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Technical Report

PowerLine Telecommunications (PLT);
MIMO PLT;
Part 2: Measurement Methods and
Statistical Results of MIMO PLT EMI

Reference
DTR/PLT-00029

Keywords
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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Powerline Telecommunications (PLT).

The present document is part 2 of a multi-part deliverable. Full details of the entire series can be found in part 1 [i.9].

Introduction

In order to study and compare MIMO (Multiple Input Multiple Output) characteristics of the LVDN network in different countries the STF 410 (Special Task Force) was set up. The present document is one of three TRs which present the result of the work of STF 410. The work items in ETSI TC PLT dealing with the results of STF 410 are TR 101 562-1 [i.9], the present document and TR 101 562-3 [i.5]. The PLT coupler used to feeding the signals into the LVDN is described in TR 101 562-1 [i.9].

The present document specified the measurement tools, set-up and procedure to record the interference potential of MIMO PLT transmissions.

1 Scope

MIMO PLT EMI review and statistical analysis taking into account such matters as earthing variation, country variation, operator differences, phasing and distribution topologies, domestic, industrial and housing types along with local network loading.

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 reference document (including any amendments) applies.

Referenced documents which are not found to be publicly available in the expected location might be found at http://docbox.etsi.org/Reference.

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.

Not applicable.

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] Sartenaer, T. & Delogne, P., "Powerline Cables Modelling for Broadband Communications", ISPLC 2001, pp. 331-337.

[i.2] R. Hashmat, P. Pagani, A; Zeddam, T. Chonavel, "MIMO Communications for Inhome PLC Networks: Measurements and Results up to 100 MHz", IEEE International Symposium on Power Line Communications and its Applications (ISPLC), Rio, Brasil, March 2010.

[i.3] A. Schwager, "Powerline Communications: Significant Technologies to become Ready for Integration" Doctoral Thesis at University of Duisburg-Essen, May 2010.

[i.4] ETSI TR 102 175 (V1.1.1): "PowerLine Telecommunications (PLT); Channel characterization and measurement methods".

[i.5] ETSI TR 101 562-3: "Powerline Telecommunications (PLT); MIMO PLT; Part 3: Measurement Methods and Statistical Results of MIMO PLT channels".

[i.6] ETSI TR 102 616 (V1.1.1): "PowerLine Telecommunications (PLT); Report from PlugtestsTM 2007 on coexistence between PLT and short wave radio broadcast; Test cases and results".

[i.7] ITU-R Recommendation BS.1284: "General methods for the subjective assessment of sound quality".

NOTE: See http://stason.org/TULARC/radio/shortwave/08-What-is-SINPO-SIO-Shortwave-radio.html.

[i.8] SCHWARZBECK MESS - ELEKTRONIK; EFS 9218 Active Electric Field Probe with Biconical Elements and built-in Amplifier 9 kHz ... 300 MHz.

NOTE: See http://www.schwarzbeck.de/Datenblatt/m9218.pdf.

[i.9] ETSI TR 101 562-1: "PowerLine Telecommunications (PLT); MIMO PLT; Part 1: Universal Coupler, Operating Instructions - Description".

[i.10] R&S®HFH2-Z2 Loop Antenna Broadband active loop antenna for measuring the magnetic field-strength; 9 kHz - 30 MHz.

NOTE: See http://www2.rohde-schwarz.com/en/products/test_and_measurement/emc_field_strength/emc_accessories/.

[i.11] CISPR 11 (Ed. 5.0): "Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement".

[i.12] CISPR 22 (Ed. 6.0): "Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement".

3 Symbols and abbreviations

3.1 Symbols

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

A_L	Inductance factor
I	Current
L	Inductance
L_{PE}	Protective earth inductance
nF	nanoFarads
nH	nanoHenry
Z	Impedance
Z_{asy}	Asymmetric impedance

3.2 Abbreviations

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

AM	Amplitude Modulation
BNC	Bayonet Nut Connector
CDF	Cumulative Distribution Function
CM	Common Mode
CMAD	Common Mode Absorption Devices
CSV	Comma separated values
DM	Differential Mode
E	Protective Earth contact
EMC	Electromagnetic Compatibility
EMI	Electro Magnetic Interference
FD	Frequency Domain
FM	Frequency Modulation
GPS	Global Positioning System
HF	High Frequency
HIFI	High Fidelity
IF	Intermediate frequency
LCZC	Line Cycle Zero Crossing
LISN	Line Impedance Stabilization Network
LVDN	Low voltage distribution network
MIMO	Multiple Input Multiple Output

N Neutral contact

NOTE: Used as decoupling filter.

NWA Network Analyzer
P Phase or life contact
PC Personal computer
PE Protective Earth
PLC PowerLine Communication
PLT Powerline Telecommunication
PSD Power Spectral Density
RF Radio Frequency
Rx Receiver
SINPO Signal, Interference, Noise, Propagation, Overall
SISO Single Input Single Output
STF Special Task Force
TD Time Domain
Tx Transmitter
VHF Very High Frequency

3.2.1 Abbreviations used for feeding styles

EPNT Signal feed mode: DELTA (differential) between E and P, PN and NE not terminated
EP Signal feed mode: DELTA (differential) between E and P, PN and NE terminated
NENT Signal feed mode: DELTA (differential) between N and E, PN and EP not terminated
NE Signal feed mode: DELTA (differential) between N and E, PN and EP terminated
PNNT Signal feed mode: DELTA (differential) between P and N, NE and EP not terminated (SISO)
PN Signal feed mode: DELTA (differential) between P and N, NE and EP terminated
CM Signal feed mode: Common mode, P, N, E terminated to ground
APN Signal feed mode: Dual wire feed (version C in [i.9]) to input P||N E in Figure 11 of [i.9]
PNE Signal feed mode: Dual wire feed (version C in [i.9]) to input PN in Figure 11 of [i.9]
EP-NET Signal feed mode: Differential between E and P, only NE terminated
NE-EPT Signal feed mode: Differential between N and E, only EP terminated

4 Major Project Phases

Table 1

No.	Period	Topic	Event
01	Sept. 2010	Project organization Definition of targets, what and how to measure	STF 410 preparatory meeting Stuttgart, Germany
02	Nov 2010	Setup of MIMO EMI measurements	Several STF 410 phone conferences
03	March 2011 to June 2011	Field measurements	In Spain, Germany, France
04	June 2011	Statistical evaluation of results	Several STF 410 phone conferences
05	June/July 2011		Drafting and STF 410 review and approval process

5 Motivation

PLT systems available today use only one transmission path between two outlets. It is the differential channel between live and neutral contact. Such systems are called SISO (Single Input Single Output) modems. MIMO PLT systems do not use one transmission path only. The utilisation of the third wire, the PE (Protective Earth) wire allows several combinations to feed and receive signals into and from the LVDN. Various research publications [i.1], [i.2], [i.3] or [i.4] describe that up to 8 transmission paths might be used simultaneously.

Further descriptions of:

- motivation for MIMO PLT;
- installation types and the existence of the PE wire in private homes;
- measurement Setup description to record throughput communication parameters and their results;

can be found in [i.5] and [i.9].

6 Measurement Description

6.1 Introduction

EMI properties of the LVDN could be recorded in in Time- (TD) or in Frequency Domain (FD). At the beginning of the work of STF 410 the pros and cons of each possibility were evaluated. STF 410 decided to use the FD approach for the following reasons.

Most of earlier EMC measurements relating to PLC were performed in FD. Thus the comparison between the results of STF 410 and those of the past is much easier in FD.

The human ear is essentially an FD analyzer.

Interferences assessed by human ears like the SINPO measurements use Consumer Electronic devices like AM or FM radio receivers. Such measurements were performed in [i.6] and [i.7]. MIMO tests signals are fed to all Tx paths simultaneously or sequentially. These investigations are conducted with a pulsed signal to allow recognition by the human ear-brain-chain.

Field levels are monitored with a calibrated antenna. It is straight forward to process this in FD. EMI measurements in TD risk that periodicities in the transmitted PN-sequence may cause additional spurs. Furthermore the measurement dynamic seems not to be adequate in TD. EMI principally occur at transmissions of PLC modems and is considered at statistical evaluations.

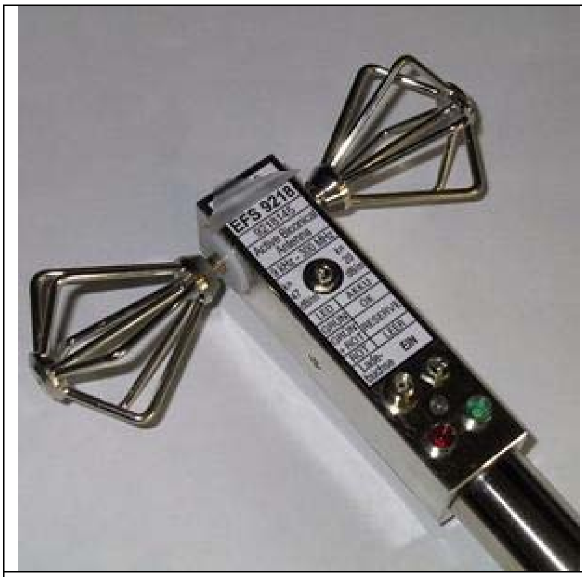
FD measurements could be done using a comb generator and spectrum (or EMI) analyser. This setup has the benefit that transmitter and receiver does not have to be synchronized. On the other hand the dynamic range or frequency resolution is limited due to the feeding energy of the comb generator has to be shared among all signal carriers.

Alternatively a sweeping source like a network analyser (NWA) might be used. Care has to be taken that especially the signals received by the antenna are not influenced by additional signal ingress into the long cables connecting it to the NWA. To minimize this effect double shielded cables, common mode absorption devices (CMADs) and ferrites have to be installed. Due to the faster recoding time of a frequency sweep and the high dynamic range this measurement method is selected by STF 410.

To enhance the number of measurements to be recorded STF 410 is split into several teams operating in parallel in various countries. Measurement campaigns where conducted in Germany, Swiss, Belgium, France and Spain. To guarantee comparability of the individually recorded data each team is equipped with identical probes or PLT couplers. The antenna is shipped to each team. The measurements itself are performed with a general purpose NWA.

Due to its frequency range of up to 100 MHz a commercial available small biconical antenna (with built-in amplifier) is used. In one location the loop antenna (limited to frequencies up to 30 MHz) is used for a comparison of this field tests with earlier measurement campaigns.

Figure 1 shows the measurement equipment used for EMI measurements.



Biconal Active Electric Field Probe [i.8]


AM, FM radio receiver: Sony® ICF-SW1000T


Biconal Antenna on wooden tripod


Loop Antenna (magnetic field) [i.10]

	
NWA, Spectum Analyzer, Amp, Isolation Transformer, LISN and power filters	NWA, Amp, mounted Antenna, and double shielded cables

NOTE: Sony® ICF-SW1000T is an example of a suitable product available commercially. This information is given for the convenience of users of the present document and does not constitute an endorsement by ETSI of this product.

Figure 1: Measurement equipment used by individual teams

6.2 General Requirements for the Measurements

At the beginning of a measurement day the power supply for the measurements equipment has to be prepared. It has to be clean and maximal separated from the grid of the living unit under test. It is recommended to use the power supply from e.g. a neighbour flat, a backup power supply or at least a power plug far away from the installation to be measured. In case of a connection to the electricity grid the power supply has to be filtered. A filtering device for phase, neutral and the protective earth is documented in [i.5]. An isolation transformer is also be included into the power supply filtering. The isolation transformer cuts the protective earth. This is necessary because usually today's power filters do not filter protective earth wire. This is also valid for the used measurement equipment.

The test signals for all EMI measurements are fed using the MIMO PLC couplers specified in [i.9].

6.3 Radiation Measurements (k-factor)

6.3.1 Set-Up

The measurement set-up basically consists of a NWA connected with coupler A to the mains. The power supply of the NWA is separated from the LVDN under test by a filter providing > 100 dB isolation for each DM path as well CM signals. To enhance the dynamic range of the setup the NWA is connect to an amplifier and the amplified signal is feed in the MIMO Coupler. On the other side the antenna is connect through a cable with ferrites to a high-pass and the receiving end of the NWA. As High pass filter the HPF-002 described in [i.5], clause 7.6.1 (Noise measurement set-up) could be used. It attenuates signals below 2 MHz. In a few cases signals below 2 MHz have been identified reducing the dynamic range of the NWA. This is why they have to be filtered.

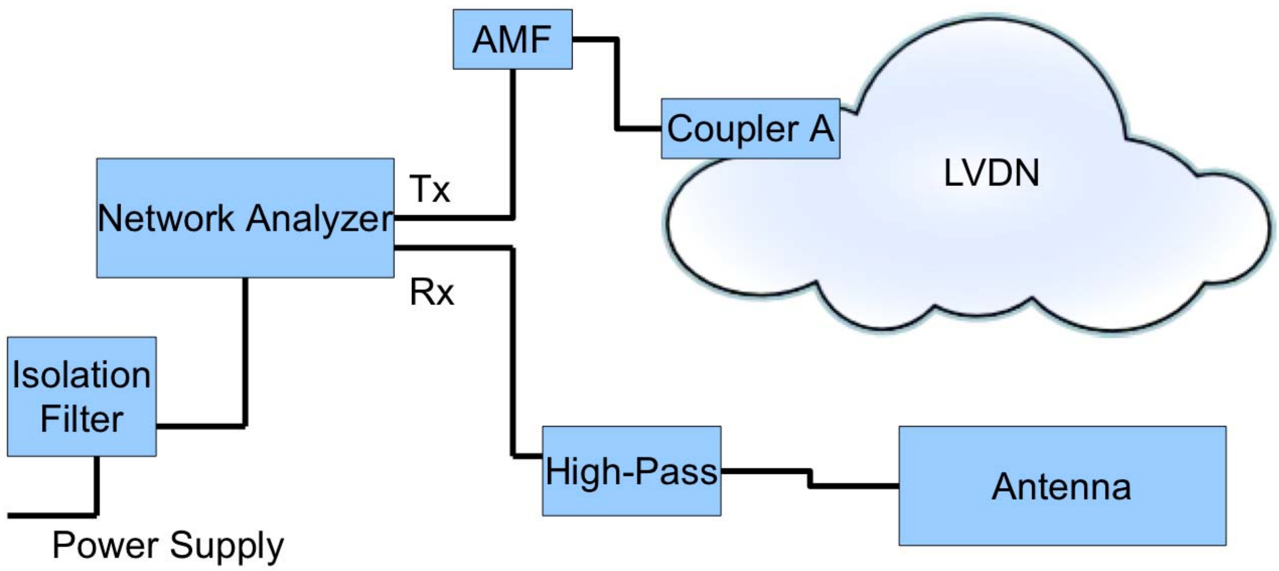


Figure 2: General measurement set-up for radiated EMI

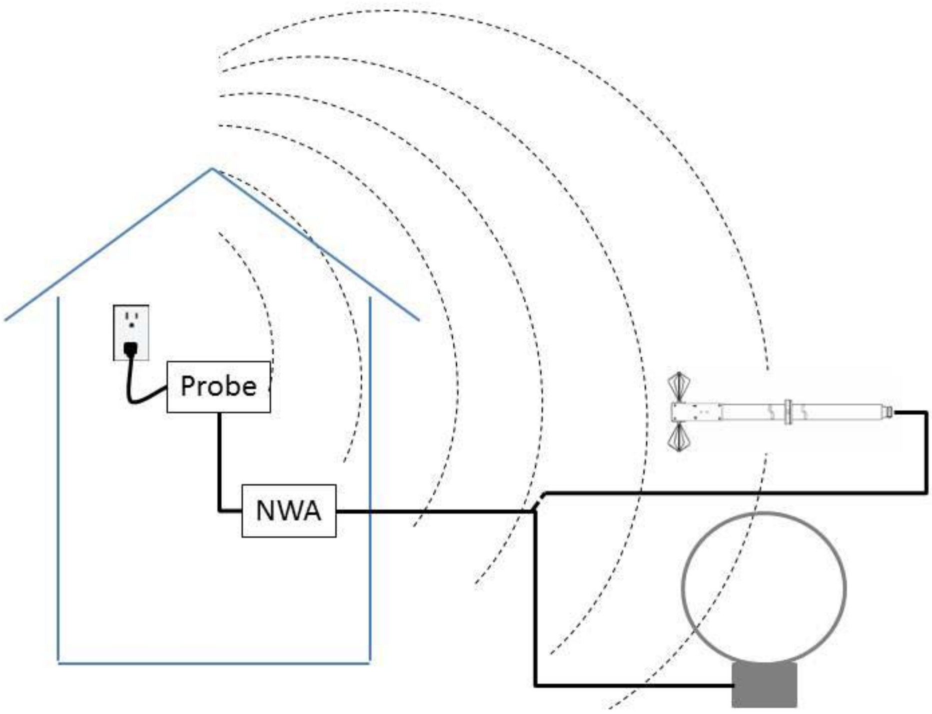


Figure 3: General measurement set-up to record the k-factor

The outlets used for feeding the signals are arbitrary selected in the building. The antenna is positioned in a distance of 10 m or 3 m from the exterior wall outside the building. Some antenna points are also selected within the building. Several antenna locations may be selected and the radiations recorded. If the measurement dynamic is not sufficient (signal has to be at least 10 dB above noise floor, i.e. the signal indicated by the NWA without the signal injection connected) an RF amplifier is placed in the line between NWA generator side and signal injection box. Care should be taken, that the output power is not more than 1 W to avoid damage of the injection boxes and disturbances of the appliances connected to the mains grid. In that case an attenuator of 30 dB has to be inserted between the cable connectors for calibration. For the calculation of the k-factor the 30 dB has to be subtracted from that derived according Eq.1.

NWA is operated using the following settings:

• Start Frequency:	1 MHz
• Stop Frequency:	100 MHz
• Number of measurement points per sweep:	1 601
• IF Bandwidth:	1 kHz
• Feeding Power:	+10 dBm, 0 dBm
• Data are recorded in ASCII format including at least:	frequency, Real part, Imaginary part, absolute value in dB.

Care has to be taken that the amplifier is not saturated.

The file name convention of the EMI record is:

Ptt_Fa_Ayy_Dp_o_xx.xx.CSV where:

- 'tt' is the number of the transmitting plug. The 1st digit indicates the level in the building where feeding was done.
- 'Fa' is the port where signals are fed differentially: EP, PN, NE, EPNT, PNNT, NENT, APN, PNE, EP-NET, NE-EPT and CM (see Figure 6).
- 'yy' identifies the location of the antenna (e.g. A01, A02, …., leading zeros are required).
- 'p' specified the place of the antenna: '0' is for 10m distance, '3' for 3m distance outside the building and 'I' for indoor.
- 'o' is the orientation of the antenna:
  - v' or 'h' in case of the biconical antenna. 'h' means the axis from dipole to dipole is in parallel to the horizon and 'v'-direction is vertically. Since this measurement campaign focus on the radiation produced by PLT, the measurements are performed with this two polarisations in agreement with typical disturbance field strengths measurements for products as defined in CISPR 11 [i.11] and CISPR 22 [i.12]. The max value out of the 2 orientations is used as specified in clause 6.3.4.
  - 'x', 'z' or 'z' in case of the loop antenna (x means H-field parallel to the building wall, z means H-field towards ground). It is common practise to measure the magnetic field in three directions (e.g. see German SchuTSEV). The vector sum of the 3 orientations will give the total H-field as specified in clause 6.3.4.
- 'xx.xx' is the timing distance to the rising LCZC at Tx coupler in ms when the sweep was recorded. If trigger of NWA was not in sync to LCZC 'xx.xx' is not applied.

E.g. if the filename is P22_PNNT_A01_D3_v.csv the feeding was done between P and N on the delta style and the 2 other ports (NE and EP) are not terminated. This is the conventional SISO style. The biconal Antenna was located at antenna position 01 in 3 m distance from the outside wall of the building in vertical orientation.

All antenna measurements are saved in the 'EMI' folder. The folder tree consists of:

STF 410→ Initials of Expert → Name of Location → EMI.

At least for the common mode injection a ground plane is required. The ground plane has to be connected directly (low inductance) to the coupling box. The size of the ground plane has to be at least 1 m^2.

For convenience the file handling tool (see annex B) can be used. This tool also can be helpful to guide through the measurements.

6.3.2 Calibration of NWA

To eliminate effects from the long cables used in the building the NWA needs to be calibrated. A response (thru) calibration is done by shortcutting the endings of both coaxial cables. As calibration kit a conventional adapter (BNC female to BNC female) is used.

Prior to the measurements the NWA has to be calibrated according to Figure 4. To prevent overload of the NWA input, the NWA generator setting has to be reduced as much as possible (typically -25 dBm). If the output power of the amplifier is still to much for the NWA input, refer to the alternative calibration procedure in annex A. Usually the Analyser automatically corrects the calibration data when the feeding power is raised after the calibration process.

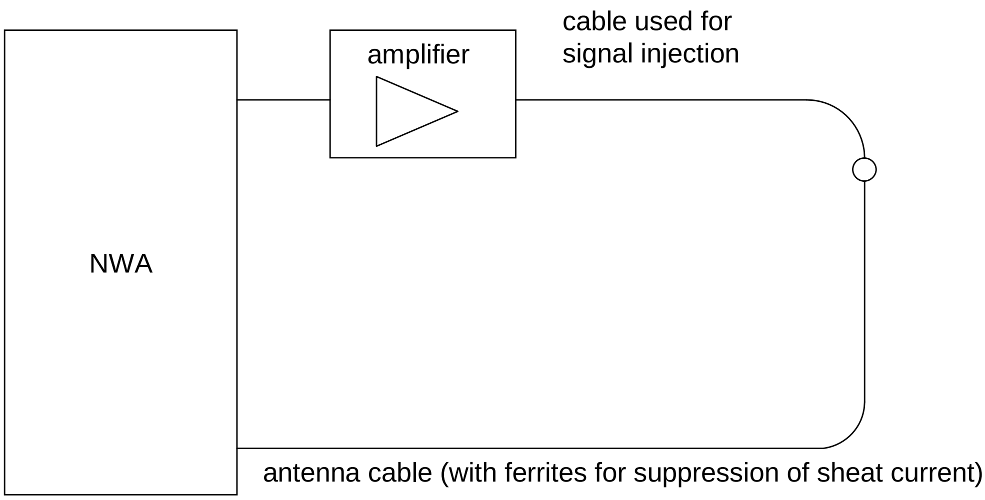


Figure 4: NWA calibration

During the measurements the cable ends of the NWA have to be connected to the MIMO coupler and the antenna according to Figure 5. The generator output power can be increased to increase the dynamic range of the measurements. Care has to be taken that the output power is not more than 1 W, to prevent overload of the MIMO coupler.

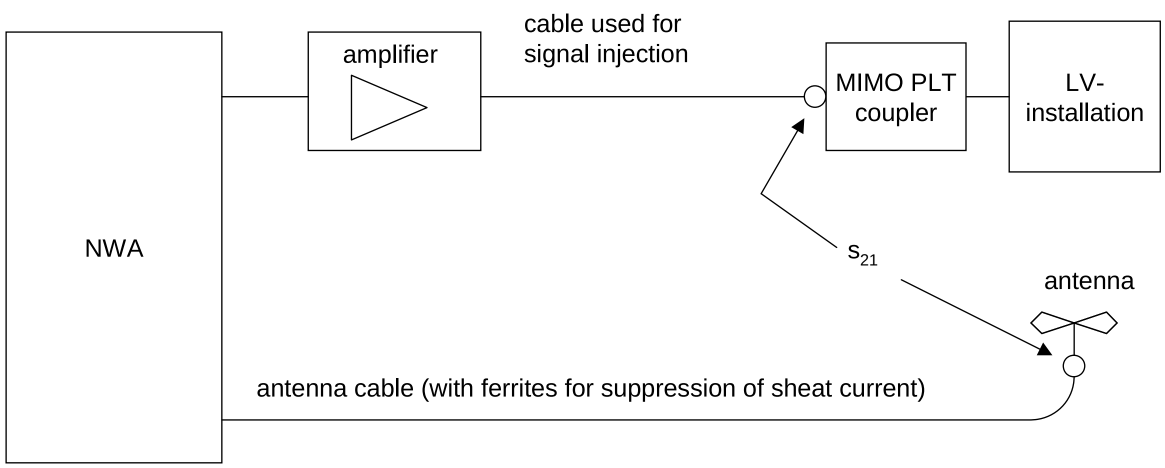
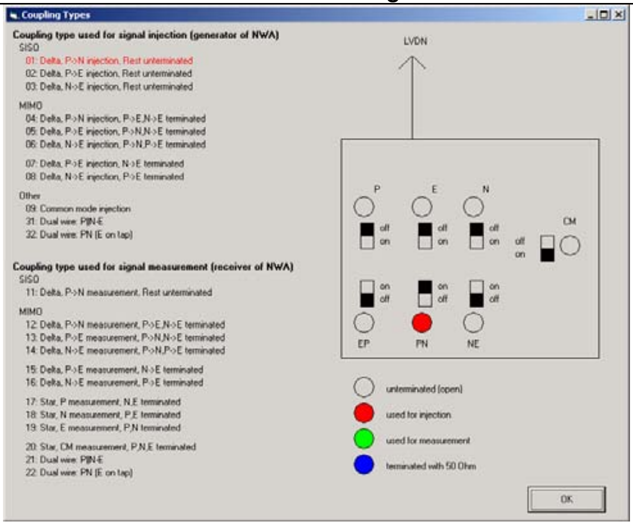


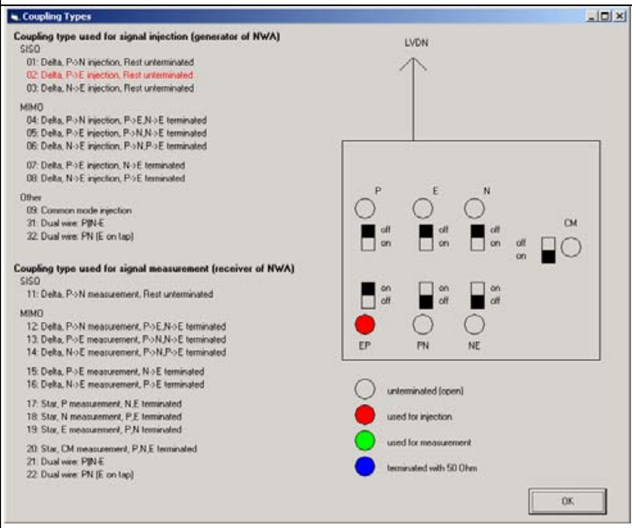
Figure 5: Use of NWA and setup for the measurements

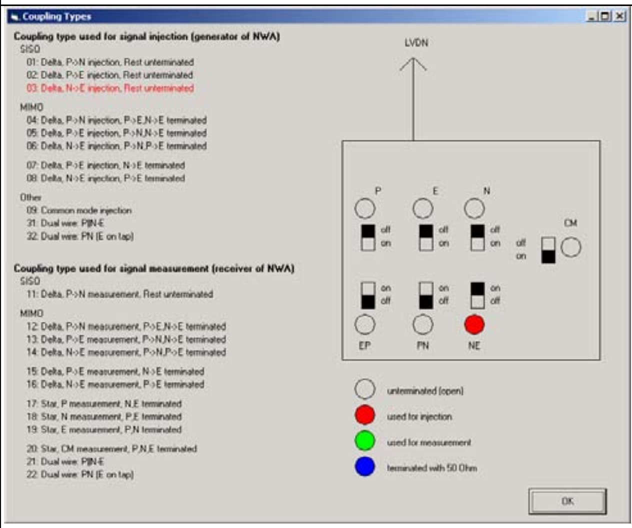
6.3.3 Signal injection

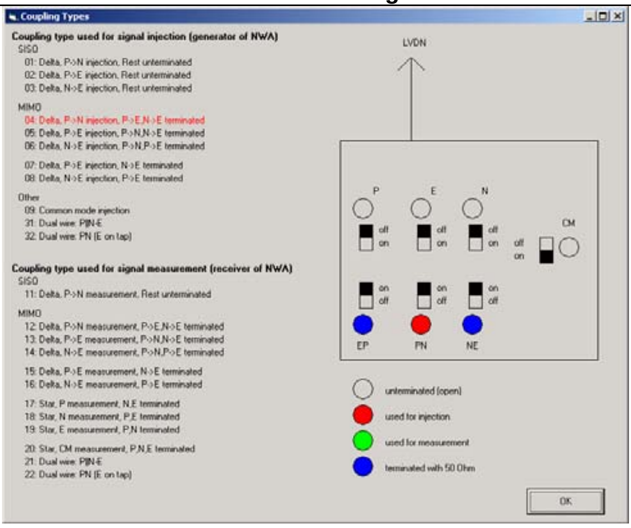
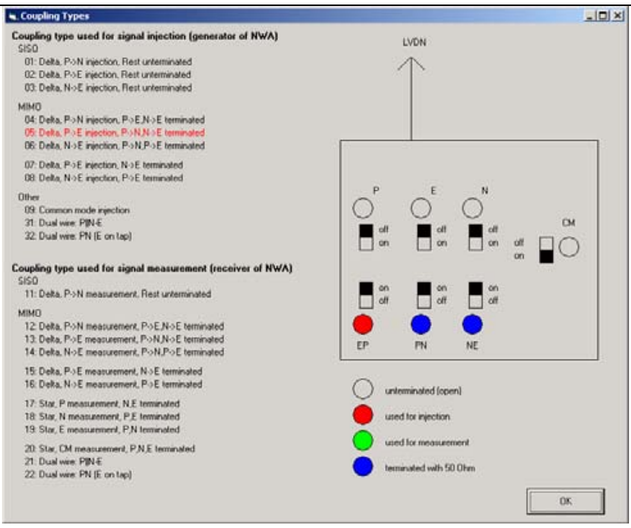
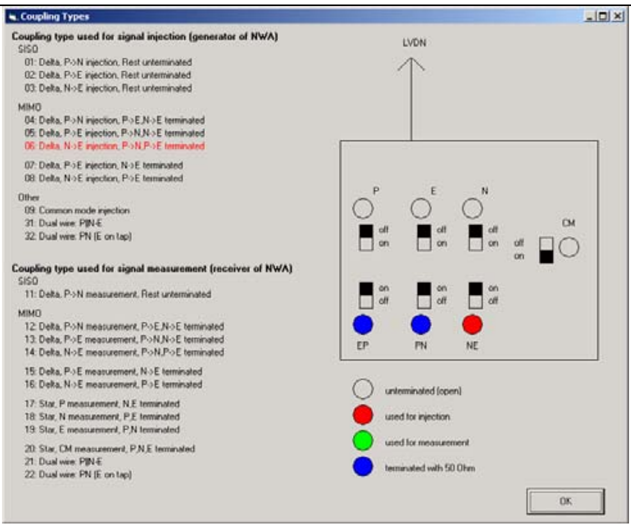
For the coupling modes the following switch settings for the boxes are to be used.

<table>
<tr><th>Coupling mode</th><th>Switch setting</th></tr>
<tr><td>PNNT

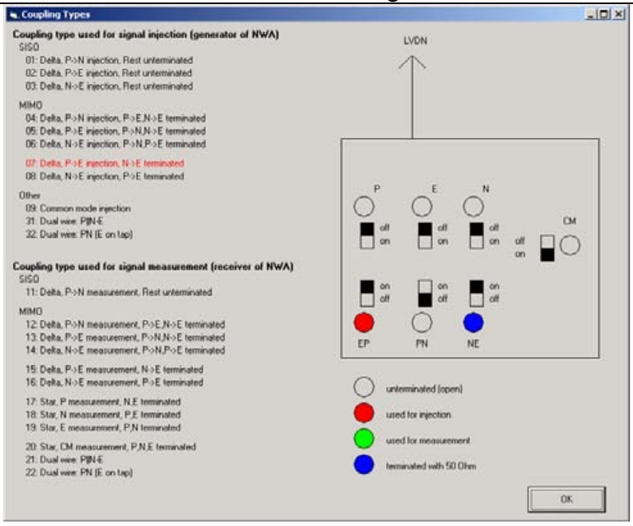
DELTA (differential) mode PN,
NE and EP NOT terminated
(standard SISO PN)
(see clause 10.1 of [i.9])</td><td>
</td></tr>
<tr><td>EPNT

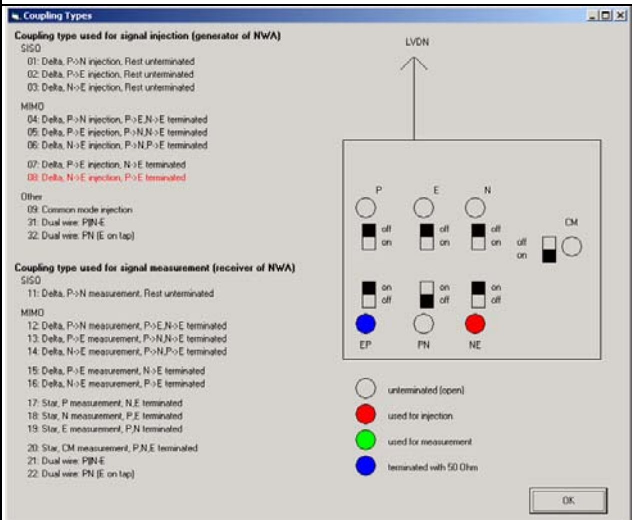
DELTA (differential) mode EP,
PN and NE NOT terminated(SISO EP)
(principle shown in clause 10.1 of [i.9])</td><td>
</td></tr>
<tr><td>NENT

DELTA (differential) mode NE,
EP and PN NOT terminated
(SISO NE)
(principle shown in clause 10.1 of [i.9])</td><td>
</td></tr>
</table>

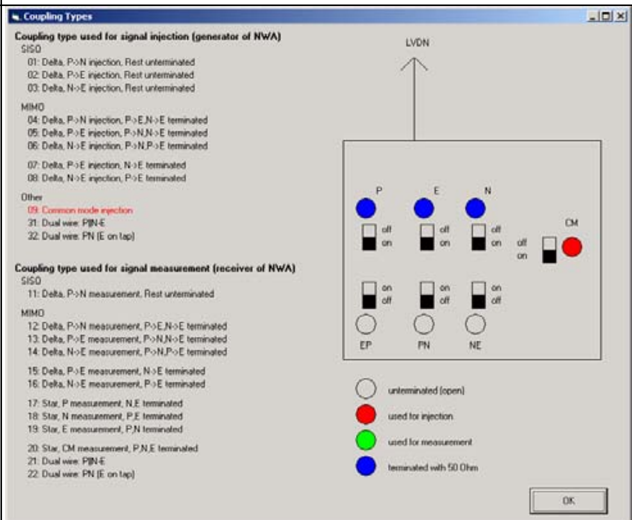
Coupling mode	Switch setting
PN DELTA (differential) mode PN, NE and EP terminated(MIMO) (principle shown in clause 10.2 of [i.9])	
EP DELTA (differential) mode EP, PN and NE terminated (MIMO) (principle shown in clause 10.2 of [i.9])	
NE DELTA (differential) mode NE, EP and PN terminated(MIMO) (see clause 10.2 of [i.9])	

<table>
<tr><th>Coupling mode</th><th>Switch setting</th></tr>
<tr><td>EP-NET

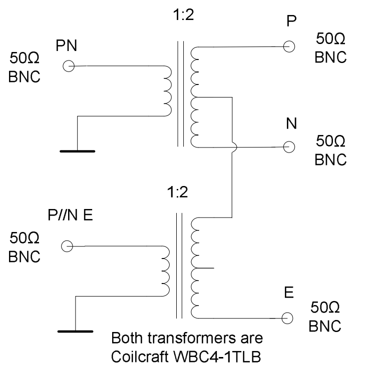
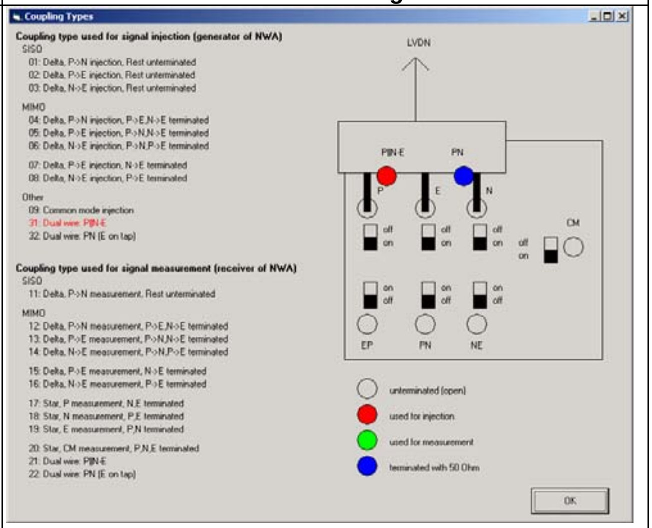
partial delta type injection,
signal between P and E,
N-E terminated,
P-N not terminated
(MIMO)</td><td>
</td></tr>
<tr><td>NE-EPT

partial delta type injection,
signal between N and E,
P-E terminated,
P-N not terminated
(MIMO)</td><td>
</td></tr>
<tr><td>CM

Common mode

(see clause 10.4 of [i.9])</td><td>
</td></tr>
</table>

<table>
<tr><th>Coupling mode</th><th>Switch setting</th></tr>
<tr><td>APN

Dual wire, input P||N - E
(see clause 10.5 (version C) of [i.9])

</td><td></td></tr>
<tr><td>PNE

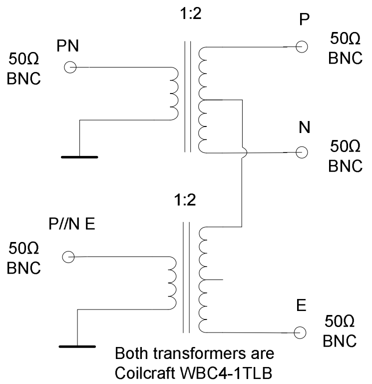
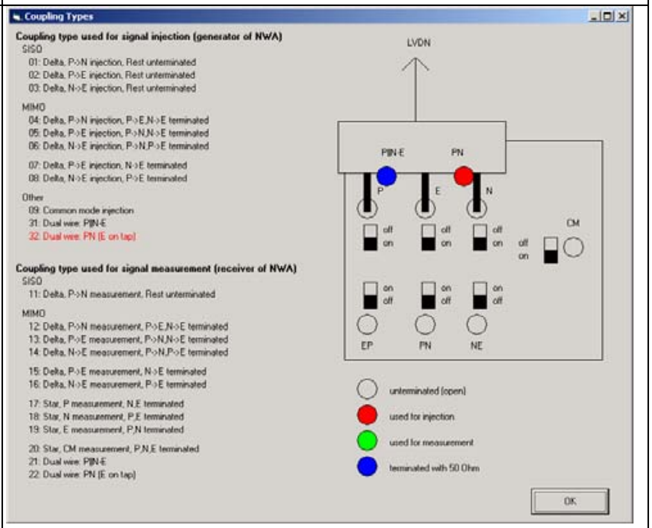
Dual wire input PN
(see clause 10.5 (version C) of [i.9])

</td><td></td></tr>
</table>

Figure 6: PLT Coupler switch settings

6.3.4 Calculation of the final k-factor

To evaluate the radiation of buildings the coupling factor (k-factor) is defined by:

$$\begin{aligned} k_{E,H} &= E_{antenna} - P_{\max,feed} \\ &= U_{Receiver} + AF - P_{\max,amp\_output} + A_{PLT\_Coupler} \\ &= P_{Receiver} + 107(\text{dB}\mu\text{V - dBm}) + AF - P_{\max,amp\_output} + A_{PLT\_Coupler} \\ &= s_{21} + 107(\text{dB}\mu\text{V - dBm}) + AF + A_{PLT\_Coupler} \end{aligned} \qquad \text{(Eq. 1)}$$

with

$E_{antenna}$: the field strength received at the location of the antenna, unit: dB(μV/m).

$P_{max,feed}$: signal at the output of the PLT coupler (in case of terminated output), unit dBm.

P_{max,amp_output}: signal at the output of the amplifier provided at the cable end (in case of termination), unit dBm.

$A_{PLT\_Coupler}$: Attenuation of the PLT coupler as described in [i.9], unit dB.

$U_{Receiver}$: voltage at the output of the antenna, unit dB(µV).

$P_{Receiver}$: power from the output of the antenna, unit dBm.

AF: antenna factor of the antenna, unit dB(1/m).

s_{21}: scattering parameter as measured by the network analyser with valid calibration, unit dB.

NOTE: If the alternative calibration procedure of annex A is used, the corrected s_{21} values have to be used in Eq. 1.

$k_{E,H}$: k-factor with regard to the electric field component (k_E) or magnetic field component (k_H), unit dB(µV/m)-dBm.

The k-factor is used first in [i.4]. The formula above says: If a signal is fed with 0 dBm into the mains of a building an electrical field of E dBµV/m is recorded outside the building.

From the recorded values s_{21} of the network analyser, the k-factor can be derived using Eq.1. Depending on the used antenna and the coupling, different values have to be used for $A_{PLT\_Coupler}$.

Table 2: Coupling types

Coupling type	$A_{PLT\_Coupler}$
EPNT, PNNT, NENT	Values taken from clause 12.1 of [i.9]
EP, PN, NE	Values taken from clause 12.2 of [i.9]
APN, PNE	Values taken from clause 12.5 of [i.9]
EP-NET, NE-EPT	Values taken from clause 12.2 of [i.9]
CM	Values taken from clause 12.4 of [i.9]

The combination of the different antenna polarisations or orientations are antenna dependent. The following calculations apply to derive a single k-factor per injection-plug - antenna location combination.

Table 3: Calculation of resulting k-factor in dependence of the antenna type

Antenna type	Calculation of the resulting k-factor
biconical	$k_{res} = \max(k_{horizontal}, k_{vertical})$
loop	$k_{res} = \sqrt{\lvert k_x \rvert^2 + \lvert k_y \rvert^2 + \lvert k_z \rvert^2}$

These calculations are performed frequency individually for each record.

6.4 Subjective Evaluation of the Interference to Radio Broadcast

6.4.1 General

Subjective evaluations of interference to AM radio reception in the HF bands was performed by ETSI STF 332 (Plugtests on coexistence between PLT and short wave radio broadcast) and is documented in [i.6]. Performing identical tests with all MIMO feeding possibilities would deliver unstable results, because the variance of received signal level (fading in time domain) is more dynamic than an operator might perform the test. At a MIMO test the interference from all MIMO feeding possibilities should be compared. Usually in HF bands the signal level is never stable of this time. [i.3] describes the dynamic changes of the received HF signal level caused by reflections at the ionosphere. Broadcasting conditions in VHF are by far more stable over time allowing a comparison of levels recorded over a time frame of a view minutes.

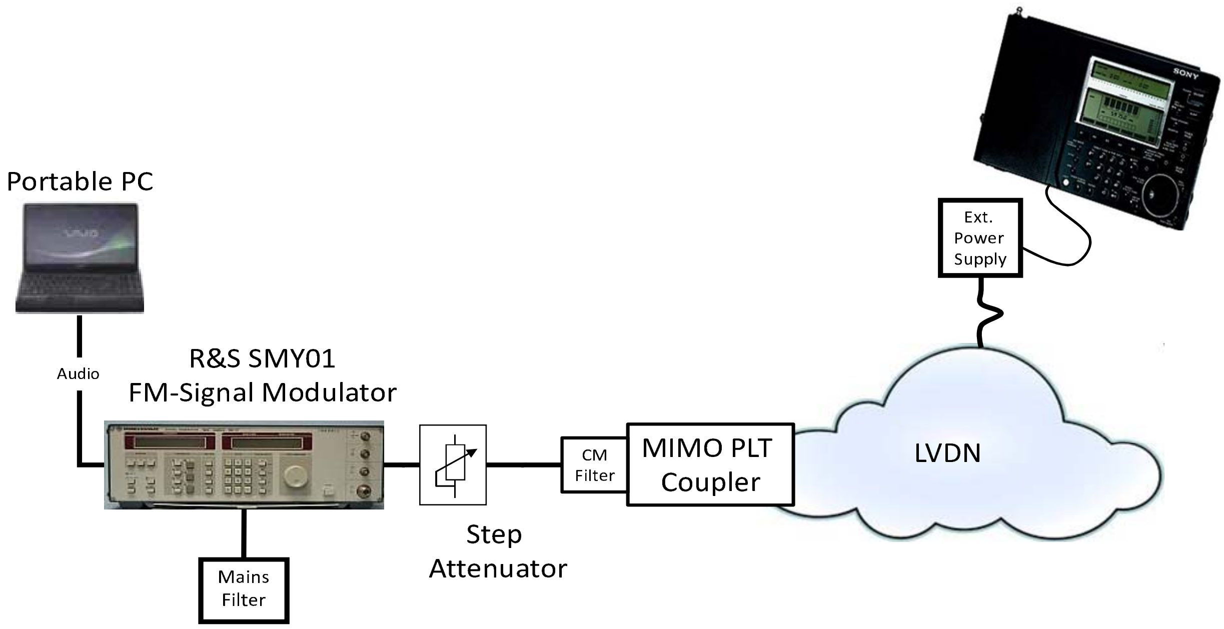


Figure 7: Basis setup for FM interference tests

Feeding the interference signal to the mains is done as described in clause 6.3.3. The source of the signal is a broadband noise generator or frequency generator with the ability for frequency modulation with variable frequency excursion (e.g. Rohde&Schwarz® SMY, see note 2). This generator is modulated with a noise signal.

NOTE 1: The noise signal can be generated via sound output of a laptop or PC using the scope software (http://www.zeitnitz.de/Christian/scope_de).

NOTE 2: Rohde&Schwarz® SMY is an example of a suitable product available commercially. This information is given for the convenience of users of the present document and does not constitute an endorsement by ETSI of this product.

The 3 dB-bandwidth of the modulated signal is at least 240 kHz for the evaluation of radio interference in the ultra short wave bands (FM-Bands).

To distinguish the disturbed and the undisturbed situation the generator could be switched on and off. A blanking input controlled with a rectangular signal (a few Hertz) is preferable. Using a software tool as described above a sweep of a sine wave might be included to the audio signal which is going to be FM modulated. The FM modulated signal will be injected as interfering signal to the mains. The sweeping tone allows human ear easily to detect this source of interference out of several interferences when listening to sensitive FM broadcastings.

An example for the spectrum realised with the noise source for the FM-Bands is shown in Figure 8.

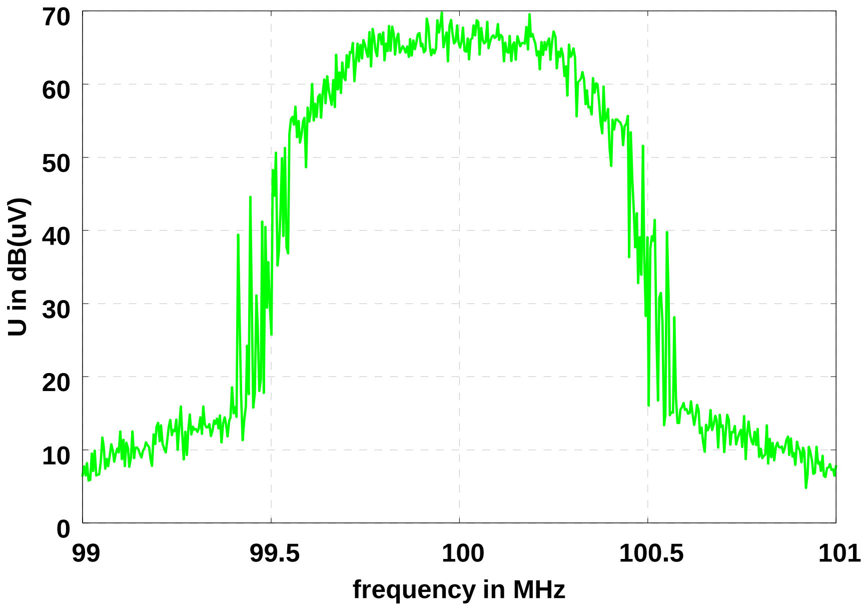


Figure 8: Output spectrum obtained with the generator SMY (frequency modulated with noise) obtained with a spectrum analyser at resolution bandwidth of 200 Hz in Clear-Write modus

6.4.2 Verification and Calibration

Prior to the test, the disturbance signal has to be analysed with a measurement receiver or spectrum analyser for documentation of the 3 dB bandwidth. In a first step the amplification between the generator output level and the signal injected into the BNC-plug of the MIMO PLT coupler has to be determined. This is done by connecting the feed cable via an attenuator of 30 dB (protection of the measurement receiver) to the measurement receiver input.

Setting of the measurement receiver:

Detector:	Average
Bandwidth:	120 kHz for measurement frequency above 30 MHz
Attenuation:	Auto
Measurement time:	1 000 ms

Feeding level of signal generator is U_{max_feed}.

6.4.3 Measurement procedure

After the calibration of the amplification has been done, the measurement can be performed. The output of the RF generator is connected via a step attenuator to the MIMO PLT coupler (see Figure 7).

As preparation a couple of radio stations, which can be received at the receiver's location, are selected.

At each frequency of a selected radio station the level of the RF generator is adjusted to a low level where no disturbance at the radio receiver is recognised. (This could be performed easily by e.g. rotating the knobs of the step attenuator to Att_{SA}.) From that value the generator level is increased until a disturbance can barely be recognised. After that the level of interference signal is verified by connecting

$$U_{gen} = U_{max\_feed} - Att_{SA} \quad \text{(Eq. 2)}$$

with the measurement receiver input for measurement of the signal level. The measured value U_{gen} (in dB(µV)) is recorded in an Excel sheet.

This procedure is repeated for each:

- coupling type;
- selected frequency;
- feeding outlet (injection point);
- radio receiver;
- radio receiver location.

Furthermore the measurements have to be done when radio receiver is battery driven and mains powered.

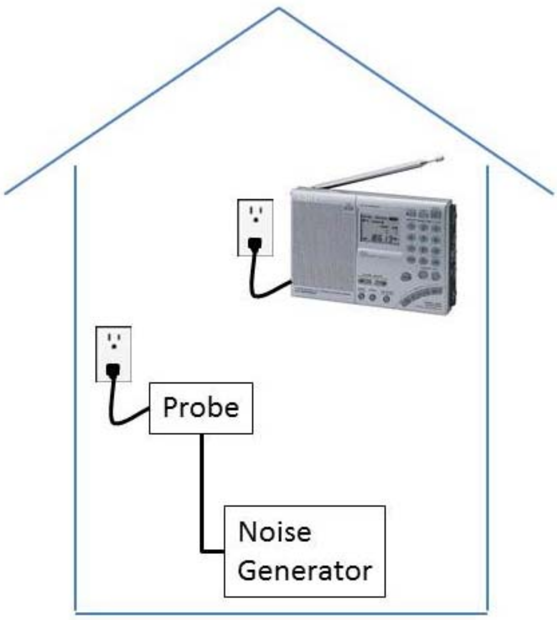


Figure 9: Radio reception in a Building with noise feeding

6.5 General Equipment List

6.5.1 Coaxial Cables

The coaxial cables used to record k-factor$_{10m}$ measurements are doubled shielded (e.g. RG214 are recommended due to their low attenuation). To avoid signal ingress to the cable going back from the antenna to the NWA the cable has to be surrounded by several ferrites and CMADs.

The coaxial cable is Ecoflex 10 (double shielded) and each 0,15 m a Suppression Axial Ferrite Bead (Würth-Elektronik part number: 74270056) is attached to the cable.

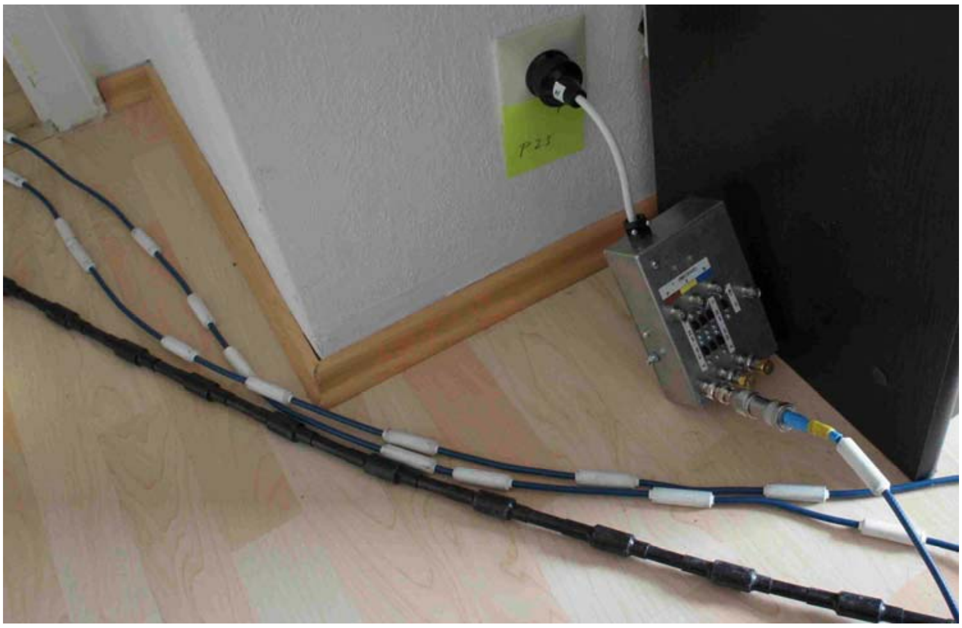


Figure 10: Cable with ferrites

6.5.2 Network Analyzer

See [i.5] for the list of NWA used for the EMI measurements.

6.5.3 Probes to connect to the LVDS

The MIMO PLC couplers for feeding and receiving signals are specified in [i.9].

6.5.4 Amplifier

The Amplifier used to increase the measurement dynamic is:

- 50WD1000 (DC - 1 GHz, AR);
- Bonn Elektronik BLWA 0310-1.

NOTE: Bonn Elektronik BLWA 0310-1 is an example of a suitable product available commercially. This information is given for the convenience of users of the present document and does not constitute an endorsement by ETSI of this product.

Figure 11: Amplifier

6.5.5 Filter to Isolate Measurement Devices from Mains

A filter as specified in clause 7.7.6 (Mains Filter) of [i.5] is used.

7 Statistical Evaluation of Results

7.1 k-factor

STF 410 measured the k-factor at 15 locations in Spain, France and Germany.

A typical sweep from 1 MHz to 100 MHz of any k-factor measurement is shown in Figure 12. Fadings characterise the shape of a k-factor sweep. In total 1 294 such sweeps are recorded by STF 410.

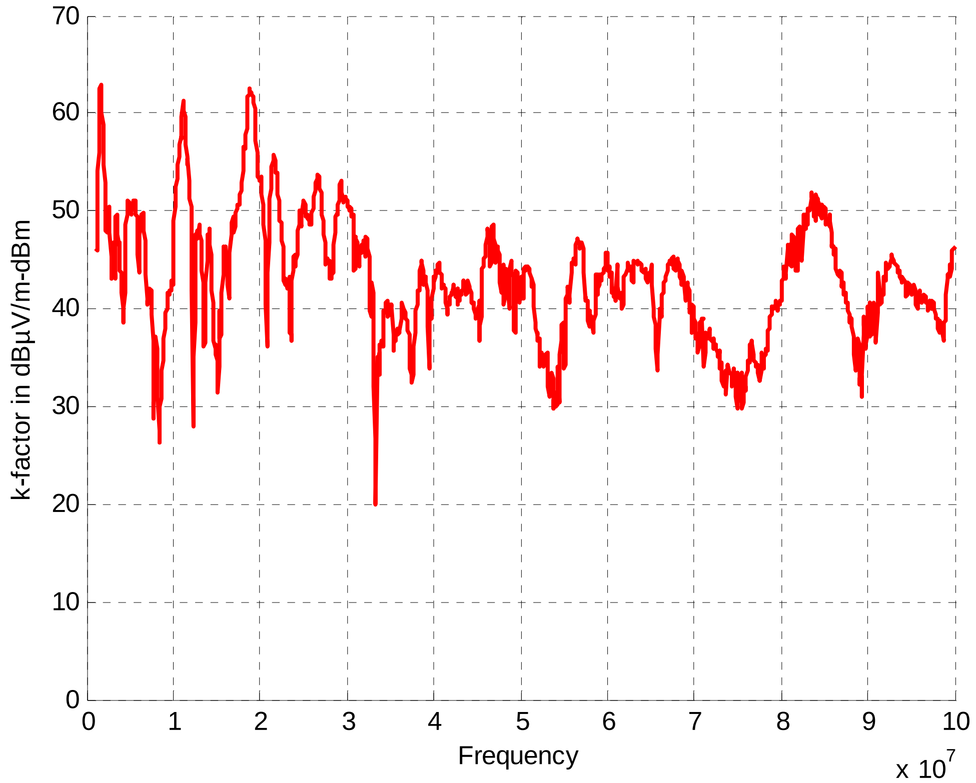


Figure 12: Typical sweep of a k-factor measurement outdoor at 10 m distance

Figure 13 shows the median of all data separated into the individual feeding possibilities. The median value for each measured frequency and feeding style is calculated individually.

NOTE: This median value is derived of the data from all antenna locations: indoor, outdoor in 3 m distance and 10 m distance from the building.

Figure 13 shows no tendency of the k-factor over frequency for all symmetrical feeding possibilities. The k-factor of CM feeding is 5 dB to 15 dB higher than the symmetrical ones and raises by 10 dB from 5 MHz to 100 MHz.

In all results presented here the attenuation of the CM feeding of the PLT coupler is considered as described in [i.9]. For CM feeding the coupler causes an insertion loss of roughly 5 dB, which is not negligible as it is for all DM feedings. Hence, from S21 CM attenuation records of the NWA this additional attenuation is subtracted in order to describe the true k-factor.

The attenuation caused by terminations of the couplers feeding ports are not considered in the present document. In all the following graphs the symmetrical feeding have individual terminations, as described in [i.9]. E.g. when feeding EPNT, NENT and PNNT the unused MIMO feeding interfaces are not terminated. When feeding EP, NE and PN the 2 unused feeding possibility at the PLT coupler are terminated with 50 Ω. At EP-NET and NE-EPT one of the two unused feeding possibility is terminated the other one not. The purpose of this presentation is to allow a comparison to the SISO style (PNNT) which is used by conventional PLT modems. The energy feed into the mains after the PLT coupler is 1,3 dB less in the 3 port termination (PN, EP and NE) compared to 1-port termination (EPNT, NENT and PNNT).

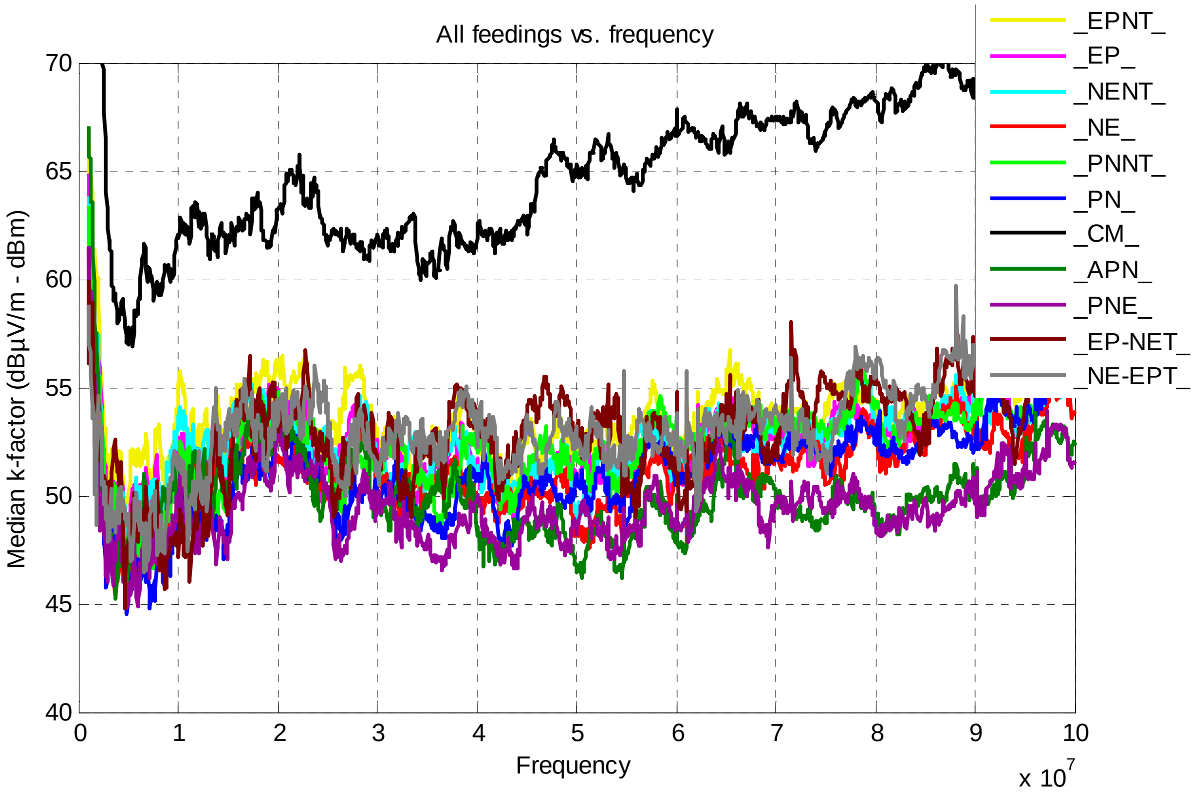


Figure 13: Median values for each feeding possibility over frequency

The legend of Figure 13 shows the feeding possibilities according to Figure 6. To wrap up the abbreviations Table 4 reminds them.

Table 4: Legend of plots

EPNT	Signal feed mode: DELTA (differential) between E and P, PN and NE not terminated
EP	Signal feed mode: DELTA (differential) between E and P, PN and NE terminated
NENT	Signal feed mode: DELTA (differential) between N and E, PN and EP not terminated
NE	Signal feed mode: DELTA (differential) between N and E, PN and EP terminated
PNNT	Signal feed mode: DELTA (differential) between P and N, NE and EP not terminated (SISO)
PN	Signal feed mode: DELTA (differential) between P and N, NE and EP terminated
CM	Signal feed mode: Common mode, P, N, E terminated to ground
APN	Signal feed mode: Dual wire feed (version C in [i.9]) to input P||N E in Figure 11 of [i.9]
PNE	Signal feed mode: Dual wire feed (version C in [i.9]) to input PN in Figure 11 of [i.9]
EP-NET	Signal feed mode: Differential between E and P, only NE terminated
NE-EPT	Signal feed mode: Differential between N and E, only EP terminated

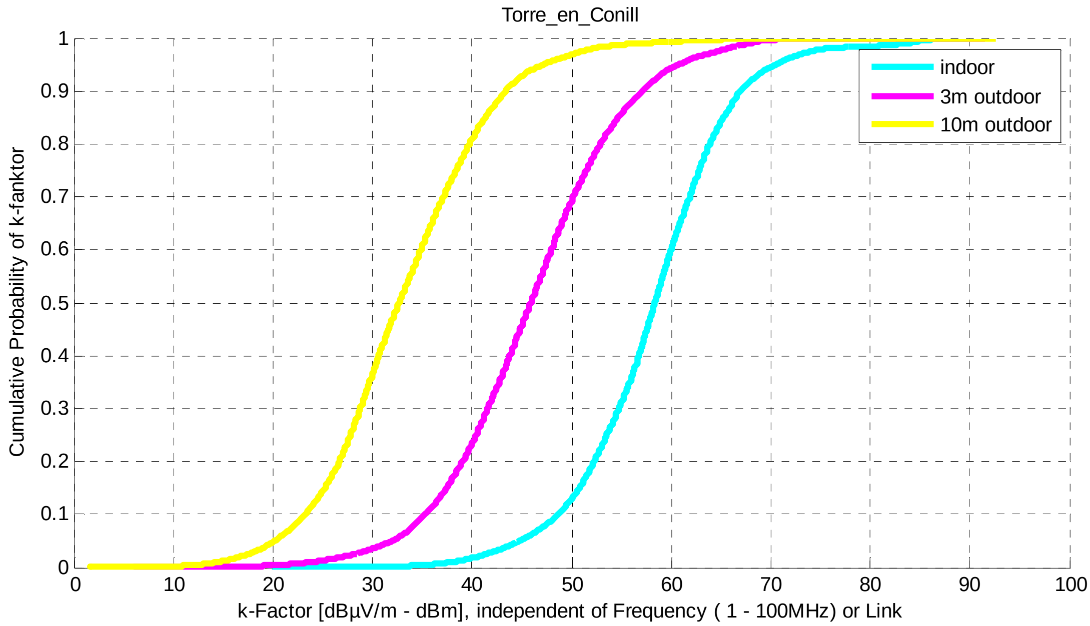
The median k-factor value of each location is given in Table 5 for all Antenna positions indoor, at 3 m distance and at 10 m distance from the outside wall of the building.

Table 5: Median coupling factors of each location

Location	Country	Median k-factor indoor in dBµV/m - dBm	Median k-factor in 3 m distance in dBµV/m - dBm	Median k-factor in 10 m distance in dBµV/m - dBm
Duerrbachstr	Germany	73,69	not measured	46,42
ImGeiger	Germany	69,94	not measured	45,83
Nauheimerstr	Germany	74,33	not measured	44,39
Rothaldenweg	Germany	74,26	not measured	52,37
Schlossbergstr	Germany	69,28	57,99	45,66
VickiBaumWeg	Germany	62,94	not measured	48,45
Boenen	Germany	71,88	62,38	not measured
Universitaet	Germany	not measured	56,61	50,85
Voerde	Germany	not measured	70,20	60,44
El_Puig	Spain	56,47	40,79	not measured
Sant_Sperit	Spain	not measured	50,19	45,63
Torre_en_Conill	Spain	58,39	45,90	32,67
Guingamp	France	74,18	61,07	55,06
RueBunuel	France	70,46	not measured	53,79
RueDepasse	France	71,62	64,09	51,68
All locations		68,68	52,03	47,76

Due to the high variance of the results between the individual locations and the low number of locations a statistical evaluation of the k-factor for each country is not calculated. Furthermore the number of records at each location is individual. Number of antenna positions was selected according to the size of the location, size of the garden and accessibility to each location. In total, over all frequencies and feeding possibilities 864 541 values (540 sweeps) are recorded in 10 m distance, 717 249 values (448 sweeps) in 3 m distance in and 489 907 values (306 sweeps) indoor. An explanation why there is such a high spread in the median values might be due to the situation at the living unit. So far the area around the building was flat, the outdoor antenna positions were located on the same level than the ground floor of the building. If the living unit was e.g. a flat located in the 2nd floor of a building or a multi level house some of the feeding outlets have additionally a vertical distance to the antenna. E.g. the k-factor measurements in France or Voerde were recorded where all feeding outlets were located in the ground floor and the area around the building is flat land. This is why the outdoor k-factors in these locations tend to be higher than at other locations.

The cumulative distribution of the k-factor of a location where all 3 antenna positions are recorded with a high number of sweeps is depicted in Figure 14.



NOTE: No. of sweeps indoor: 33, in 3 m: 66, in 10 m: 33.

Figure 14: Cumulative distribution of k-factor of a location

For MIMO feedings the potential of interference relative to the SISO case is of interest. Figure 15 and Figure 16 show the difference of the k-factor between the SISO style and other feeding possibilities. The SISO case is the feeding style used by conventional (non MIMO) PLT modems. Figure 16 is a zoom into Figure 15 at the median value (50 % point). The lines presented in Figure 15 are calculated by subtracting the k-factor of the PNNT from all other k-factor measurements. For the PNNT feeding this subtraction has to result in zero. This is why the PNNT line is presented as vertical line, here. This operation was calculated only with data where both records were captured when feeding was done at the identical outlet and the signals are received at identical antenna positions. Here it becomes obvious that the k-factor of CM signals is in median 12,2 dB higher than k-factor of SISO signals. The signals feed in PN and PNE style show a high correlation to PNNT.

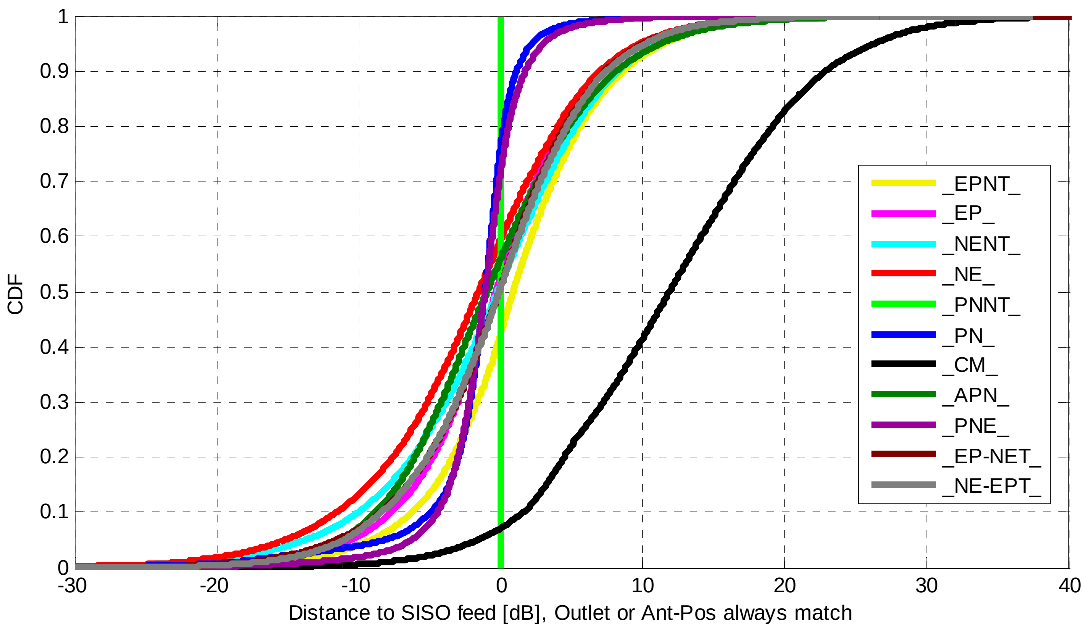


Figure 15: Relative Difference of MIMO feeding possibilities to SISO feeding (PN and others non terminated)

The zoom in Figure 16 and Table 6 show that only the feeding style EPNT tend to show higher radiation than traditional SISO feeding. All other differential feeding possibilities radiate less.

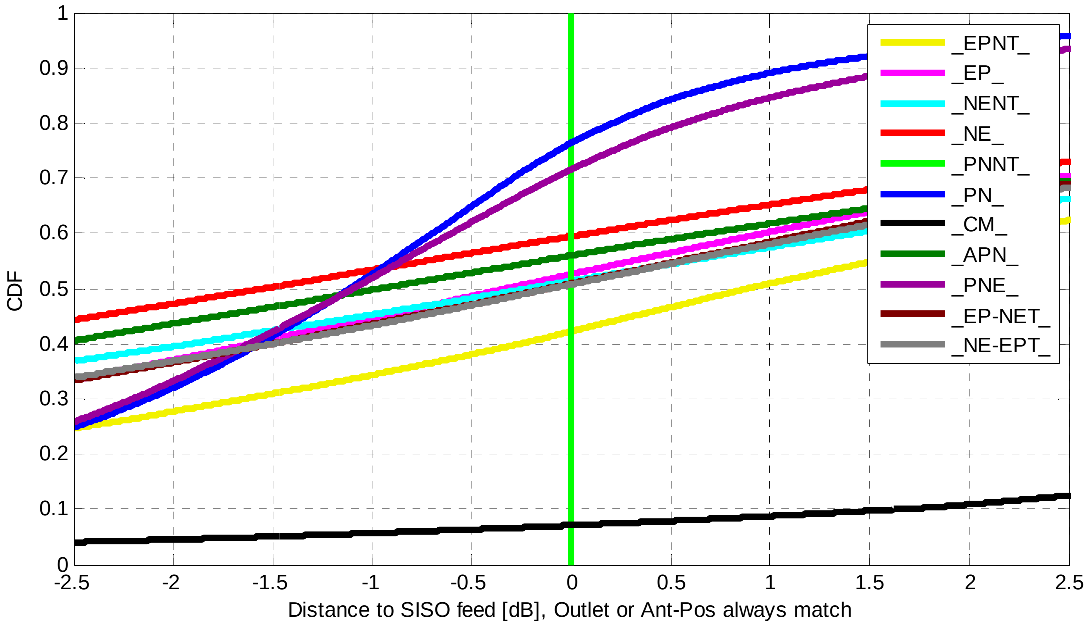


Figure 16: Zoom showing the difference between SISO and MIMO feedings

Table 6 presents the median values of Figure 15 and Figure 16 in numbers.

Table 6: Median difference at k-factor of feeding style to SISO

Feeding Style	Difference to SISO feed in dB
EPNT	0,89
EP	-0,32
NENT	-0,21
NE	-1,54
PNNT	0,00
PN	-1,11
CM	12,20
APN	-0,96
PNE	-1,09
EP-NET	-0,11
NE-EPT	-0,10

Comparison of the magnetic field (H-field) and electric field (E-field) are recorded at the location of Voerde in Germany. Therefore the radiations of a building are recorded are recorded at identical antenna positions at 3 m and 10 m using the E-filed biconal antenna [i.8] and the H-field ring antenna [i.10]. To compare the H-field records versus the E-field values the magnetic fields - recorded in dBµA/m - are converted to electric fields using the wave impedance of free space of 377 Ω = 51,5 dBΩ. Figure 17 to Figure 18 show some correlation between H- and E-filed at 3 m distance. Obviously the location of 3 m may still be the near field, where the free space wave impedance of 377 Ω cannot be applied. At 10 m distance of the building the E- and H- fields match better, as expected in the far field (see Figure 19 and Figure 20). The graphs stop at 30 MHz because the loop antenna [i.10] is specified only up to this frequency. At frequencies above 30 MHz it is expected that far field radiation conditions from a building are valid at closer distances or even indoor.

The records of the k-factor in the present document are performed using the E-field antenna, because in the frequency range up to 100 MHz magnetic EMC antennas are not available. Furthermore the consumer electronic devices in a private home use an E-filed antenna (stick or whip) in the HF and VHF bands.

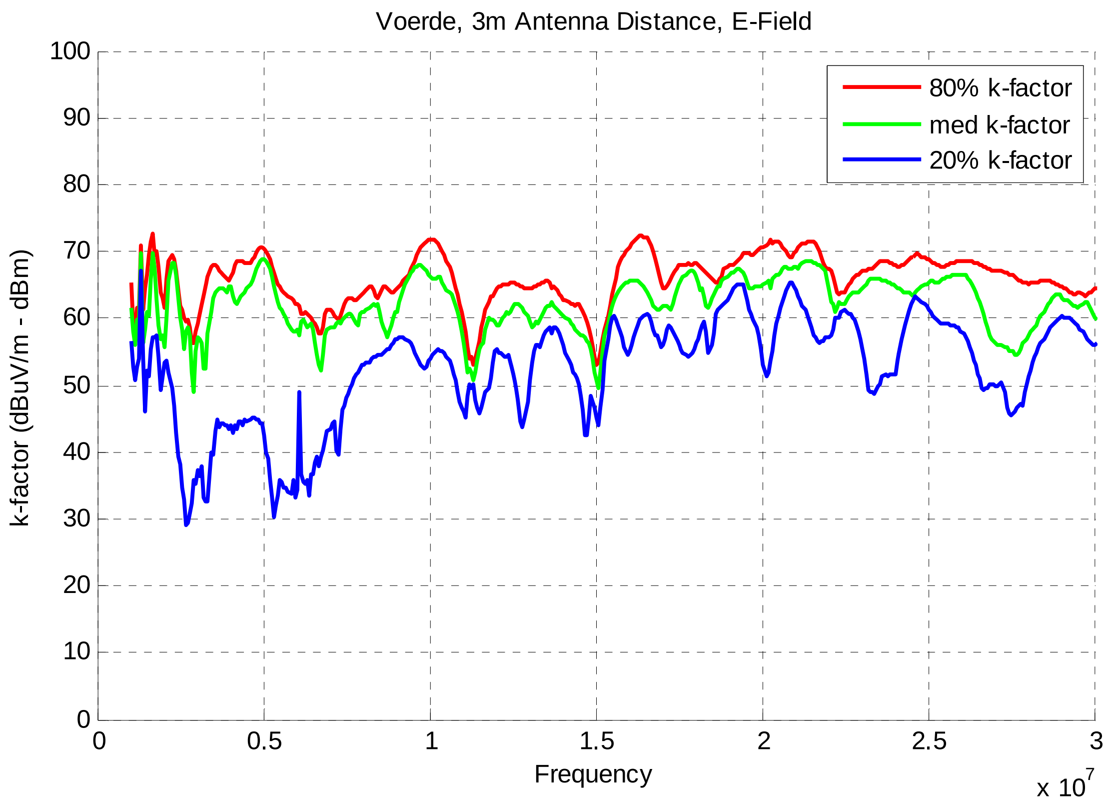


Figure 17: k-factor measured with biconal antenna in 3 m distance

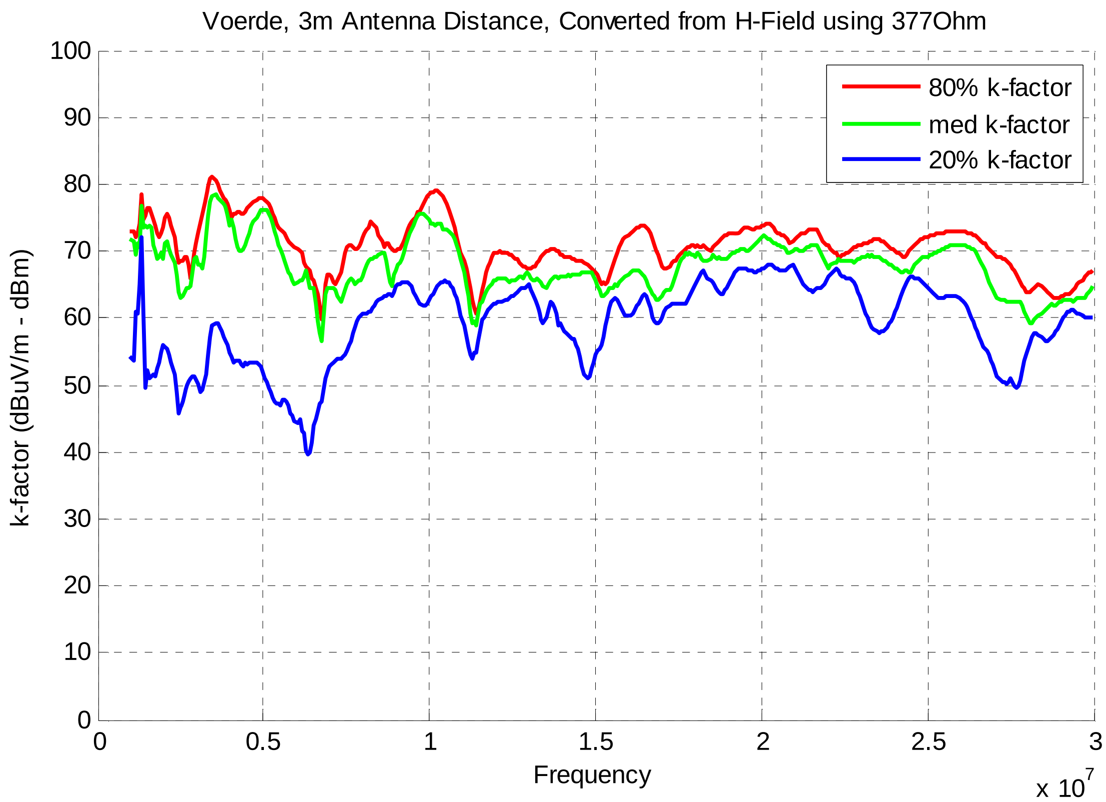


Figure 18: k-factor measured with loop antenna in 3 m distance and converted to E-filed

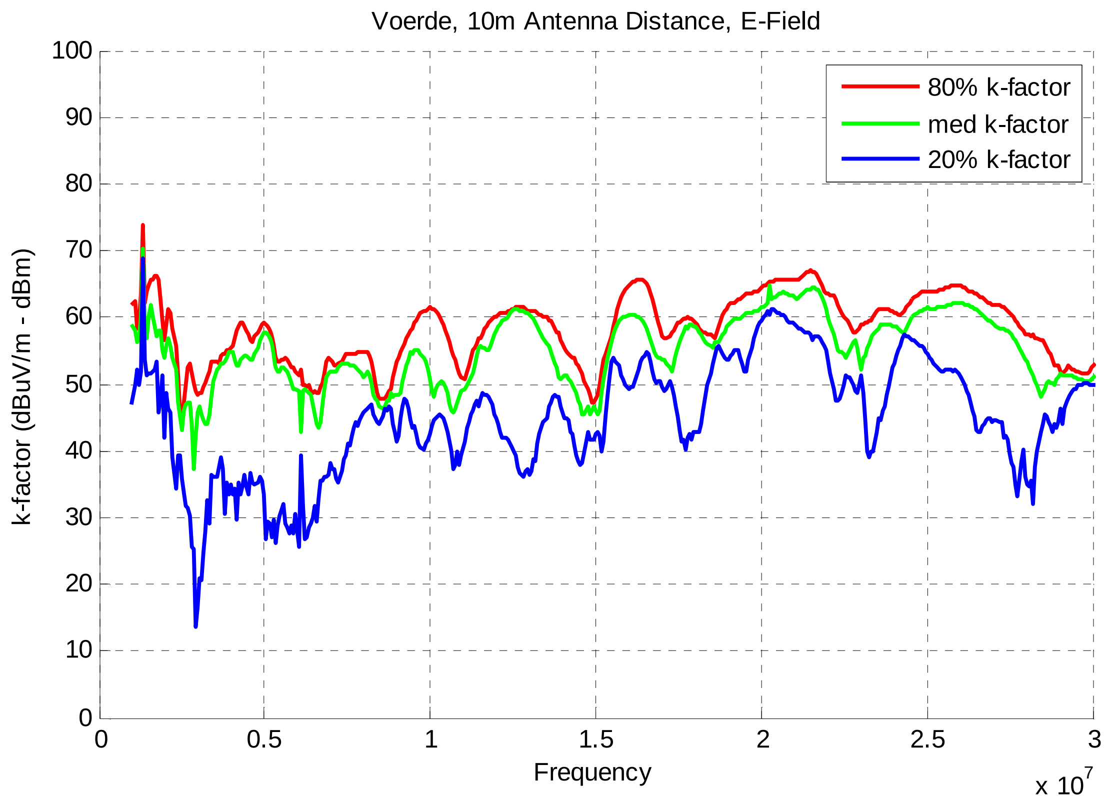


Figure 19: k-factor measured with biconal antenna in 10 m distance

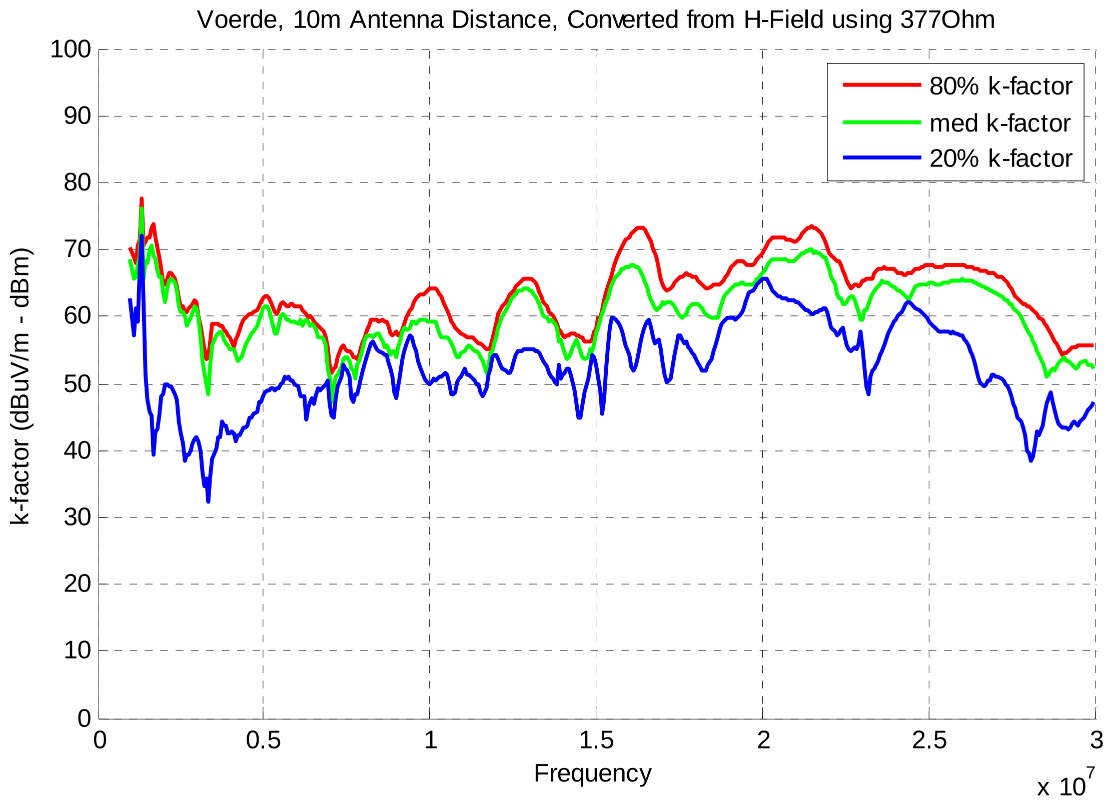


Figure 20: k-factor measured with loop antenna in 10 m distance and converted to E-filed

7.2 Interference threshold to FM Radio Broadcast

Testing the level of interference to FM radio broadcast was performed at 10 locations. In total the subjective assumption at which level noise from PLT could be noticed by human ears in an FM radio service was conducted 1 179 times. This were 9 feeding styles times 131 radio stations and/or radio devices and/or radio positions.

A measurement protocol produced in a location is like the example in Table 7. Several radio stations were interfered by the noise signals feed in various styles into one or more outlets. Various radio devices, battery driven and with power supply are monitored. The threshold when human ears are able to detect the interference is noted in the protocol.

Usually the sensitive radio stations which are hardly to receive are interfered by lowest PLT levels.

Table 7: Measurement protocol of FM interference threshold in a home

				Threshold								
Frequency	Radio station	Receiver	Injection	PNNT	EPNT	NENT	PN	EP	NE	CM	APN	PNE
in MHz		location	Point	in dBm (120kHz) into the plug								
92,2	SWR 3	Bose System	P42	-4,5	-23,5	-31,5	-4,5	-30,5	-19,5	-27,5	-30,5	-3,5
107,7	Die neue 107,7	Bose System	P42	-31,5	-43,5	-39,5	-25,5	-43,5	-40,5	-43,5	-37,5	-25,5
101,3	Antenne1	Sony Radio	P42	1,5	-6,5	-4,5	0,5	-4,5	-5,5	-25,5	-17,5	-7,5
92,2	SWR 3	Sony Radio	P42	-6,5	-19,5	-16,5	-3,5	-18,5	-10,5	-25,5	-9,5	-0,5
107,7	Die neue 107,7	Sony Radio	P42	-22,5	-33,5	-33,5	-33,5	-28,5	-24,5	-47,5	-29,5	-28,5
101,3	Antenne1	Sony Radio Bat	P42	4,5	-4,5	-1,5	5,5	-3,5	-0,5	-26,5	4,5	5,5
92,2	SWR 3	Sony Radio Bat	P42	-4,5	-16,5	-13,5	1,5	-16,5	-16,5	-22,5	-3,5	1,5
107,7	Die neue 107,7	Sony Radio Bat	P42	-18,5	-20,5	-18,5	-13,5	-16,5	-17,5	-35,5	-27,5	-22,5
107,7	Die neue 107,7	Bose System	P42	1,5	-10,5	-5,5	4,5	-9,5	-7,5	-12,5	-9,5	-8,5

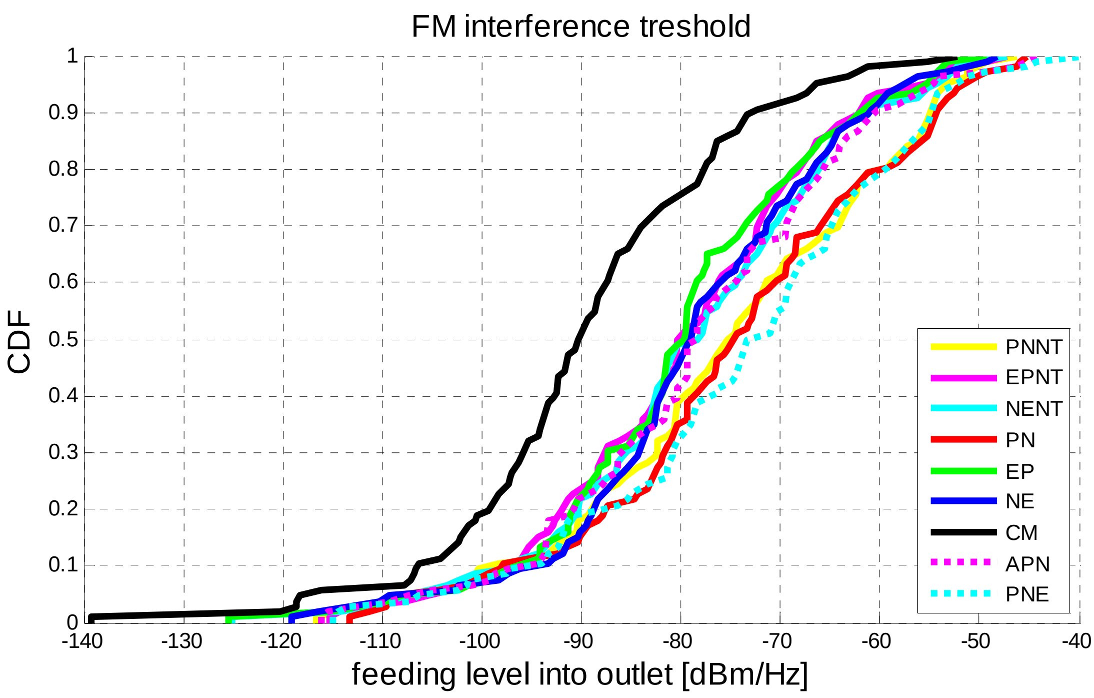


Figure 21: Cumulative distribution function of threshold when interference is noticeable by human ears

Figure 21 shows the cumulative distribution of the threshold of all radio services at all locations independent of the used radio device or power supply. The individual lines represent the individual feeding styles. The x-axis is the feeding PSD injected to an power outlet. As expected, the interference potential of the CM feeding is the highest, so the threshold when the injected noise is noticeable is the lowest. Table 8 list the values of the 80 %, 90 %, 99 % and 100 % threshold when FM radio becomes interfered.

Table 8: CDF values of interference threshold for FM radio

	50 % value in dBm/Hz	80 % value in dBm/Hz	90 % value in dBm/Hz	99 % value in dBm/Hz	100 % value in dBm/Hz
PNNT	-78	-93	-105	-114	-117
EPNT	-81	-95	-103	-114	-115
NENT	-81	-96	-105	-114	-125
PN	-77	-91	-104	-111	-113
EP	-82	-94	-102	-115	-125
NE	-79	-92	-102	-116	-119
CM	-92	-106	-118	-120	-139
APN	-79	-94	-101	-115	-116
PNE	-78	-93	-106	-114	-115

Figure 22 and Figure 23 show the influence on a particular radio device (Sony® ICF-SW1000T, see note) when the device is battery driven or power supplies from the mains. The location of radio device during both tests was identical. In the case of the battery driven radio receiver only the radiated coupling path from the mains to receiver is present. When the radio receiver is mains powered radiated as well conducted coupling paths exist.

NOTE: Sony® ICF-SW1000T is an example of a suitable product available commercially. This information is given for the convenience of users of the present document and does not constitute an endorsement by ETSI of this product.

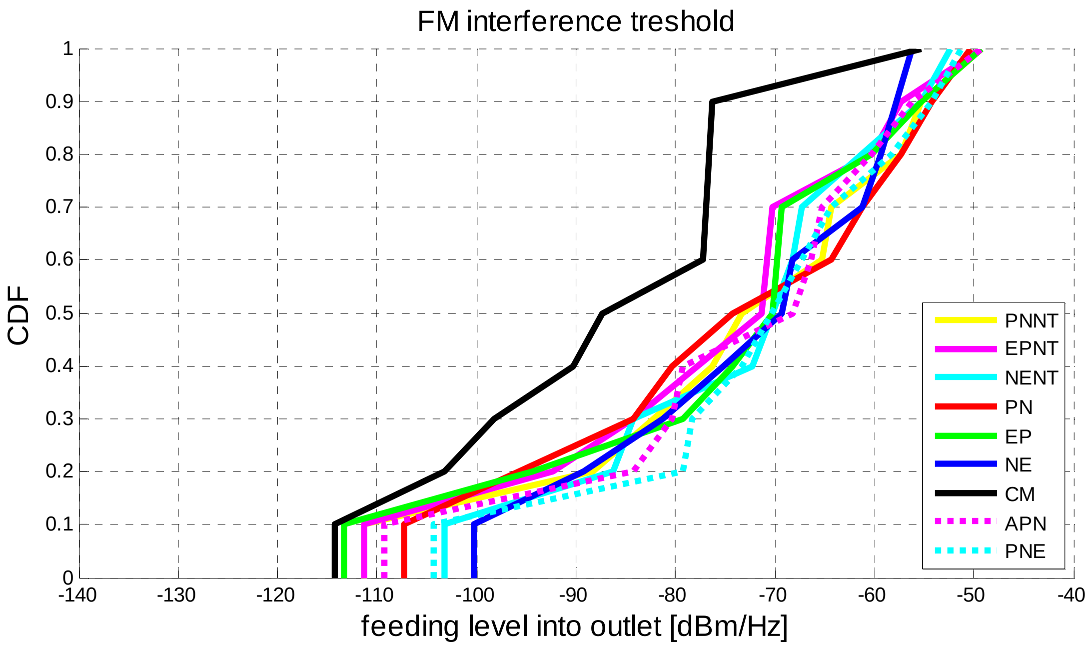


Figure 22: CDF of interference threshold for Sony® ICF-SW1000T with power supply

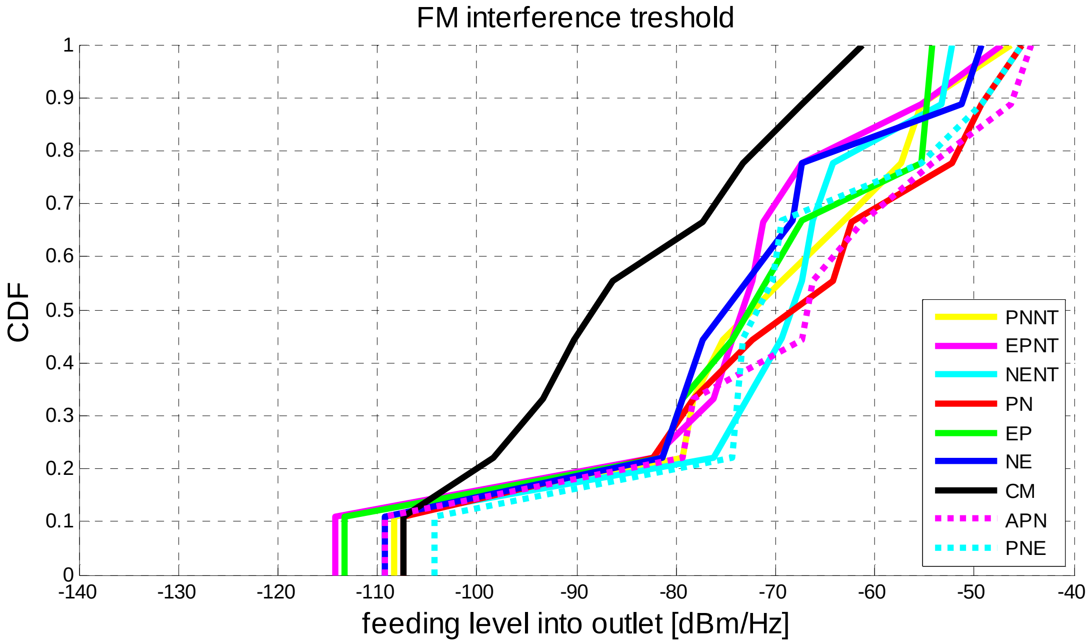


Figure 23: CDF of interference threshold for Sony® ICF-SW1000T battery driven

The graphs in Figure 22 and Figure 23 are pretty identical. The conducted coupling path from mains interferer to the radio device in the VHF range seams not to be dominant. Or the FM radio used in this test is sufficiently isolated to mains interferer.

The STF 410 FM radio immunity field tests are performed using the Sony® ICF-SW1000T device and the radio device owned by the habitant of the flat. The immunity of all radio devices was pretty much identical. No dependency among device manufacturers or HIFI radio systems versus kitchen radio could be found.

Annex A: Alternative procedure for NWA calibration in case that the amplifier output power is too high for the NWA input

If the output power of the amplifier is too high for the NWA input than an attenuator (of sufficient power) is inserted between amplifier output and NWA input during calibration (see Figure A.1). An attenuation of 30 dB is recommended.

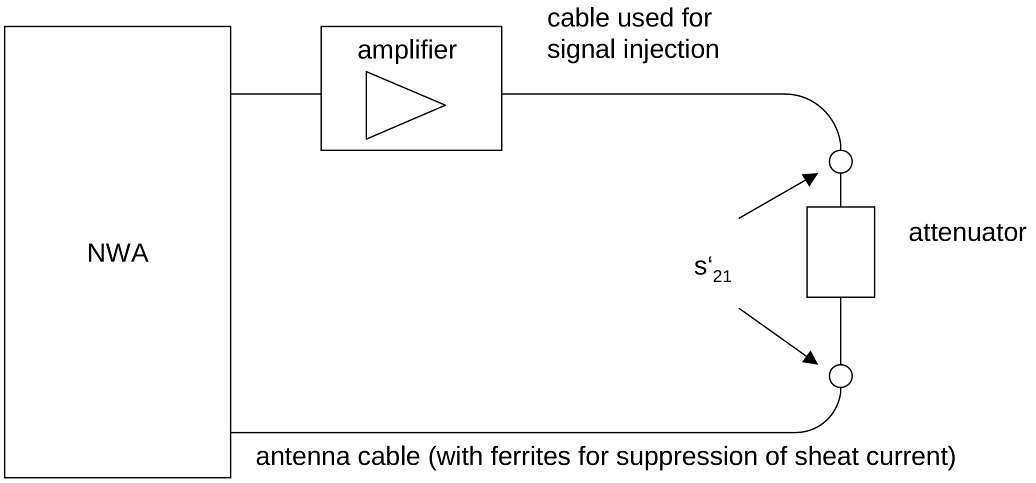


Figure A.1: Alternative NWA calibration

The "through" calibration is made in the usual way.

During the measurements the attenuator is removed. The setup is shown in Figure 5. The operator has to correct the measured data before archiving them in the STF 410 database. The true s_{21} value is derived from the measured s_{21} values by subtracting the attenuation of the attenuator.

Annex B:
Software for automatic file naming

B.1 General

According to experience collected from other measurement campaigns a structured procedure for acquiring the wanted data is sometimes critical. In [i.5] a scheme based on a page that should be completed during the tests is used for this structured approach. Here a software has been developed in order to avoid different file naming, typographic error for the filename and similar error, which at the end would lead to manual corrections for the statistic evaluation. Although the software is equipped with an interface to readout the NWA and store the data in the correct file, it can also be used just for managing the measurements. All data is stored in an ASCII-form so it can be read with a large number of software tools for further investigations. The software is available to all STF 410 members as source.

B.2 Main Dialog

After the start the main dialog show up.

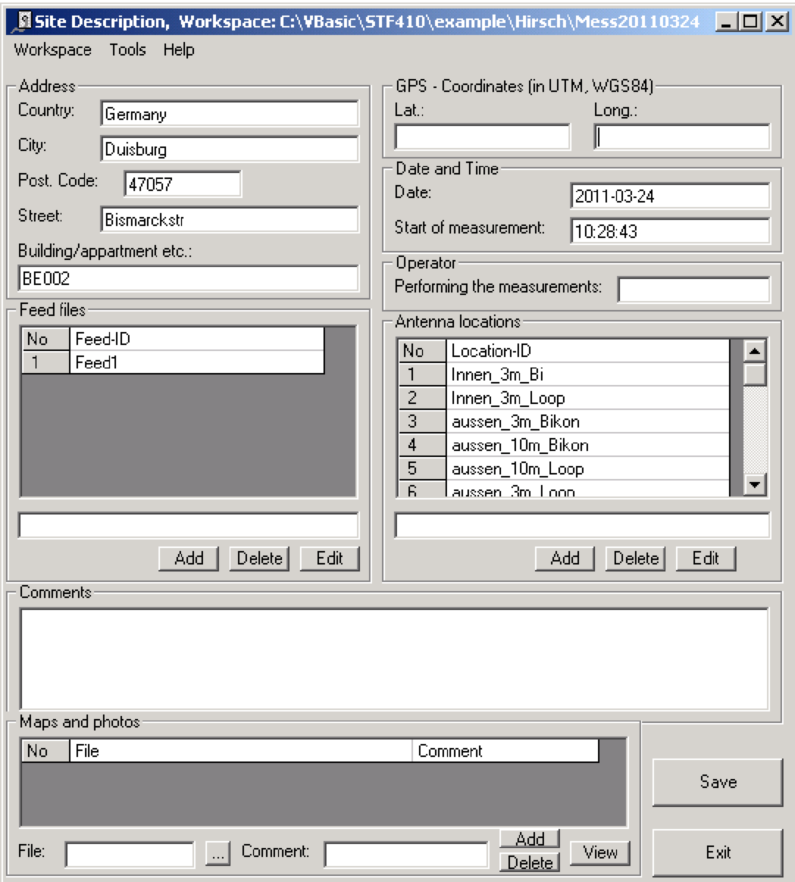


Figure B.1: STF 410 Software, Site Description

The first step is to assign a certain file folder for the site specific data and measurement results. The folder has to be created in advance. After selecting the Menu "Workspace" a file dialog show up, with which the folder can be assigned.

After that the user should fill in the general information associated with the measurement site, i.e.: Country, City, Zip, Street, Building No (if applicable), GPS Coordinates, Date and Time of the Measurements, Persons, who perform the measurements. The general descriptions can be completed by arbitrary comments. To allow better interpretation of results obtained from the specific measurement site, some photos including remarks on what is shown on the photos are helpful. This information is stored with "Save".

After the general information the associated antenna locations and feed locations (plugs) need to be defined. This is easily be done by placing an unique ID for the location in the text box below the tables for feed files and antenna locations. A click on the "Add" button will put the ID into the corresponding list.

B.3 Antenna Location Description Dialog

A predefined antenna location can be edited either by double click on an entry in the antenna locations table. The following dialog appears.

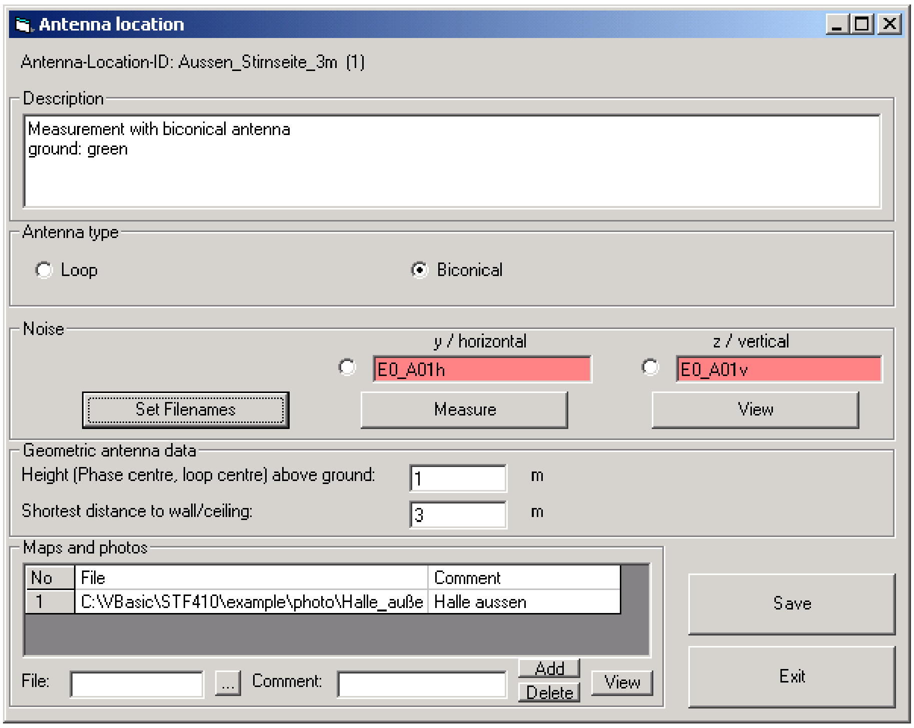


Figure B.2: STF 410 Software, Antenna Location

Again some general information can be given to describe this special antenna location. Also some photos showing the antenna and its relation to the building are helpful. As antenna type either the loop antenna or the biconical antenna is possible. The antenna height and distance information is needed for an automatic evaluation and statistics.

When "Set Filenames" is pressed the text boxes in the frame Noise are filled. Since these files are not yet present, the background is set to a red color. If the files exist it will be green. If a recognized measurement receiver is connected to the PC a klick on the button "Measure" will perform the measurement and store the data in the selected file. In the version on the FTP-site the receiver ESIB from Rohde&Schwarz is supported. Support of other receivers may be available upon request.

B.4 Feed Point Description Dialog

A predefined feed file can be edited either by double click on an entry in the antenna locations table. The following dialog appears.

Figure B.3: STF 410 Software, Feeding settings

Again some general information can be given to describe this special feed location. Also some photos showing the plug with the attached adapter its relation to the structure of the building are helpful.

The consequence of the injection to the field strength at a certain antenna location can be addressed by selecting one of the predefined antenna locations. A press of the button "Set filenames" defines all the necessary file name and measurements. If a NWA is connected to the PC the measurements can directly be started by selection of a certain permutation an a press on the button "Measure". In the version on the FTP-site the NWA ZVRE from Rohde&Schwarz is supported. Support of other NWA may be available upon request. After completion the corresponding file is marked in green indicating that this measurement has been done. Pressing the "View" button calls the grafic tool Gnuplot (public domain tool) for graphical representation of the measured data.

Besides the pure emi-measurement the software can also manage Noise, S_{11} and Transfer Function measurements by selecting the corresponding tabulator.

B.5 Help for Injection Types

To assist in the right setting of the switches of the box a help function can be called from the main dialog (menu entry Help - Coupling Types) or by double click on the coupling type (e.g. P-E) in the feed file dialog.

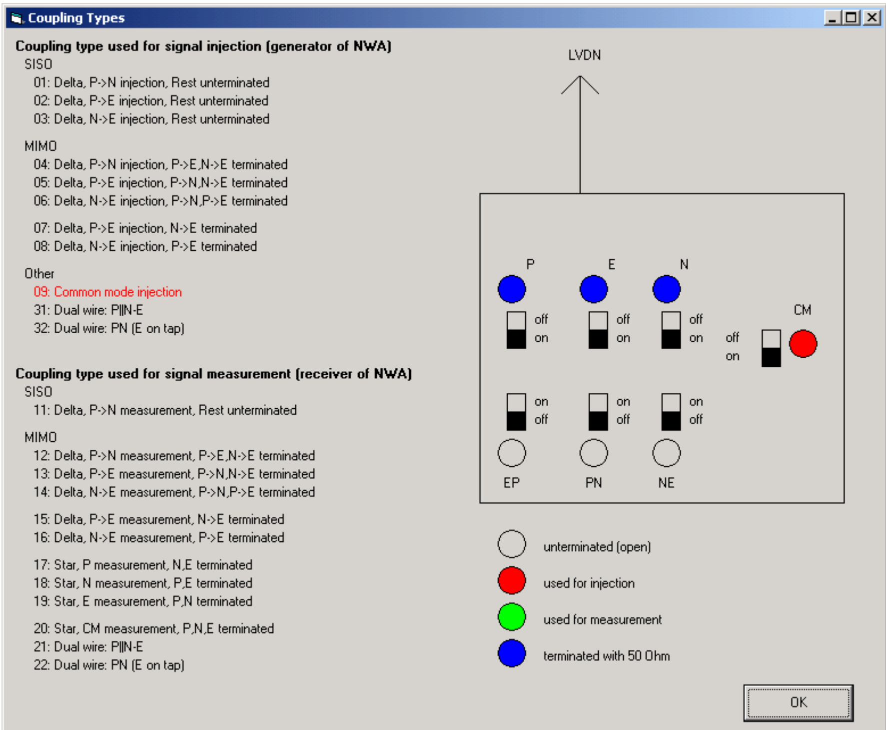


Figure B.4: STF 410 Software, Coupling Types

This dialog shows how to adjust the switches, which BNC plugs to be terminated and how the measurement instruments are connected. The different permutations can be shown in this dialog by simple click on the coupling type on the left side.

B.6 File Formats

For better exchange a simple ASCII-Format is used for data storage.

For data measured with the network analyser, one header line indicating the number of points and some settings is followed by a table with the measurement results.

Its form looks like:

```
Number of points: 1601, Startfrequency: 1e+006,  Stopfrequency: 1e+008,  Label:'XFR:POW:S12'

1e+006 -0.000272393 -0.000801793 0.0008468 -1.89829 -61.4444

1.06188e+006 -0.000102707 -0.000721605 0.000728877 -1.71218 -62.7469

1.12375e+006 -0.000300805 -0.000974474 0.00101985 -1.8702 -59.8293

...
```

The values in the table are:

frequency in Hz, s12 real part, s12 imaginary part, s12 magnitude (linear), s12 phase, s12 magnitude (in dB)

In case of data from a measurement receiver there is no header. The data is just stored as table, which looks like:

```
1000000       23.5484161376953           9.04364013671875

 1005000       21.0335845947266           14.4008636474609

 1010000       22.5505752563477           14.3177490234375

...
```

The values in the table are:

- frequency in Hz;
- peak detector reading in dB(µV);
- average detector reading in dB(µV).

B.7 Creation of the data for the FTP server

Since the software uses an internal file naming scheme the file names and file formats need to be converted into the format defined in clause 6.3.1. This can be done by selecting "rename files to WI28 and WI29" from the "Tools" menu of the main dialog.

Annex C: Bibliography

Terms of Reference for Specialist Task Force STF 410 (TC PLT) on "Measurements to Verify Feasibility of MIMO PLT", version: 1.1, 6 May 2010.

History

Document history		
V1.1.1	August 2011	Publication