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Technical Report

PowerLine Telecommunications (PLT); MIMO PLT; Part 3: Setup and Statistical Results of MIMO PLT Channel and Noise Measurements

Reference
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Keywords
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ETSI

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - NAF 742 C
Association à but non lucratif enregistrée à la
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Contents

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Foreword

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

The present document is part 3 of a multi-part deliverable covering the MIMO PLT as identified below:

Part 1: "Measurement Methods of MIMO PLT";

Part 2: "Setup and Statistical Results of MIMO PLT EMI Measurements";

Part 3: "Setup and Statistical Results of MIMO PLT Channel and Noise Measurements".

Introduction

The STF 410 (Special Task Force) was set up in order to study and compare MIMO (Multiple Input Multiple Output) characteristics of the LVDN network in different countries. The present document is one of three parts of TR 101 562 which contain the findings of STF 410 research.

1 Scope

MIMO PLT Channel and noise is reviewed and statistical analysis performed, which takes into account earthing variations, country variation, operator differences, phasing and distribution topologies, domestic, industrial and residential types, as well as 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 document 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] CISPR 16-1-1: "Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-1: Radio disturbance and immunity measuring apparatus - Measuring apparatus".

[i.5] ETSI TR 101 562-1 (V1.3.1): "Powerline Telecommunications (PLT); MIMO PLT; Part 1: Measurement Methods of MIMO PLT".

[i.6] ETSI TR 101 562-2 (V1.2.1): "PowerLine Telecommunications (PLT); MIMO PLT; Part 2: Setup and Statistical Results of MIMO PLT EMI Measurements".

[i.7] Paulraj, A., Nabar, R. & Gore, D.: "Introduction to Space-Time Wireless Communications"; Cambridge University Press, 2003.

3 Symbols and abbreviations

3.1 Symbols

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

B	Bandwidth
C	Channel Capacity
D	Diagonal Matrix
f	Frequency
k	kilo, most used at kilo Ohms
H	Channel Matrix
Hz	Hertz
I	Current
L	Inductance
λ	Singular Value or Eigen Value
nF	nanoFarads
R	Resistor
U,V	unitary matrices
uH	micro Henry
Z	Impedance

3.2 Abbreviations

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

AC	Alternating Current
ADC	Analog to Digital Converter
AGC	Automatic Gain Control
AMN	Artificial Mains Network
AMP	Amplifier
AWG	Arbitrary Waveform Generator
BG	Band Gap
BNC	Bayonet Nut Connector
C-CDF	Complementary Cumulative Distribution Function (1-CDF)
CDF	Cumulative Distribution Function
CM	Common Mode
CSV	Comma Separated Values
DAC	Digital to Analog Converter
DC	Direct Current
DM	Differential Mode
DSO	Digital Storage Oscilloscope
E	Protective Earth Contact
EMC	Electromagnetic Compatibility
EMI	Electro Magnetic Interference
FD	Frequency Domain
FM	Frequency Modulation
HD-TV	High Definition Television
HP	High Pass
IF	Intermediate frequency
LCZC	Line Cycle Zero Crossing
LISN	Line Impedance Stabilization Network
LP	Low Pass
LVDN	Low Voltage Distribution Network
MIMO	Multiple Input Multiple Output
MS	Mega Sample
N	Neutral contact
N_R	Number of Receive ports

N_T	Number of Transmit ports
NWA	Network Analyzer
P	Phase or life contact
PE	Protective Earth
PLC	PowerLine Communication
PLT	PowerLine Telecommunications
PSD	Power Spectral Density
PWR	Power
RCD	Residual Current Device
Rx	Receiver
S_{11}, S_{21}	Scattering parameters, reflection, transmission
SBF-FM	Stop Band Frequency- Frequency Modulation
SISO	Single Input Single Output
SMA	SubMiniature version A
SNR	Signal to Noise Ratio
STF	Special Task Force
SVD	Singular Value Decomposition
SW	Short Wave
T	Transformer
TD	Time Domain
Tx	Transmitter
UK	United Kingdom
Z_{DM}	Impedance Differential Mode

3.2.1 Abbreviations Used for Feeding Styles

APN	Signal feed mode: Dual wire feed (version C of clause 7.1.4.5 in [i.5]) to input P‖N E in figure 28 of [i.5]
CM	Signal feed mode: Common mode, P, N, E terminated to ground
EP	Signal feed mode: DELTA (differential) between E and P, PN and NE terminated
EP-NET	Signal feed mode: Differential between E and P, only NE terminated
EPNT	Signal feed mode: DELTA (differential) between E and P, PN and NE not terminated
NE	Signal feed mode: DELTA (differential) between N and E, PN and EP terminated
NE-EPT	Signal feed mode: Differential between N and E, only EP terminated
NENT	Signal feed mode: DELTA (differential) between N and E, PN and EP not terminated
PN	Signal feed mode: DELTA (differential) between P and N, NE and EP terminated
PNE	Signal feed mode: Dual wire feed (version C of clause 7.1.4.5 in [i.5]) to input PN in figure 28 of [i.5]
PNNT	Signal feed mode: DELTA (differential) between P and N, NE and EP not terminated (SISO)

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 PLT measurements (EMI, Channel and Noise)	Several STF 410 phone conferences. Drafting of measurement specification
03	Dec. 2010	1st version of the STF410 couplers	Coupler to send and receive MIMO PLT signals developed
04	Jan 2011 and later	Verification of couplers and filters developed for STF410.14 identical couplers are manufactured and shipped to the STF experts	Couplers are used by STF410 experts in field measurements in private homes
05	March 2011	Agreement on STF410 logistics, when and where to perform field measurements	
06	April 2011	Approval of 1st TR on STF410 couplers	ETSI PLT#59

No.	Period	Topic	Event
07	March 2011 to June 2011	Field measurements in Spain, Germany, France, Belgium and the United Kingdom	
08	June 2011	Statistical evaluation of results	Several STF 410 phone conferences
09	July 2011	Approval of 2nd TR on EMI results	ETSI PLT #60
10	Oct. 2010 to August 2011	Evaluation of worldwide presence of PE wire	
11	June to August 2011	Drafting and STF 410 review and approval process	
12	Sept. 2011	Presentation of channel and noise measurement to ETSI PLT plenary	ETSI PLT #61
13	Oct 2011	Revision and rearrangement of TR content for all 3 parts	
14	Nov 2012	Approval of all 3 parts of TR 101 562	ETSI PLT #62

5 Motivation

PLT systems available today use only one transmission path between two outlets. It is the differential mode channel between the phase (or live) and neutral contact of the mains. These systems are called SISO (Single Input Single Output) modems. In contrast, MIMO PLT systems make use of the third wire, PE (Protective Earth), which provides several transmission combinations for feeding and receiving signals into and from the LVDN. Various research publications [i.1], [i.2] or [i.3] describe that up to 8 transmission paths might be used simultaneously.

Further description 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.6].

6 Measurement Description

6.1 Introduction

At the beginning of the measurement campaign, different strategies were discussed on how to best measure a set of desired properties. The main question was if LVDN properties should be recorded in Time- (TD) or Frequency Domain (FD). Each method has pros and cons. Please read the comparison chart below for an overview.

Table 2: Comparison of TD and FD Measurements

Channel Measurements	TD	FD
Concept	Full MIMO Channel has to be calculated from reference symbols	Full MIMO Channel is derived by superposition of individual sweeps
	Fast during field measurements	Individual paths are measured sequentially
Tools	Arbitrary Waveform Generator + Dig. Storage scope	Network Analyzer
AGC?	AGC needs to be tuned	No AGC
Dynamic Range	Limited to resolution of DSO (usually 8 bit)	Huge: > 100 dB
Size of Data	Amount of data to be collected is huge (f(Sample) + duration of record)	Depends on number of points (1 601 / sweep)
Sync to LCZC	Synchronization with AC line cycle at AWG	Synchronization with AC line cycle is difficult with NWA
	Frequent sync with receiver necessary	Record channel on LCZC
Uncertainties		Accuracy is better, measurement uncertainty is less
Noise	Noise information is free (in a limited dynamic range)	Using NWA, noise might cause errors, without the operator noticing
	Noise measurements in dependency of LCZC in TD to record phase of the 4 paths possible	

Channel measurements are conducted in FD due to the larger dynamic range and better accuracy. Also, noise is recorded in TD.

In order to increase the number of measurements recorded, STF 410 was split into several teams operating in parallel in various countries. Measurement campaigns where conducted in Belgium, Germany, France, Spain and the United Kingdom. To guarantee comparability of the individually recorded data, each team is equipped with identical probes or PLT couplers. The measurements themselves are performed with general purpose equipment like NWA (Network Analyzers) and DSO (Digital Storage Oscilloscopes).

Figure 1 shows each team's measurement equipment.

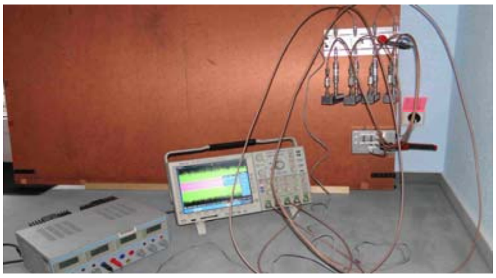
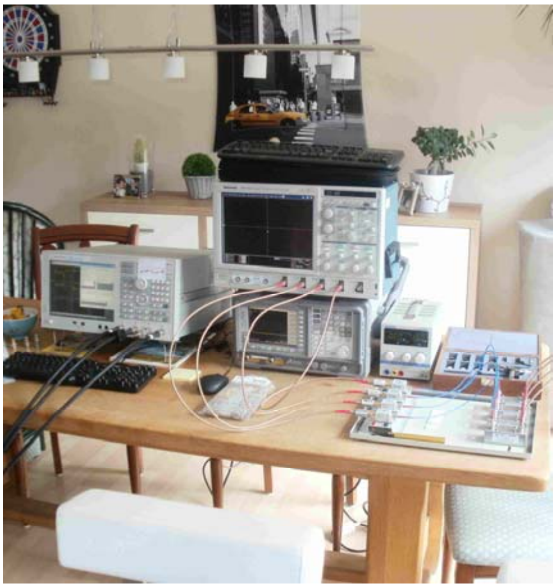
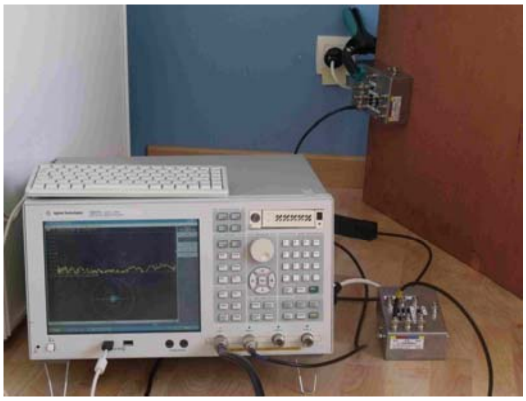
NWA (top), Spectrum Analyzer, Amplifier and isolation transformer (bottom), LISN (right)  DSO and filter bank mounted to ground plane, 	NWA (left) DSO top, Spectrum analyzer, power supply and filters for noise recording 
Equipment of the team in Germany	Equipment of the team in Belgium / Germany / UK
DSO, amplifiers and filters:  NWA performing an EMI measurement, here: 	Noise measurement  NWA: 
Equipment of the team in Spain	Equipment of the team in France

Figure 1: Measurement Equipment used by Individual Teams

6.2 Couplers to Connect Measurement Equipment to the LVDN

The MIMO PLC couplers for feeding and receiving signals are specified in [i.5].

6.3 General Set-up Before Starting Measurements

The power supply for measurement equipment has to be prepared prior to starting measurements. The supply must be clean and maximally separated from the grid of the residential unit being tested. It is recommended that the power supply be taken from a neighboring flat, a backup power supply or a least a plug far away from the installation to be assessed. This mains should be filtered using the AMN [i.4]. To prevent the RCD from failing, an insolation transformer may be used. For the safety of the operating team and measurement equipment, grounding of the AMN at e.g. the heating of the building is recommended.

Completing the measurement protocol from clause A.2 helps to not any operation when performing field measurements.

Select outlets to be measured. Check location of the phase and label the outlets and phase location using a sticker. In a multi-level building, use the first digit of the plug number for the floor level and the second digit for numbering the outlet.

The list of equipment used may be found in clause A.1 of the present document.

6.4 Channel Transfer Function Measurements (S_{21})

6.4.1 Set-Up

The measurement set-up basically consists of a NWA connected to coupler A and coupler B to the mains. The power supply of the NWA is isolated from the LVDN being tested by a filter with > 1 kΩ differential mode- and > 1 kΩ common mode impedance.

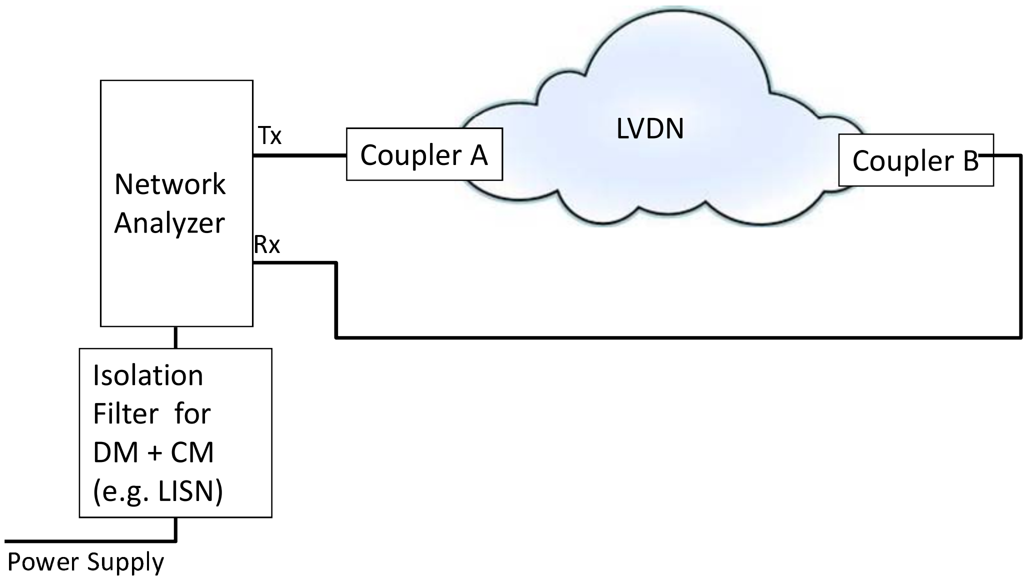


Figure 2: General Measurement Set-up for Channel Transfer Function Measurements (S_{21})

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
- Data are recorded in a CSV format including 3 columns: frequency, Real part, Imaginary part
- Measurement format: S_{21}

Feeding and receiving signals should be performed as described in clause 7.1.4.2 in [i.5]. (This is MIMO differential transmitting and MIMO star style plus CM receiving).

The file name convention is ('F' for feed and 'R' for receive, which are the connectors from STF410 coupler).

Pt_F_Pr_R_xx.xx.CSV where:

- 't' is the number of the transmitting plug. The last digit in the number is an arbitrary number of the outlet. The first digit should be equivalent to the floor level where the outlet is located.
- 'F' is the port where signals are fed differentially: EP, PN, NE, APN, PNE
  The individual feeding styles are introduced in clauses 7.1.4.2 and 7.1.4.5 of [i.5]. The feeding possibilities where unused coupler Tx ports are unterminated are not measured during channel measurements.
- 'r' is the number of the receiving plug.
- 'R' is the port where signals are received in star mode or common mode: P, E N or CM. See clause 7.1.4.2 of [i.5].
- '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 with LCZC 'xx.xx' should not be applied.

E.g. if the filename is P2_NE_P12_P_03.45.csv feeding was done at Plug number 2 on port NE (differentially between Neutral and Protective Earth) and receiving was done at Plug number 12 in star style on Phase. The trigger occurred 3,45 ms after the rising edge of the LCZC at Tx coupler.

The receiving coupler is connected to a ground plane with a surface of ~1 m^2. The function of this ground plane is to establish a capacitive coupling path that provides a low impedance connection for the common mode signals to ground. The ground plane must be large enough to reduce measurement errors at lower frequencies. Proof that the ground plane is of a sufficient size is the fact that an increase in size has a negligible effect upon the measured data. If human touch on measurement equipment does not cause any change in the measurement results, the size of the ground plane is large enough.

All Channel Transfer (S_{21}) measurements should be saved in the 'S_{21}' folder of the STF410 data repository.

6.4.2 Calibration of NWA

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

In the measurements recorded here the MIMO PLT couplers [i.5] are considered to be part of the PLT channel. If a reader of the recorded data wants to eliminate the attenuation of couplers from the channel measurements, he will find the verification data where 2 couplers were just connected using the 19,2 dB pad in clause 7.1.6 of [i.5].

6.4.3 Functional Test Before Starting Channel Transfer Function Measurements

From time to time, one should perform functional tests with the calibration pad in order to make sure that everything still works properly, before starting transfer function measurements on the LVDN. When equipment like cables, connectors, etc. is used in the field, there is some risk of damage. Frequent repetition of functional tests enables early detection of any damage.

6.4.3.1 Functional Test of the Δ Interfaces

This test should be performed in the SISO mode, because it is best to check the Delta mode transmission.

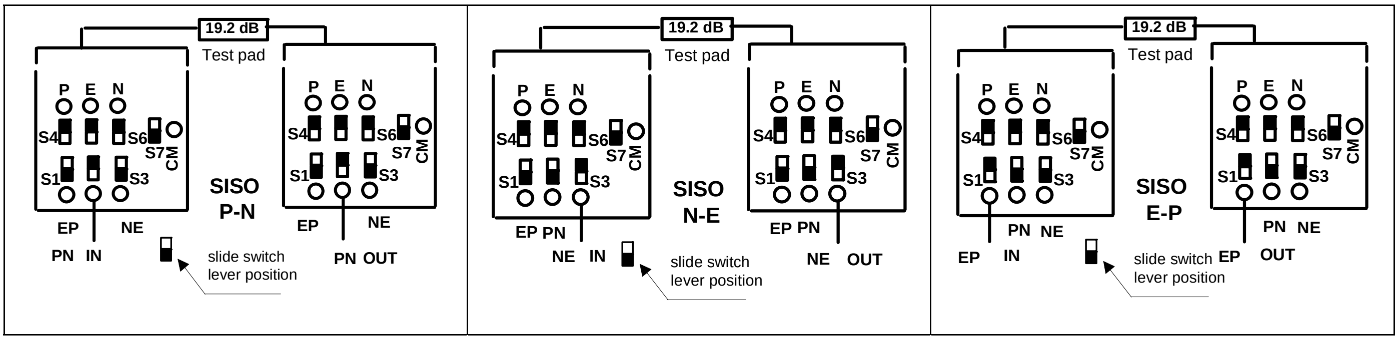


Figure 3: Coupler Configuration: Feed and Receive Differentially

6.4.3.1.1 Slide Switch Positions

Table 3: Switch Positions of Functional Test at Δ Interface

PN Feed & Receive

P (S4)	**E (S5)**	**N (S6)**	**CM (S7)**
off	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	on	off	

NE Feed & Receive

P (S4)	**E (S5)**	**N (S6)**	**CM (S7)**
off	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	off	on	

EP Feed & Receive

P (S4)	**E (S5)**	**N (S6)**	**CM (S7)**
off	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
on	off	off	

6.4.3.1.2 Typical Insertion Loss for All Three Channels

Table 4: Insertion Loss of Functional Test at Δ Interface

	10	30	80	**MHz**
- S_{21}	22	22	23	**dB**

6.4.3.2 Functional Test of the Star Interfaces

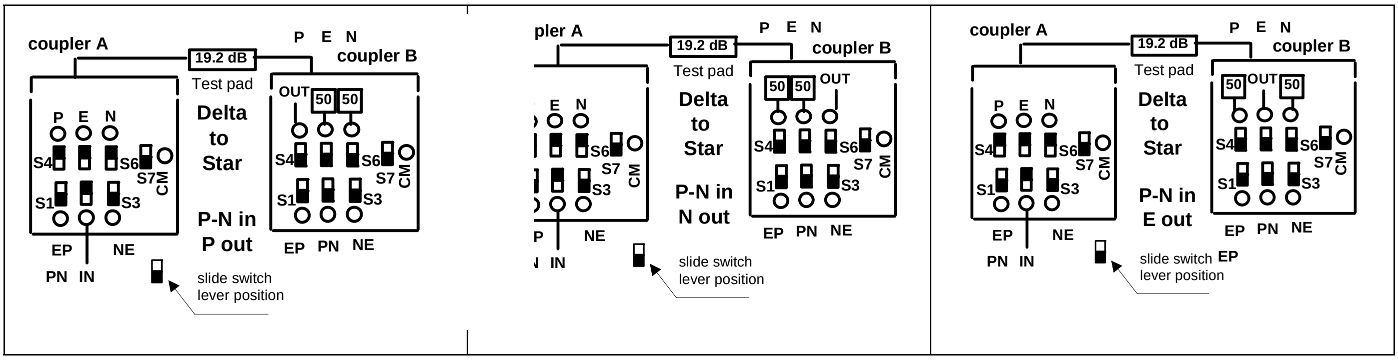


Figure 4: Repeat the Test with Couplers A and B Interchanged

Table 5 shows Slide Switch Positions to be set for the functional tests.

Table 5: Switch Positions of Functional Test at Star Interface

Coupler A: for all configurations

P (S4)	**E (S5)**	**N (S6)**	**CM (S7)**
off	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	on	off	

Coupler B: P out

P (S4)	**E (S5)**	**N (S6)**	**CM (S7)**
on	on	on	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	off	off	

Coupler B: N out

P (S4)	**E (S5)**	**N (S6)**	**CM (S7)**
On	on	on	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
Off	off	off	

Coupler B: E out

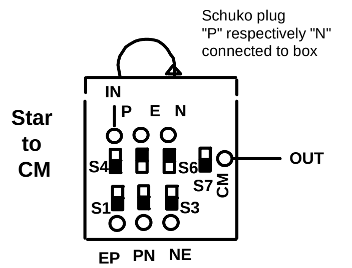
P (S4)	**E (S5)**	**N (S6)**	**CM (S7)**
on	on	on	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	off	off	

Table 6 shows Typical Insertion Loss to be measured at functional test at Star interface.

Table 6: Insertion Loss of Functional Test at Star Interface

		10	30	80	**MHz**
- S_{21}	**P-out**	24	24	25	
- S_{21}	**N-out**	24	24	25	**MHz**
- S_{21}	**E-out**	> 40	> 40	> 40	**dB**

6.4.3.3 Functional Test of the Common Mode Interface



Slide Switch Positions

Coupler A for all configurations			
P (S4)	**E (S5)**	**N (S6)**	**CM (S7)**
on	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	off	off	

Figure 5: Coupler Configuration: Feed into Single Conductor and Receive CM

6.4.3.3.1 Typical Insertion Loss

Table 7: Insertion Loss of Functional Test of the CM Interface

		3	10	30	**MHz**
- S_{21}	**"P" respectively "N" to out**	2,5 to 2,8	2,5 to 2,8	3,0 to 4,0	**dB**
NOTE: Only connect "P" respectively "N" to the box, isolate the other one.					

6.4.4 Coupler Configuration for Transfer Function Measurements

6.4.4.1 Transmitter Side Coupler Configuration for Transfer Function Measurements

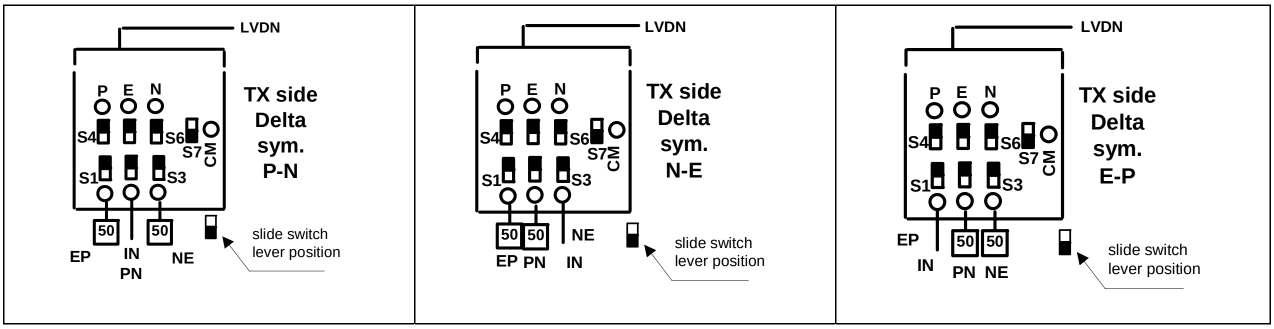


Figure 6: Coupler Configuration: Feed Differentially

6.4.4.1.1 Slide Switch Positions

Table 8: Switch Positions of Transfer Function Measurements

Feed PN

P (S4)	E (S5)	N (S6)	CM (S7)
off	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
on	on	on	

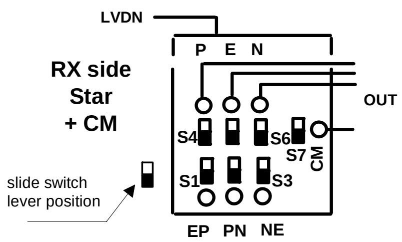
Feed NE

P (S4)	E (S5)	N (S6)	CM (S7)
off	Off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
on	On	on	

Feed EP

P (S4)	E (S5)	N (S6)	CM (S7)
off	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
on	on	on	

6.4.4.2 Receiver Side Coupler Configuration for Transfer Function Measurements



Slide Switch Positions

P (S4)	E (S5)	N (S6)	CM (S7)
on	on	on	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	off	off	

When P, E and N are measured CM must not be terminated. The cable at CM port must be disconnected.
When CM is measured P, E and N must be terminated with 50 Ohm.

Figure 7: Coupler Configuration: Receive from Single Conductor and CM

6.4.5 Conducting Channel Transfer (S_{21}) Measurements

If the equipment is set-up and the network analyzer calibrated as described above field measurements can be conducted in private residential units. A protocol-sheet is prepared in clause A.2 for each measurement site, to be filled out during field tests.

S_{21} have to be measured with every combination of feeding (NE, PN, EP, APN, PNE) and receiving (P, N, E, CM).

To protect the NWA from damage, the coupler should be connected to the outlet before the coaxial wire is connected and when removing the coupler from the outlet, the coaxial cable should be disconnected first.

6.5 Reflection (S_{11}) Measurements

6.5.1 Measurement Principle

The LVDN is a network with an undefined complex characteristic impedance. The often measured absolute value of the input impedance has little practical significance. Adding a short piece of mains cable may change the results considerably.

Thus STF 410 measured the reflection loss S_{11} at the 'Delta' terminals of the Universal couplers instead of the impedance.

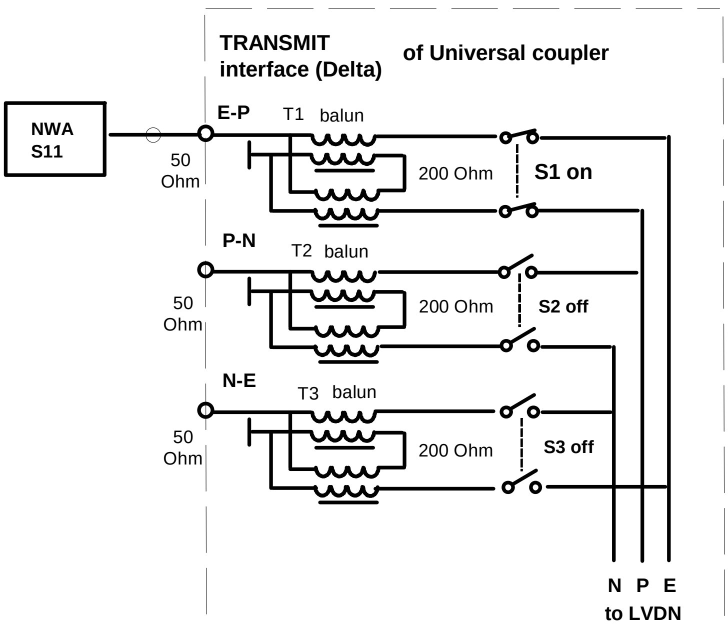


Figure 8: Principle for DM Impedance (S_{11}) measurement via the Baluns of the Universal Couplers (Example: P_N)

6.5.2 Set-Up

At S_{11}, reflection measurements signals are fed and received at one and the same coupler.

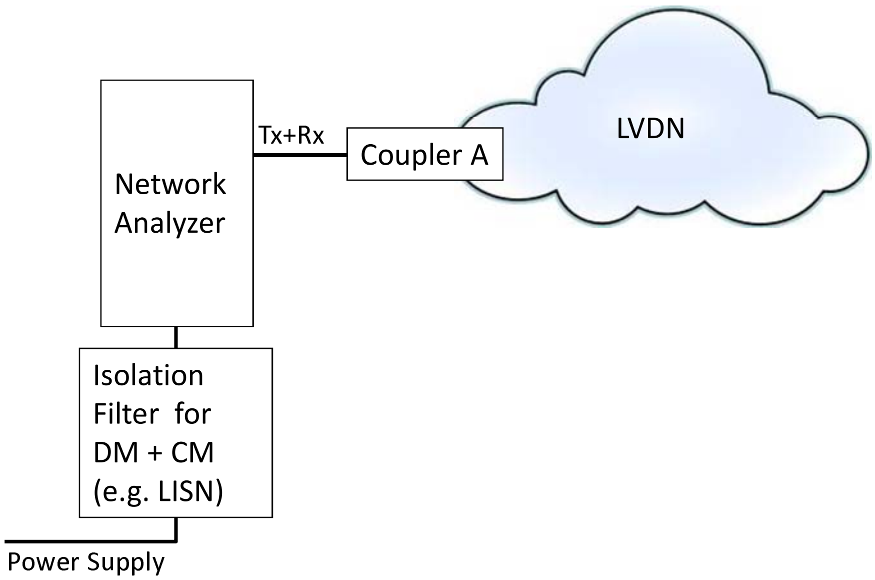


Figure 9: Set-up S_{11} Measurements: Feed and Receive Differentially

The file name convention of reflection (S_{11}) measurements is:

Pt_Fa_Rb_xx.xx.CSV where:

- 't' is the number of the transmitting plug.
- 'Fa' is the port where signals are fed differentially: EP, PN, NE, EPNT, PNNT, NENT, APN, PNE and CM. When feeding 'NT' is used the two other ports at the delta coupler should not be terminated. This allows a comparison with SISO PLC.
  The individual feeding styles are introduced in clause 6.1.5 in [i.6].
- 'Rb' is the port where signals are received differentially: EP, PN or NE. For reflection (S_{11}) measurements the identical feeding and receiving port is used. 'a' is identical to 'b'.
- 'xx.xx' is the timing distance to the rising LCZC at the Tx coupler in ms when the sweep was recorded. If the NWA trigger was not in sync with LCZC 'xx.xx' should not be applied.

E.g. if the filename is P2_PN_PN.csv the reflection was recorded at Plug number 2 differentially between Phase and Neutral.

All reflection (S_{11}) measurements should be saved in the 'S_{11}' folder of the STF410 data repository.

6.5.3 Calibration of NWA

The NWA has to be calibrated with a full 1-port reflection calibration at the end of the coaxial wire. As calibration kits 'short', 'open' (do not connect anything) and 'broadband load' (50 Ohm termination) has to be used.

In the measurements recorded here the MIMO PLT couplers [i.5] are considered to be part of the PLT channel.

S_{11} is a complex value which is a function of the load impedance and of the characteristic impedance of the measurement system. In our case the measurement system consists of the network analyzer, which has a characteristic impedance of 50 Ω and the 1:2 balun inside the Universal coupler, which transforms the 50 Ω to 200 Ω.

S_{11} on the 50 Ω side is identical to S_{11} on the 200 Ω side, except for a phase shift due to the length of the transmission lines inside the balun.

The real and the imaginary parts of S_{11} are recorded.
The absolute value is $|S_{11}|$ = `sqrt((real(S11)^2 + imag(S11)^2))`
and the phase angle is φ = `atan(imag(S11)/ real(S11))`

For engineering purposes the absolute value $|S_{11}|$ is sufficient in most cases. It allows us to calculate the load impedance depending on the line length.

$$Z_{DMmax} = Z_o (1 + |r|) / (1 - |r|)$$

$$\text{with } Z_o = 200\ \Omega \text{ and } |r| = 10^{(-|S_{11}|/20)}$$

Knowing φ one may calculate Z_{DM} for each frequency when considering the line length of the balun which is about x = 0,3 m.

$$Z_{DM} = Z_o (1 + |r| * e^{j(\varphi + \beta x)}) / (1 - |r| * e^{j(\varphi + \beta x)}) \quad \text{where } \beta = \omega / \upsilon \qquad \upsilon\text{: speed of propagation in the balun.}$$

6.5.4 Functional Test Before Starting Reflection (S_{11}) Measurements

From time to time, one should perform a $|S_{11}|$ check, before starting reflection measurements with the LVDN, by connecting the mains plug of the coupler to the test pad. The characteristic DM-impedance of the pad is 80 Ω.

Ideally $|S_{11}|$ is - 7,4 dB.

Because of loss and impedance mismatch in the coupler and of the Schuko plug the value is somewhat frequency dependent.

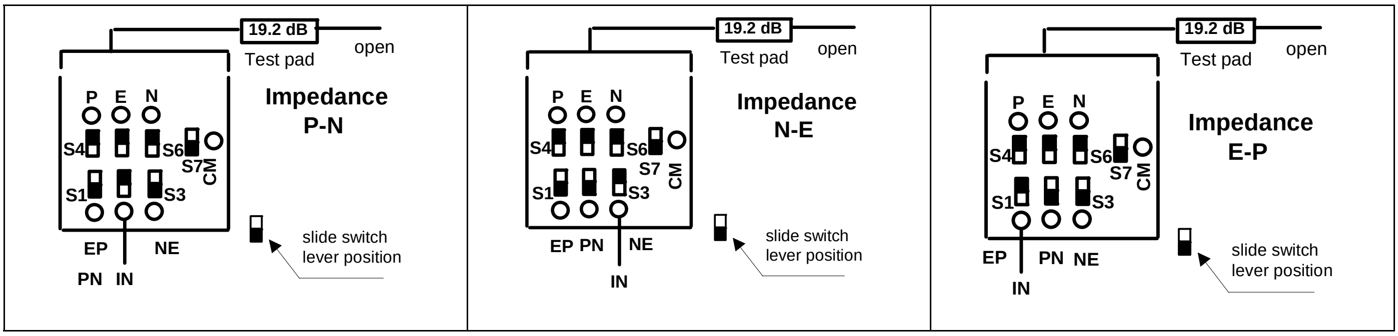


Figure 10: Coupler Configuration: Feed Differentially

6.5.4.1 Slide Switch Positions

Table 9: Switch Positions of Functional Test for Reflection Measurements

Feed & Receive PN

P (S4)	E (S5)	N (S6)	CM (S7)
off	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	on	off	

Feed & Receive NE

P (S4)	E (S5)	N (S6)	CM (S7)
off	off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
off	off	on	

Feed & Receive EP

P (S4)	E (S5)	N (S6)	CM (S7)
off	Off	off	on
E-P (S1)	**P-N (S2)**	**N-E (S3)**	
on	Off	off	

6.5.4.2 Typical Return Loss for Inputs P-N; N-E and E-P

Table 10: Return Loss of Functional Test for Reflection Measurements

	10	30	80	**MHz**
$\mathbf{|S_{11}|}$	7,2 to 7,5	7,7 to 8,6	7,5 to 10,5	**dB**

6.5.5 Conducting Reflection (S_{11}) Measurements

If the equipment is set-up and the network analyzer calibrated as described above, field measurements can be conducted in private residences. A protocol-sheet is prepared in clause A.2 for each measurement site to be completed during field tests.

All combinations of feeding and receiving (NE, PN, EP, NENT, PNNT, EPNT, APN, PNE, CM) are recorded. Any combination where feeding and receiving did not take place on the same port (line conversion reflections) was not measured by STF410.

To protect the NWA from damage the coupler should be connected to the outlet before the coaxial wire is connected and when removing the coupler from the outlet the coaxial cable should be disconnected first.

6.6 Set-Up for Noise Measurements

6.6.1 Set-Up

The full setup for noise measurement is given in figure 11.

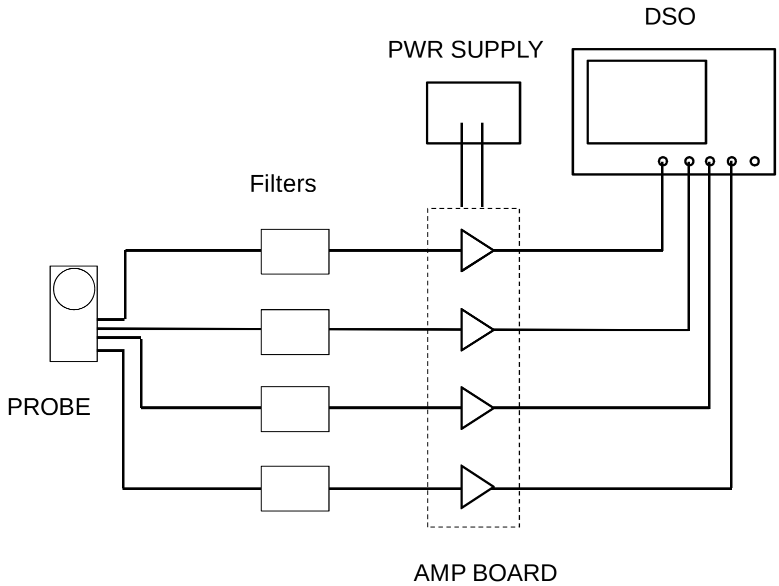


Figure 11: Noise Measurement Setup

The MIMO coupler is used in receiver mode in the star configuration. In order to receive signals on 4 ports, including the CM signal, the P, N and E switches need to be closed and the CM switch left open ('on' position).

The filters are used in 4 different configurations called Band 1 to Band 4 as given in table 11.

Table 11: Filter Configuration for each Frequency Band

Band	Filter configuration	Comment
Band 1	HPF-002 + LPF-100	2-100 MHz band
Band 2	HPF-002 + LPF-100 + SBF-FM	2-100 MHz band with FM notch
Band 3	4HPF-025 + LPF-200	30-100 MHz band
Band 4	HPF-025 + LPF-100 + SBF-FM	30-100 MHz band with FM notch

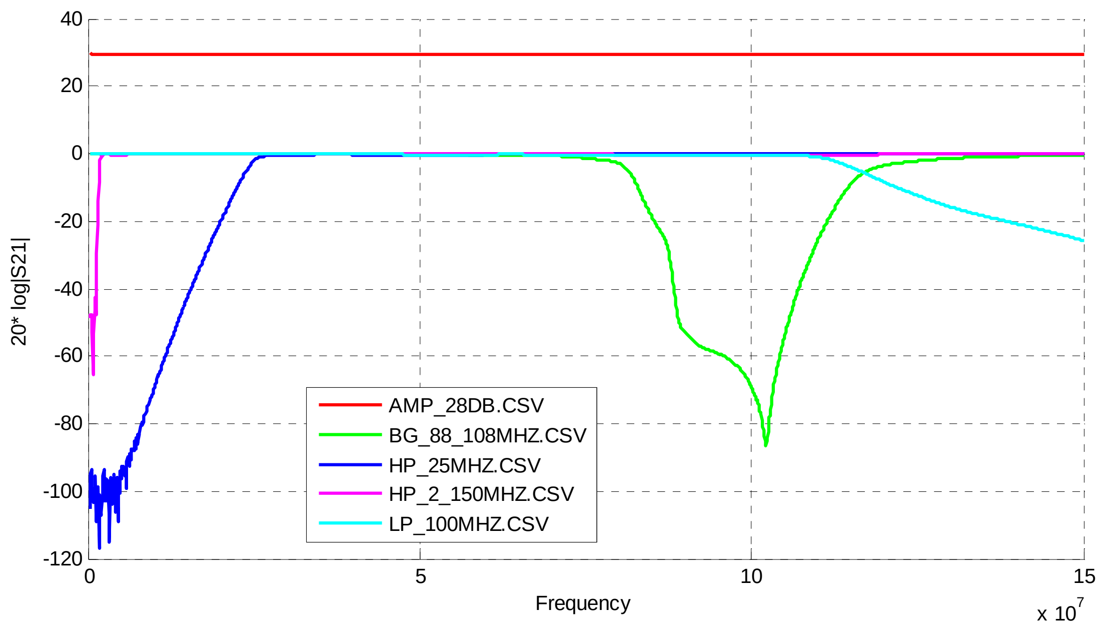


Figure 12: Frequency Response at 0 < f < 150 MHz of Filters and Amplifier used

After the filter stage, each signal is connected to the DSO using this convention:

- Port 1: P signal
- Port 2: E signal
- Port 3: N signal
- Port 4: CM signal

At the beginning of the measurement, the settings of the DSO should be set as follows:

Vertical settings: the vertical gain of each port is set to the minimum, that is, the observation scale is set to the maximum. In the case of the LeCroy WaveRunner 64Xi VL, the maximum observation scale is 1,00 V/div.

Horizontal settings: the sampling frequency of the DSO is set to 500 MS/s. The observation duration is set to 20 ms (i.e. 2 ms/div on most DSOs). In this configuration, the memory requirement for each port is 10 MS.

Termination: the ports of the scope should be terminated internally with 50 Ohm.

Amplifiers are optionally used when the received signal is too weak. Thus, the measurement process for each band should be as follows.

1) Connect the coupler to the outlet (see important notes about equipment attachment below).
2) Connect the coupler outputs to the filters inputs and the filters outputs to the DSO ports
3) Observe the noise measurements on the DSO and, for each port individually, increase the vertical gain in order to span the signal across the full observation scale. Make sure that there is no clipping of the received signal on any port.
4) If the noise level for all 4 ports is < 10 mV (measured before the amplifiers), attach optional amplifier board and repeat step 2 (see important notes about equipment attachment below).
5) Record noise waveform.
6) Detach optional amplifier board (see important note about equipment attachment below).
7) Detach DSO and filters from coupler.

8) Detach coupler from outlet.

Important notes about equipment attachment:

- Connecting and disconnecting the coupler from the outlet creates impulsive noise that can damage the equipment. Thus, connecting the coupler to the outlet should be the first step in the equipment attachment process. Similarly, disconnecting the coupler from the outlet should be the last step in the equipment detachment process.
- Powering up the amplifier board without a load on the amplifier output can damage the amplifiers. So powering up the amplifier should be the last step in the equipment attachment process. Similarly, powering down the amplifier from the outlet should be the first step in the equipment detachment process.
- Operating conditions of each Mini-circuit ZFL-500LNB+ power amplifier are 15 V and 60 mA. The amplifier board (consisting of 4 amps) should be fed with a stabilized power supply delivering 15 V and 240 mA. Depending on the type of power supply, it might be necessary to check these values using a multi-meter.

In order to synchronize all measurements with the LCZC, the DSO trigger must be set up and the mains line signal must be used at zero crossing (with a positive slope) as a trigger.

To ensure that all 4 paths are recorded at the same time, a 'single trigger' shot has to be recorded, before saving the data.

The file name convention for noise measurements is: Paa_BDb_Gcc_d_yyyy.eee where:

- 'aa': Two digit Receive Plug (outlet) number
- 'b': Filtered band number (1 to 4)
- 'cc': Two digit amplifier gain in dB. Usually 'cc' is 28 when amplifiers are present and 'cc' equals 00 if the amplifier is not used
- 'd': Signal at Rx Star- coupler: P, E, N or CM
- 'yyyy': if the recording was done in a special environment, this may be noted here. E.g. 'yyyy' may be 'all appliances_on' or 'noise_from_PC_power_supply'. If several noise shots are recorded using one and the same setting, an index of 'yyyy' can be used
- 'eee': File extension: 'trc' for LeCroy DSO, 'wfm' or 'isf' for Tektronix DSO

E.g. if the filename is P04_BD2_G28_E.trc, receiving was done at Plug number 4 at connector E (Protective Earth). The filtered band is BD2, i.e. 2-100 MHz with FM notch. An amplifier with 28 dB gain was used.

Please verify that the y-axis settings are included in the record. If not, please include the voltage per division settings in the filename.

6.7 General Equipment List

6.7.1 Coaxial Cables

The coaxial cables used to conduct the measurements must enable results of a dynamic range of up to 120 dB. Therefore double shielded cables like RG214 are required.

6.7.2 Network Analyzer

The following NWA are used by the measurement teams.

6.7.2.1 Agilent E5071B

The team in Germany used an Agilent E5071B.

Figure 13: Agilent E5071B

Table 12: Technical Properties of Agilent E5071B

Property	Value	Comment
Type	E5071B ENA	
Manufacturer	Agilent	
Output power	+12 dBm	in the frequency domain; into 50 Ω
Out- / Input impedance	50 Ω	
Frequency range	300 kHz to 8,5 GHz	
Max Dynamic Range	125 dB	

6.7.2.2 Agilent E5071C

The teams in Belgium and France, Lannion used a Agilent E5071C ENA Network Analyzer.

Figure 14: Agilent E5071C

Table 13: Technical Properties of Agilent E5071C

Property	Value	Comment
Type	E5071C ENA	
Manufacturer	Agilent	
Output power	+10 dBm	in the frequency domain; into 50 Ω
Out- / Input impedance	50 Ω	
Frequency range	9 kHz to 6,5 GHz	
Max Dynamic Range	123 dB	

6.7.2.3 Rohde & Schwarz ZVB4

The team in Spain used a Rohde & Schwarz ZVB4 Network Analyzer.

Figure 15: Rohde & Schwarz ZVB4

Table 14: Technical Properties of R&S ZVB4

Property	Value	Comment
Type	ZVB4	
Manufacturer	Rohde & Schwarz	
Output power	-40 dBm to + 13 dBm	
Out / Input Impedance	50 Ω	
Frequency Range	300 kHz to 4 GHz	
Max Dynamic Range	> 123 dB	at 10 Hz IF bandwidth
Number of ports	4	
Number of measurement points	1 to 60 001	

6.7.2.4 CM Choke Absorber between Coupler and NWA

To ensure that coupler and the counterpoise provide a set-up for reproducible measurements, CM signals from the coupler need to be isolated from NWA. In the measurement configuration shown in figure 16, the counterpoise is decoupled by chokes with absorbent ferrites. The choke, or chokes in the case of multi-channel measurements, should be placed close to the RX coupler.

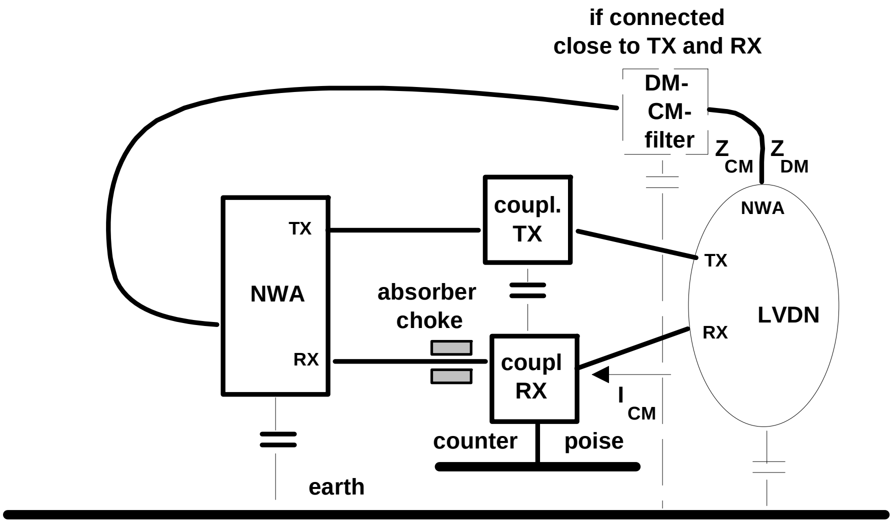


Figure 16: Improved Measurement Configuration

Figure 17 shows a possible design with a toroidal ferrite core and a RG-316 or similar cable.

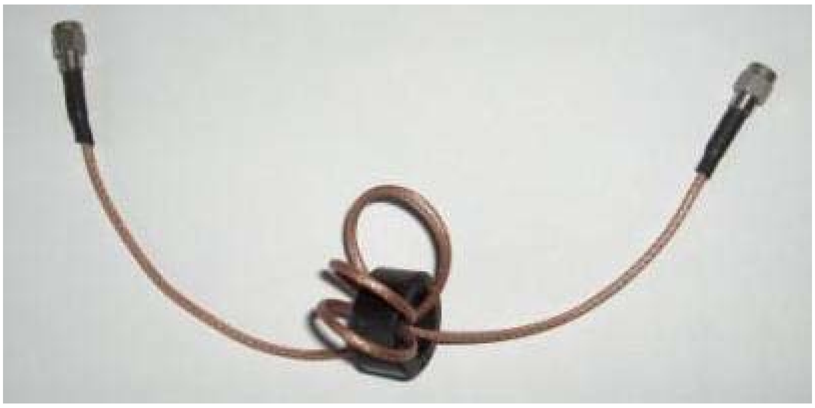


Figure 17: Choke Absorber

CM Impedance of Choke Absorber (recorded choke data with 4 turns)

Table 15: Impedance of CM Choke

	3	10	30	60	80	100	**MHz**
|Z|	255	660	920	530	370	250	**Ω**
φ	78	38	2	- 30	- 60	- 50	**degree**

6.7.3 Digital Sampling Oscilloscope

The following DSO are used by the measurement teams.

6.7.3.1 Tektronix DPO4104

The team in southern Germany used Tek DPO4104.

http://www.tek.com/products/oscilloscopes/mso4000/http://www.tek.com/products/oscilloscopes/mso4000/

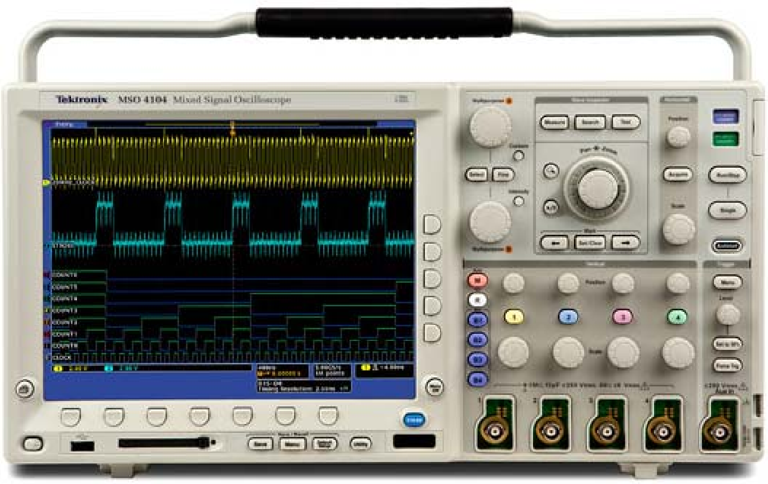


Figure 18: Tek DPO4104

Table 16: Technical Properties of Tektronix DPO4104

Property	Value	Comment
Type	DPO4104	
Manufacturer	Tektronix	
No of Channels	4	Plus external trigger
Input impedance	50 Ω	
Resolution	8 bit	Additionally 'High Resolution' option averaging values acquired by oversampling
Max Bandwidth	1 GHz	
Memory depth	10 M samples	for each of the 4 channels

6.7.3.2 Tektronix DPO7254

The team in Belgium / North-Western Germany /United Kingdom used a DPO 7254.

See http://www.tek.com/products/oscilloscopes/dpo7000/.

Figure 19: Tektronix DPO725

Table 17: Technical Properties of Tektronix DPO7254

Property	Value	Comment
Type	DPO7254	
Manufacturer	Tektronix	
No of Channels	4	Plus external trigger
Input impedance	50 Ω	
Resolution	8 bits	(> 11 bits with averaging)
Max Bandwidth	2,5 GHz	
Memory depth	10 GS/s	for each of the 4 channels

6.7.3.3 LeCroy WaveRunner 64Xi VL

The team in France, Lannion used a LeCroy WaveRunner 64Xi VL.

http://www.lecroy.com/Oscilloscope/OscilloscopeModel.aspx?modelid=1939&capid=102&mid=504

Figure 20: LeCroy WaveRunner 64Xi VL

Table 18: Technical Properties of LeCroy WaveRunner 64XiVL

Property	Value	Comment
Type	WaveRunner 64Xi VL	
Manufacturer	LeCroy	
No of Channels	4	Plus external trigger
Input impedance	50 Ω	
Resolution	8 bit	
Max Bandwidth	600 MHz	
Memory depth	12,5 Msamples	for each of the 4 channels

6.7.3.4 Agilent DSO8104A

The team in Spain used a Agilent DSO8104A.

Figure 21: Agilent DSO8104A

Table 19: Technical Properties of Agilent DSO8104A

Property	Value	Comment
Type	DSO8104A	
Manufacturer	Agilent	
Number of channels	4	
Input impedance	50 Ω / 1 MΩ	
Resolution	8 bit	
Max Bandwidth	1 GHz	
Memory depth	8 Mpts / 4 Mpts	2 channels / 4 channels
Sample rate	4 Gsa/s	

6.7.4 Amplifiers for Noise Measurements

Four Mini-circuit ZFL-500LNB+ amplifiers were used by all teams conducting noise measurements.

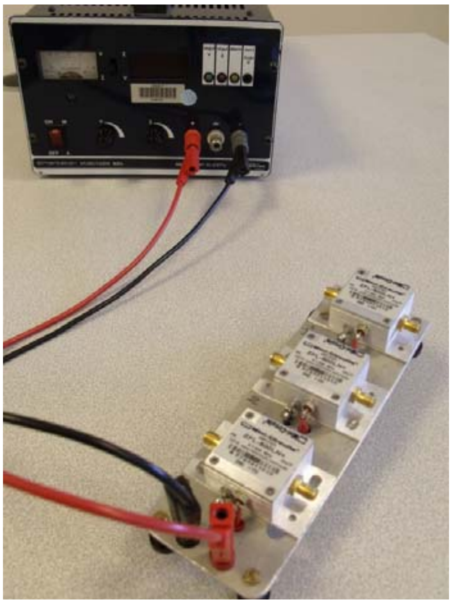


Figure 22: Array of 3 amplifiers with Power Supply

Table 20: Technical Properties of Mini-circuit Amps

Property	Value	Comment
Type	Wideband low noise	
Manufacturer	Mini-circuit	
Max Output level	~7,5 dBm	
Max Gain	~30 dB	

The frequency transfer function of the amplifiers is depicted in figure 12.

The amplifier output power was checked against varying input power levels in order to evaluate the amplifier 3 dB compression point. Observation results are given in figure 23. According to the measurements, the amplifier reaches its 3 dB compression point at an input power of -17 dBm.

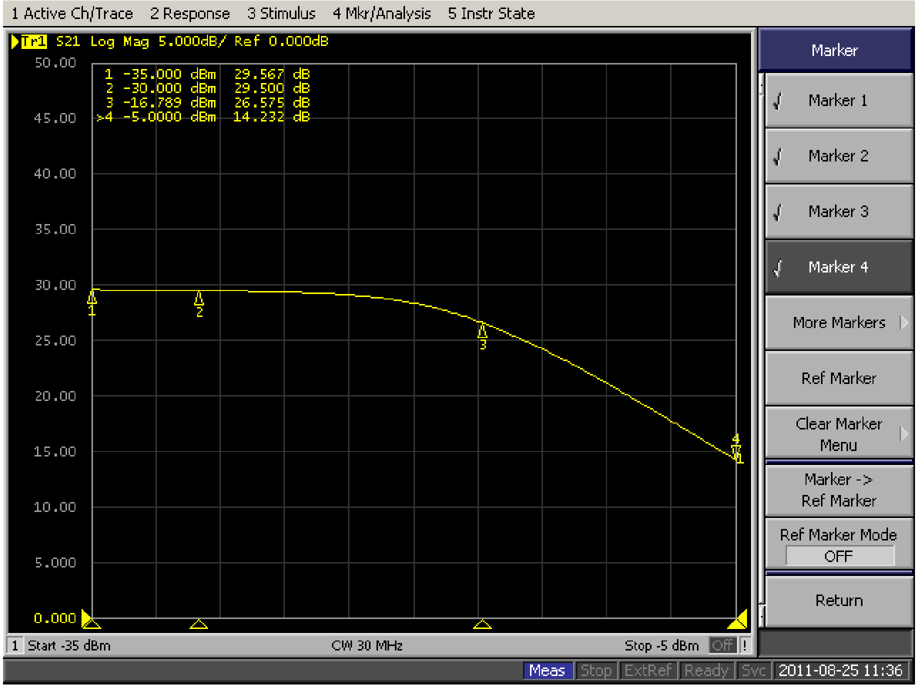


Figure 23: Evaluation of the Amplifier 3 dB Compression Point

6.7.5 LISN or Filter to Isolate Measurement Devices from Mains

Figure 24: AMN

Table 21: Technical properties of AMN

Property	Value	Comment
Type	ESH3-Z5	
Manufacturer	Rohde & Schwarz	
PE connection	50 µH "on"	

An additional filter must be inserted in sequence into the LISN in order to isolate the PE wire, and is described in the following clause.

6.7.6 Mains Filter

Test instruments (namely the network analyzer) connected to the mains section being tested, constitute an additional load during channel and transfer measurements and may cause measurement errors.

The instruments should be connected to another mains section, e.g. in a neighboring apartment, via a mains extension cable when possible. Otherwise, the MIMO mains filter described herein can be used to minimize the influence.

Even with a filter, mains outlets immediately beside feeding and receiving points should be avoided. The filter should be inserted between measurement equipment and the LISN.

This filter was produced several times by STF410 and distributed to each measurement team.

6.7.6.1 Schematic Diagram

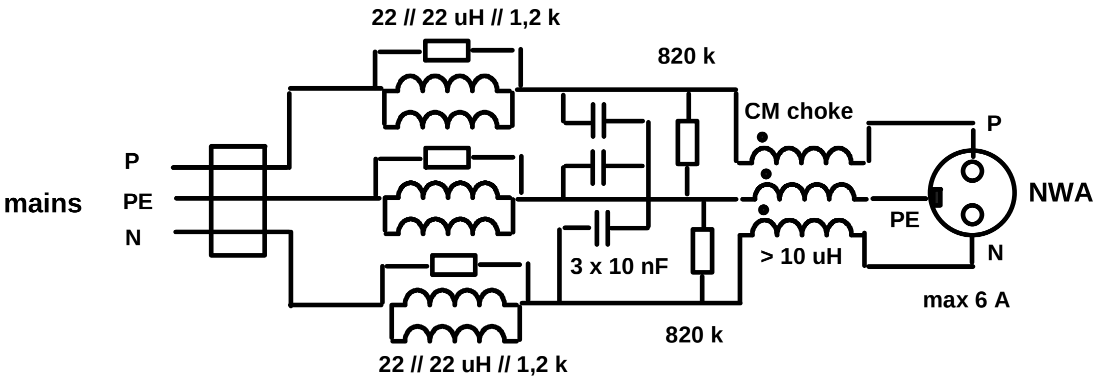


Figure 25: Schematic of Mains Filter

6.7.6.2 Typical Impedances of Decoupling Components

6.7.6.2.1 R / L Combinations - Mains Side

Table 22: Impedance R/L Circuit on Mains Side of STF410 Mains Filter

MHz	1,59	3	10	30	60	80	100	
|Z|	79	135	450	1 100	650	440	340	**Ω**
φ	58	58	64	- 4	- 50	- 60	- 60	**degree**

6.7.6.2.2 Common Mode Choke - Instrument (NWA) Side (4 turns)

Table 23: Impedance of CM Choke in STF410 Mains Filter

MHz	1,59	3	10	30	60	80	100	
|Z|	110	240	610	850	580	400	310	**Ω**
φ	89	82	42	- 16	- 51	- 62	- 64	**degree**

6.7.6.3 Images of Mains Filter

Figure 26: Mains Filter with Closed Cover

Figure 27: Filter Inside View

6.7.7 Ground Plane

A huge ground plane is necessary to achieve a low impedance or high capacity connection to ground. The ground plane is especially important when trying to replicate the CM signals we received. The size of the ground plane is sufficient when human touch no longer influences measurement results.

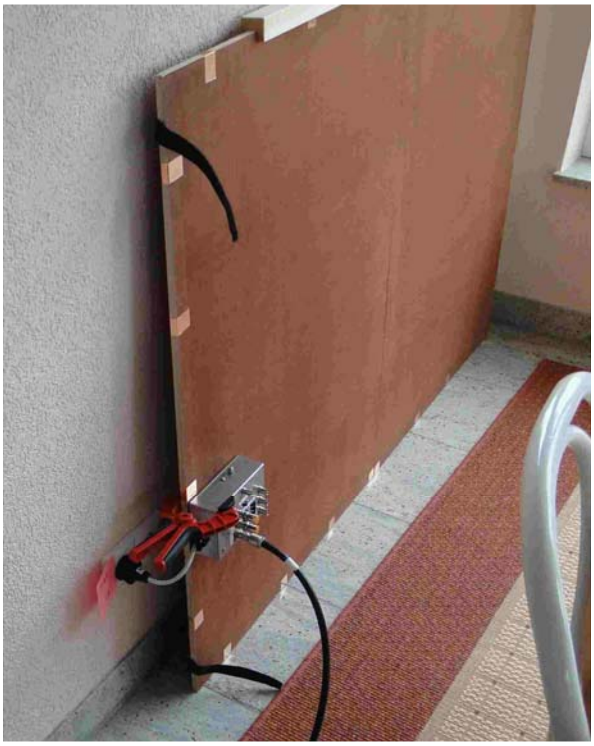


Figure 28: Ground Plane with PLC Coupler Connected Tightly

7 Statistical Evaluation of Results

7.1 Channel Transfer Function

S_{21} of MIMO PLC channels was recorded at 34 locations. In total 4 588 frequency sweeps of S_{21} measurements were conducted. Each sweep consists of 1 601 measurement values in frequency domain totalling 7 345 388 values used in the statistical evaluations below.

The figures shown below represent the cumulative probability of measuring such an attenuation. Usually a stretched S-style line from the bottom left to top right corner is depicted in the graph. These figures may be read in the following way:

- Lower left corner, the 0 % or 'definitely never' point: The attenuation was never larger than 100 dB in figure 29.
- Median or 50 % point: every 2nd measured value provides higher or lesser attenuation than roughly 53 dB in figure 29.
- 90 % point at yellow line in figure 29: 90 % of all measured values provide higher attenuation than 38 dB when feeding style APN is selected.
- Top left corner, 100 % or 'always' point: the minimum recorded value in figure 29 is 5 dB attenuation.

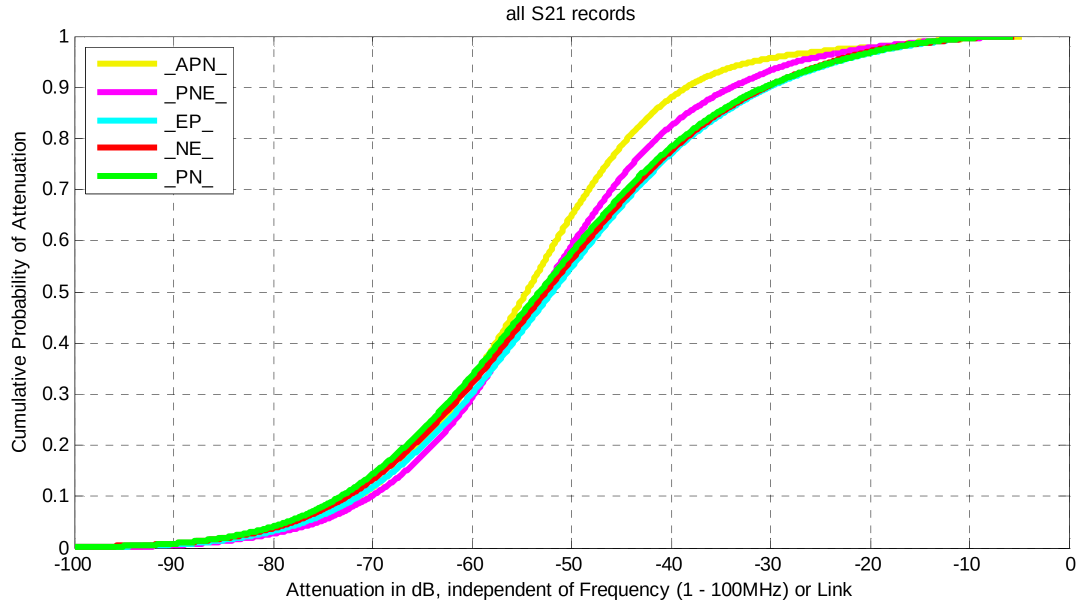


Figure 29: Cumulative Probability of Attenuation (S_{21}) for All Feeding Styles

All S_{21} measurements - independent of location, country or frequency – are separated into individual feeding possibilities: PN, EP NE, APN and PNE (figure 29). A zoom into the high attenuated records (figure 30) show that APN and PNE provide better PLT coverage. They are less attenuated than other feeding styles. The 2 wires used for traditional PLT modems (P-N) show the worst coverage in this case.

NOTE: The unused ports at the coupler were terminated with 50 Ω in these measurements. The classical SISO style modems operate by sending and receiving signals symmetrically via P and N. Unused feeding combination in SISO, are either open or unterminated. Termination of unused ports, when identical energy is fed into the couplers, theoretically requires 1,96 dB of signal energy from mains wires compared to an unterminated coupler where no loss takes place.

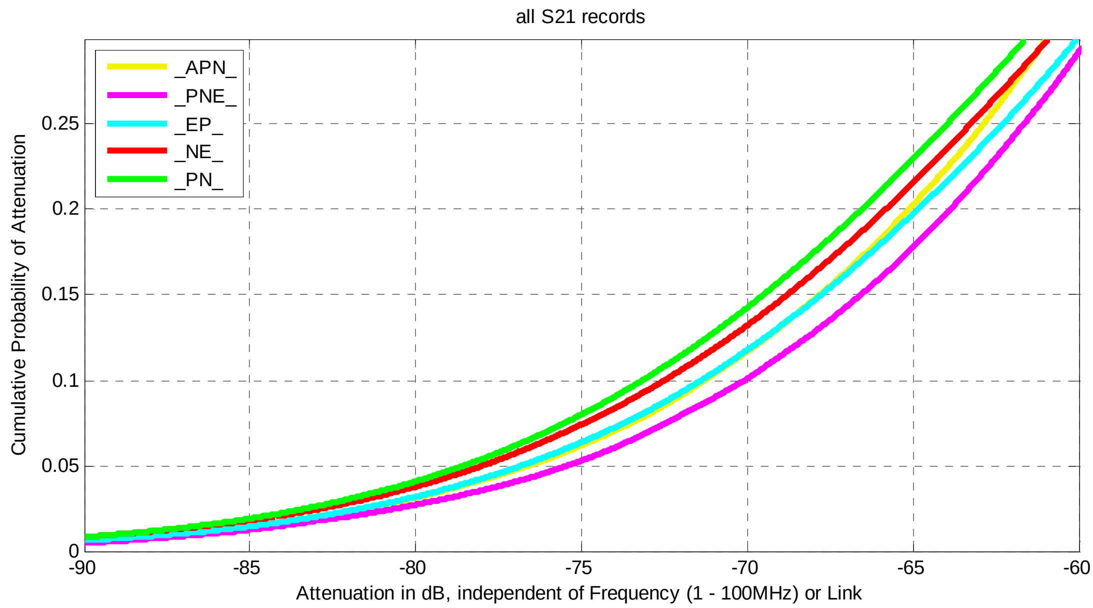


Figure 30: Cumulative Probability of Attenuation (S_{21}) for All Feeding Styles, Close-up of High Attenuated Records

Results for the possibility of receiving, identical analytical process as above, are displayed in figure 31 and figure 32. Figure 32 is a close-up of the high attenuated values. These statistics are derived from identical measurements already presented in figure 29, but sorted by individual receiving styles. Of the receiving possibilities displayed, CM reception provides the best coverage.

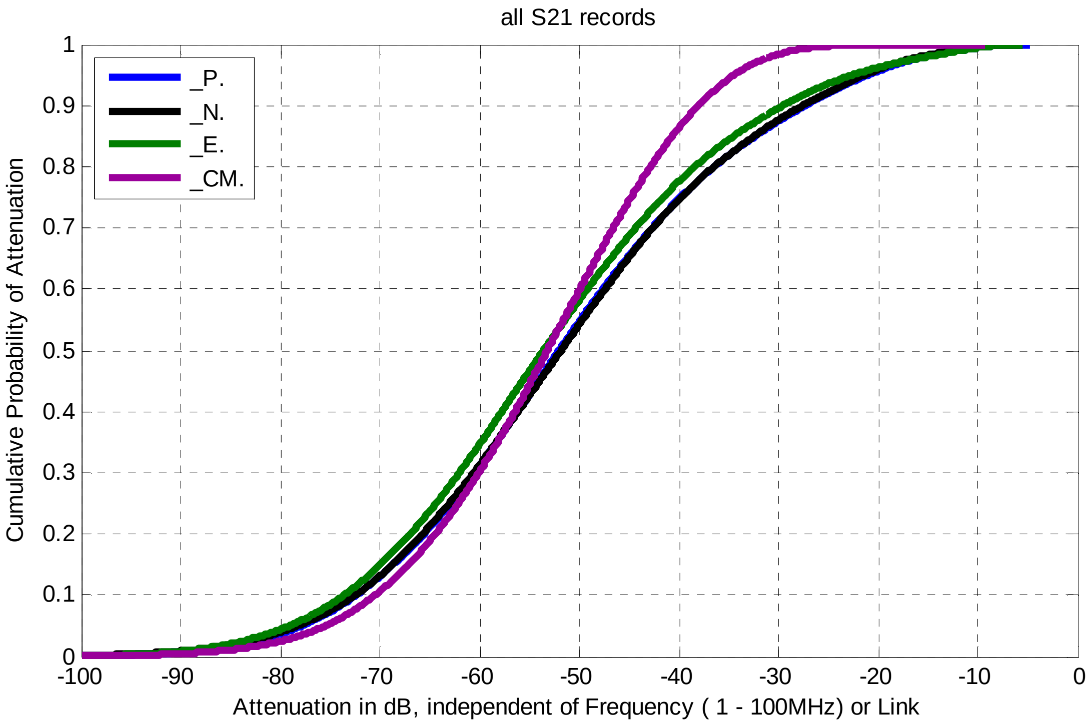


Figure 31: Cumulative Probability of Attenuation (S_{21}) of All Receiving Styles

Figure 32 provides a closer look at the higher attenuated values of figure 31. It is clearly visible that CM reception provides better coverage for PLT modems. However, a low impedance connection to ground is essential for CM reception. Only a huge ground plane can support low frequencies. An HD-TV may be the only consumer electronic device, used in a private home, equipped with an adequate ground plane. At frequencies above 30 MHz the required size of the ground plane becomes smaller and which enables the use of many devices.

NOTE: The coupler itself is considered to be part of the channel in these statistics. [i.5] in clause 7.1.6 shows that CM reception with the STF410 coupler increases attenuation by 3 dB to 4 dB compared to reception on P, N or E. If someone is interested in the channel attenuation without the influence of the STF 410 coupler, the values from [i.5] might be considered causing the CM line to move to the right. The gap between the CM line and the others becomes larger at higher attenuated values.

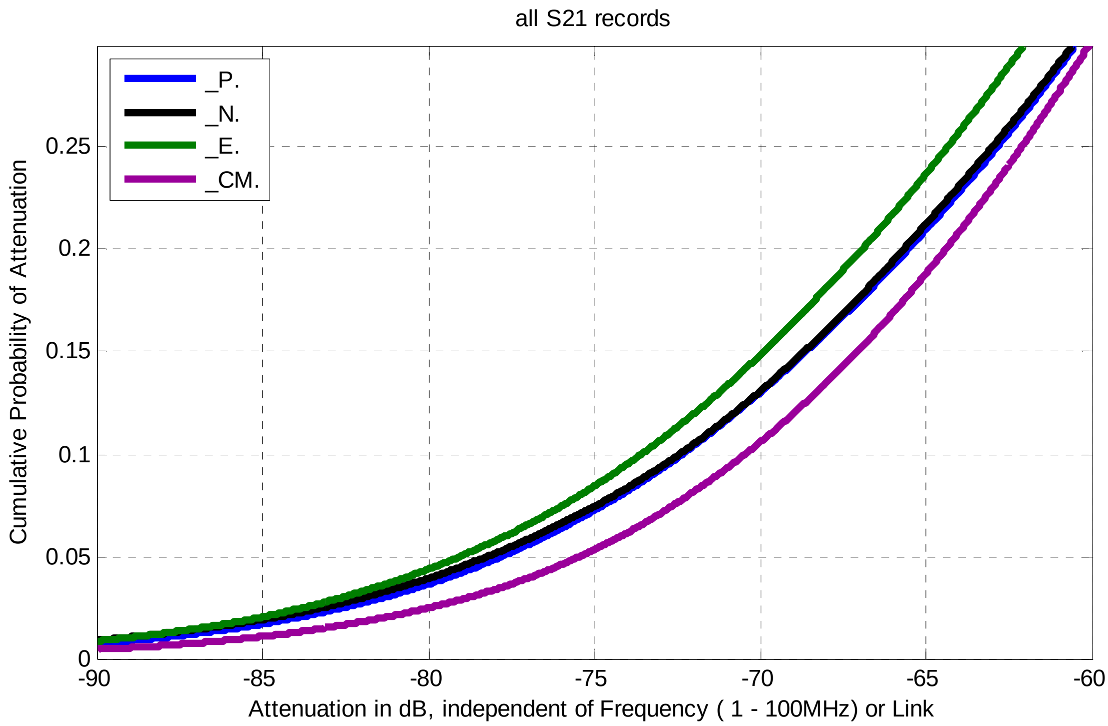


Figure 32: Cumulative Probability of Attenuation (S_{21}) of All Receiving Styles, Close-up of Higher Attenuated Records

The median values at each frequency, for all feeding and receiving styles are shown in figure 33. A constant trend from 5 MHz to 100 MHz can be seen in higher frequencies being more attenuated than lower frequencies. This trend seems to be independent of feeding or receiving style. This slope is 0,2 dB/MHz.

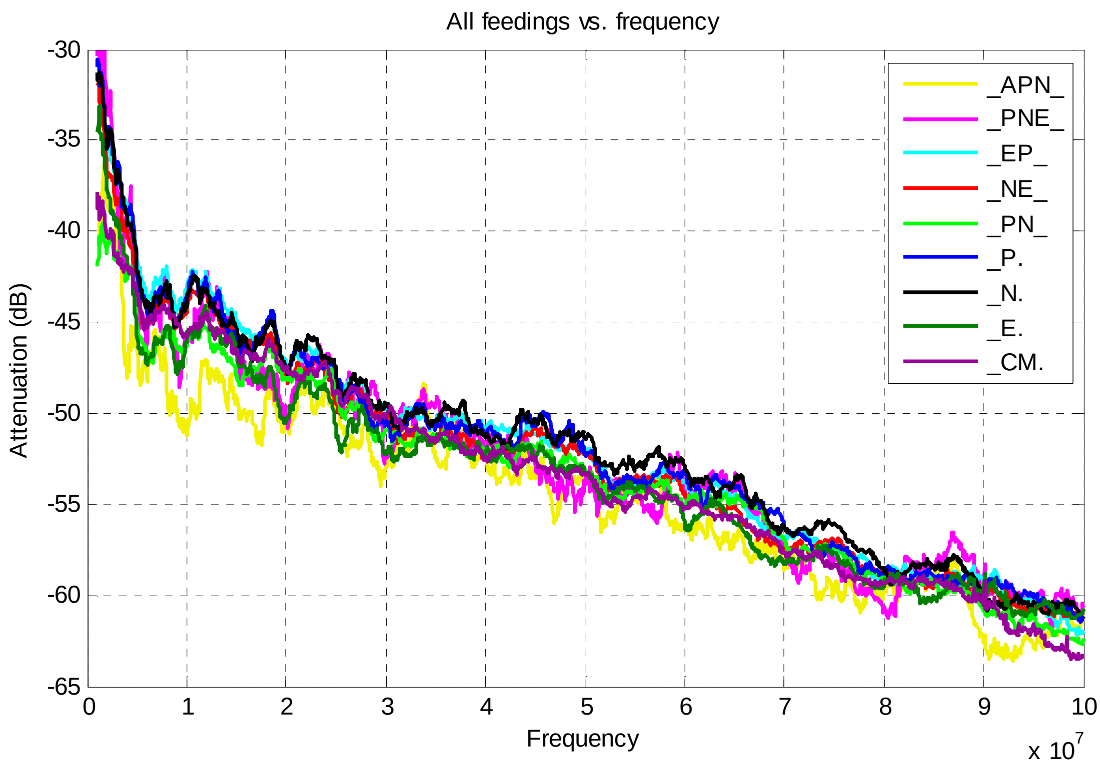


Figure 33: Median Value of Attenuation (S_{21}) Depending on Frequency and Feeding or Receiving style

Figure 32 shows that the CM provides less attenuation in higher attenuated channels. Figure 34 shows a graph of the top 10 % of attenuated values depending on frequency. The phenomena of the CM having less attenuation than the differential mode signals or single ended lines (P, N or E) exists at all frequencies.

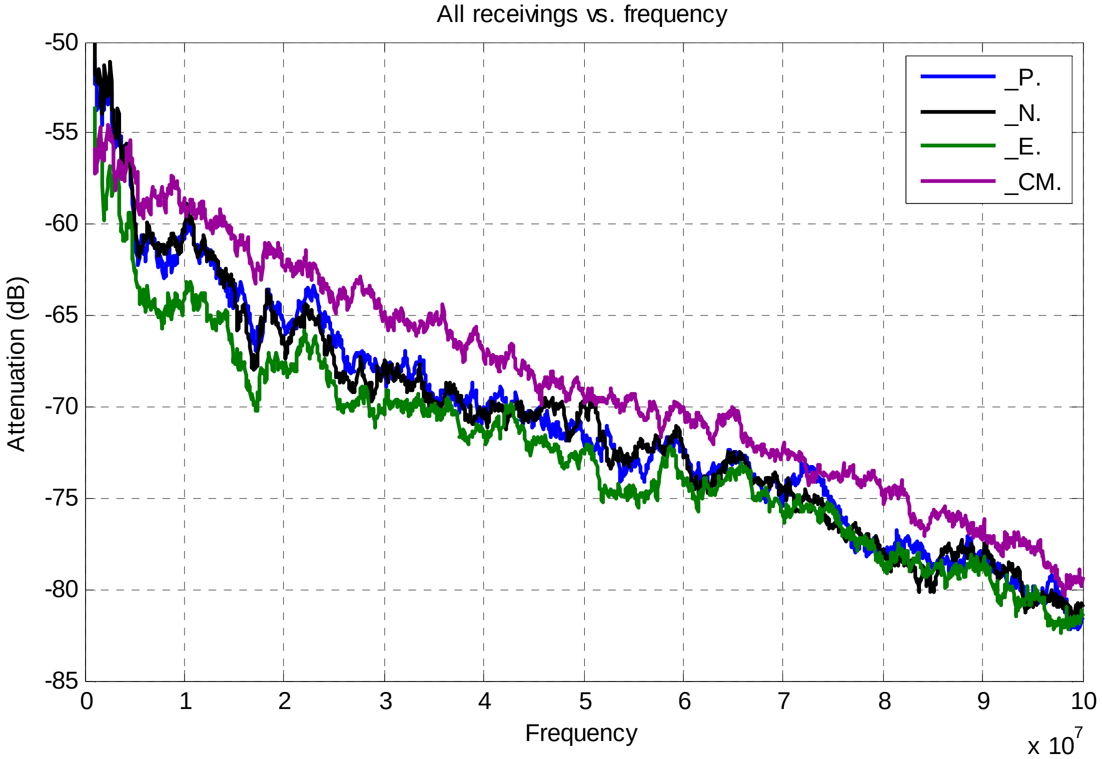


Figure 34: Statistical 10 % Value of Attenuation (S_{21}) at Higher Attenuated Records Depending on Frequency and Receiving Style

Figure 35 through figure 43 show the minimum, 20 %, median, 80 % and maximum attenuation (S_{21}) of each feeding or receiving style depending on frequency.

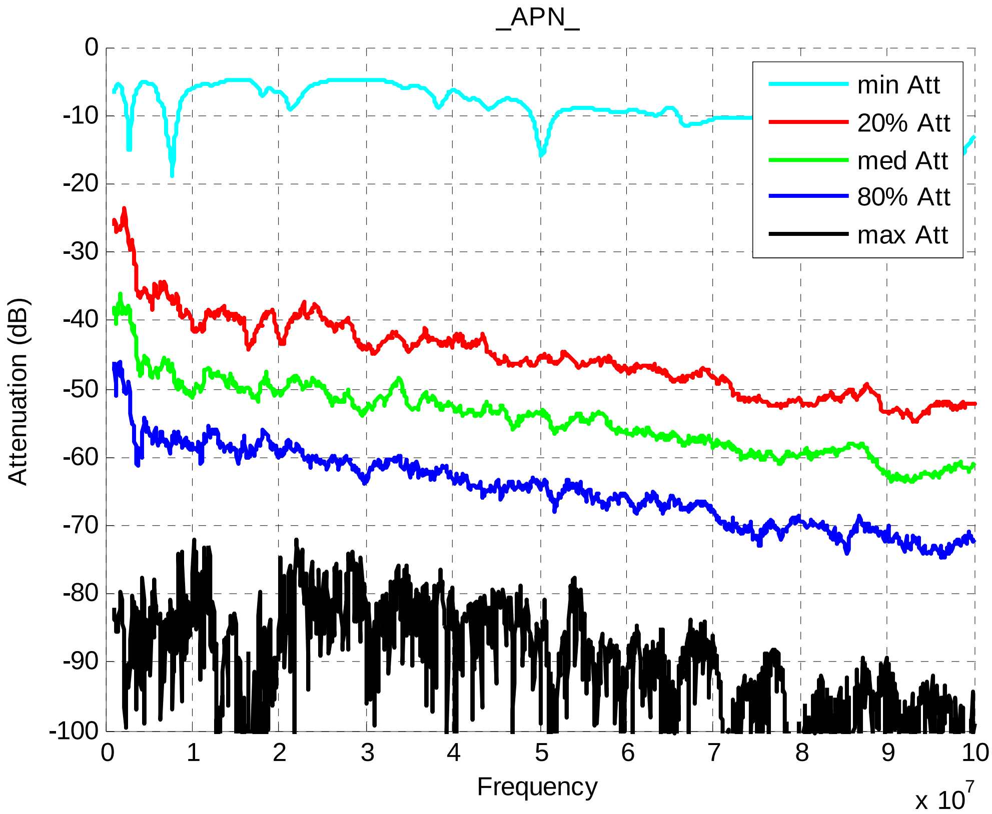


Figure 35: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency in APN Feeding Style

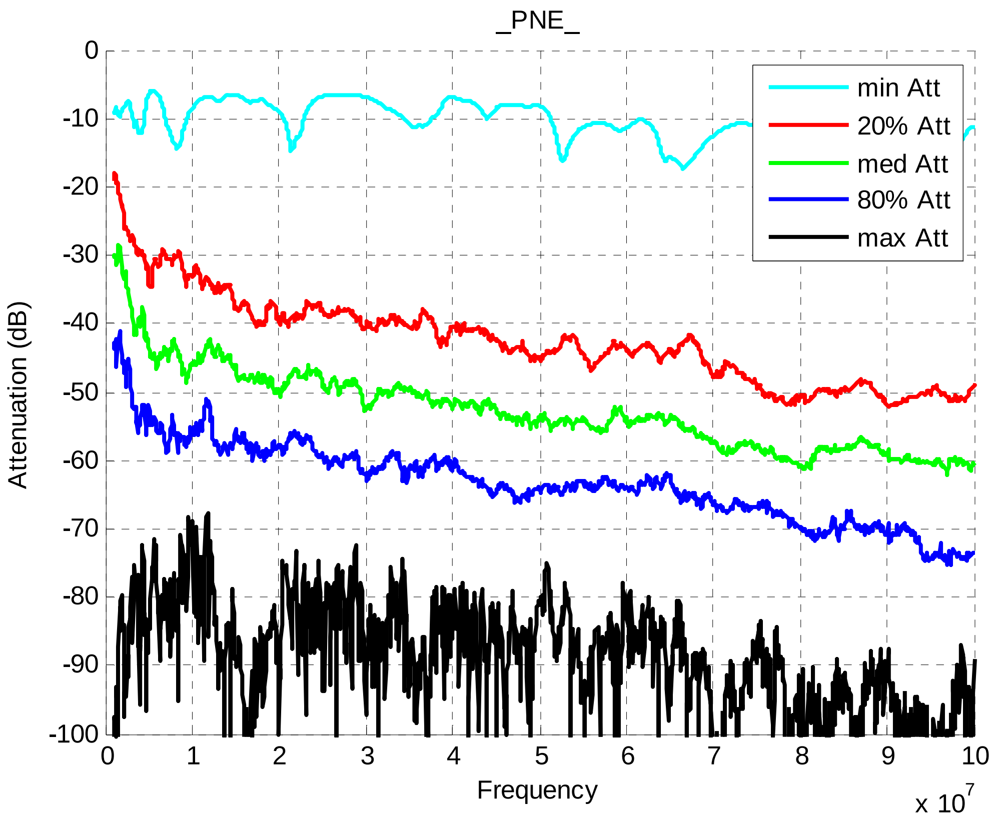


Figure 36: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency in PNE Feeding Style

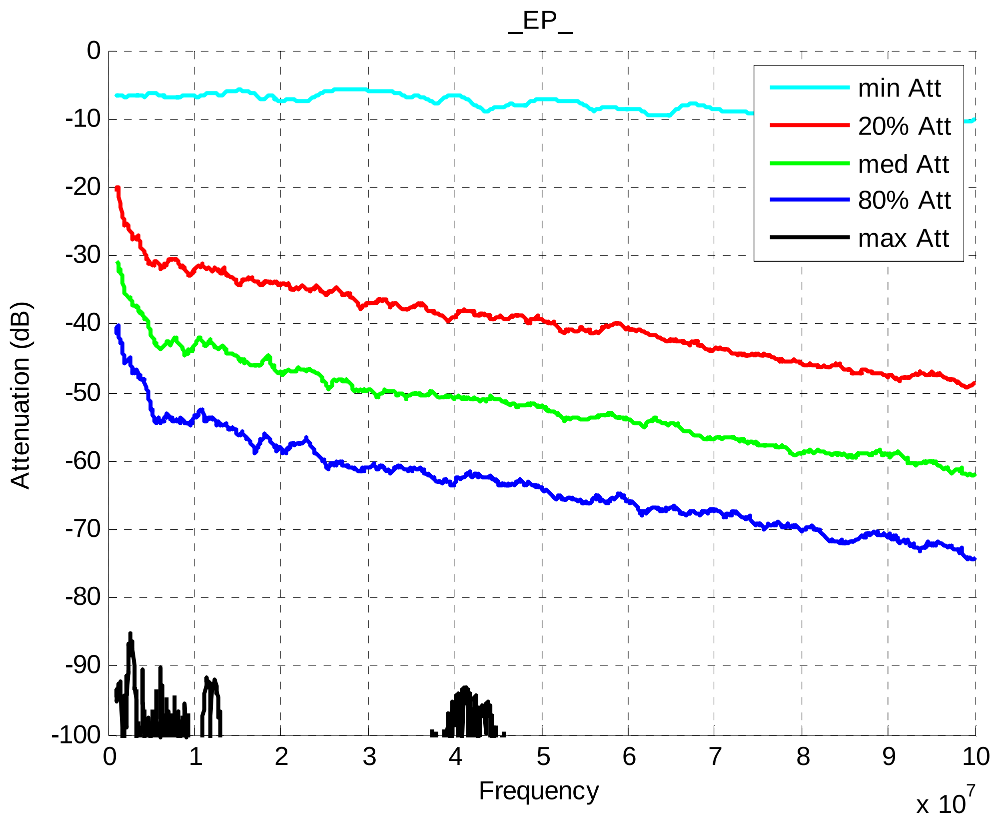


Figure 37: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency in EP Feeding Style

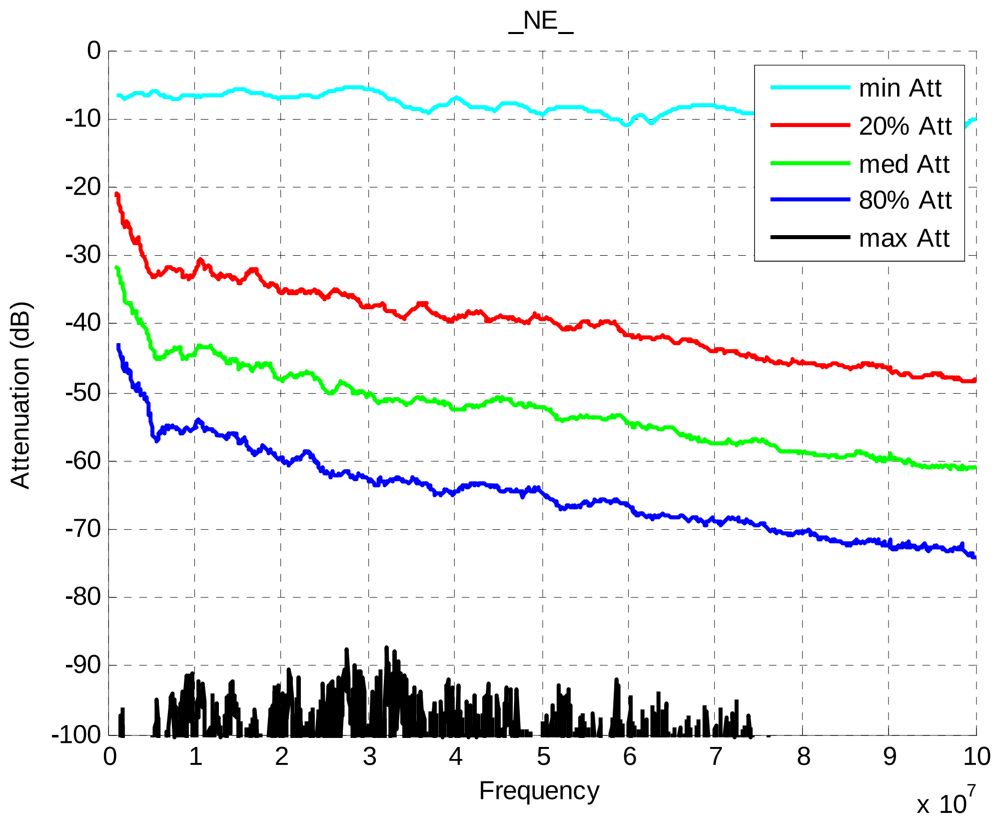


Figure 38: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency in NE Feeding Style

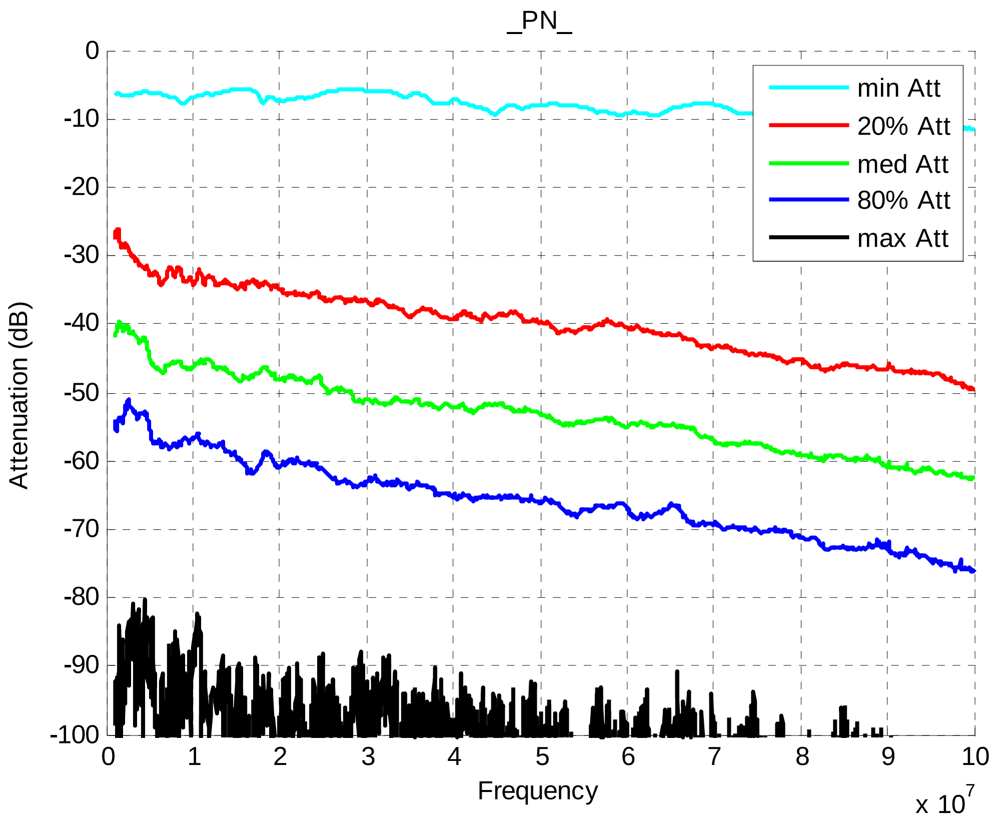


Figure 39: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency in PN Feeding Style

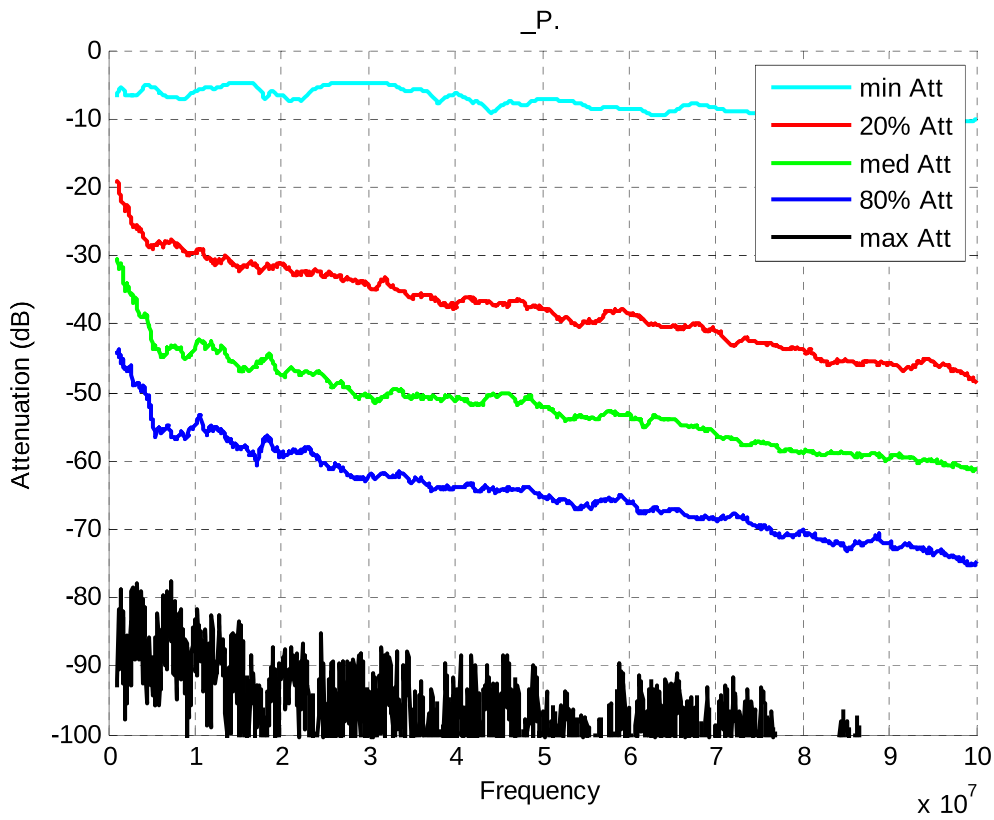


Figure 40: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency when Receiving in P Style

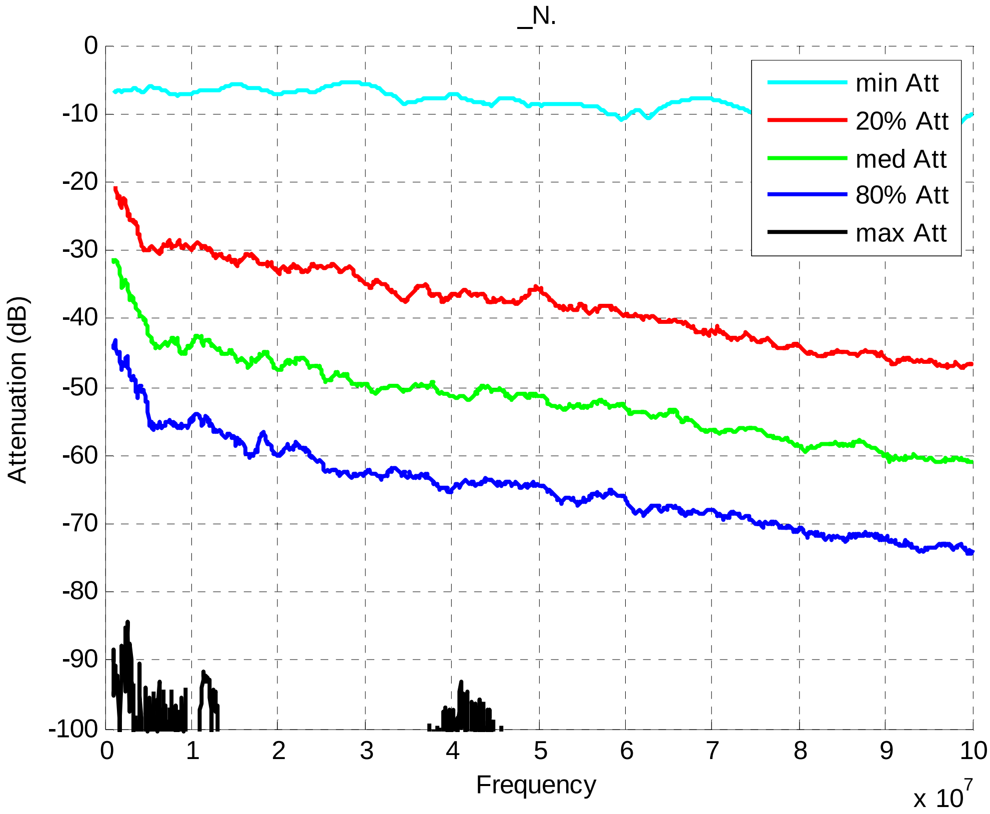


Figure 41: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency when Receiving in N Style

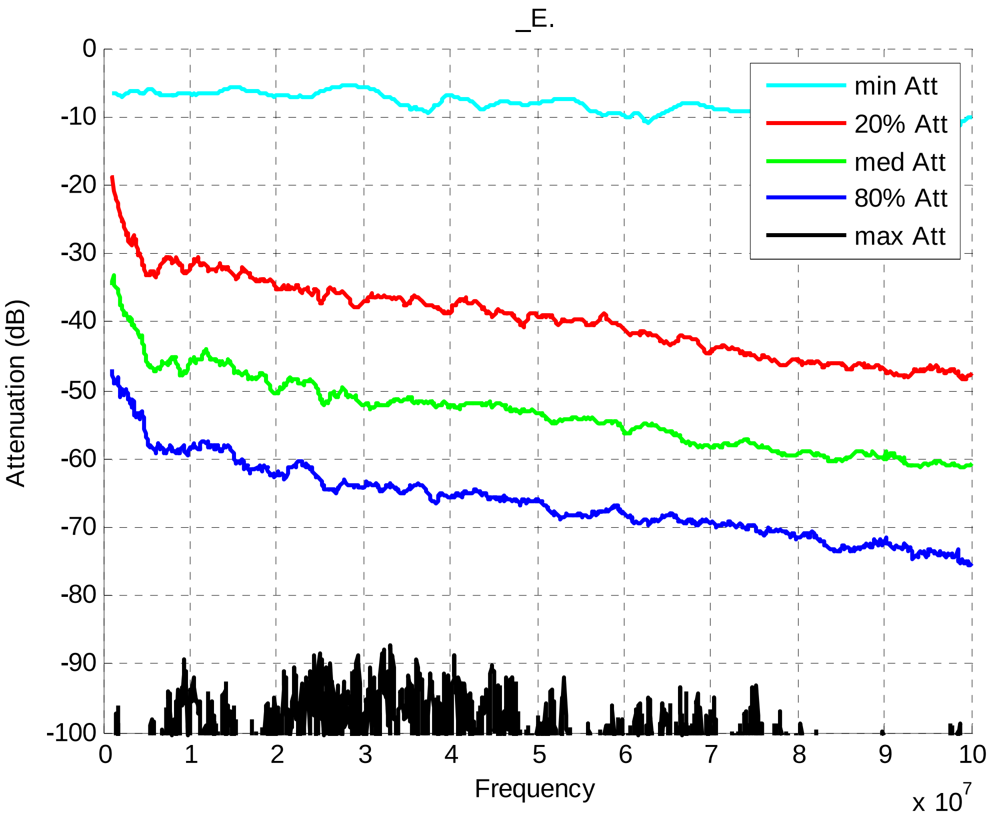


Figure 42: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency when Receiving in E Style

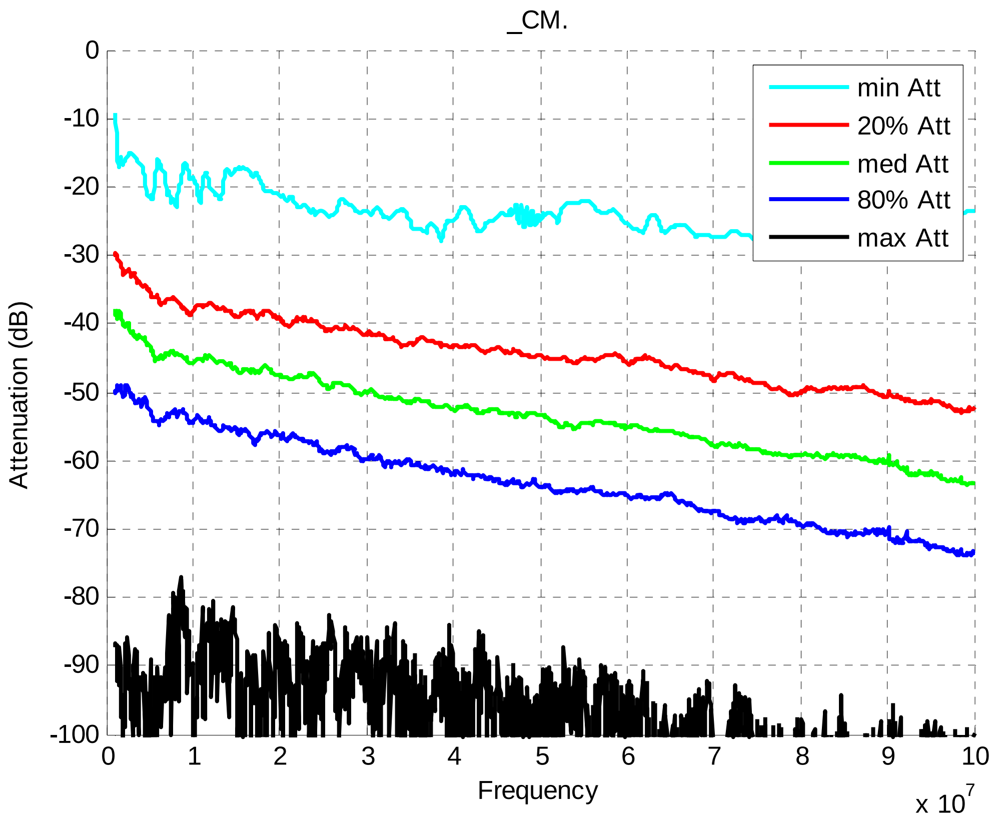


Figure 43: Min., 20 %, Median, 80 % and Max. Attenuation (S_{21}) found per Frequency when Receiving in CM Style

Table 24 presents median values of attenuation at each location. The number of sweeps at each location gives an indication of the size and maturity of the statistics. Table 25 shows the median for each country of all measurements taken. The high attenuation recorded in German buildings can be explained by the 3-phase installations there.

Table 24: Median S_{21} Value, Size and No. of Sweeps at each Location, Independent of Feeding or Receiving Style

Location	Country	Median S_{21} in dB	Size of flat or building in m²	No of sweeps recorded at this location
Duerrbachstr	Germany	-57,57	115	120
ImGeiger	Germany	-53,91	130	120
Nauheimerstr	Germany	-53,23	95	220
Rothaldenweg	Germany	-58,16	122	180
Schlossbergstr	Germany	-64,02	140	60
VickiBaumWeg	Germany	-64,87	150	120
Boenen	Germany	-56,98		144
Calicanto	Spain	-52,63	200	120
Paiporta	Spain	-48,15	96	120
Valencia_46012	Spain	-47,21	78	120
Valencia_46015	Spain	-51,61	87	120
Xirivella	Spain	-51,73	110	72
Bourg-La-Reine	France	-41,12	85	120
Spidcom-Lab	France	-62,33	180	60
DeGrandRyStrasse	Belgium	-55,96	130	144
Heidhoehe	Belgium	-56,93	160	144
Huette	Belgium	-54,11	110	144
InDenSiepen	Belgium	-54,61	110	144
Simarstrasse	Belgium	-57,64	150	144
AlsdorferStrasse	Germany	-52,65	110	144
Eichelhaeherweg	Germany	-61,61	85	144
Schlossstrasse	Germany	-69,04	120	144
SchurzelterWinkel	Germany	-61,36	150	144
Wasserkall	Germany	-63,82		144
ColchesterDrive	United Kingdom	-60,13	145	144
WilliamsRoad	United Kingdom	-45,05	97	144
WindmillAvenue	United Kingdom	-48,24	170	144
WindsorClose	United Kingdom	-35,16	75	144
Devolo-Lab	Germany	-64,12	250	24
Cavan	France	-36,25	66	120
Guingamp	France	-45,22	135	252
RueBunuel	France	-35,36	120	120
RueDepasse	France	-54,05	120	180
Trebeurdun	France	-37,31	56	180

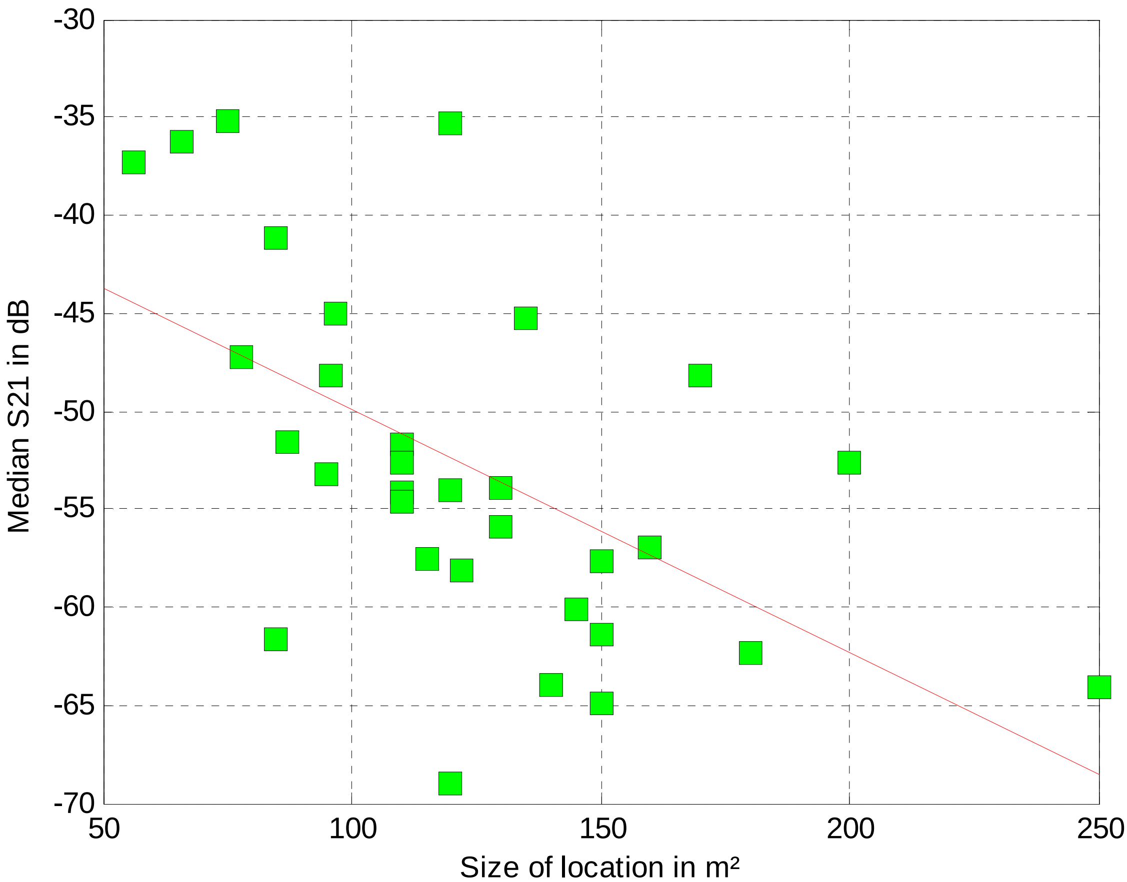


Figure 44: Size of Location under Measurement vs. Median S_{21}

Figure 44 displays the relationship between the size of the location under measurement and the attenuation between two outlets. Assuming a linear relationship between these two parameters a fitting line can be drafted into figure 44. The formula of this line is

$$S_{21} \text{ [dB]} = -0{,}1240 \text{ dB/m}^2 * \text{size [m}^2\text{]} -37{,}5546 \text{ dB}$$

Table 25: S_{21} Median Value and No. of Sweeps for each Country, Independent of Feeding or Receiving Style

Location	Country	Median S_{21} in dB	No of sweeps recorded
	Germany	-59,06	1 708
	Spain	-49,93	552
	France	-43,42	1 032
	Belgium	-55,72	720
	UK	-47,07	576
All locations		-52,69	4 588

7.2 Reflection (S_{11}) Measurements

Reflection measurements were conducted in 33 locations in Germany, Spain, France, Belgium and the United Kingdom. In total 565 frequency sweeps have been recorded with 1 601 points in frequency domain each. This results in a statistical compilation of 904 565 values.

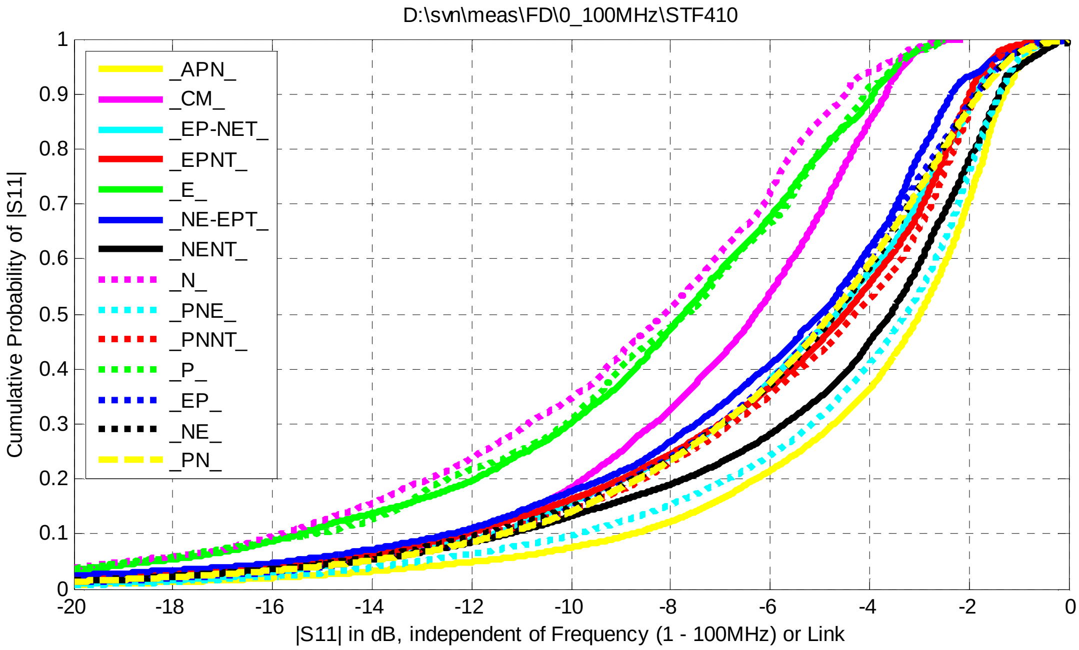


Figure 45: CDF of Magnitude of S_{11} from all Feeding or Receiving Styles Independent of Location or Frequency

Figure 45 shows an overview of the probability of measuring a reflection parameter. Indoor powerline networks show weak impedance conditions. It is difficult to implement impedance matching couplers, due to the time, frequency and location dependent characteristics which influence the coupler's feeding or receiving properties. If the S_{11} parameter is less (more negative) than -6 dB more than half of the feed signals are reflected back to the coupler and the connected outlet. This is the case for more than 60 % of all S_{11} measurements conducted using delta- or the T-feeding style.

Reflection parameters of a star-style probe, the single ended lines E, N and P as well as the CM seem to provide better impedance matching than differential couplings. The T-Style coupler shows less impedance matching than the alternatives.

The CDF is presented after conversion of the S_{11} parameter to impedance Z using Z_0 = 200 Ω in figure 46.

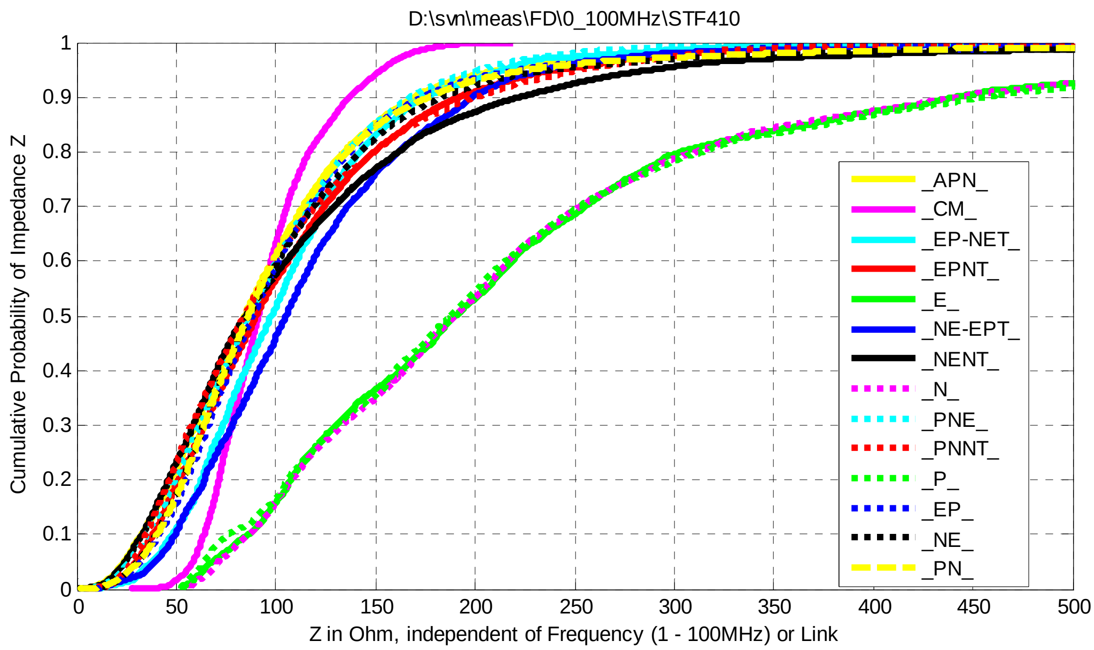


Figure 46: CDF of Impedance Z of all Feeding or Receiving Styles Independent of Location or Frequency

Table 26 shows median impedances.

Table 26: Median Impedance for each Feeding/Receiving style

Feeding / receiving style	Impedance in Ω all locations	Impedance in Ω all locations except UK	Impedance in Ω locations in UK only
APN	84,24		
CM	91,29		
EP-NET	97,75		
EPNT	90,02		
E	190,41		
NE-EPT	105,12		
NENT	84,79		
N	190,30		
PNE	86,23		
PNNT	84,03		
P	185,65		
EP	88,24	89,11	81,96
NE	86,21	87,31	78,31
PN	85,34	86,36	77,14

The impedances of PN, EP and NE at typical locations are shown per frequency in figure 47. It is interesting to see that the variance of the impedance values becomes smaller in higher frequencies.

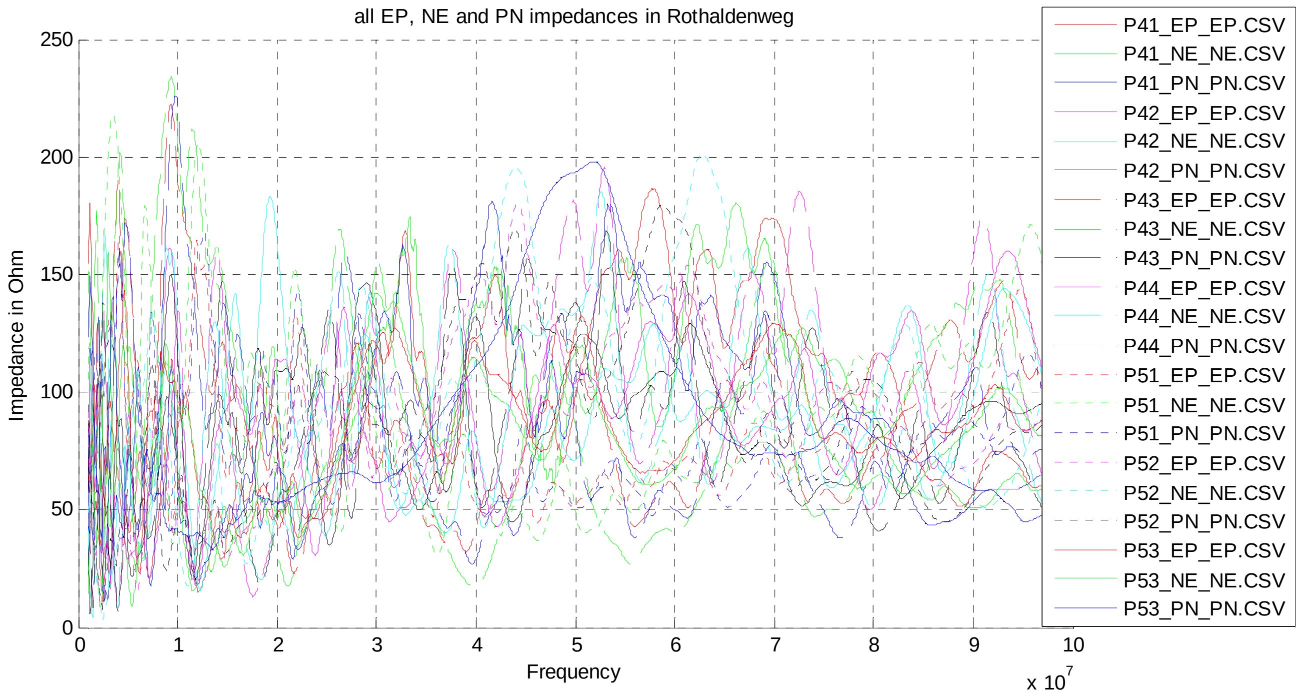


Figure 47: Impedance Z of a Typical Location

The mains installation in the UK uses a ring wire on each housing level. The outlets are daisy chained along the ring. As a result each outlet is connected to two set of wires, each going in a different direction in the room. Electrical installations in the rest of Europe follow a combination of star (at the fuse cabinet) and tree style (branches into rooms, outlets, light switches, etc.). It may be interesting to see S_{11} and input impedance of UK installations compared to the values recorded on the continent. Table 26 also includes the median impedances of UK installations with all measurements recorded outside UK. Figure 48 to figure 51 show a comparison of S_{11} and Impedance Z between the UK and the continental measurements. As expected the UK installations show lower impedance but not half the value than found on the continent.

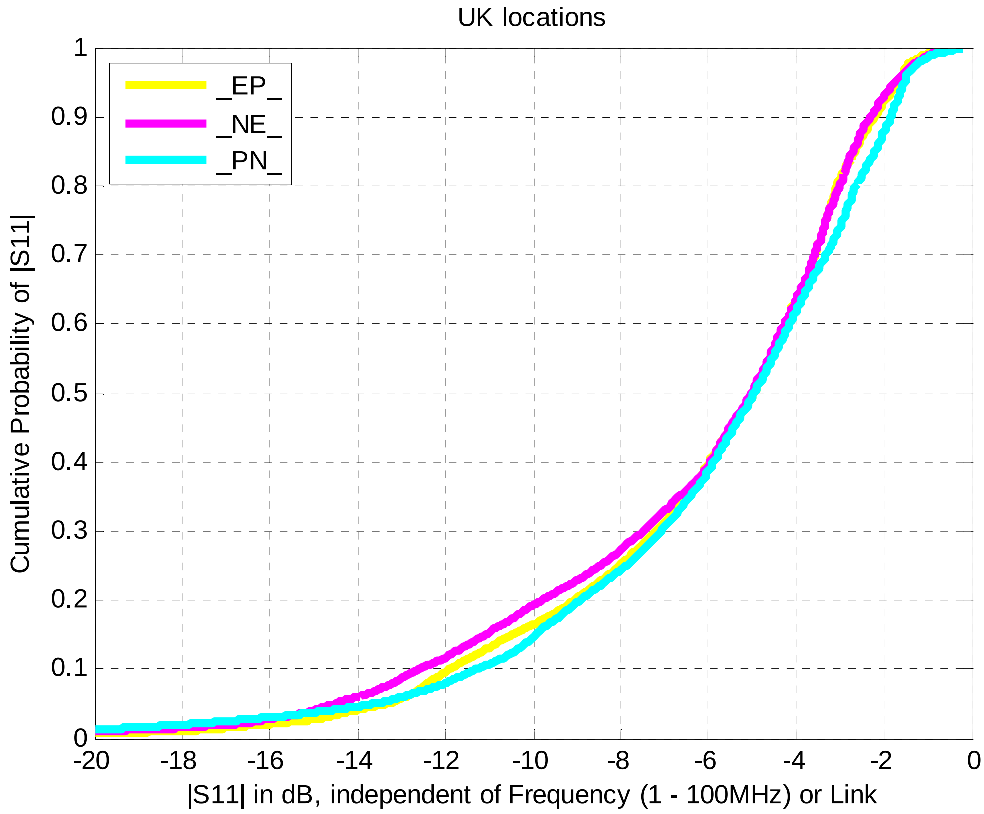


Figure 48: CDF of S_{11} Recorded in UK

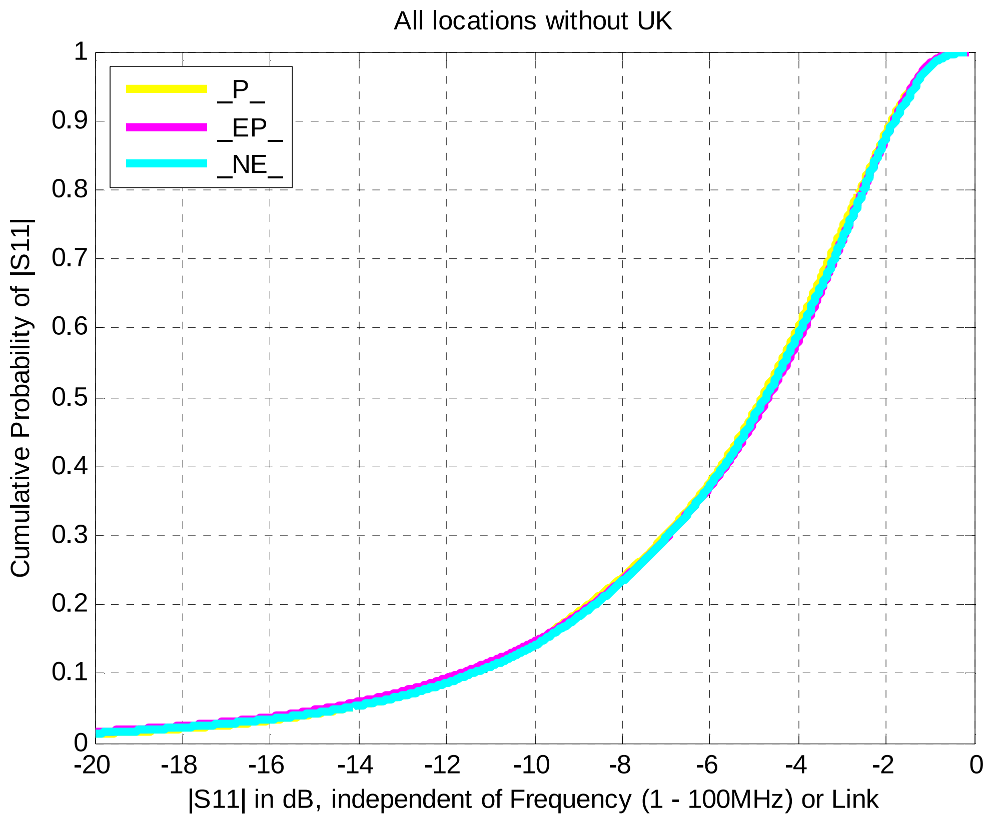


Figure 49: CDF of S_{11} Recorded on the European Continent

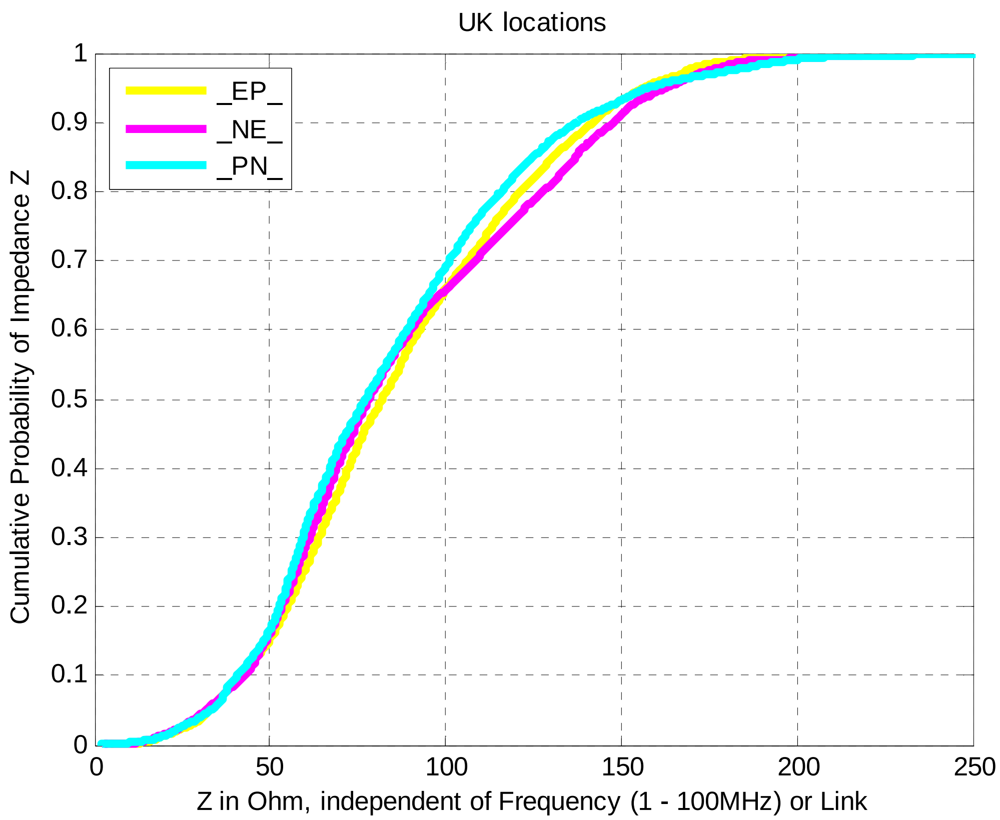


Figure 50: CDF if Impedance Z recorded in UK

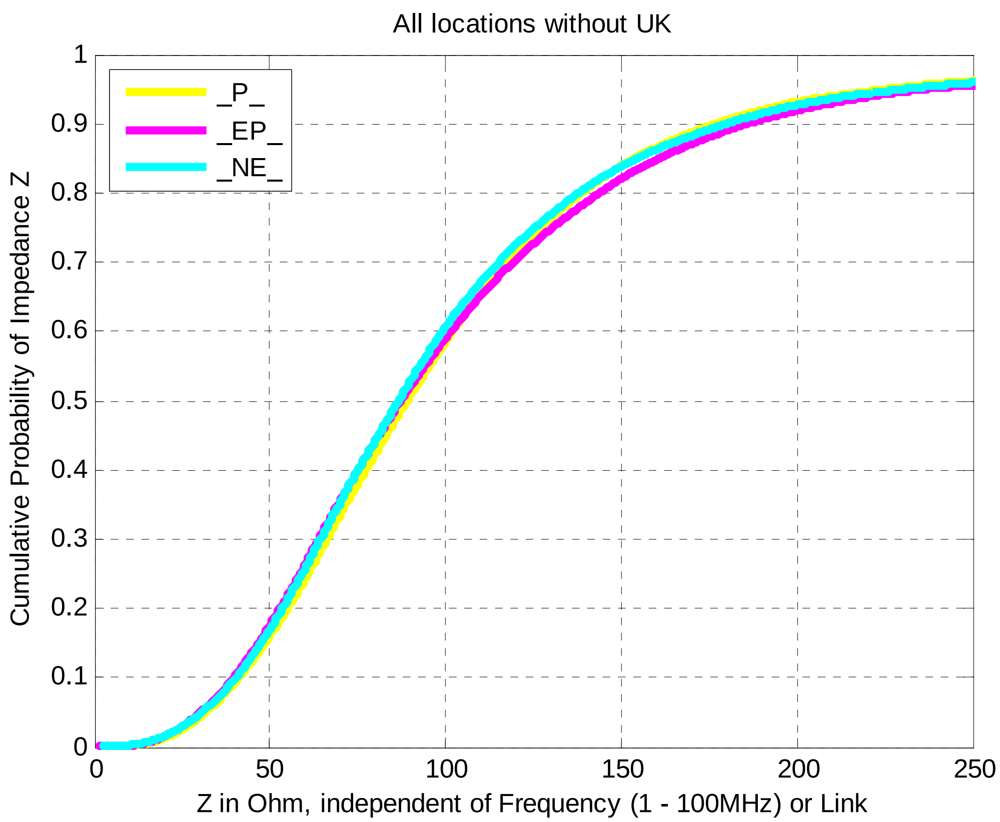


Figure 51: CDF of Impedance Z Recorded on the European Continent

Figure 52 to figure 60 show the frequency dependence of S_{11} parameters. The full set of all feeding combinations within S_{11} parameters was not conducted at all locations. The frequency dependent behavior of PN, NE, EP, PNE, APN, PNNT, NENT, EPNT and CM can be analyzed in the figures below. The STF 410 coupler matches the impedance of the mains best around 50 MHz at all differential mode couplings.

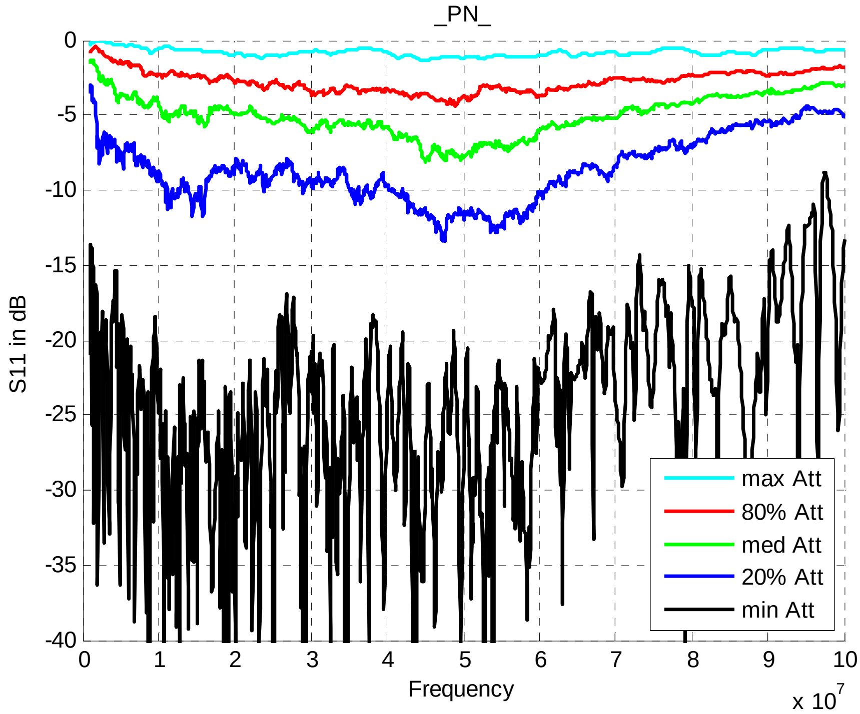


Figure 52: Probability of Measuring S_{11} at PN Dependent on Frequency (Statistics based on 139 Sweeps)

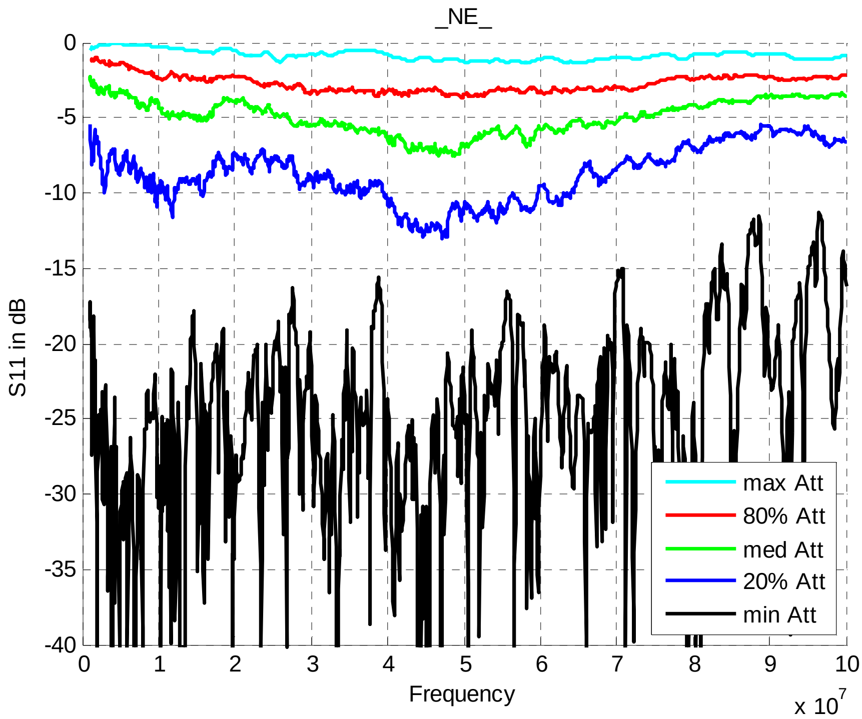


Figure 53: Probability of Measuring S_{11} at NE Dependent on Frequency (Statistic based on 139 Sweeps)

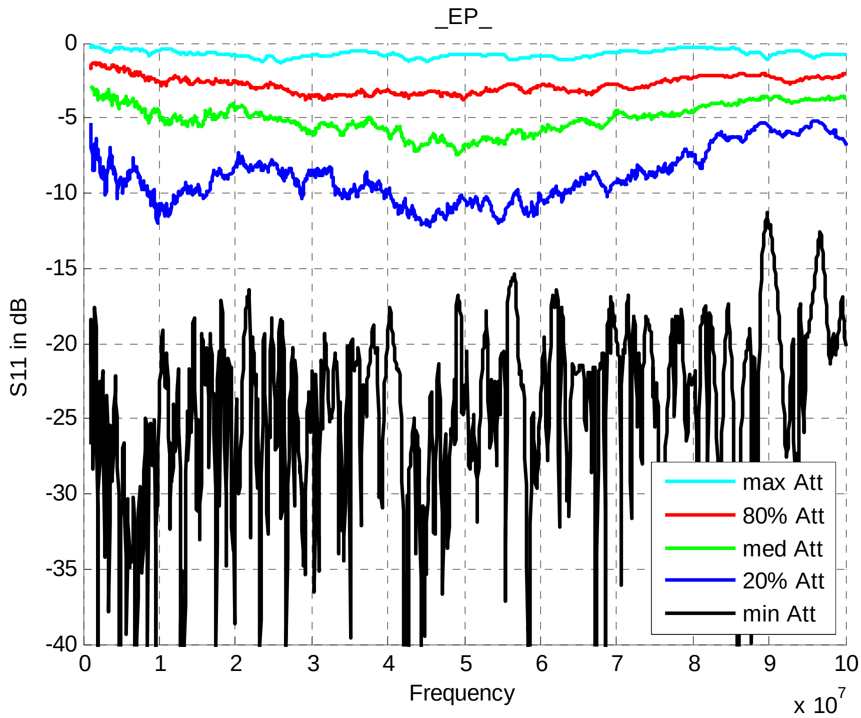


Figure 54: Probability of Measuring S_{11} at EP Dependent on Frequency (Statistic based on 138 Sweeps)

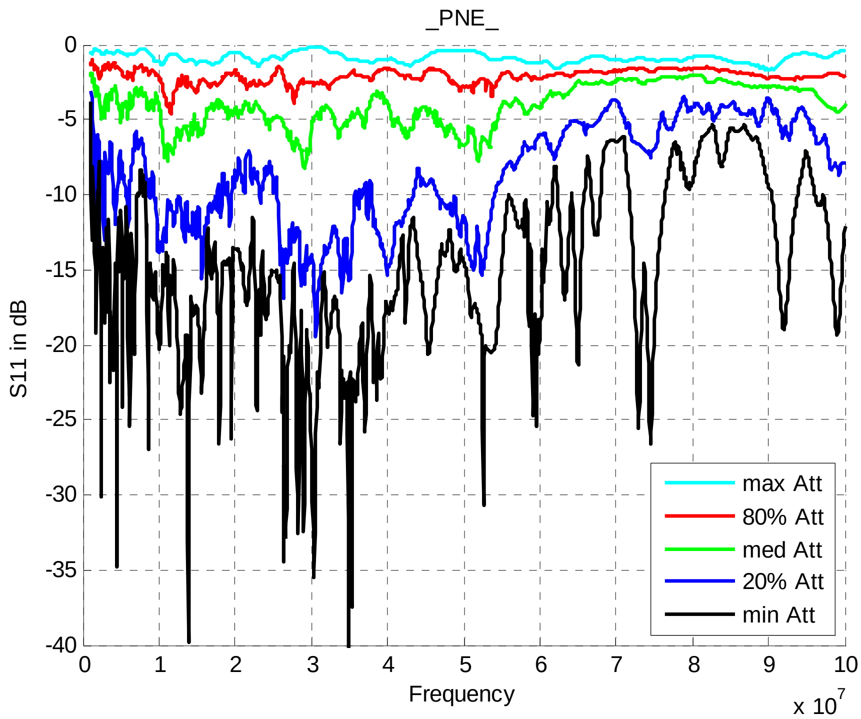


Figure 55: Probability of Measuring S_{11} at PNE Dependent on Frequency (Statistic based on 28 Sweeps)

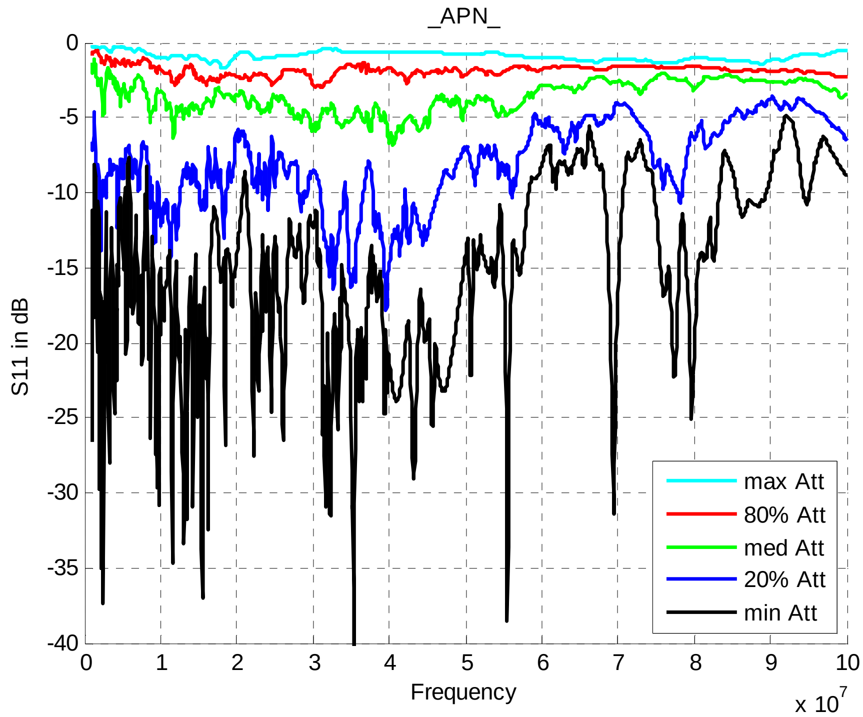


Figure 56: Probability of Measuring S_{11} at APN Dependent on Frequency (Statistic based on 28 Sweeps)

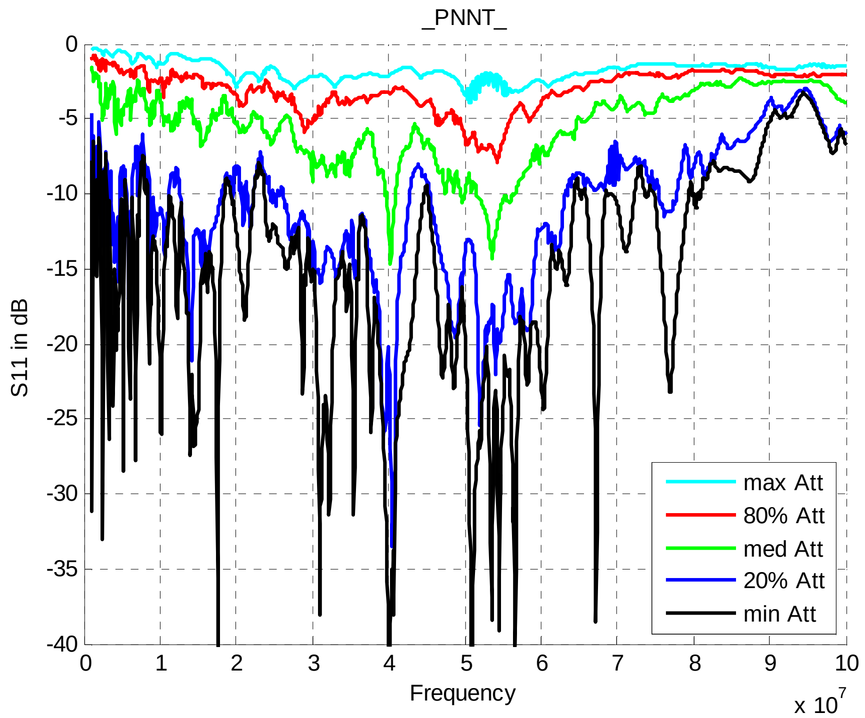


Figure 57: Probability of Measuring S_{11} at PNNT Dependent on Frequency (Statistic based on 18 Sweeps)

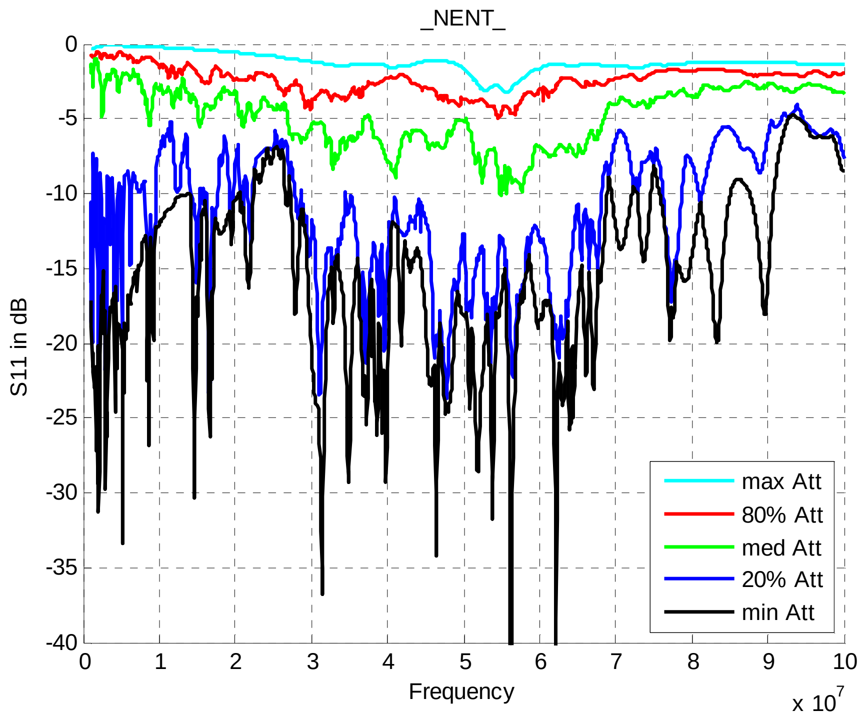


Figure 58: Probability of Measuring S_{11} at NENT Dependent on Frequency (Statistic based on 18 Sweeps)

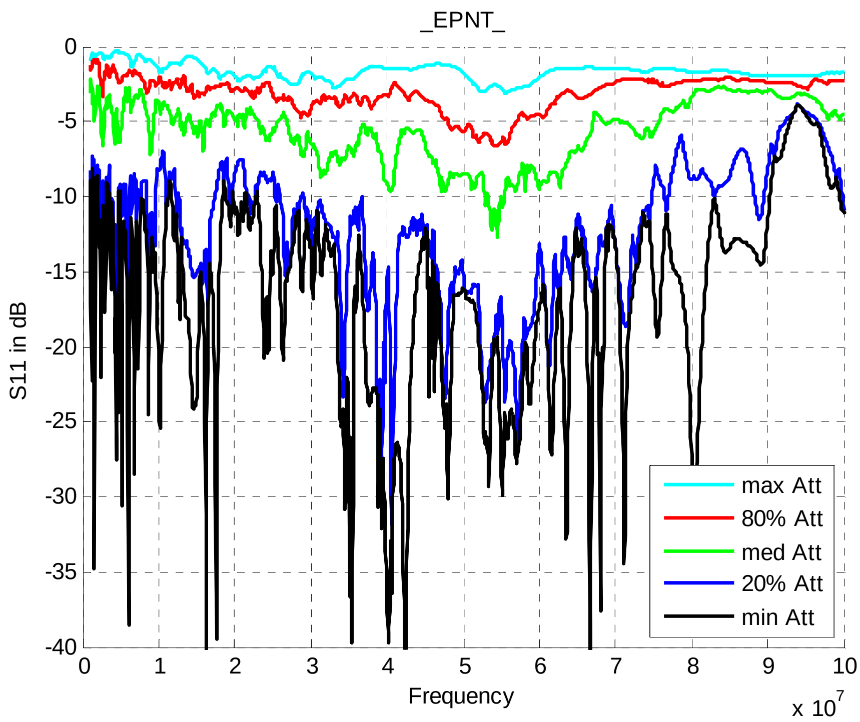


Figure 59: Probability of Measuring S_{11} at EPNT Dependent on Frequency (Statistic based on 18 Sweeps)

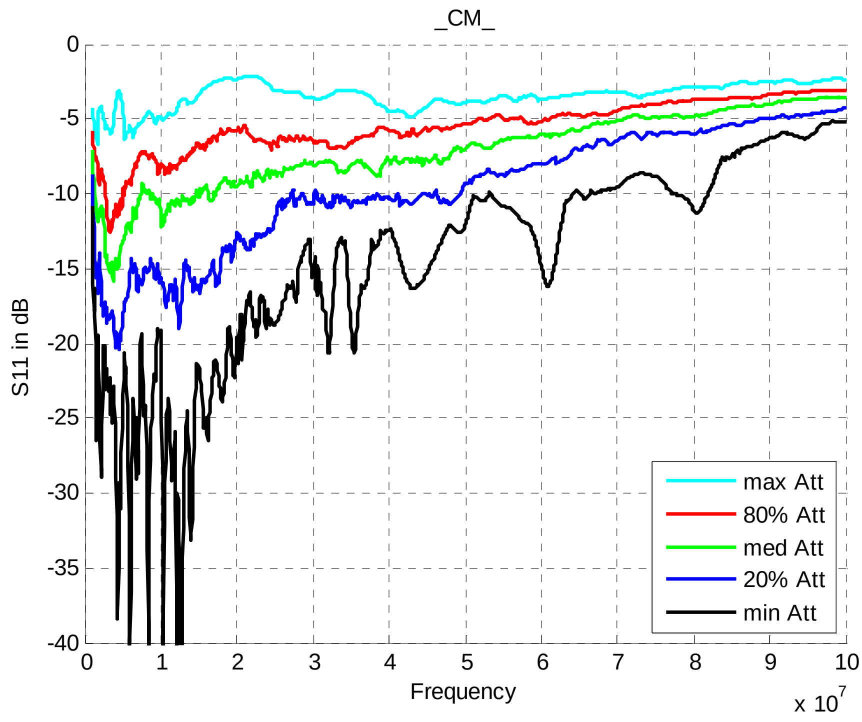


Figure 60: Probability of Measuring S_{11} at CM Dependent on Frequency (Statistic based on 48 Sweeps)

7.3 Noise

7.3.1 Frequency Domain Noise Statistics

Noise measurements of MIMO PLC channels were recorded at 31 locations, in Germany, Spain, France, Belgium and the United Kingdom. Measurements consist of P, E, N and CM signals, each recorded using 4 different bands (see clause 6.6). In total, 2 420 time domain records of 20 ms duration each were collected. Some configurations (same location, same outlet) were recorded several times. E.g. more than one successive line cycle was recorded. The statistics presented below consider only one measurement per configuration, which leads to a statistical set of 1 928 measurements.

From the time domain measurements, the noise Power Spectral Density (PSD) was computed using Welch's averaged modified periodogram method of spectral estimation. This method leads to 1 639 noise samples over a frequency band of 0 MHz to 100 MHz. Hence, the total number of noise samples is 3 159 992.

For all noise samples recorded with the help of an amplifier, the amplifier gain was removed from the raw DSO measurement by post-processing. For a small number of samples (6 %), we noticed that the amplifier was not delivering full amplification, due to non-linear amplifier behavior with respect to input power (see clause 6.7.4). These samples were corrected accordingly, using a lower amplification factor.

The use of the Welch method was parameterized to lead to a resolution bandwidth of 122 kHz in the frequency domain. In the figures below the graphs are converted to a PSD level in dBm/Hz to simplify comparisons of resolution bandwidths like 9 kHz or 120 kHz that are common in the world of EMC.

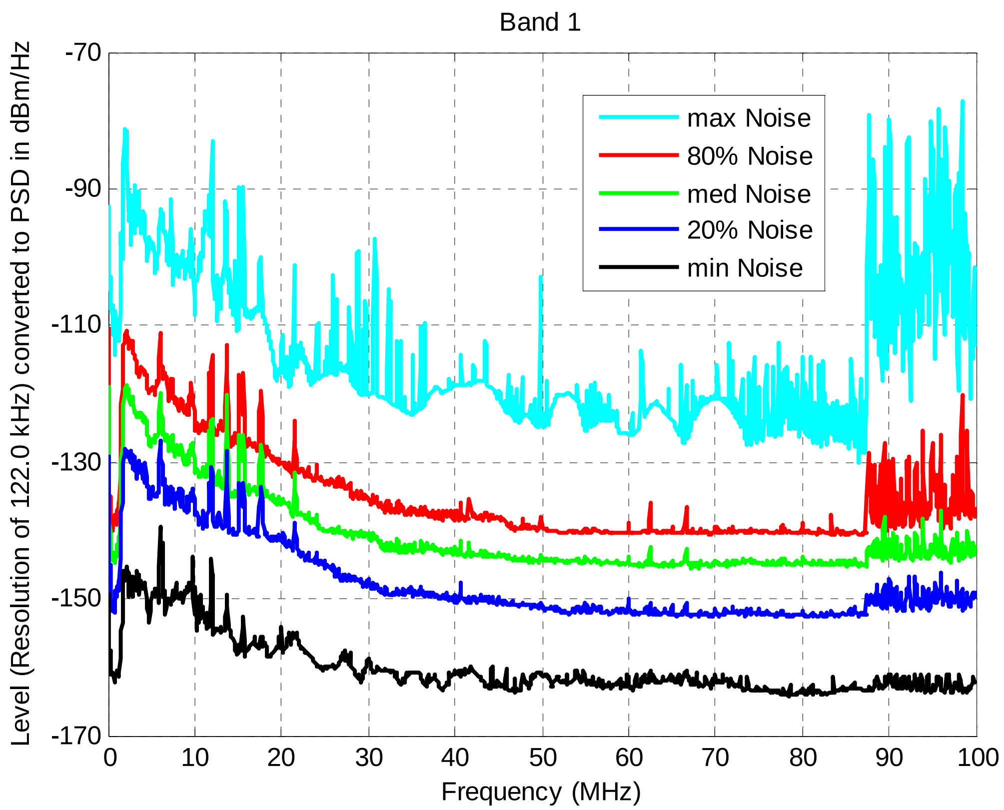


Figure 61: Min., 20 %, Median, 80 % and Max. PSD Noise found per Frequency on Band 1

Figure 61 presents the statistics of the PSD noise measured for all outlets, in all locations and all Rx ports. The received Noise PSD varies between -160 dBm/Hz and -80 dBm/Hz. The presence of Short Wave (SW) broadcast frequencies is clearly noticeable at 6 MHz, 7,3 MHz, 9,5 MHz, 12 MHz, 13,5 MHz, 15,5 MHz ,17,5 MHz and 21 MHz (Meter Bands of 49 m, 41 m, 31 m, 25 m, 22 m, 19 m, 16 m and 13 m respectively). Similarly, above 88 MHz, the spectrum is occupied by FM broadcasting frequencies.

It should be noted that the minimum noise level may be influenced by DSO capabilities. In particular, the quantization noise increases when measuring large voltage signals. For this reason, measurements were also taken over reduced bands. Thus, Band 2 covers the 2 MHz to 80 MHz band, Band 3 covers the 30 MHz to 100 MHz band, and Band 4 covers the 30 MHz to 80 MHz band. It is thus possible to define a composite band, selecting for each frequency the narrowest available band, to limit the signal level and thus reduce the quantization noise.

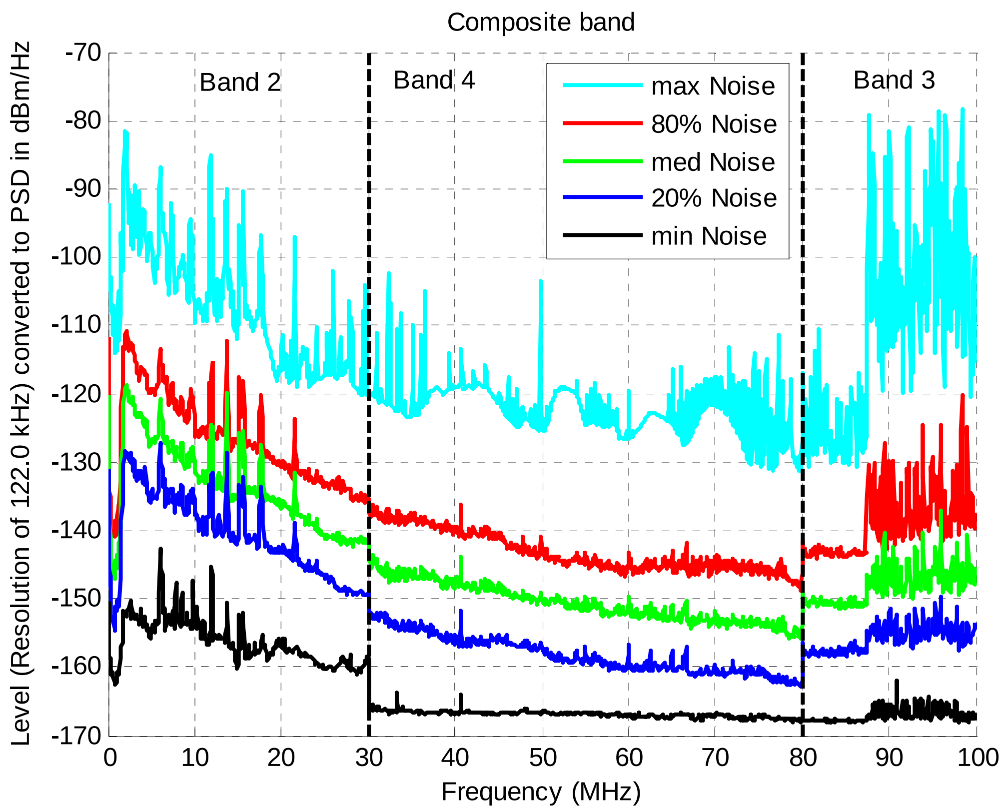


Figure 62: Min., 20 %, Median, 80 % and Max. PSD Noise found per Frequency over the Composite Band

Figure 62 presents the same statistics as figure 61, over the composite band. When SW and FM signals are rejected, in band 4 for instance, the minimum noise PSD decreases down to -168 dBm/Hz. Using the composite band instead of Band 1 mainly affects the lowest statistics: for the median, 80 % and maximum curves, the values observed in the composite band are similar to the ones observed in Band 1.

Figure 63 presents the cumulative probability of the noise PSD for all outlets, in all locations, and all Rx ports, independently of the frequency. Here again, one can observe the noise level recorded for Band 1 is somewhat larger than for the composite band, especially for the lower percentiles. This is due to the higher quantization noise of the DSO when the observation band is wider.

Figure 64 gives the cumulative probability of the noise PSD, for each Rx port separately. One can clearly observe that the noise PSD recorded on the CM port is stronger than on other Rx ports, by about 5 dB. This can be due to the higher potential of the CM to receive external noise from radiating sources. In this statistical study, the coupler itself is considered to be part of the channel. From the STF410 coupler validation in [i.5], clause 7.1.6, it appears that CM reception leads to an increase in attenuation by 3 dB to 4 dB compared to receiving on P, N or E. Hence, the CM noise curve would further shift to the right with respect to the P, N or E curves when using a coupler with similar reception properties for all Rx ports. Comparing the noise PSD statistics for the P, N and E ports, it appears, that the E port is slightly more affected by noise than the P or N ports (by 1 dB) when it comes to the largest noise values (90 % percentile). For the lowest noise values (10 % percentile), the P port is slightly less affected by noise than the E or N ports (by 3 dB).

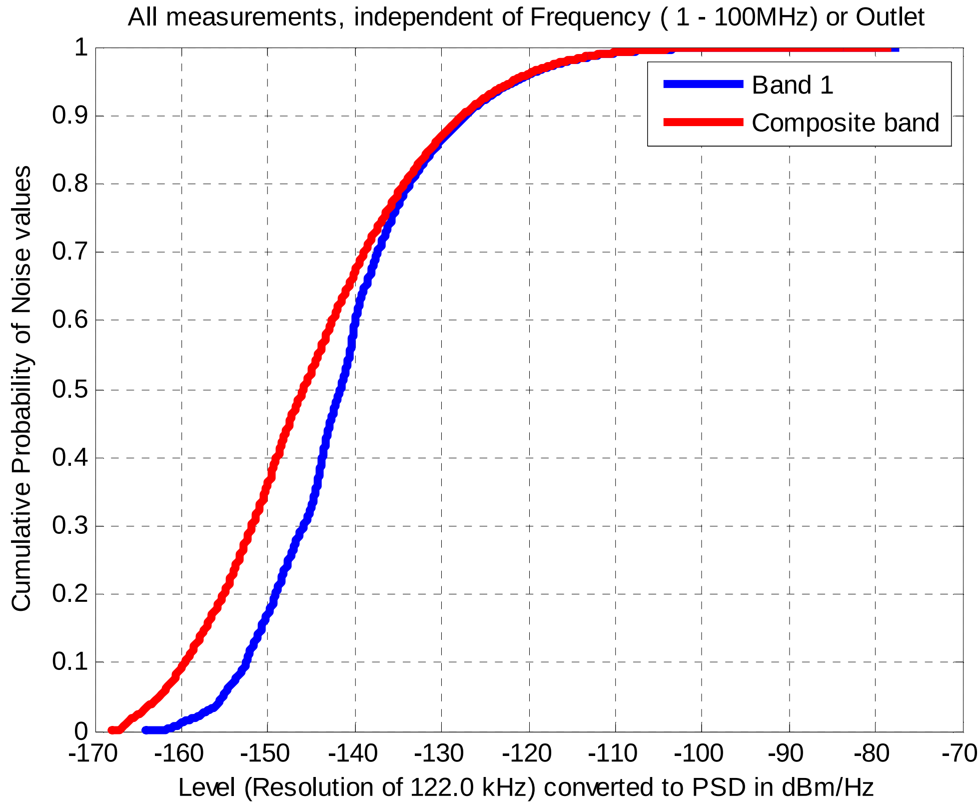


Figure 63: Cumulative Probability of PSD Noise of all Rx Ports

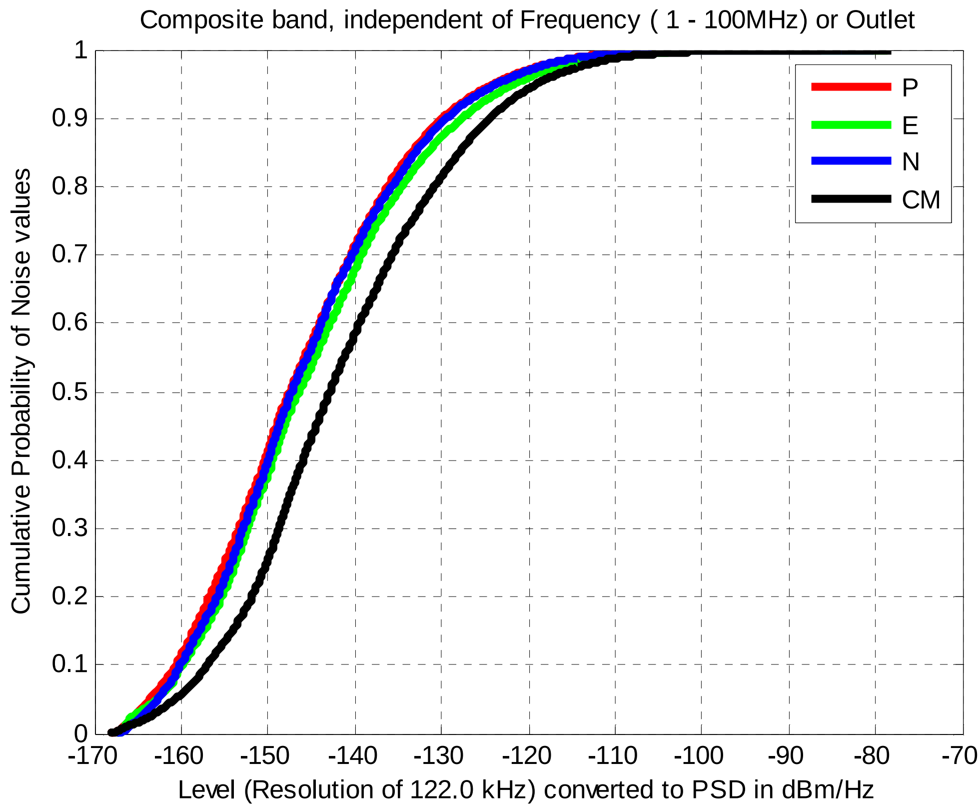


Figure 64: Cumulative Probability of PSD Noise for each Rx Port

Figure 65 presents the median noise PSD measured on Band 1 by frequency for all outlets and all locations, separated by Rx port. Here again, we observe that the CM port is more sensitive to noise than the other ports. The gap between the CM port and other ports is larger for low frequencies below 40 MHz. For high frequencies up to the FM band, one can distinguish the P, N, E and CM ports, which are increasingly affected by noise in this order.

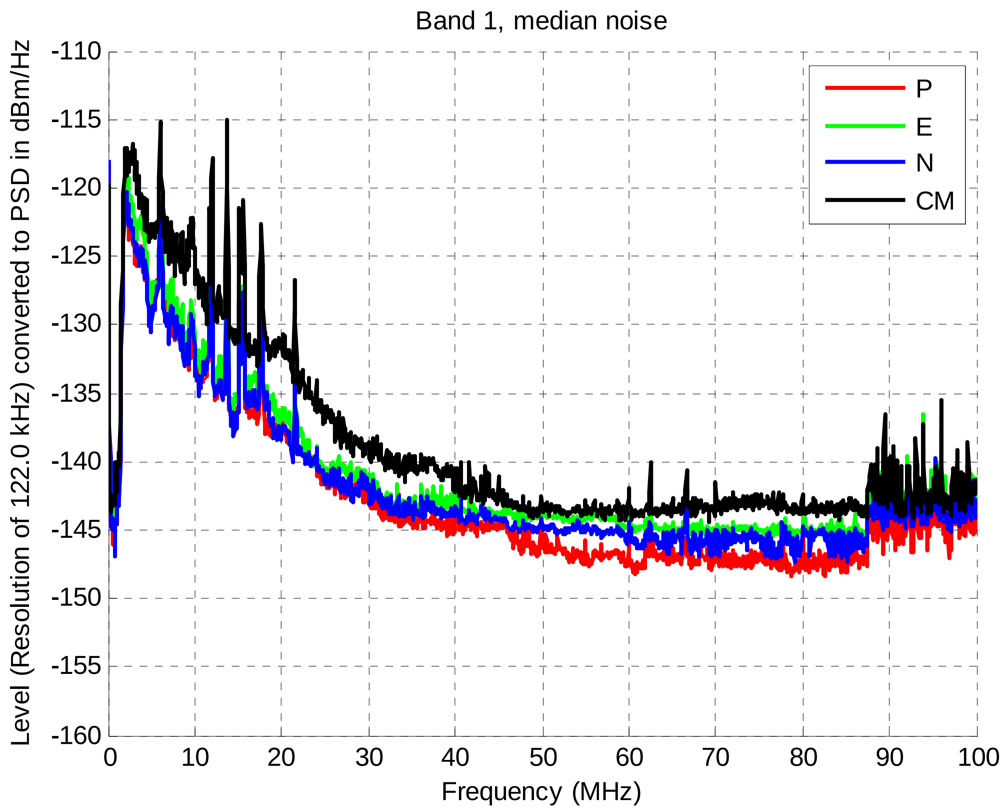


Figure 65: Median PSD Noise found by Frequency over Band 1 for Different Rx Ports

Figure 66 to figure 69 show the minimum, 20 %, median, 80 % and maximum noise PSD presented on the composite band by frequency for each Rx port.

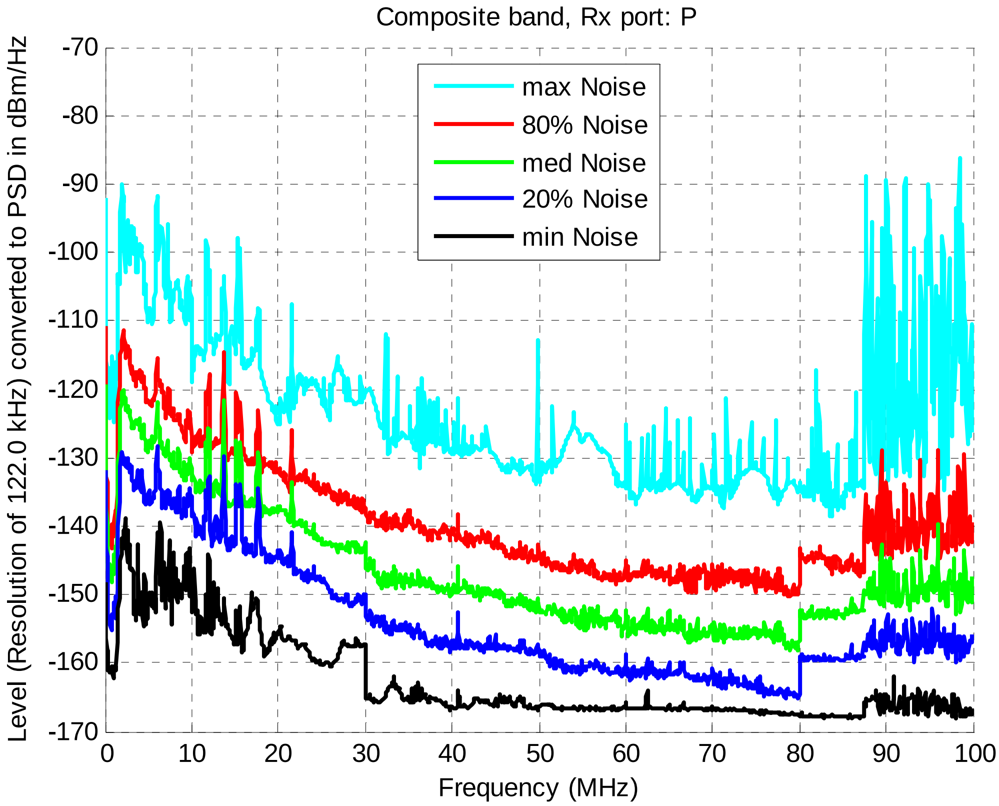


Figure 66: Min., 20 %, Median, 80 % and Max PSD Noise for Rx Port P over the Composite Band

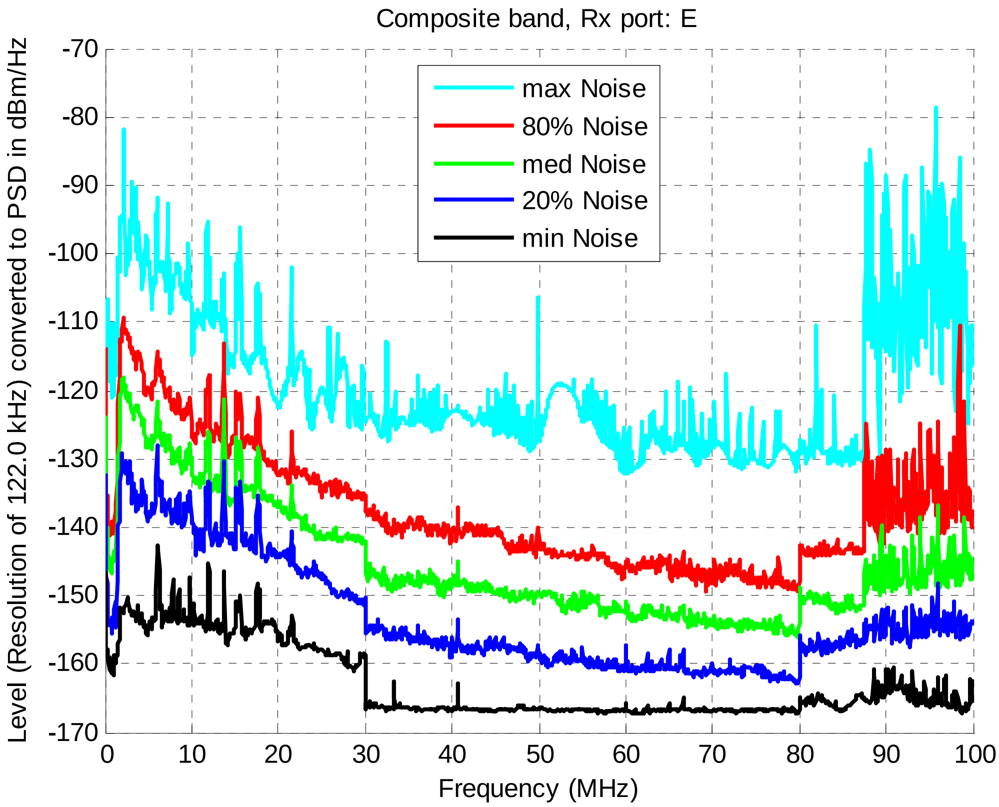


Figure 67: Min., 20 %, Median, 80 % and Max Noise PSD for Rx Port E over the Composite Band

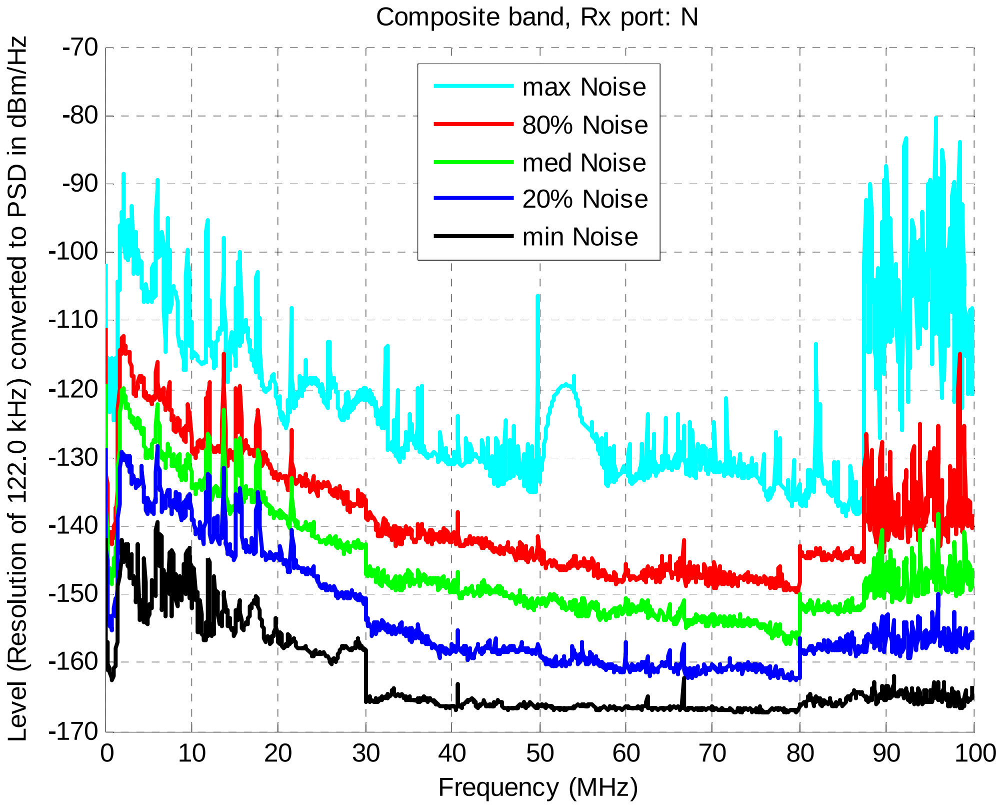


Figure 68: Min., 20 %, Median, 80 % and Max Noise PSD for Rx Port N over the Composite Band

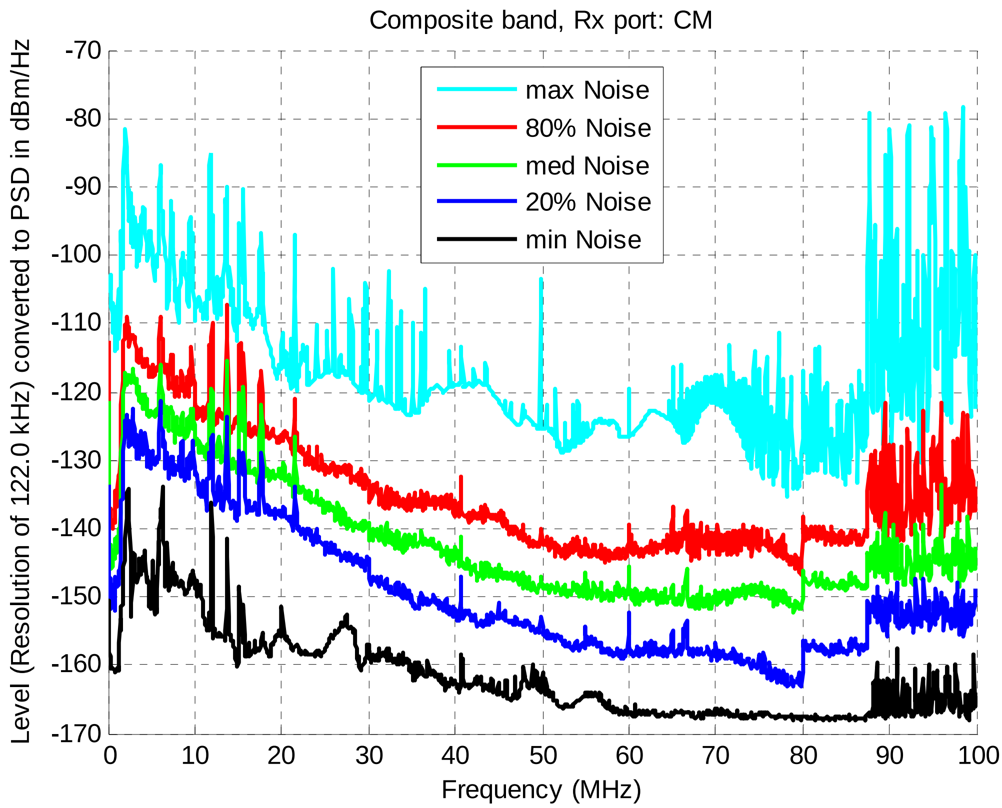


Figure 69: Min., 20 %, Median, 80 % and Max Noise PSD for Rx Port CM over the Composite Band

Table 27 compares where the noise PSD was measured, the size of the flat or building and the number of sweeps recorded for each location. In addition, the minimum, median and maximum noise PSD recorded on Band 1 is provided. If there is e.g. a high maximum noise value an excellent radio broadcast reception can be expected in this location.

Table 27: Min., Median and Max. PSD Noise Value, Size and No. of Sweeps at each Location, Independent of Rx Port, for Band 1

Location	Country	Min noise PSD in dBm/Hz	20 % noise	Median noise PSD in dBm/Hz	80 % noise	Max noise PSD in dBm/Hz	Size of flat or building in m²	No of sweeps
Duerrbachstr	Germany	-156,48	-154,04	-146,56	-139,18	-95,63	115	64
ImGeiger	Germany	-155,76	-152,85	-146,85	-135,6	-93,91	130	16
Nauheimerstr	Germany	-156,6	-155,94	-152,96	-143,15	-100,47	95	16
Rothaldenweg	Germany	-150,18	-146,62	-143,54	-135,22	-79,83	122	32
VickiBaumWeg	Germany	-150,44	-144,83	-139,78	-132,15	-91,61	150	48
Calicanto	Spain	-158,09	-151,39	-146,77	-137,91	-93,47	200	48
Paiporta	Spain	-157,84	-150,53	-144,58	-132,11	-78,39	96	48
Valencia_46012	Spain	-146,98	-137,78	-135,83	-124,45	-81,19	78	48
Valencia_46015	Spain	-158,01	-153,8	-148,82	-135,94	-104,25	87	47
Xirivella	Spain	-158,05	-151,76	-143,79	-132,39	-81,43	110	48
Bourg-La-Reine	France	-144,79	-143,42	-140,69	-126,99	-92,37	85	112
Spidcom-Lab	France	-148,22	-143,58	-138,9	-130,72	-92,37	180	64
DeGrandRyStrasse	Belgium	-153,23	-150,9	-144,8	-135,37	-94,56	130	64
Heidhoehe	Belgium	-149,73	-146,23	-140,23	-139,23	-77,27	160	64
Huette	Belgium	-154,04	-152,07	-140,27	-132,31	-98,43	110	64
InDenSiepen	Belgium	-151,7	-140,87	-139,49	-132,67	-80,16	110	64
Simarstrasse	Belgium	-156,26	-152,3	-148,29	-135,4	-85,87	150	64
AlsdorferStrasse	Germany	-145,96	-143,94	-139,13	-132,75	-89,51	110	45
Eichelhaeherweg	Germany	-149,5	-146,92	-139,06	-128,83	-95,07	85	64
Schlossstrasse	Germany	-161,83	-154,36	-141,1	-135,12	-97,1	120	64
SchurzelterWinkel	Germany	-153,44	-150,6	-143,06	-136,06	-98,54	150	64
Wasserkall	Germany	-145,96	-143,18	-138,26	-131,19	-85,88		64
ColchesterDrive	United Kingdom	-156,15	-148,87	-145,19	-134,38	-89,7	145	64
WilliamsRoad	United Kingdom	-157,38	-151,94	-146,57	-134,56	-102,8	97	64
WindmillAvenue	United Kingdom	-150	-144,73	-141,66	-134,84	-93,2	170	64
WindsorClose	United Kingdom	-164,23	-159,93	-156,76	-146,01	-106,8	75	64
Cavan	France	-162,5	-144,43	-141,11	-132,48	-103,17	66	80
Guingamp	France	-155,94	-144,31	-140,11	-134,66	-79,11	135	108
RueBunuel	France	-157,1	-153,22	-145,68	-136,62	-96,03	120	80
RueDepasse	France	-156,15	-146,36	-142,73	-133,45	-94,12	120	96
Trebeurdun	France	-156,73	-148,36	-142,09	-133,11	-93,75	56	96

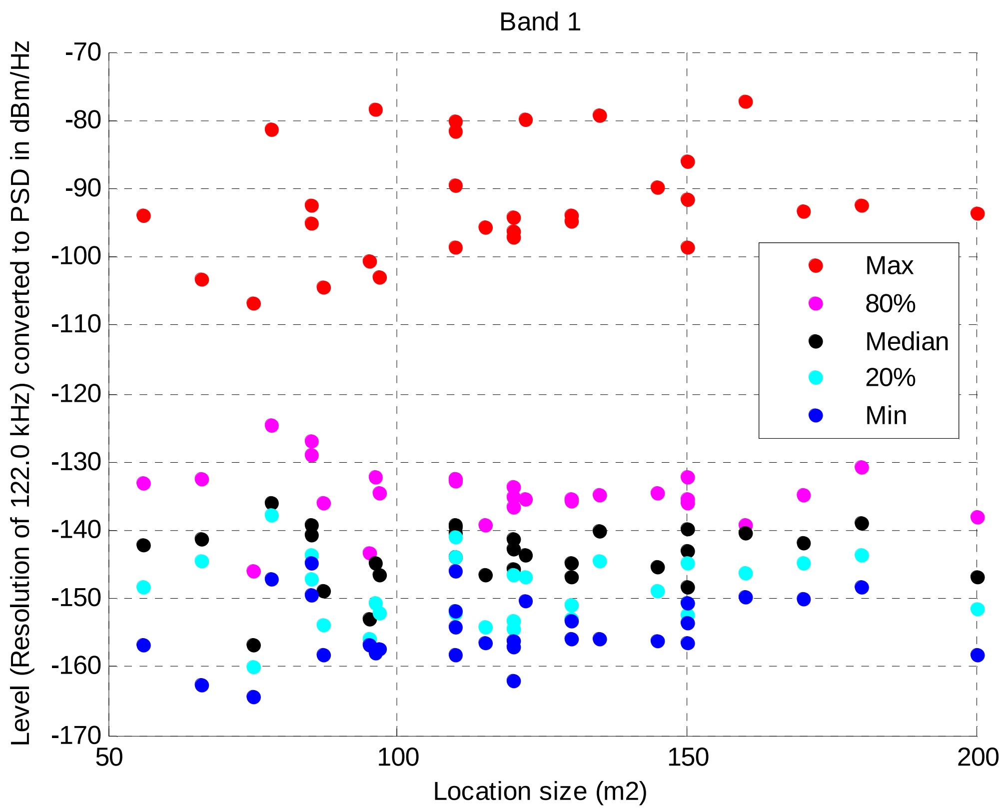


Figure 70: Min., median and max. PSD Noise versus Size of Location

Figure 70 presents a graphical view of the minimum, medium and maximum noise PSD recorded for each location vs. the size of the location. This graph shows that there is no relationship between the noise level received and the size of location. It seems that the noise level recorded at a given outlet is a function of the close electromagnetic environment of this outlet, and is thus not affected by the size of the electrical network or the number of connected appliances.

Figure 71 gives the median noise PSD measured on the composite band vs. frequency for all outlets and all Rx ports, separated by country. The noise PSD measured in France, Germany and UK is similar. The noise PSD recorded in Spain presents the highest level of low frequencies below 10 MHz, but is among the lowest values for the band 40 MHz to 80 MHz. Measurements performed in Belgium are the ones with the lowest level for all frequencies from 2 MHz to 80 MHz. However, the electrical network seems more sensitive to FM signals in Belgium than in other countries.

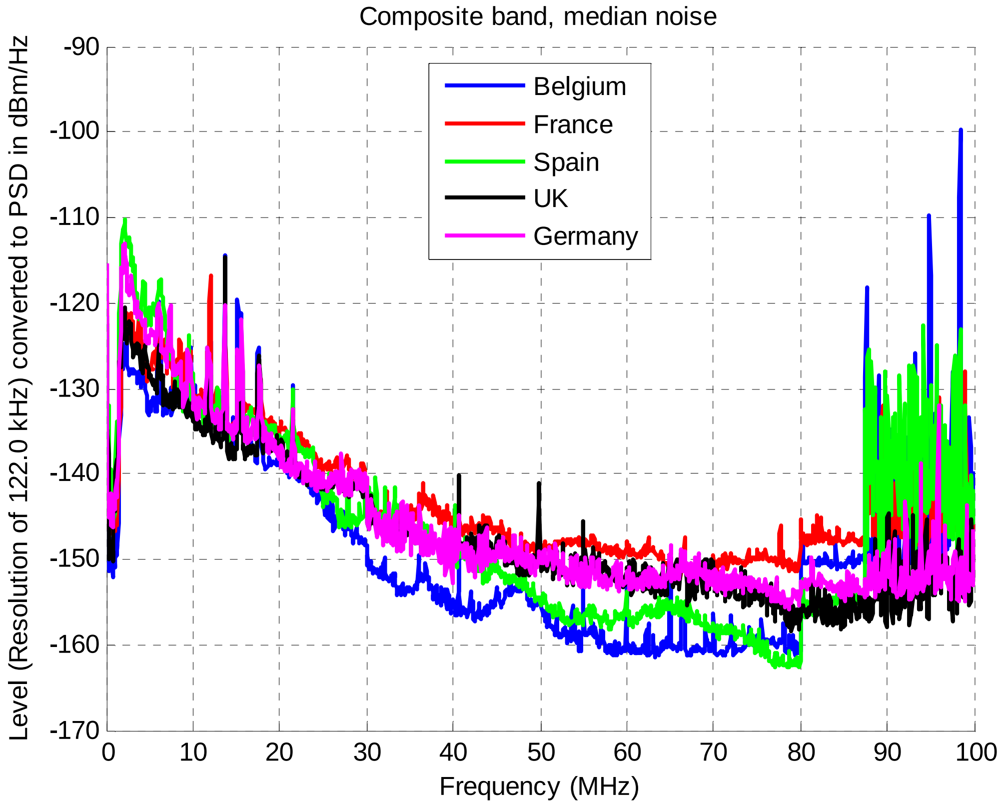


Figure 71: Median Noise PSD found over Frequency over the Composite Band for Different countries

7.3.2 Time Domain Noise Statistics

Noise measurements were performed in time domain using a DSO. It is possible to analyze detailed time domain characteristics of noise received. Among the collection of measurements, several typical noise shapes were observed as presented in the following images.

For a number of measurements, such as the location presented in figure 72, no variations of the noise characteristics could be observed over the 20 ms observation window. One can identify this typical observation as stationary noise, with no periodicity with respect to the 50 Hz electrical signal.

Other measurements present a periodical structure, such as the one illustrated in figure 73. In this typical example, a given noise pattern is reproduced every 10 ms, with a 100 Hz repetition rate. This noise sample is synchronous with the 50 Hz mains period. It can be explained by the periodical variation in impedance at different branches of the network, hence causing a structured noise pattern.

In other examples, the noise structure is not synchronous with the 50 Hz mains period. For instance, figure 74 presents a noise sample with an impulsive structure, but the noise pattern is not reproduced regularly. This typical structure can be called asynchronous impulsive noise.

Finally, figure 75 presents an example of strong impulsive noise, where very short impulses are repeated periodically. The duration between successive impulses is about 1 ms, leading to a repetition rate of 1 kHz. Such noise can be caused by electronic appliances or energy saving lamps for instance.

A quick subjective assessment of the relatively small number of recorded data of all noise samples measured on band 1 provides the following noise occurrence probability:

- 60 % of the noise records present no periodicity (e.g. figure 72)
- 15 % of the noise records present a periodical, synchronous structure with 50 Hz period (e.g. figure 73)
- 15 % of the noise records present an impulsive, asynchronous structure with 50 Hz period (e.g. figure 74)

- 10 % of the noise records present a strong impulsive structure (e.g. figure 75)

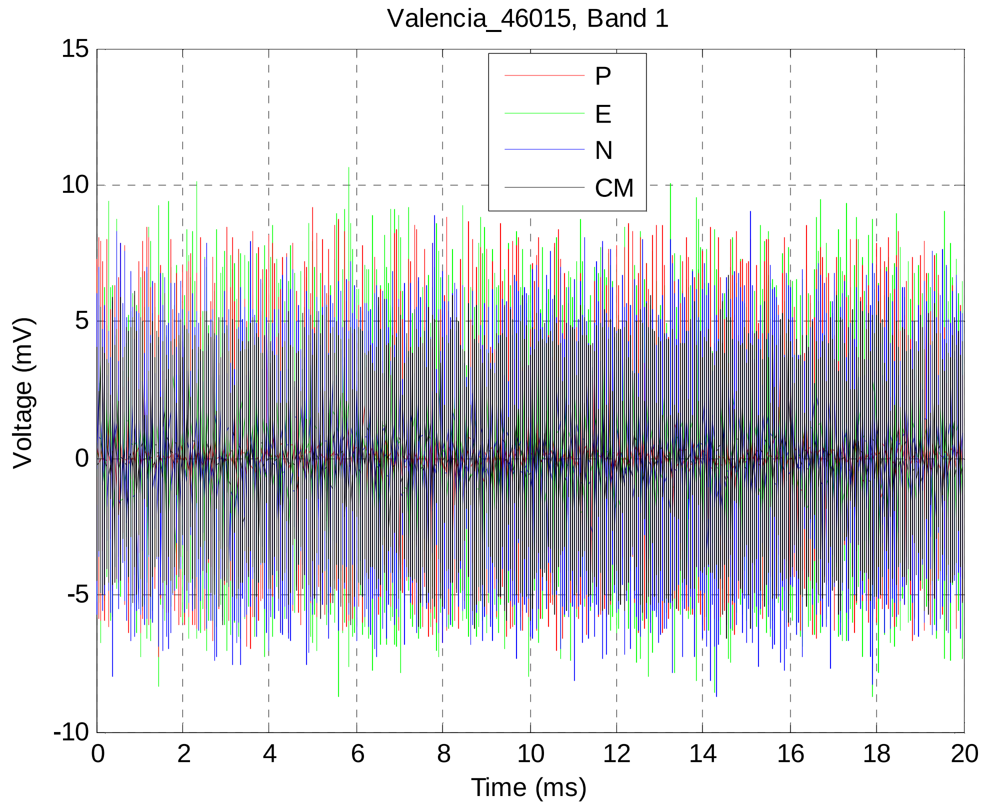


Figure 72: Time Domain Noise Record of a Location, No Periodicity

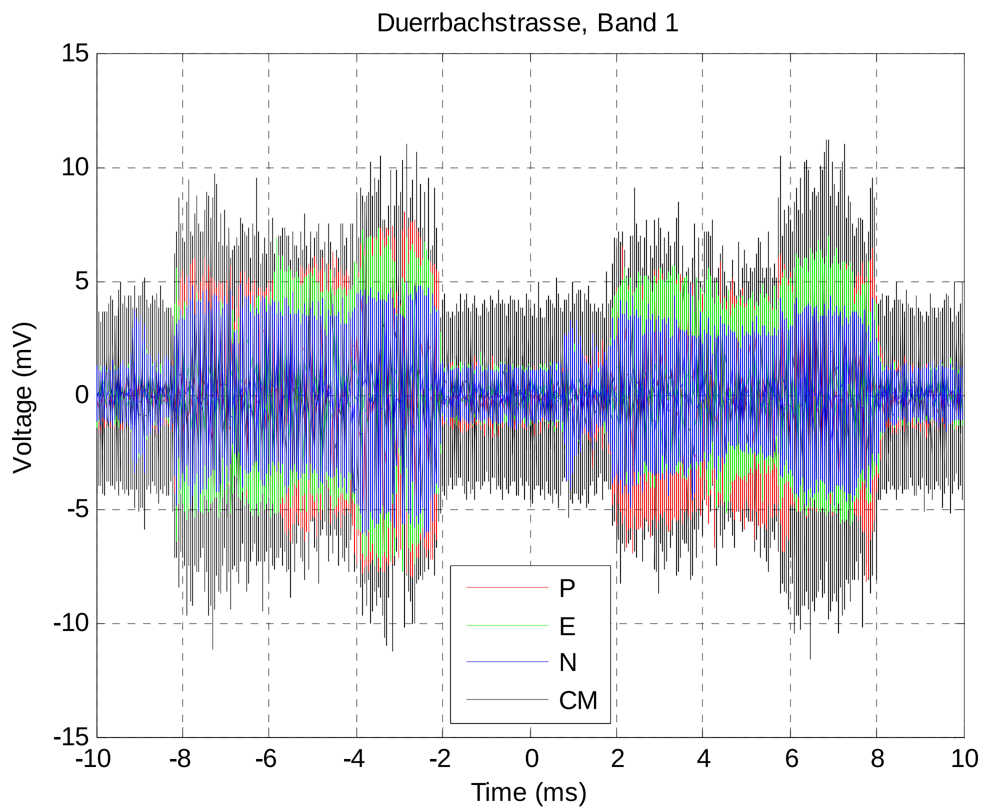


Figure 73: Time Domain Noise Record of a Location, Periodical Structure Synchronous with 50 Hz Period

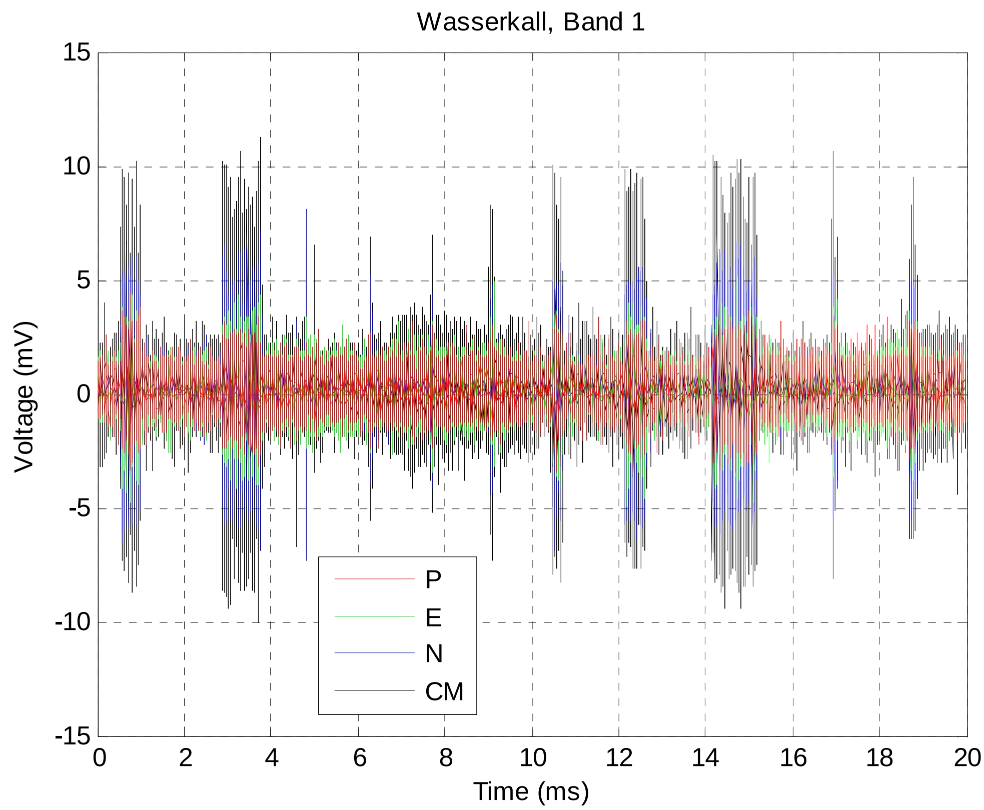


Figure 74: Time Domain Noise Record of a Location, Impulsive Structure, Asynchronous with 50 Hz

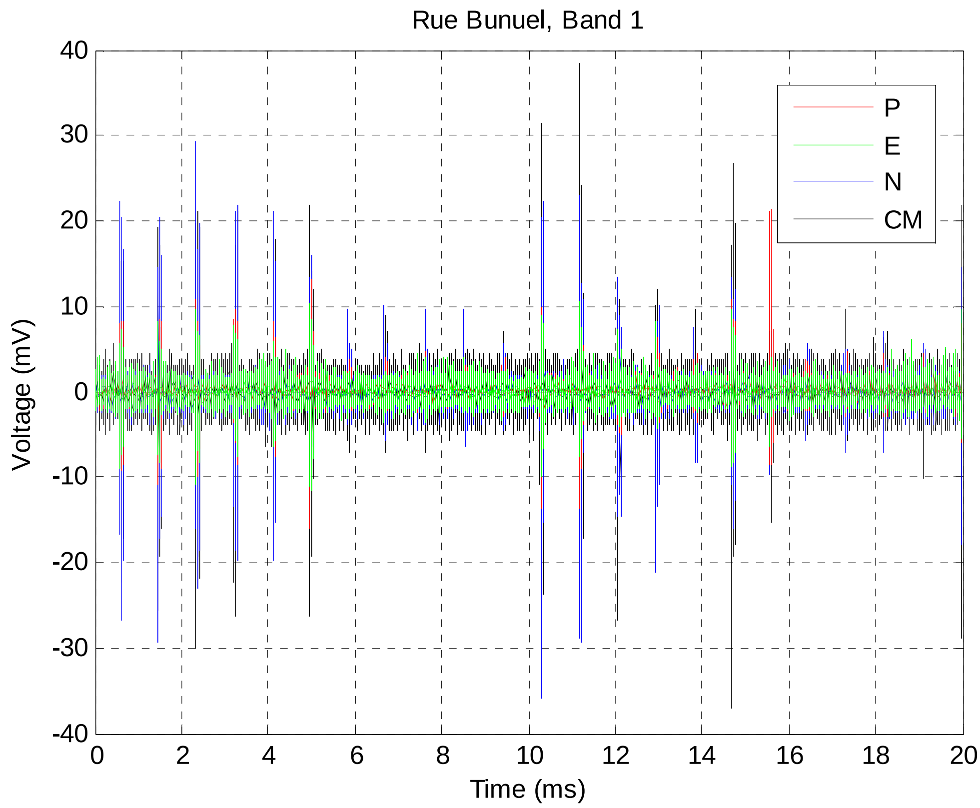


Figure 75: Time Domain Noise Record of a Location, Strong Impulsive Noise with 1 kHz Period

Interestingly, the periodic or impulsive nature of the noise samples can be linked to the frequency, due to the availability of successive measurements performed in different bands. Figure 76 compares the time domain noise records for a given location in two frequency bands: Band 1 (2 MHz to 100 MHz) and Band 4 (30 MHz to 80 MHz). In Band 1, one can observe the periodic appearance of noise at a higher absolute level. In Band 4, not only the measured noise level is much lower (note the change in y-axis scale), but the periodic shape of the noise completely disappears. Hence, the bursts of strong noise level observed in Band 1 probably correspond to electromagnetic ingress received in the SW or FM broadcasting bands.

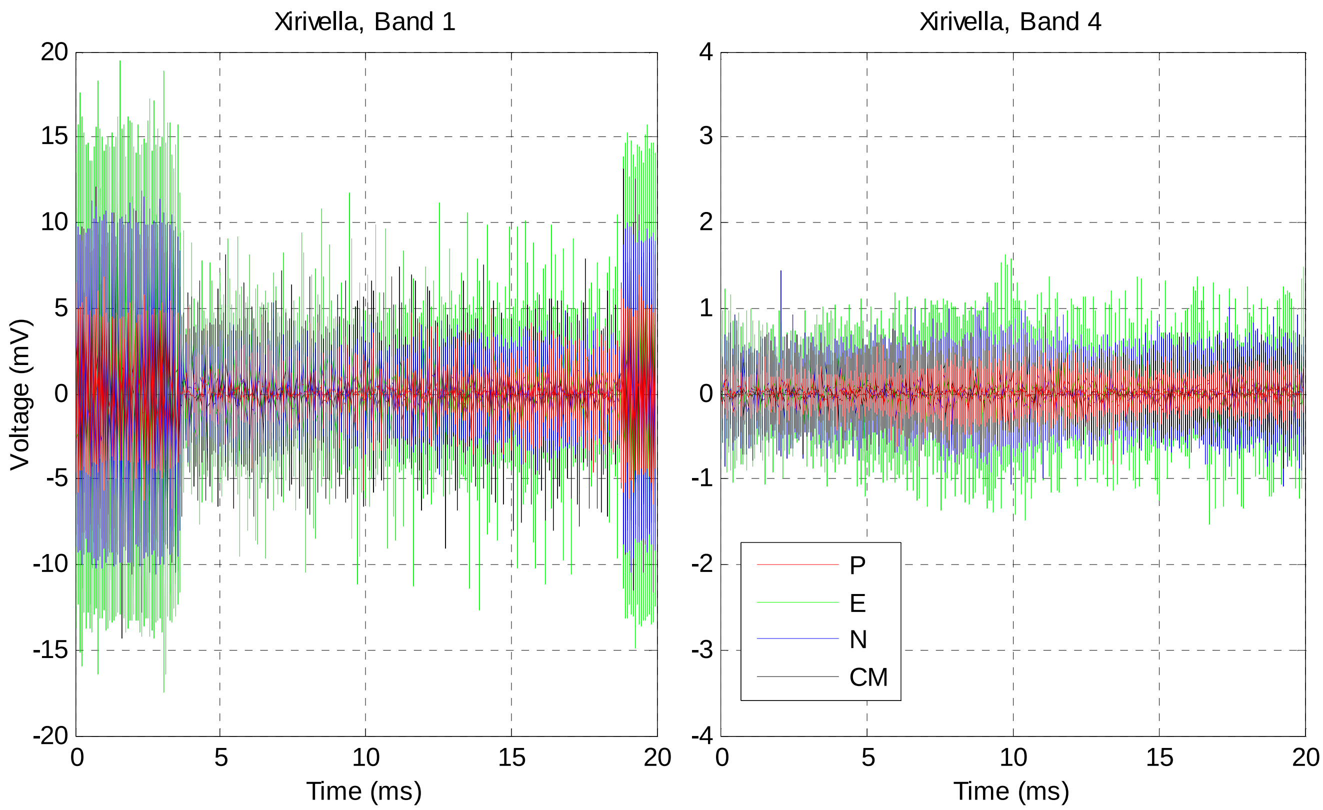


Figure 76: Comparison of Time Domain Noise Records of a Location, for Band 1 and Band 4

In the following, we will consider the correlation between noise samples received on a given band at two different Rx ports. The correlation is characterized by the correlation parameter $\rho_{i,j}$, computed from two time domain noise samples $n_i(t)$ and $n_j(t)$ as:

$$\rho_{i,j} = \frac{\langle n_i(t)\, n_j(t)\rangle - \langle n_i(t)\rangle\langle n_j(t)\rangle}{\sqrt{\left(\langle |n_i(t)|^2\rangle - |\langle n_i(t)\rangle|^2\right)\left(\langle |n_j(t)|^2\rangle - |\langle n_j(t)\rangle|^2\right)}} \qquad \text{(Eq. 1)}$$

where $\langle\ \rangle$ denotes the time domain average.

Figure 77 and figure 78 give the cumulative probability of the absolute value of ρ for all Rx ports combinations, for Band 1 and Band 4 respectively. As a first observation, the correlation coefficient spans the entire range from 0 (fully decorrelated) to 1 (fully correlated), for all Rx ports combinations. From Band 1, one can observe that Rx ports P and E present the highest degree of correlation, while Rx ports E and CM present the lowest degree of correlation. This difference is less obvious for Band 4, where the CDF move closer together.

In general, the correlation coefficient is smaller by roughly 0,1 in Band 4 when compared to Band 1. From this, one can conjecture that signals received via SW and FM bands tend to increase the correlation of noise recorded over different Rx ports.

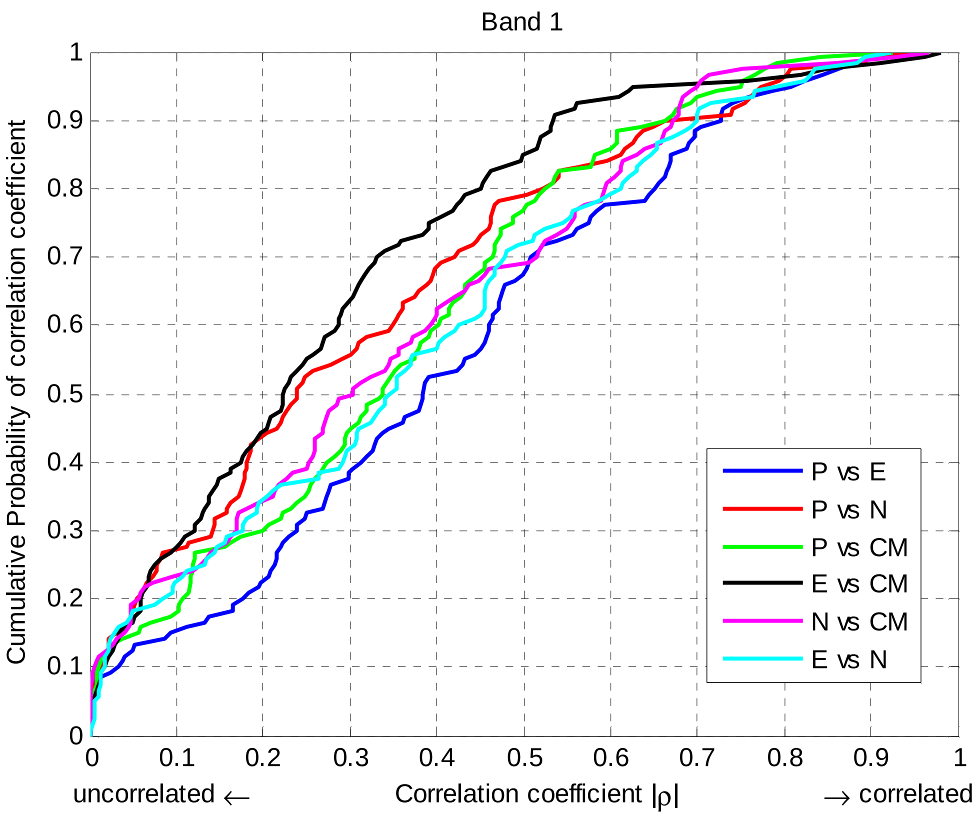


Figure 77: Cumulative Probability of Correlation Coefficient for Band 1 Noise Measurements

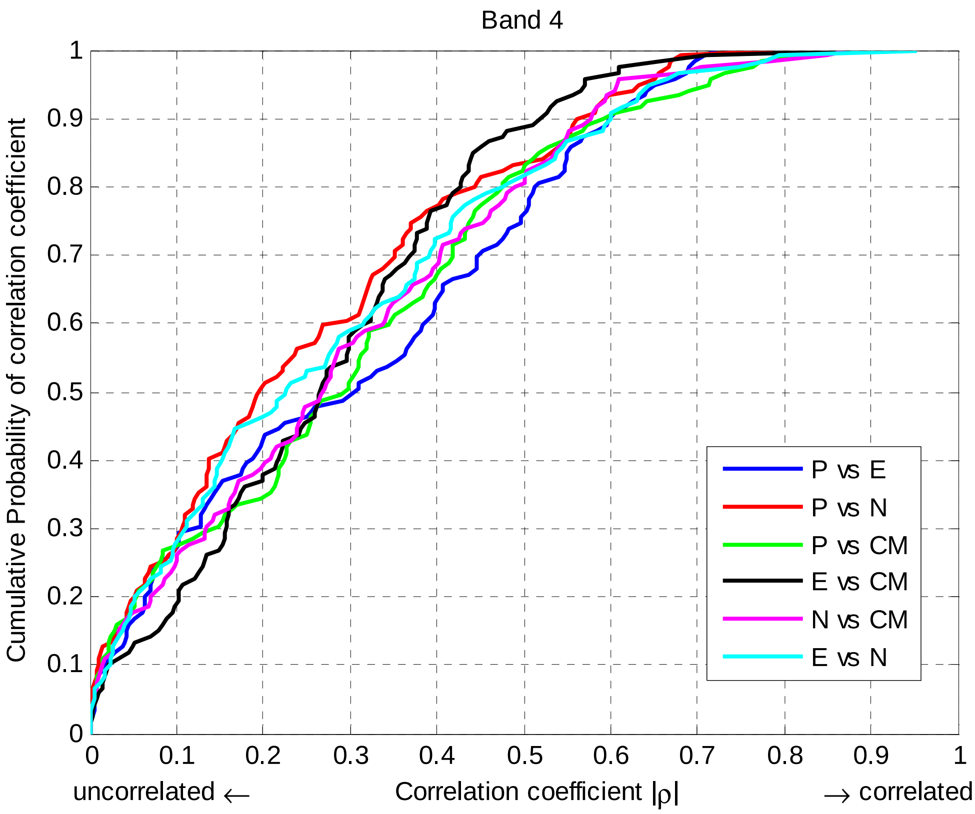


Figure 78: Cumulative Probability of Correlation Coefficient for Band 4 Noise Measurements

7.4 Channel Capacity, Spatial Correlation and Singular Values

7.4.1 Singular Values and Spatial Correlation

The channel transfer function measurements (S_{21} measurements, see clause 7.1) are the basis of the singular value and spatial correlation considerations. The transmit and receive ports used define the MIMO-PLC channel (see left side of figure 79 for two transmit and four receive ports). For each measurement frequency, the complex coefficient h_{mn} from transmit port n (n=1,…,N_T) to receive port m (m=1,…,N_R) define the channel matrix **H** of this frequency:

$$\mathbf{H} = \begin{pmatrix} h_{11} & \cdots & h_{1N_T} \\ \vdots & \ddots & \vdots \\ h_{N_R 1} & \cdots & h_{N_R N_T} \end{pmatrix}$$

The channel matrix **H** can be decomposed by means of the singular value decomposition (SVD)

$$\mathbf{H} = \mathbf{UDV^H} \quad ,$$

where **U** and **V** are unitary matrices (^{H} is the hermitian operator) and **D** is a diagonal matrix which contains the singular values $\sqrt{\lambda_j}$ (j=1,…,r). The number of non-zero singular values depends on the number of transmit and receive ports: $r = \min(N_T, N_R)$. Since **D** is a diagonal matrix, the MIMO channel is decomposed in r independent SISO paths and the singular values describe the logical paths of the MIMO channel (see right side of figure 79).

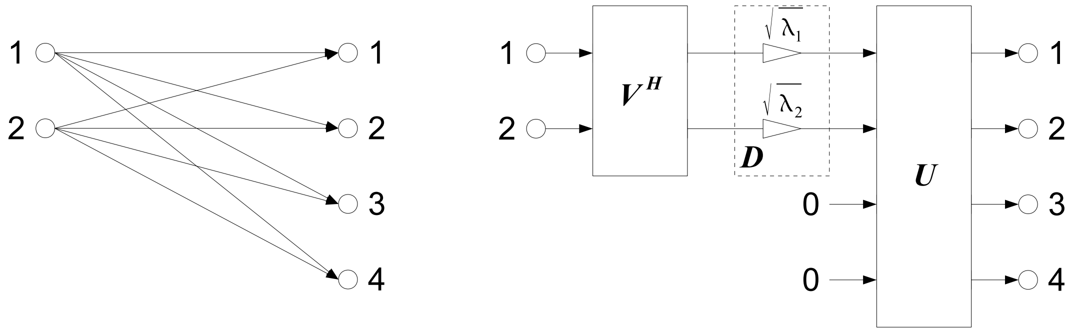


Figure 79: Channel Matrix and Singular Value Decomposition

Figure 80 shows the cumulative probability of the singular values for all measurement sweeps (338 in total) for different MIMO configurations. If only one transmit port is used, the number of logical paths is one. If two transmit ports are used and more than two receive ports are used, two logical paths are available. The solid lines in figure 80 represent the logical path 1 while the dashed lines represent the second logical path. Figure 80 shows the SISO configuration with PN feeding and receiving on P as the SISO reference. However, the SISO configuration with PN feeding and receiving on N shows exactly the same behavior with respect to the cumulative probability. The 2x4 MIMO configuration shows the gain of MIMO compared to SISO (1x1 configuration): At the 50 % point (median) an improvement of 11 dB is provided on the first logical path compared to SISO. The second path adds communication capabilities which are 3 dB less than SISO at the 50 % point. The MIMO gain is even more visible for the highly attenuated channels which are important for meeting coverage requirements. Figure 81 shows a zoomed plot of figure 80 at the 10 % point. The first path of the 2x4 configuration gains 13 dB compared to SISO while the second path provides a decreased communication capacity of 1,5 dB compared to SISO.

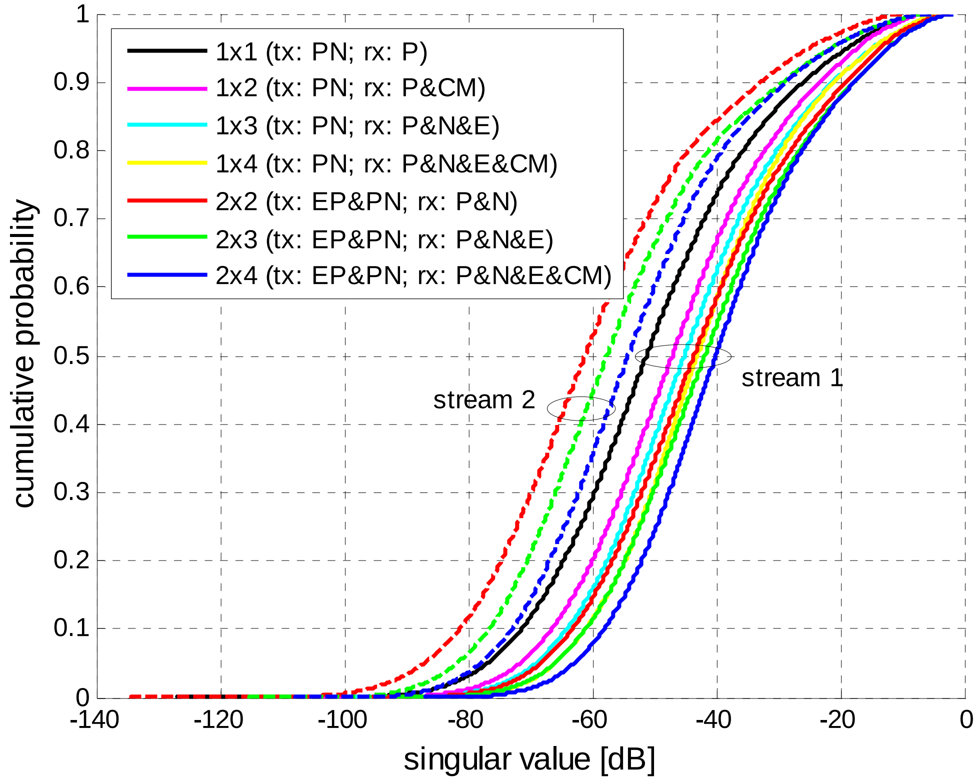


Figure 80: Singular Values

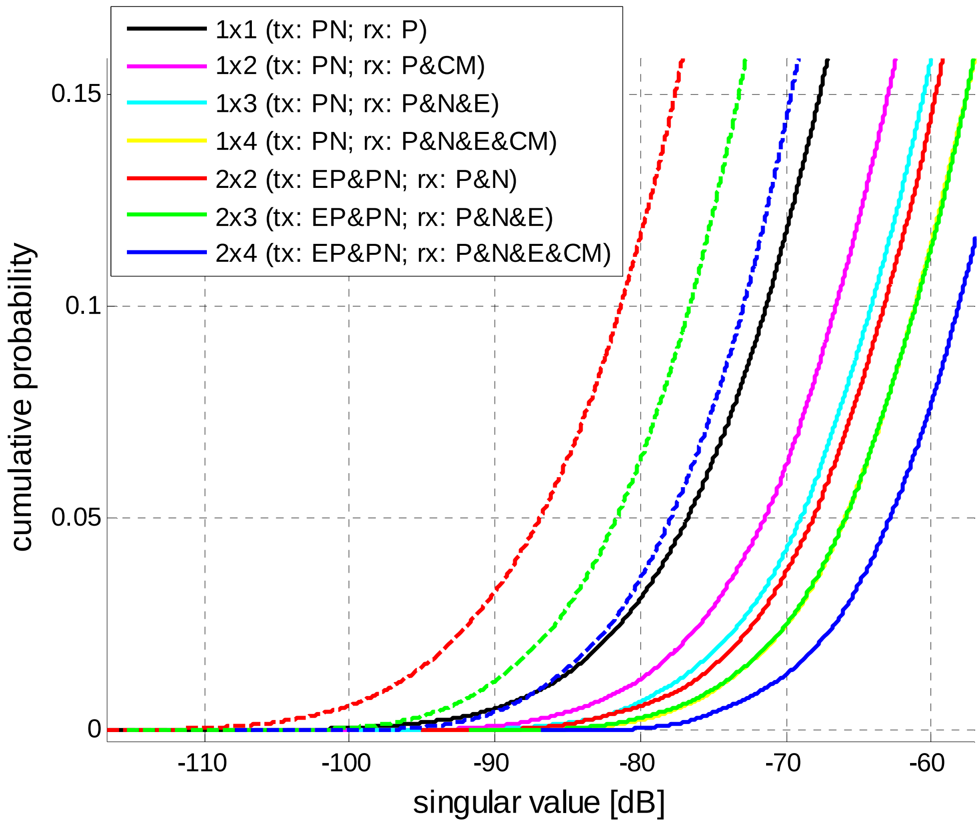


Figure 81: Singular Values, Zoom of Important Area to show Maximum Coverage

Figure 82 shows the cumulative probability of the ratio of the singular values. Note that without the loss of generality the first singular value is assumed to be larger than the second singular value. The figure shows the ratio in dB according to:

$$20*\log_{10}\left(\sqrt{\lambda_1}/\sqrt{\lambda_2}\right)$$

The ratio is calculated for each measurement and frequency point before calculating the cumulative probability. The higher the ratio, the lower the second stream is, indicating a high spatial correlation. The highest spatial correlation is observed for the 2x2 MIMO configuration. The slow slope at high values of the cumulative probability shows that only a few measured channels have a very high spatial correlation.

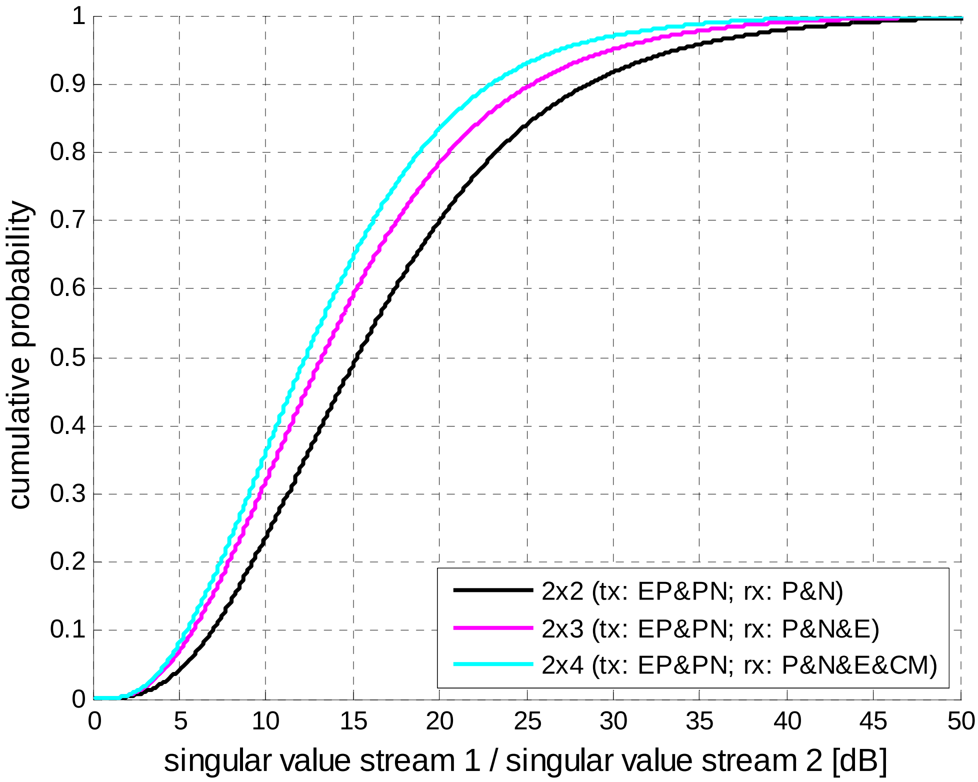


Figure 82: Spatial Correlation

Figure 82 shows that e.g. for 60 % of the channels, the smallest singular value is 10 times smaller or more than the largest singular value. In radio applications, this would not achieve a doubling of the channel capacity because the SNR is too small. In PLC, due to the large quantity of available SNR, even unbalanced singular values produce a large capacity increase. Additionally, beam forming improves the SNR of the first path. Therefore, PLC performance improvement is not only caused by the 2nd path. This is another difference to WiFi MIMO.

7.4.2 Channel Capacity

The decomposition into independent streams described by the SVD is the basis of the channel capacity calculation. The MIMO channel capacity is the sum of the capacity of each single stream [i.7]:

$$C = B\frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{2}\log_2\left(1+\frac{\rho}{N_T}\lambda_{i,j}\right) bit/s,$$

$\lambda_{i,j}$ is the eigenvalue (squared singular value) of stream *j* and frequency point *i*. *N* is the total number of frequency points and *B* is the bandwidth (here: 100 MHz). ρ is the ratio of the transmit power spectral density to the noise power spectral density and is assumed to be constant over the frequency, here. ρ = 95 dBm/Hz is used which corresponds e.g. to a transmit power spectral density of -55 dBm/Hz and a noise power spectral density of -150 dBm/Hz at each receive port (this is a quiet environment, roughly 80 % of the noise value of the noise measurements, see figure 61 or figure 63). The noise is assumed to be uncorrelated for each receive port, in this case. The factor $1/N_T$ divides the total transmit power among the available transmit ports, i.e. it is assumed that the total transmit power is the same for SISO and MIMO. The channel capacity gives the theoretical achievable bitrate. Actual modem implementations will not achieve these bitrates, meaning that the limited dynamic range of ADC and DAC does not allow such signal over noise ratios.

Figure 83 shows the complementary cumulative probability (C-CDF) of the channel capacity for different MIMO configurations (identical MIMO configurations are used in clause 7.4.1 for the singular values).

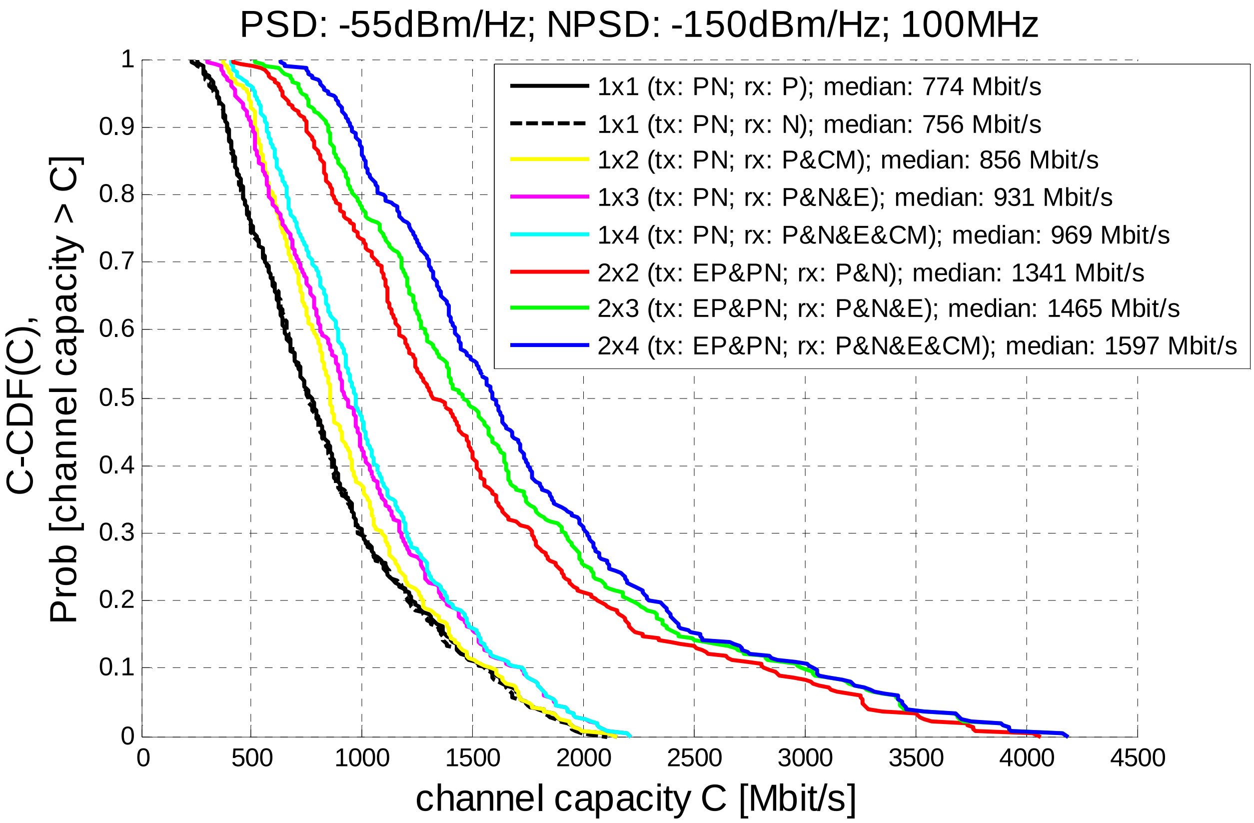


Figure 83: Channel Capacity for Different MIMO Configurations

Figure 84 is a zoomed in version of figure 83 at the high coverage point. Here, the gain is better visible compared to the median values. Considering e.g. the 98 % point, SISO achieves 286 Mbit/s while 2x2 MIMO obtains 574 Mbit/s (gain compared to SISO of factor 2) and 2x4 MIMO obtains 759 Mbit/s (gain compared to SISO of factor 2,7).

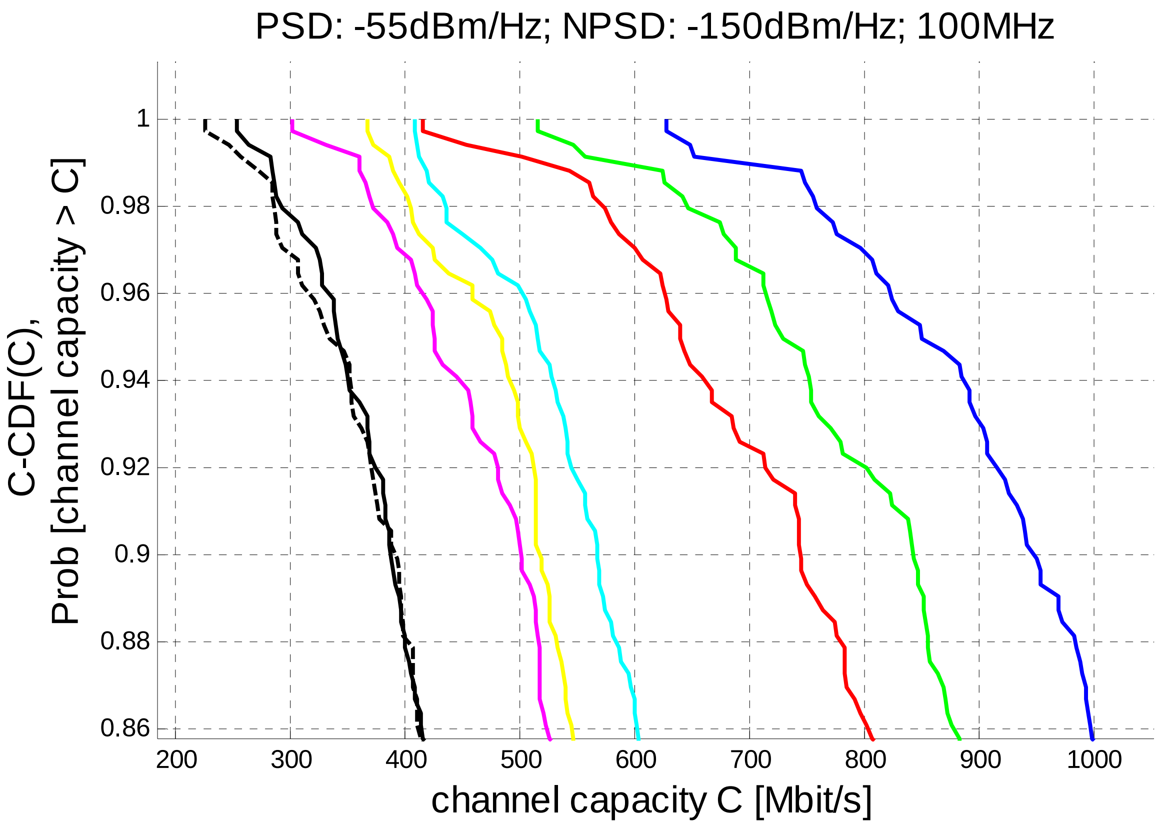


Figure 84: Channel Capacity for Different MIMO Configurations: Zoom at High Coverage Point, for key see figure 83

Table 28 summarizes the median values of the channel capacity for the different configurations for each country individually. The table also shows the gain compared to SISO (PN feeding and P receiving).

Table 28: Median MIMO Channel Capacity for Different Configurations

			All		Germany		Spain		France		Belgium		UK	
Number of channels			**338**		**119**		**30**		**81**		**60**		**48**	
Confi-guration	**Tx ports**	**Rx ports**	**Mbit/s**	**gain**	**Mbit/s**	**gain**	**Mbit/s**	**gain**	**Mbit/s**	**gain**	**Mbit/s**	**gain**	**Mbit/s**	**gain**
1x1	**PN**	**P**	774		561		787		1 082		692		1 039	
1x1	**PN**	**N**	756		536		766		1 117		676		1 061	
1x2	**PN**	**P& CM**	856	1,11	658	1,17	897	1,14	1 177	1,09	817	1,18	1 095	1,05
1x3	**PN**	**P,N,E**	931	1,20	687	1,22	952	1,21	1 280	1,18	828	1,20	1 230	1,18
1x4	**PN**	**P,N,E, CM**	969	1,25	728	1,30	1 006	1,28	1 302	1,20	888	1,28	1 254	1,21
2x2	**EP, PN**	**P,N**	1 341	1,73	1 019	1,82	1 434	1,82	1 892	1,75	1 177	1,70	1 824	1,76
2x3	**EP, PN**	**P,N,E**	1 465	1,89	1 123	2,00	1 582	2,01	2 043	1,89	1 274	1,84	2 018	1,94
2x4	**EP, PN**	**P,N,E, CM**	1 597	2,06	1 230	2,19	1 679	2,13	2 192	2,03	1 440	2,08	2 130	2,05

Table 29: MIMO Channel Capacity for Different Configurations at 98 % Coverage

			All		Germany		Spain		France		Belgium		UK	
Number of channels			**338**		**119**		**30**		**81**		**60**		**48**	
Confi-guration	**Tx ports**	**Rx ports**	**Mbit/s**	**gain**	**Mbit/s**	**gain**	**Mbit/s**	**gain**	**Mbit/s**	**gain**	**Mbit/s**	**gain**	**Mbit/s**	**gain**
1x1	**PN**	**P**	287		264		498		457		381		350	
1x1	**PN**	**N**	284		246		513		466		377		407	
1x2	**PN**	**P& CM**	402	1,40	372	1,41	625	1,26	539	1,18	459	1,21	484	1,38
1x3	**PN**	**P,N,E**	369	1,29	332	1,26	676	1,36	578	1,26	455	1,20	501	1,43
1x4	**PN**	**P,N,E, CM**	432	1,50	410	1,55	735	1,48	626	1,37	498	1,31	542	1,55
2x2	**EP, PN**	**P,N**	565	1,96	453	1,71	960	1,93	829	1,81	751	1,97	823	2,35
2x3	**EP, PN**	**P,N,E**	642	2,23	546	2,07	1 081	2,17	921	2,01	754	1,98	916	2,62
2x4	**EP, PN**	**P,N,E, CM**	755	2,62	648	2,45	1 214	2,44	1 034	2,26	849	2,23	1 007	2,88

Annex A: Useful Information to perform Field Tests

A.1 Equipment List used for Field Tests

- All measurements
    - Cable drum to take power supply from neighbor
    - Isolation transformer
    - LISN, AMN and additional mains power filter
    - Stickers to label the outlets
    - Ground plane 1 m²
- 2 MIMO PLC STF410 universal couplers
- S_{21} channel measurements + S_{11} reflection measurements
    - NWA
    - Calibration kit, BNC Short, Open, 50 Ohm termination and through
    - Long coaxial cables. Double shielded, long enough to reach all electrical outlets in the house under examination. It is recommended to use RG214 cables due to their low attenuations
    - CM choke absorber
- Spectrum Analyzer to verify any noise ingress signals overloading NWA's input
- Noise measurements
    - DSO
    - 4* HPF-002 High Pass Filter with fc = 1,8 MHz
    - 4* HPF-025 Mini-circuit SHP-25+ High Pass Filter with fc = 25 MHz
    - 4* LPF-100 Mini-circuits SLP-100+ Low Pass Filter with fc = 100 MHz
    - 4* SBF-FM 4 Mini-circuits NSBP-108+ Stop Band Filter rejecting the FM band
    - AMP BOARD Mini-circuits ZFL-500LNB+ (4x) Board including 4 low noise amplifiers
    - PWR SUPPLY Team dependent Supplying DC 15 V and 240 mA
    - DSO Team dependent Digital Sampling Oscilloscope
    - CABLE up to 12 Cable with 2 male SMA connectors
    - Adapters from N-connector, BNC, SMA to all combinations

A.2 Check Lists to Monitor progress at field tests

Following Check lists may be filled during field tests. This helps to memory not to miss any record.

Measurement Protocol for STF410 MIMO PLC measurements

Network Analyser settings: Frequency range: 1MHz -> 100MHz, Maximum number of measuremtn points: 1601, max. feeding Power: 10dBm, min acce
save Frequ, Real, Imag in CSV file.

Location (Country, Town, zip-code, street, number, location and size in m² of the flat/house under test):

Take a photograph of each connected outlet and from the building.

Channel Measurements: Through Calibratation (S21) of NWA at the endings of the long cables. Both cables shortcutted

Channel Measurements Naming convention: Pt_F_Pr_R_xx.xx.CSV for feeding at plug No t to port F={'EP', 'PN', 'NE'} and receiving at plug No r from poı
'xx.xx' is the timing distance to the rising LCZC at Tx probe in ms when the sweep was recorded. If trigger of NWA was not in sync to LCZC 'xx.:

Receive	P1				P2				P3				P				P				P				P				P				P				
Phase (L1, L2 or L3):	P	E	N	CM	P	E	N	CM	P	E	N	CM	P	E	N	CM	P	E	N	CM	P	E	N	CM	P	E	N	CM	P	E	N	CM	P	E	N	CM	
Feed																																					Feed
EP																																					EP
P1 PN																																					P1 PN
NE																																					NE
APN																																					APN
PNE																																					PNE
EP																																					EP
P2 PN																																					P2 PN
NE																																					NE
APN																																					APN
PNE																																					PNE
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P PN																																					P3 PN
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A.3 Data Format to save Recorded Measurements

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

For data measured with the network analyzer, some header lines indicating the column settings, followed by a table with the measurement results.

Its form looks like:

```
# Channel 1

# Trace 1

Frequency, Formatted Data, Formatted Data

1000000, 2.109846e-002, 2.714015e-002
```

```
1061875, 2.740054e-002, 2.134098e-002

1123750, 2.862551e-002, 9.963092e-003

...

...

...

99876250, -3.873063e-004, -2.140583e-004

99938125, -3.182144e-004, -2.049750e-004

100000000, -3.223578e-004, -1.644584e-004
```

The values in the table are:

frequency in Hz, S_{21} real part, S_{21} imaginary part

History

Document history		
V1.1.1	February 2012	Publication