0.919 0.925 0.930 0.934
0.938 0.943 0.949 0.956 0.964 0.972 0.978 0.983 0.987 0.988 0.988 0.988
0.988 0.988 0.989 0.992 0.994 0.997 0.999 1.000 0.999 0.996 0.992 0.987
0.982 0.978 0.975 0.972 0.971 0.969 0.967 0.963 0.958 0.951 0.943 0.934
0.924 0.916 0.908 0.901 0.895 0.890 0.883 0.876 0.866 0.855 0.843 0.829
0.816 0.803 0.791 0.780 0.770 0.760 0.750 0.738 0.725 0.710 0.693 0.676
0.658 0.640 0.624 0.609 0.595 0.582 0.568 0.553 0.537 0.518 0.497 0.475
0.453 0.431 0.411 0.392 0.375 0.358 0.341 0.323 0.302 0.280 0.255 0.229
0.202 0.176 0.151 0.129 0.108 0.088 0.068 0.047 0.024 -0.002 -0.031 -0.063
-0.094 -0.126 -0.155 -0.181 -0.205 -0.227 -0.248 -0.271 -0.297 -0.327 -0.361 -0.399
-0.438 -0.476 -0.511 -0.542 -0.567 -0.589 -0.609 -0.630 -0.657 -0.692 -0.735 -0.787
-0.843 -0.900 -0.949 -0.984 -1.000 -0.991 -0.957 -0.899

A.1.3 36 kHz Tone

Frequency for waveform generator: 36 kHz

Amplitude for waveform generator: 378 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.805 -0.722 -0.634 -0.546 -0.463 -0.388 -0.325 -0.274 -0.235 -0.206 -0.185 -0.169
-0.154 -0.138 -0.118 -0.094 -0.064 -0.030 0.007 0.046 0.083 0.119 0.151 0.180
0.204 0.224 0.243 0.260 0.277 0.296 0.317 0.341 0.367 0.394 0.422 0.449
0.475 0.498 0.519 0.537 0.553 0.567 0.580 0.593 0.608 0.624 0.641 0.660
0.680 0.700 0.719 0.737 0.754 0.768 0.780 0.790 0.798 0.807 0.815 0.824
0.835 0.846 0.859 0.872 0.886 0.898 0.910 0.919 0.927 0.933 0.938 0.941
0.944 0.947 0.951 0.956 0.962 0.969 0.976 0.983 0.989 0.994 0.998 1.000
1.000 0.999 0.997 0.994 0.992 0.991 0.990 0.991 0.992 0.994 0.995 0.995
0.995 0.993 0.989 0.983 0.976 0.969 0.961 0.954 0.947 0.941 0.937 0.933
0.929 0.925 0.920 0.914 0.906 0.896 0.885 0.873 0.860 0.847 0.835 0.823
0.812 0.803 0.794 0.785 0.776 0.766 0.754 0.741 0.726 0.710 0.692 0.674
0.655 0.638 0.621 0.606 0.592 0.578 0.565 0.551 0.536 0.520 0.501 0.481
0.459 0.435 0.411 0.388 0.365 0.344 0.324 0.306 0.288 0.271 0.253 0.234
0.212 0.189 0.162 0.134 0.105 0.075 0.046 0.018 -0.008 -0.032 -0.054 -0.074
-0.094 -0.115 -0.139 -0.165 -0.194 -0.227 -0.263 -0.300 -0.338 -0.374 -0.408 -0.438
-0.465 -0.488 -0.509 -0.529 -0.550 -0.576 -0.607 -0.644 -0.689 -0.741 -0.796 -0.852
-0.905 -0.950 -0.983 -1.000 -0.999 -0.977 -0.937 -0.878

A.1.4 41 kHz Tone

Frequency for waveform generator: 41 kHz

Amplitude for waveform generator: 297 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.778	-0.693	-0.603	-0.514	-0.428	-0.351	-0.283	-0.227	-0.183	-0.150	-0.126	-0.109
-0.095	-0.083	-0.069	-0.051	-0.029	-0.002	0.029	0.064	0.101	0.138	0.174	0.207
0.236	0.262	0.283	0.302	0.318	0.333	0.348	0.365	0.383	0.404	0.427	0.452
0.477	0.504	0.529	0.552	0.574	0.592	0.608	0.622	0.634	0.645	0.656	0.668
0.681	0.695	0.711	0.729	0.747	0.765	0.782	0.798	0.813	0.825	0.835	0.843
0.850	0.856	0.862	0.868	0.875	0.883	0.893	0.903	0.915	0.926	0.936	0.946
0.954	0.960	0.964	0.967	0.968	0.968	0.969	0.969	0.971	0.973	0.976	0.981
0.986	0.990	0.995	0.998	1.000	1.000	0.998	0.995	0.991	0.986	0.980	0.975
0.971	0.967	0.965	0.964	0.963	0.962	0.960	0.958	0.954	0.948	0.941	0.932
0.922	0.911	0.900	0.890	0.880	0.871	0.863	0.856	0.849	0.843	0.836	0.828
0.819	0.808	0.795	0.781	0.765	0.749	0.732	0.716	0.700	0.686	0.672	0.660
0.649	0.637	0.626	0.613	0.598	0.582	0.564	0.544	0.522	0.500	0.477	0.455
0.434	0.414	0.396	0.379	0.363	0.348	0.331	0.314	0.295	0.274	0.250	0.224
0.196	0.167	0.138	0.110	0.083	0.058	0.035	0.014	-0.005	-0.024	-0.044	-0.065
-0.088	-0.115	-0.145	-0.178	-0.213	-0.250	-0.288	-0.324	-0.358	-0.388	-0.415	-0.439
-0.459	-0.479	-0.498	-0.520	-0.546	-0.578	-0.617	-0.662	-0.713	-0.768	-0.825	-0.879
-0.928	-0.966	-0.991	-1.000	-0.991	-0.962	-0.916	-0.853				

A.1.5 46 kHz Tone

Frequency for waveform generator: 46 kHz

Amplitude for waveform generator: 238 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.763	-0.685	-0.602	-0.518	-0.435	-0.357	-0.284	-0.220	-0.164	-0.118	-0.081	-0.052
-0.030	-0.013	0.000	0.012	0.025	0.039	0.055	0.076	0.100	0.128	0.159	0.192
0.226	0.260	0.293	0.324	0.352	0.378	0.400	0.418	0.435	0.449	0.462	0.474
0.487	0.501	0.516	0.534	0.553	0.573	0.595	0.618	0.640	0.662	0.683	0.702
0.718	0.733	0.745	0.756	0.765	0.773	0.780	0.787	0.795	0.804	0.814	0.826
0.838	0.852	0.865	0.879	0.892	0.905	0.916	0.925	0.932	0.938	0.942	0.945
0.946	0.947	0.948	0.950	0.952	0.955	0.959	0.965	0.970	0.977	0.983	0.989
0.994	0.997	0.999	1.000	0.999	0.996	0.992	0.987	0.982	0.976	0.971	0.967
0.963	0.960	0.958	0.957	0.956	0.956	0.954	0.953	0.949	0.945	0.939	0.931
0.922	0.911	0.900	0.887	0.875	0.863	0.852	0.842	0.832	0.824	0.816	0.809
0.802	0.795	0.787	0.777	0.766	0.754	0.740	0.724	0.706	0.688	0.669	0.650
0.631	0.613	0.596	0.580	0.566	0.552	0.539	0.526	0.513	0.499	0.484	0.468
0.449	0.428	0.405	0.381	0.355	0.329	0.302	0.276	0.251	0.228	0.206	0.185
0.166	0.148	0.131	0.113	0.095	0.075	0.052	0.028	0.000	-0.030	-0.063	-0.097
-0.132	-0.168	-0.203	-0.236	-0.267	-0.295	-0.321	-0.343	-0.364	-0.383	-0.402	-0.422
-0.445	-0.471	-0.501	-0.537	-0.579	-0.625	-0.676	-0.730	-0.785	-0.839	-0.889	-0.932
-0.967	-0.990	-1.000	-0.996	-0.976	-0.942	-0.894	-0.834				

A.1.6 51 kHz Tone

Frequency for waveform generator: 51 kHz

Amplitude for waveform generator: 195 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.742	-0.584	-0.419	-0.264	-0.135	-0.038	0.026	0.065	0.090	0.112	0.141	0.183
0.237	0.300	0.365	0.425	0.475	0.513	0.541	0.563	0.585	0.611	0.642	0.680
0.721	0.761	0.795	0.822	0.841	0.853	0.863	0.873	0.887	0.905	0.927	0.949
0.969	0.983	0.991	0.992	0.989	0.984	0.982	0.982	0.986	0.993	0.998	1.000
0.996	0.986	0.970	0.951	0.933	0.916	0.904	0.895	0.887	0.876	0.861	0.839
0.811	0.779	0.745	0.712	0.684	0.659	0.637	0.615	0.590	0.558	0.518	0.472
0.423	0.373	0.327	0.287	0.252	0.220	0.186	0.145	0.096	0.036	-0.031	-0.100
-0.166	-0.224	-0.272	-0.312	-0.349	-0.392	-0.448	-0.523	-0.616	-0.723	-0.831	-0.923
-0.984	-1.000	-0.963	-0.874								

A.1.7 56 kHz Tone

Frequency for waveform generator: 56 kHz

Amplitude for waveform generator: 164 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.731	-0.580	-0.420	-0.267	-0.132	-0.023	0.056	0.109	0.141	0.163	0.182	0.208
0.243	0.290	0.346	0.407	0.467	0.520	0.564	0.597	0.621	0.640	0.657	0.676
0.699	0.729	0.763	0.798	0.832	0.862	0.884	0.899	0.907	0.912	0.915	0.920
0.929	0.941	0.957	0.973	0.987	0.997	1.000	0.997	0.989	0.977	0.965	0.955
0.948	0.945	0.943	0.942	0.939	0.930	0.916	0.895	0.870	0.842	0.813	0.788
0.765	0.747	0.731	0.714	0.694	0.669	0.637	0.598	0.555	0.509	0.464	0.422
0.386	0.354	0.325	0.295	0.261	0.219	0.169	0.110	0.046	-0.021	-0.085	-0.142
-0.191	-0.232	-0.268	-0.305	-0.350	-0.408	-0.483	-0.575	-0.678	-0.785	-0.883	-0.959
-1.000	-0.999	-0.951	-0.859								

A.1.8 61 kHz Tone

Frequency for waveform generator: 61 kHz

Amplitude for waveform generator: 142 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.701	-0.541	-0.374	-0.215	-0.078	0.031	0.108	0.158	0.186	0.203	0.219	0.241
0.275	0.321	0.376	0.437	0.496	0.548	0.590	0.621	0.643	0.659	0.674	0.691
0.714	0.743	0.776	0.811	0.845	0.873	0.894	0.908	0.915	0.917	0.919	0.923
0.931	0.943	0.959	0.975	0.988	0.997	1.000	0.996	0.986	0.974	0.961	0.950
0.943	0.939	0.938	0.937	0.934	0.925	0.910	0.889	0.863	0.834	0.805	0.779
0.758	0.740	0.724	0.708	0.689	0.663	0.631	0.592	0.548	0.501	0.456	0.415
0.379	0.348	0.320	0.291	0.257	0.216	0.165	0.106	0.041	-0.027	-0.091	-0.148
-0.195	-0.234	-0.269	-0.305	-0.349	-0.407	-0.483	-0.576	-0.681	-0.789	-0.888	-0.962
-1.000	-0.993	-0.938	-0.837								

A.1.9 66 kHz Tone

Frequency for waveform generator: 66 kHz

Amplitude for waveform generator: 121 mV$_{\text{pp}}$

Data points for one cycle, normalized to ±1:

-0.685 -0.534 -0.376 -0.220 -0.079 0.041 0.135 0.203 0.248 0.275 0.292 0.306
0.323 0.349 0.384 0.430 0.482 0.538 0.593 0.642 0.684 0.715 0.738 0.753
0.764 0.774 0.787 0.803 0.825 0.851 0.880 0.909 0.936 0.957 0.972 0.979
0.981 0.977 0.972 0.968 0.966 0.967 0.973 0.981 0.989 0.997 1.000 0.998
0.990 0.975 0.956 0.934 0.911 0.891 0.873 0.859 0.848 0.839 0.829 0.817
0.799 0.775 0.744 0.708 0.667 0.626 0.585 0.548 0.516 0.487 0.462 0.438
0.411 0.380 0.341 0.294 0.239 0.178 0.114 0.051 -0.008 -0.060 -0.105 -0.142
-0.176 -0.210 -0.249 -0.300 -0.364 -0.444 -0.539 -0.643 -0.749 -0.847 -0.928 -0.982
-1.000 -0.978 -0.915 -0.815

A.1.10 71 kHz Tone

Frequency for waveform generator: 71 kHz

Amplitude for waveform generator: 107 mV$_{\text{pp}}$

Data points for one cycle, normalized to ±1:

-0.658 -0.500 -0.335 -0.175 -0.030 0.091 0.185 0.251 0.293 0.317 0.330 0.340
0.355 0.378 0.412 0.457 0.509 0.564 0.619 0.667 0.708 0.738 0.758 0.771
0.780 0.789 0.799 0.815 0.836 0.862 0.891 0.920 0.946 0.966 0.980 0.986
0.986 0.982 0.975 0.970 0.967 0.968 0.973 0.981 0.990 0.997 1.000 0.997
0.988 0.973 0.953 0.930 0.906 0.885 0.867 0.853 0.843 0.834 0.825 0.812
0.794 0.770 0.739 0.701 0.661 0.618 0.578 0.541 0.508 0.481 0.456 0.433
0.407 0.376 0.337 0.289 0.234 0.172 0.107 0.044 -0.015 -0.067 -0.110 -0.147
-0.179 -0.212 -0.250 -0.300 -0.365 -0.446 -0.542 -0.648 -0.755 -0.854 -0.934 -0.986
-1.000 -0.973 -0.903 -0.796

A.1.11 76 kHz Tone

Frequency for waveform generator: 76 kHz

Amplitude for waveform generator: 94,4 mV$_{\text{pp}}$

Data points for one cycle, normalized to ±1:

-0.657 -0.514 -0.362 -0.212 -0.070 0.057 0.165 0.250 0.313 0.356 0.383 0.399
0.409 0.419 0.433 0.453 0.483 0.520 0.565 0.613 0.663 0.710 0.752 0.787
0.813 0.831 0.842 0.848 0.851 0.854 0.859 0.868 0.881 0.898 0.919 0.940
0.961 0.979 0.992 0.999 1.000 0.995 0.984 0.970 0.955 0.941 0.929 0.920
0.915 0.912 0.912 0.912 0.909 0.904 0.892 0.875 0.852 0.823 0.790 0.755
0.720 0.686 0.656 0.629 0.606 0.586 0.568 0.549 0.526 0.499 0.465 0.423
0.374 0.320 0.261 0.202 0.143 0.089 0.041 -0.001 -0.037 -0.069 -0.099 -0.131
-0.170 -0.219 -0.279 -0.353 -0.440 -0.537 -0.640 -0.742 -0.836 -0.915 -0.972 -1.000
-0.996 -0.957 -0.885 -0.783

A.1.12 81 kHz Tone

Frequency for waveform generator: 81 kHz

Amplitude for waveform generator: 84,9 mV$_{pp}$

Data points for one cycle, normalized to ±1:

-0.630 -0.482 -0.326 -0.171 -0.027 0.102 0.209 0.294 0.355 0.395 0.419 0.432
0.439 0.446 0.457 0.476 0.504 0.541 0.585 0.633 0.682 0.729 0.770 0.804
0.829 0.845 0.854 0.858 0.859 0.861 0.865 0.873 0.885 0.902 0.922 0.943
0.964 0.981 0.994 1.000 1.000 0.993 0.982 0.967 0.951 0.936 0.923 0.914
0.908 0.906 0.906 0.906 0.903 0.897 0.886 0.868 0.845 0.815 0.781 0.746
0.710 0.676 0.645 0.619 0.597 0.577 0.559 0.541 0.519 0.491 0.457 0.415
0.366 0.311 0.252 0.192 0.133 0.079 0.032 -0.009 -0.044 -0.074 -0.104 -0.135
-0.173 -0.221 -0.282 -0.356 -0.444 -0.542 -0.645 -0.748 -0.842 -0.920 -0.975 -1.000
-0.992 -0.948 -0.870 -0.763

A.1.13 86 kHz Tone

Frequency for waveform generator: 86 kHz

Amplitude for waveform generator: 74,2 mV$_{pp}$

Data points for one cycle, normalized to ±1:

-0.630 -0.498 -0.357 -0.214 -0.075 0.055 0.173 0.274 0.357 0.422 0.471 0.503
0.524 0.536 0.543 0.549 0.557 0.569 0.587 0.612 0.643 0.680 0.721 0.763
0.805 0.845 0.879 0.907 0.928 0.942 0.949 0.950 0.948 0.942 0.937 0.932
0.930 0.931 0.936 0.944 0.955 0.968 0.980 0.990 0.997 1.000 0.997 0.988
0.973 0.954 0.930 0.903 0.875 0.847 0.822 0.799 0.779 0.763 0.749 0.738
0.727 0.715 0.699 0.680 0.655 0.623 0.585 0.541 0.492 0.439 0.385 0.330
0.278 0.229 0.185 0.147 0.113 0.083 0.055 0.027 -0.003 -0.039 -0.083 -0.137
-0.202 -0.278 -0.364 -0.458 -0.558 -0.658 -0.754 -0.840 -0.913 -0.966 -0.996 -1.000
-0.977 -0.926 -0.849 -0.749

A.1.14 91 kHz Tone

Frequency for waveform generator: 91 kHz

Amplitude for waveform generator: 68,0 mV$_{pp}$

Data points for one cycle, normalized to ±1:

-0.608 -0.470 -0.326 -0.179 -0.037 0.095 0.213 0.315 0.397 0.461 0.507 0.538
0.556 0.565 0.570 0.573 0.578 0.589 0.605 0.629 0.660 0.696 0.737 0.779
0.821 0.859 0.893 0.920 0.940 0.953 0.959 0.959 0.955 0.948 0.941 0.936
0.933 0.933 0.938 0.946 0.957 0.969 0.981 0.991 0.998 1.000 0.996 0.987
0.971 0.950 0.925 0.897 0.869 0.841 0.814 0.791 0.772 0.755 0.742 0.731
0.720 0.708 0.693 0.674 0.649 0.617 0.578 0.534 0.484 0.431 0.375 0.321
0.268 0.220 0.176 0.138 0.105 0.076 0.050 0.023 -0.007 -0.043 -0.087 -0.141
-0.206 -0.283 -0.370 -0.465 -0.565 -0.666 -0.762 -0.848 -0.920 -0.971 -0.999 -1.000
-0.973 -0.918 -0.836 -0.731

A.1.15 96 kHz Tone

Frequency for waveform generator: 96 kHz

Amplitude for waveform generator: 62,4 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.584 -0.442 -0.293 -0.143 0.001 0.135 0.254 0.356 0.438 0.500 0.544 0.572
0.588 0.595 0.597 0.598 0.601 0.610 0.625 0.648 0.678 0.714 0.754 0.796
0.837 0.875 0.908 0.934 0.953 0.964 0.969 0.967 0.961 0.953 0.945 0.939
0.935 0.935 0.939 0.947 0.957 0.970 0.982 0.992 0.998 1.000 0.996 0.986
0.969 0.947 0.922 0.893 0.864 0.835 0.808 0.785 0.765 0.749 0.736 0.725
0.715 0.703 0.688 0.669 0.644 0.611 0.573 0.527 0.477 0.423 0.367 0.312
0.260 0.211 0.168 0.131 0.099 0.071 0.045 0.019 -0.011 -0.046 -0.089 -0.143
-0.209 -0.286 -0.374 -0.470 -0.571 -0.672 -0.768 -0.854 -0.925 -0.975 -1.000 -0.998
-0.967 -0.908 -0.822 -0.712

A.1.16 101 kHz Tone

Frequency for waveform generator: 101 kHz

Amplitude for waveform generator: 56,0 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.602 -0.356 -0.097 0.147 0.354 0.509 0.608 0.660 0.677 0.679 0.682 0.699
0.735 0.790 0.854 0.916 0.966 0.995 1.000 0.983 0.952 0.917 0.886 0.865
0.856 0.856 0.855 0.845 0.819 0.770 0.699 0.612 0.518 0.427 0.348 0.285
0.234 0.189 0.136 0.063 -0.042 -0.182 -0.352 -0.540 -0.723 -0.876 -0.975 -1.000
-0.943 -0.805

A.1.17 106 kHz Tone

Frequency for waveform generator: 106 kHz

Amplitude for waveform generator: 51,9 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.582 -0.331 -0.067 0.180 0.387 0.540 0.636 0.683 0.696 0.693 0.693 0.707
0.742 0.796 0.859 0.921 0.970 0.997 1.000 0.981 0.948 0.911 0.879 0.857
0.849 0.848 0.847 0.838 0.810 0.760 0.689 0.601 0.506 0.415 0.337 0.274
0.225 0.181 0.129 0.056 -0.048 -0.189 -0.361 -0.549 -0.732 -0.884 -0.979 -1.000
-0.937 -0.792

A.1.18 111 kHz Tone

Frequency for waveform generator: 111 kHz

Amplitude for waveform generator: 48,3 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.563 -0.306 -0.038 0.211 0.418 0.570 0.663 0.706 0.714 0.707 0.704 0.716
0.749 0.802 0.865 0.926 0.973 0.999 1.000 0.979 0.944 0.905 0.871 0.849
0.840 0.840 0.839 0.830 0.802 0.751 0.678 0.589 0.494 0.402 0.324 0.263
0.215 0.172 0.122 0.050 -0.055 -0.197 -0.369 -0.558 -0.741 -0.891 -0.984 -1.000
-0.931 -0.780

A.1.19 116 kHz Tone

Frequency for waveform generator: 116 kHz

Amplitude for waveform generator: 45,2 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.546 -0.283 -0.011 0.241 0.448 0.598 0.688 0.727 0.731 0.721 0.714 0.724
0.756 0.807 0.869 0.930 0.976 1.000 0.999 0.976 0.938 0.897 0.863 0.840
0.831 0.830 0.830 0.820 0.792 0.740 0.666 0.576 0.480 0.389 0.311 0.250
0.204 0.163 0.113 0.042 -0.063 -0.205 -0.378 -0.567 -0.749 -0.898 -0.988 -1.000
-0.925 -0.768

A.1.20 121 kHz Tone

Frequency for waveform generator: 121 kHz

Amplitude for waveform generator: 42,4 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.529 -0.261 0.015 0.268 0.476 0.624 0.711 0.746 0.746 0.732 0.722 0.730
0.760 0.811 0.872 0.932 0.977 1.000 0.997 0.972 0.933 0.890 0.855 0.832
0.822 0.822 0.821 0.811 0.782 0.730 0.656 0.565 0.468 0.377 0.299 0.239
0.194 0.154 0.106 0.034 -0.071 -0.213 -0.387 -0.576 -0.758 -0.905 -0.992 -1.000
-0.920 -0.757

A.1.21 126 kHz Tone

Frequency for waveform generator: 126 kHz

Amplitude for waveform generator: 37,5 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.551 -0.333 -0.101 0.130 0.343 0.527 0.674 0.779 0.843 0.872 0.875 0.861
0.842 0.825 0.819 0.827 0.849 0.882 0.920 0.958 0.986 1.000 0.994 0.968
0.921 0.859 0.786 0.710 0.638 0.574 0.522 0.481 0.449 0.420 0.387 0.341
0.274 0.182 0.062 -0.084 -0.250 -0.427 -0.602 -0.760 -0.887 -0.971 -1.000 -0.970
-0.881 -0.738

A.1.22 131 kHz Tone

Frequency for waveform generator: 131 kHz

Amplitude for waveform generator: 35,3 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.533 -0.311 -0.075 0.157 0.371 0.555 0.700 0.802 0.864 0.890 0.889 0.872
0.850 0.831 0.823 0.830 0.851 0.884 0.922 0.959 0.987 1.000 0.993 0.965
0.917 0.853 0.780 0.703 0.630 0.566 0.514 0.474 0.443 0.415 0.382 0.336
0.269 0.177 0.056 -0.091 -0.258 -0.435 -0.610 -0.768 -0.893 -0.974 -1.000 -0.966
-0.873 -0.725

A.1.23 136 kHz Tone

Frequency for waveform generator: 136 kHz

Amplitude for waveform generator: 33,4 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.515 -0.289 -0.050 0.185 0.400 0.584 0.727 0.828 0.886 0.909 0.905 0.885
0.859 0.838 0.829 0.834 0.855 0.887 0.925 0.961 0.988 1.000 0.992 0.962
0.913 0.848 0.772 0.695 0.621 0.557 0.505 0.465 0.435 0.407 0.375 0.329
0.263 0.170 0.049 -0.099 -0.266 -0.444 -0.619 -0.776 -0.899 -0.977 -1.000 -0.962
-0.864 -0.711

A.1.24 141 kHz Tone

Frequency for waveform generator: 141 kHz

Amplitude for waveform generator: 31,6 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.498 -0.268 -0.026 0.211 0.428 0.611 0.754 0.852 0.908 0.928 0.920 0.897
0.868 0.845 0.834 0.838 0.857 0.889 0.926 0.962 0.989 1.000 0.991 0.960
0.910 0.843 0.767 0.688 0.614 0.549 0.498 0.458 0.428 0.401 0.370 0.324
0.258 0.165 0.043 -0.105 -0.274 -0.452 -0.627 -0.783 -0.905 -0.981 -1.000 -0.958
-0.856 -0.699

A.1.25 146 kHz Tone

Frequency for waveform generator: 146 kHz

Amplitude for waveform generator: 30,1 mV_{pp}

Data points for one cycle, normalized to ±1:

-0.482 -0.249 -0.004 0.235 0.453 0.636 0.777 0.873 0.927 0.943 0.933 0.906 0.876 0.850
0.837 0.840 0.859 0.890 0.928 0.963 0.990 1.000 0.990 0.958 0.906 0.838 0.761 0.681
0.606 0.542 0.490 0.452 0.422 0.396 0.364 0.320 0.253 0.160 0.038 -0.111 -0.280 -0.459
-0.634 -0.789 -0.910 -0.984 -1.000 -0.955 -0.848 -0.687

Annex B (normative): Random Impulse Noise Sample Points

This annex lists data points for random impulse noise that you can load into a waveform generator.

B.1 Random Impulse Noise Sample Points

This annex provides sample data points for the random impulse noise waveform described in clause 5.3. You can copy the values directly from the present document and paste them into a text file for loading into waveform generator 1. If your generator does not accept this normalized format, convert the values to a format that is compatible with your generator; see your generator's operator's manual.

The waveform includes the following information:

- The frequency to which you shall set the waveform generator.
- The amplitude to which you shall set the waveform generator.

A list of the samples for one full cycle of the waveform, normalized to a maximum value of +1,0 and a minimum value of -1,0.

B.1.1 120 Hz Random Impulse

Frequency for waveform generator: 120 Hz

Amplitude for waveform generator: 4,4 V_{pp}

Data points for one cycle, normalized to ±1:

0.084 0.082 0.072 0.067 0.062 0.057 0.050 0.043 0.035 0.026 0.018 0.011 0.002 -0.001 -
0.025 0.000 0.005 0.002 0.016 0.031 0.057 0.059 0.033 0.077 0.056 0.082 0.064 0.091
0.085 0.090 0.090 0.113 0.112 0.111 0.110 0.122 0.123 0.123 0.127 0.129 0.131 0.131
0.131 0.130 0.127 0.125 0.122 0.118 0.113 0.109 0.106 0.102 0.100 0.099 0.100 0.099
0.096 0.094 0.093 0.091 0.094 0.094 0.095 0.096 0.096 0.100 0.106 0.111 0.113 0.114
0.114 0.114 0.111 0.112 0.116 0.117 0.118 0.121 0.127 0.151 0.245 0.313 0.287 0.304
0.384 0.417 0.347 0.277 0.259 0.238 0.196 0.152 0.117 0.085 0.053 0.015 -0.022 -0.056 -
0.090 -0.122 -0.151 -0.177 -0.199 -0.216 -0.231 -0.242 -0.250 -0.256 -0.256 -0.253 -0.245
-0.233 -0.218 -0.200 -0.179 -0.152 -0.125 -0.096 -0.068 -0.041 -0.010 0.018 0.047 0.072
0.097 0.124 0.150 0.175 0.198 0.218 0.236 0.251 0.265 0.276 0.286 0.293 0.299 0.302
0.305 0.305 0.304 0.304 0.302 0.295 0.279 0.267 0.260 0.251 0.240 0.230 0.220 0.200
0.186 0.174 0.150 0.143 0.138 0.125 0.115 0.107 0.102 0.105 0.114 0.122 0.127 0.127
0.134 0.140 0.136 0.133 0.134 0.139 0.143 0.149 0.157 0.155 0.150 0.151 0.153 0.156
0.158 0.165 0.172 0.176 0.176 0.180 0.186 0.190 0.192 0.195 0.198 0.197 0.196 0.193
0.189 0.184 0.178 0.172 0.166 0.162 0.157 0.153 0.148 0.142 0.136 0.129 0.123 0.116
0.110 0.103 0.098 0.093 0.089 0.085 0.080 0.077 0.072 0.067 0.062 0.057 0.052 0.047
0.043 0.040 0.037 0.036 0.034 0.032 0.031 0.030 0.029 0.029 0.030 0.031 0.033 0.037
0.042 0.047 0.051 0.055 0.061 0.064 0.066 0.069 0.072 0.077 0.079 0.084 0.090 0.101
0.113 0.109 0.104 0.101 0.099 0.093 0.087 0.082 0.077 0.073 0.068 0.063 0.059 0.053
0.047 0.040 0.033 0.025 0.018 0.011 0.005 -0.001 -0.005 -0.009 -0.012 -0.014 -0.016 -
0.018 -0.021 -0.022 -0.023 -0.023 -0.023 -0.022 -0.019 -0.017 -0.014 -0.011 -0.007 -0.006
-0.004 -0.004 -0.004 -0.004 -0.003 -0.003 -0.003 -0.002 -0.001 0.000 0.000 0.000 -0.001 -
0.002 -0.003 -0.004 -0.005 -0.006 -0.006 -0.004 -0.003 -0.002 -0.001 0.000 0.000 0.000 -
0.001 -0.002 -0.002 -0.003 -0.002 -0.001 0.001 0.003 0.006 0.008 0.010 0.012 0.015 0.018
0.021 0.026 0.030 0.035 0.042 0.048 0.054 0.059 0.064 0.067 0.070 0.074 0.076 0.078
0.081 0.084 0.088 0.090 0.092 0.094 0.094 0.093 0.092 0.090 0.089 0.088 0.085 0.084
0.083 0.083 0.082 0.080 0.080 0.077 0.075 0.072 0.068 0.065 0.063 0.063 0.062 0.062
0.064 0.065 0.066 0.067 0.067 0.068 0.072 0.076 0.080 0.082 0.090 0.100 0.107 0.113
0.121 0.130 0.140 0.146 0.159 0.165 0.169 0.252 0.290 0.293 0.322 0.355 0.371 0.384
0.395 0.397 0.396 0.396 0.390 0.379 0.369 0.356 0.307 0.241 0.189 0.144 0.096 0.044 -
0.009 -0.057 -0.104 -0.152 -0.195 -0.230 -0.266 -0.295 -0.312 -0.322 -0.342 -0.345 -0.345

```
-0.328  -0.317  -0.317  -0.308  -0.278  -0.256  -0.247  -0.223  -0.187  -0.147  -0.103  -0.066  -0.010
0.026  0.064  0.109  0.153  0.170  0.161  0.171  0.204  0.231  0.248  0.264  0.294  0.314  0.290
0.296  0.303  0.302  0.299  0.301  0.317  0.296  0.243  0.221  0.223  0.212  0.190  0.172  0.159
0.144  0.130  0.116  0.105  0.092  0.081  0.073  0.066  0.060  0.053  0.050  0.049  0.049  0.050
0.054  0.063  0.063  0.065  0.071  0.083  0.097  0.090  0.085  0.096  0.108  0.116  0.126  0.148
0.152  0.134  0.141  0.152  0.157  0.162  0.174  0.176  0.175  0.185  0.172  0.173  0.174  0.179
0.194  0.188  0.169  0.186  0.212  0.221  0.224  0.229  0.229  0.221  0.223  0.233  0.235  0.231
0.234  0.241  0.243  0.244  0.244  0.246  0.251  0.243  0.240  0.242  0.242  0.240  0.238  0.233
0.229  0.229  0.223  0.222  0.219  0.215  0.211  0.208  0.203  0.196  0.190  0.181  0.171  0.164
0.155  0.146  0.140  0.132  0.125  0.120  0.110  0.114  0.136  0.115  0.121  0.137  0.146  0.151
0.155  0.162  0.167  0.172  0.175  0.176  0.177  0.175  0.173  0.173  0.169  0.164  0.161  0.158
0.151  0.142  0.134  0.129  0.099  0.076  0.062  0.036  0.005  -0.024  -0.053  -0.081  -0.113  -0.165
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-0.272  -0.250  -0.226  -0.202  -0.176  -0.147  -0.115  -0.081  -0.048  -0.012  0.023  0.056  0.084
0.114  0.143  0.170  0.195  0.218  0.242  0.264  0.286  0.307  0.324  0.357  0.422  0.494  0.526
0.563  0.598  0.617  0.638  0.643  0.644  0.639  0.624  0.630  0.652  0.640  0.625  0.606  0.581
0.541  0.426  0.341  0.280  0.272  0.241  0.186  0.127  0.018  -0.012  -0.030  -0.145  -0.225  -0.272
-0.331  -0.389  -0.438  -0.476  -0.505  -0.526  -0.541  -0.547  -0.547  -0.506  -0.492  -0.494  -0.444
-0.397  -0.386  -0.347  -0.307  -0.275  -0.215  -0.169  -0.127  -0.078  -0.031  0.015  0.054  0.091
0.131  0.168  0.202  0.230  0.261  0.282  0.289  0.300  0.310  0.309  0.301  0.294  0.288  0.268
0.248  0.228  0.206  0.179  0.147  0.115  0.086  0.057  0.026  -0.006  -0.039  -0.069  -0.097  -0.125
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-0.189  -0.173  -0.156  -0.138  -0.118  -0.097  -0.077  -0.057  -0.036  -0.013  0.009  0.029  0.048
0.064  0.077  0.091  0.102  0.115  0.125  0.135  0.143  0.151  0.158  0.163  0.167  0.168  0.168
0.165  0.162  0.157  0.151  0.145  0.138  0.132  0.125  0.119  0.112  0.104  0.097  0.088  0.080
0.074  0.067  0.062  0.057  0.051  0.047  0.046  0.042  0.039  0.037  0.035  0.032  0.029  0.027
0.026  0.026  0.026  0.028  0.030  0.034  0.037  0.040  0.042  0.045  0.047  0.051  0.055  0.059
0.064  0.068  0.074  0.086  0.096  0.102  0.111  0.119  0.133  0.153  0.171  0.187  0.201  0.215
0.227  0.238  0.247  0.255  0.260  0.262  0.263  0.264  0.261  0.260  0.256  0.252  0.249  0.244
0.239  0.222  0.229  0.216  0.201  0.199  0.202  0.202  0.199  0.196  0.195  0.194  0.192  0.191
0.190  0.187  0.185  0.184  0.183  0.181  0.185  0.177  0.180  0.184  0.169  0.174  0.161  0.157
0.147  0.139  0.125  0.120  0.115  0.101  0.099  0.095  0.087  0.081  0.087  0.080  0.063  0.068
0.067  0.053  0.058  0.054  0.051  0.046  0.047  0.048  0.048  0.052  0.047  0.036  0.045  0.033
0.036  0.044  0.039  0.039  0.039  0.034  0.063  0.068  0.072  0.086  0.102  0.114  0.122  0.131
0.138  0.145  0.154  0.160  0.163  0.165  0.167  0.165  0.163  0.158  0.150  0.143  0.134  0.125
0.119  0.110  0.092  0.062  0.047  0.022  -0.009  -0.038  -0.064  -0.086  -0.108  -0.128  -0.144  -
0.157  -0.168  -0.177  -0.183  -0.187  -0.189  -0.189  -0.186  -0.180  -0.171  -0.159  -0.145  -0.128
-0.109  -0.090  -0.070  -0.050  -0.029  -0.008  0.014  0.036  0.057  0.076  0.097  0.120  0.135
0.187  0.203  0.227  0.270  0.300  0.325  0.350  0.357  0.366  0.372  0.368  0.360  0.350  0.337
0.321  0.301  0.280  0.258  0.234  0.212  0.190  0.168  0.147  0.128  0.111  0.094  0.078  0.065
0.053  0.041  0.030  0.023  0.018  0.014  0.011  0.013  0.019  0.025  0.031  0.038  0.049  0.060
0.071  0.078  0.089  0.105  0.114  0.123  0.135  0.145  0.155  0.159  0.159  0.157  0.157  0.155
0.150  0.142  0.135  0.128  0.119  0.112  0.101  0.091  0.081  0.071  0.061  0.050  0.040  0.031
0.023  0.018  0.015  0.012  0.011  0.010  0.010  0.010  0.012  0.015  0.019  0.024  0.030  0.038
0.046  0.054  0.063  0.070  0.077  0.083  0.091  0.098  0.106  0.113  0.121  0.128  0.135  0.142
0.147  0.152  0.155  0.156  0.156  0.155  0.154  0.152  0.150  0.147  0.145  0.141  0.139  0.136
0.131  0.126  0.120  0.115  0.111  0.106  0.102  0.101  0.105  0.100  0.093  0.094  0.094  0.094
0.093  0.090  0.095  0.098  0.108  0.112  0.113  0.120  0.127  0.130  0.135  0.137  0.138  0.139
0.140  0.141  0.140  0.141  0.140  0.139  0.139  0.137  0.133  0.130  0.124  0.120  0.113  0.106
0.101  0.095  0.090  0.085  0.081  0.077  0.074  0.070  0.066  0.062  0.058  0.054  0.051  0.051
0.051  0.052  0.054  0.057  0.061  0.064  0.067  0.071  0.074  0.077  0.083  0.090  0.102  0.117
0.130  0.158  0.201  0.273  0.303  0.334  0.362  0.389  0.414  0.428  0.436  0.444  0.448  0.448
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0.027  0.068  0.101  0.137  0.170  0.205  0.234  0.261  0.281  0.298  0.308  0.314  0.316  0.315
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0.062  -0.060  -0.055  -0.049  -0.042  -0.035  -0.026  -0.018  -0.009  0.000  0.009  0.022  0.036
0.053  0.071  0.087  0.104  0.121  0.134  0.146  0.158  0.167  0.174  0.181  0.186  0.191  0.194
0.199  0.202  0.204  0.205  0.203  0.200  0.197  0.192  0.187  0.182  0.176  0.171  0.166  0.161
0.156  0.149  0.143  0.136  0.128  0.120  0.114  0.105  0.100  0.096  0.091  0.089  0.086  0.084
0.083  0.082  0.083  0.082  0.083  0.086  0.087  0.092  0.087  0.119  0.112  0.123  0.171  0.214
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0.437  0.421  0.404  0.387  0.364  0.344  0.313  0.270  0.238  0.198  0.143  0.096  0.052  -0.001  -
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0.281  0.291  0.300  0.308  0.309  0.304  0.298  0.288  0.280  0.270  0.259  0.245  0.230  0.215
```

```
0.201 0.186 0.171 0.155 0.140 0.124 0.109 0.095 0.084 0.074 0.066 0.058 0.051 0.045
0.040 0.034 0.028 0.024 0.021 0.018 0.016 0.017 0.018 0.021 0.024 0.029 0.033 0.038
0.043 0.048 0.052 0.058 0.064 0.069 0.075 0.081 0.090 0.097 0.103 0.110 0.116 0.119
0.123 0.124 0.127 0.129 0.130 0.132 0.133 0.135 0.135 0.135 0.134 0.131 0.129 0.126
0.124 0.122 0.120 0.119 0.118 0.117 0.117 0.117 0.116 0.114 0.112 0.110 0.108 0.106
0.105 0.105 0.107 0.108 0.110 0.112 0.113 0.115 0.116 0.118 0.120 0.122 0.126 0.131
0.137 0.144 0.151 0.160 0.168 0.175 0.184 0.192 0.203 0.217 0.293 0.348 0.376 0.397
0.366 0.420 0.462 0.471 0.486 0.452 0.388 0.443 0.401 0.315 0.301 0.286 0.236 0.195
0.148 0.104 0.068 0.028 -0.013 -0.054 -0.088 -0.118 -0.144 -0.167 -0.184 -0.198 -0.201 -
0.200 -0.197 -0.180 -0.145 -0.031 0.034 0.061 0.111 0.164 0.211 0.253 0.291 0.325 0.349
0.371 0.393 0.411 0.379 0.317 0.266 0.223 0.172 0.116 0.066 0.014 -0.043 -0.100 -0.158 -
0.211 -0.262 -0.310 -0.353 -0.390 -0.422 -0.448 -0.467 -0.480 -0.488 -0.491 -0.488 -0.478
-0.465 -0.444 -0.418 -0.387 -0.352 -0.314 -0.271 -0.228 -0.185 -0.142 -0.096 -0.053 -0.010
0.031 0.068 0.102 0.137 0.171 0.200 0.225 0.247 0.265 0.278 0.288 0.293 0.295 0.293
0.289 0.282 0.273 0.262 0.248 0.232 0.215 0.197 0.177 0.157 0.136 0.118 0.099 0.083
0.071 0.058 0.046 0.034 0.022 0.011 0.001 -0.008 -0.015 -0.021 -0.025 -0.026 -0.026 -
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0.122 0.122 0.120 0.119 0.117 0.116 0.114 0.114 0.113 0.112 0.112 0.111 0.109 0.106
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0.099 0.100 0.102 0.104 0.107 0.111 0.115 0.118 0.120 0.122 0.123 0.124 0.123 0.123
0.124 0.124 0.125 0.125 0.125 0.125 0.124 0.123 0.121 0.117 0.115 0.112 0.110 0.108
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0.112 0.111 0.110 0.108 0.106 0.104 0.101 0.098 0.096 0.094 0.092 0.089 0.086 0.083
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0.534 0.540 0.545 0.549 0.543 0.528 0.514 0.504 0.481 0.448 0.416 0.378 0.342 0.302
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0.129 0.151 0.171 0.187 0.199 0.208 0.214 0.218 0.220 0.219 0.216 0.211 0.204 0.194
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0.135 0.141 0.147 0.141 0.132 0.131 0.122 0.115 0.111 0.106 0.104 0.101 0.099 0.098
0.098 0.101 0.107 0.116 0.129 0.138 0.165 0.226 0.275 0.337 0.382 0.431 0.471 0.502
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0.269 0.222 0.167 0.121 0.080 0.032 -0.034 -0.087 -0.107 -0.144 -0.195 -0.241 -0.277 -
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0.107 0.106 0.106 0.105 0.103 0.102 0.101 0.100 0.099 0.098 0.099 0.100 0.102 0.102
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0.055 0.057 0.062 0.066 0.070 0.073 0.077 0.078 0.083 0.088 0.092 0.097 0.105 0.115
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History

Document history		
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