Potential Effects of Power Line Communication on xDSL Inside the Home Environment

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***Abstract*—Power line communication (PLC) is a recent and rapidly evolving technology using the existing electricity power lines for data transmissions at high rates (higher than 1 Mbit/s). As these lines have not been designed for high data rate transmissions, they will produce unintentional radio frequency emissions that may adversely cause high interferences in a wider frequency range than their own bandwidth (due to frequency harmonics and the statistical properties of noise like interference). Digital subscriber line technology is currently used to deliver high data rates to users that are using the existing telephone lines. The lines of the two networks (the electricity power distribution and the telephone) are found close to each other in residential places and offices (sometimes in the same duct). Therefore, service providers are concerned about the influence of the PLC transmission on the delivery of services over VDSL2, where the two technologies overlap in frequency range. In this paper, the interference on telephone lines caused by PLC will be studied. Electrical measurements are presented that show the impact of PLC on xDSL in various scenarios. It is demonstrated that readily available in-line radio frequent interference filters are effective solution to minimize the interference levels.**

***Index Terms*—crosstalk, interference, PLC, xDSL**

I. Introduction

Line Communication is a system that uses the low-voltage distribution network as a transmission line to exchange data between in-house customer premises equipment or between a customer premises equipment and an access node. Dedicated transmission lines have a low and predictable level of radiated emission. However, the low-voltage distribution network is not designed as a transmission channel for data signals up to 30 MHz, but is designed to transport electrical power at 50 Hz in many countries (or at 60 Hz in other parts of the world). A number of differences between a cable intended to be used as a transmission line and a power line exist, which have their influence on the propagation properties and radiation of the cable. The low-voltage distribution network consists of electrical lines which are not shielded and not twisted. This implies that the unwanted emission caused by PLC is stronger than the one caused by technologies that use dedicated transmission lines like Digital Subscriber Lines (xDSL). Accurate impact predictions are impossible at this time due to the lack of validated interference models for the new broadband wire line technologies. Therefore, developing models and tools applicable to the assessment of interference caused by the mentioned technologies is very important at this stage.

This paper addresses the concerns raised by service providers about the unintentional radio interference that may be caused by using the electricity lines to transmit high data rates. It presents electrical measurements showing the impact of PLC on xDSL in various scenarios and proposes a solution to the interference.

II. PLC Emission Models- theoretical background

The power line can be considered as a two-conductor transmission line as shown in figure 1, where, I_d is the differential-mode current which easily can be predicted by the transmission line model; I_c is the common-mode current which is unintentional and undesired component of the currents (not necessary for the functional performance of the product). Common mode currents originate from cable unbalance and its magnitude is difficult to predict. The differential-mode currents are oppositely directed and their radiated electric fields tend to subtract. On the other hand the radiated fields from the common-mode currents tend to add as the common-mode currents are in the same direction. Therefore, the common-mode currents produce stronger emissions than the differential-mode currents. Equations 1 and 2 mathematically define the differential and the common-mode currents.

$$I_d = \frac{I_1 - I_2}{2} \tag{1}$$

$$I_c = \frac{I_1 + I_2}{2} \tag{2}$$

Where, I_1 and I_2 are the total currents on the conductors directed to the right.

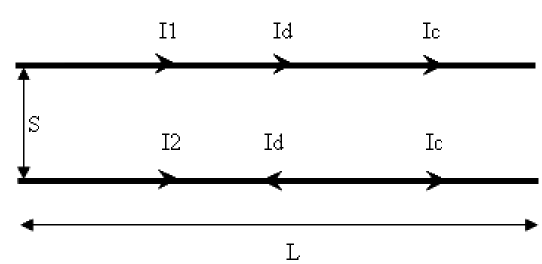


Fig. 1: Two-conductor transmission line

To obtain the emission models for the differential and common- mode currents [1], suppose that the observation point is located at distance d from the two conductors and that the conductors have small sections compared to their length, so that the current distributions can be reasonably considered constant in magnitude along the conductors. In general this is true since the in house power line sections in Europe are typically 2,5 mm2 (or sometimes 1,5 mm2), which ensures a radius of a section to be much smaller then the length of the lines (several meters). Also, for the sake of simplicity, the worst case of geometry location for the telephone wires will be considered; that is, they are supposed to be positioned in the plane of the conductors and perpendicular to the electrical power distribution wires. The electrical fields for both differential and common-mode currents can be approximated by the equations 3 and 4.

$$|E_{d,max}| \approx \frac{f^2.L.S|I_d|}{d} \qquad V/m \tag{3}$$

$$|E_{c,max}| \approx \frac{f.L|I_c|}{d} \qquad V/m \tag{4}$$

where f is the working frequency.

One can calculate the required differential and common-mode currents to meet exactly the FCC requirement (100μV/m) for a cable with S= 50 mil (1 mil=2.54$\times 10^{-5}$ m), L = 1m and d=3m. A differential-mode current of 20 mA at 30MHz will produce a radiated emission just equal to the FCC requirements, and a common-mode current of 8 μA will produce the same level of emission i.e, a common-mode current that is smaller than a differential-mode current by 2500 times will produce the same level of radiation. Thus, seemingly very small common-mode currents can produce significant radiated emission levels.

In addition to the mentioned radiated field (the far field), also the guided field (the near field) must be considered. The guided field decreases with distance as $1/d^3$, compared to $1/d$ for the radiated field (equations 3 and 4); so the radiated field dominates beyond a certain distance [2]. In the kHz-region, the radiated part of the field is very small and the guided field dominates in the vicinity of the wires. In the MHz-region, the power line wires become very effective radiators (antennas). Therefore, in MHz-region (10 MHz) the radiated field is the dominating part even in the vicinity of the two wires.

III. Interference between PLC-systems and telephone lines

With the increasing penetration of in-home PLC, systems that use telephone lines to deliver services to in-home users (like xDSL) are subject to be affected by the interference generated by the new PLC systems. This interference or coupling should be taken into consideration to guarantee the coexistence between the PLC technology and the already deployed ones like xDSL. To estimate the amount of this coupling, the coupling factor a_k has been measured between the interference source U_S generated by the PLC and the interfering signal U_I measured on the telephone line. The measurement setup is shown in figure 2.

$$a_k = 20 \times log_{10}(\frac{U_I}{U_S}) \tag{5}$$

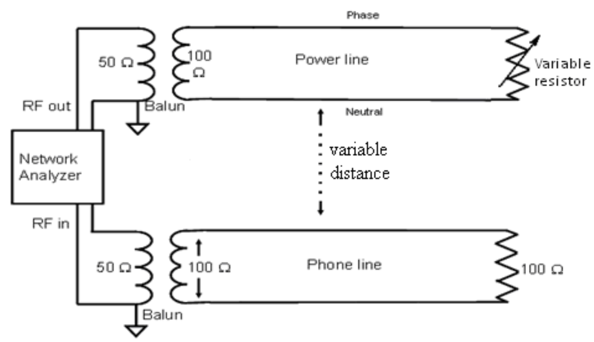


Fig. 2: The physical measurement setup used to measure the crosstalk between the power and telephone lines

The measurements were conducted using balanced connections to inject and measure signals into the power cable and from the telephone line as shown in figure 2. The connections were balanced using impedance-matching baluns. The telephone line end is matched to 100 Ohm. In real life, the impedance attached to the power line is time variant and depends on the connected equipment. In the measurement set-up the load on the power line was varied using a range of values. The coupling is expected to be influenced by the following factors:

1) The cables length;
2) The coupling length;
3) The power line load;
4) The distance between the two cables;
5) The cable geometry, i.e. how the cables are placed relative to each other;
6) The use of twisted pairs and the rate of twists;
7) The frequency.

A. The influence of cable length and power line load

The interference shows a significant increase when the frequency increases towards the frequency corresponding to the quarter wavelength. This result supports the theoretical assumptions that in MHz-region the dominant interference is caused by the electromagnetic radiation. Note that the dielectric properties of the insulation of the power lines will reduce the effective length of the antennas. Although in realistic installations the cables length is not likely to meet the quarter wave length as the power lines are all connected inside the home in addition to their connection with the public electricity network, sub-sections of the cabling may meet the resonance requirement. Such a sub-section of the powerline network may be caused by branches, impedance discontinuities, bends, transformers or other devices. For a velocity of propagation of approximately $2 \times 10^8 m/s$, the resonance frequency yields 25 MHz for a 2 m cable and 17 MHz for a 3 m cable. These frequencies correspond reasonably well with the regions where a steep increase in interference is observed (Figure 3). There is a clear effect of varying the load connected to the power line [3], especially in the regime where the conducted field dominates. In the regime where the radiated field dominates, the overall interference level is independent of load but the exact position of the peaks and valleys highly depend on the load. The characteristic impedance of a line is frequency dependent, certainly if the line is highly unbalanced as is generally the case for power lines. As a result, for a given load the line may show good propagation properties at a given frequency, but may behave worse at another frequency. When the load is changed, the line may show reduced transmission quality at some frequencies and improved quality at other tones. The same effect may be observed in the properties of the interference channel.

B. The influence of the separation distance between the two cables

The influence of the separation distance between the power and telephone cables is measured using 3m long cables. The results are depicted in figure 4. The influence of the separation distance on the interference is not that strong, which agrees with the findings in [4]. This is due to the influence of the radiated field which decreases slowly with the distance from the emitting cable. The total interference is influenced by two contributions, the conducted field contribution (capacitive and inductive coupling) and the radiated field contribution. The conducted field contribution vanishes after a certain distance and the radiated field contribution dominates; refer to section II. The influence of the conducted field can be noticed at small distances [5](the case of 0 cm in figure 4), and at low frequencies where the radiated field is negligible.

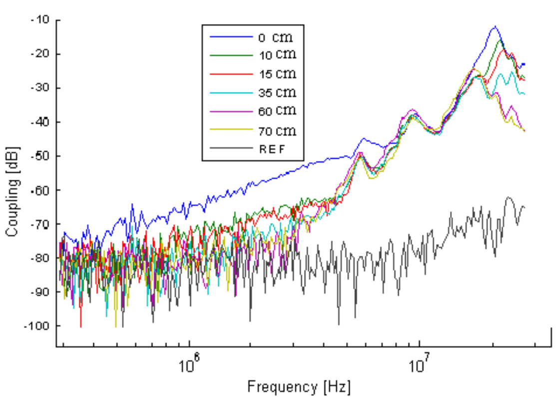


Fig. 4: The influence of the separation distance between the power and telephone lines

C. The influence of the frequency

To simulate realistic scenarios and to avoid having quarter wave antennas, cables of 22m long were used with a separation distance of about 1.5m, and a new measurement campaign was conducted. The interference is depicted in figure 5. At frequencies up to about 2 MHz, the interference was almost of the same level as the background noise. At this frequency range the dominating field is the conducting one and almost no radiation can be noticed. At higher frequencies (more than 2 MHz) the interference starts to increase with a slope of about 80 dB/decade up to a certain cut-off frequency (about 10 MHz in figure 5), and then it stays almost constant; i.e, the radiated field starts to increase linearly with the frequency up to a certain value (saturation value) and then stays constant. At this frequency value, the radiation efficiency of the wires reaches its optimum. The cut-off frequency value depends on the radiating cables length and dielectric properties of the insulation used materials. In this saturation region, peaks and valleys can be seen. The peaks could reach interference values of about -16 dB as shown in figure 6.

TABLE I: The interference between PLC and telephone line-some important values

Frequency[MHz]	≤ 2	4.3	8.8	15	22.7
Interference[dB]	$\leq$ -70	-39	-28	-18	-16
Gain[dB]	≈ 0	36	56.5	57	57.5

D. The influence of the coupling length

The coupling length is the distance when the two cables are close to each other or in the same duct. Four different measurements were conducted using 22m long cables with different coupling lenght, ranging from 2 to 10m. The influence of the coupling length was not that high because of the strong influence of the radiated field. Therefore, the dominant interference is the emission interference and the conducted interference influence is not that strong to create a clear difference between the different coupling lengths. Some important interference values are listed in table I, where the *Gain* is the difference in dB between the total coupling and the noise floor (the ground) at a certain frequency.

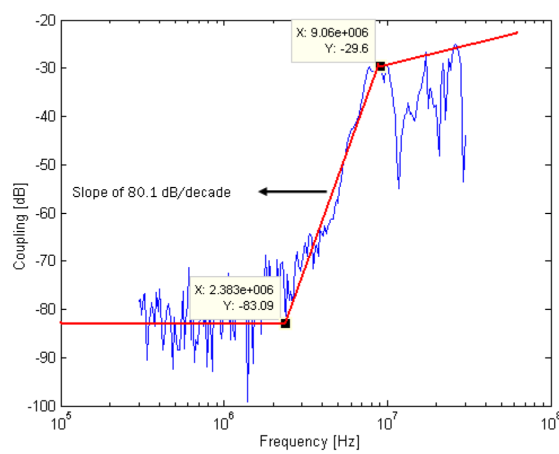
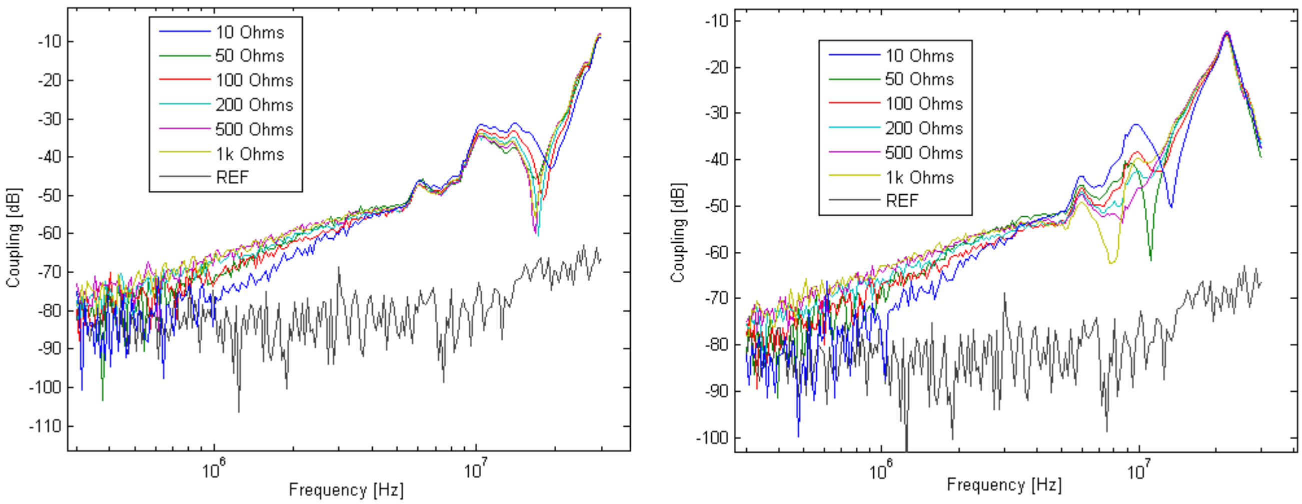


Fig. 5: The influence of the frequency



(a) cables length is about 2 m

(b) cables length is about 3 m

Fig. 3: The influence of power line length and its impedance

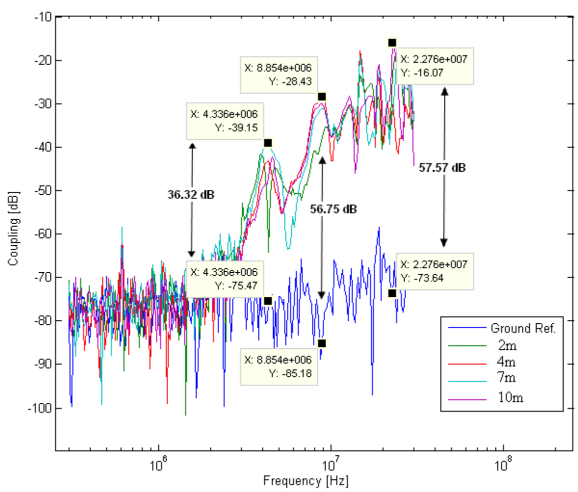


Fig. 6: The interference values and the influence of the coupling length

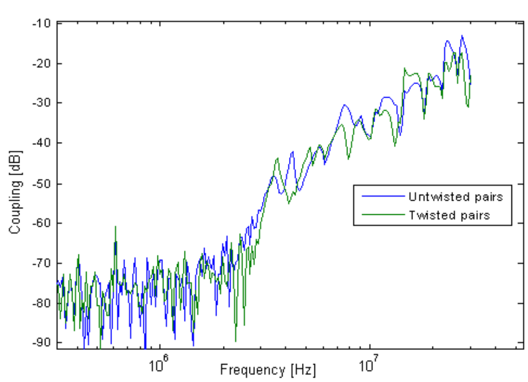


Fig. 7: Twisted pairs Vs untwisted ones

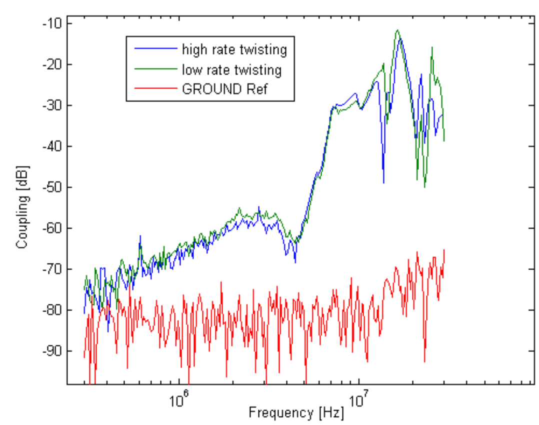


Fig. 8: High rate twists Vs low rate twists

E. The influence of using twisted telephone lines and the rate of twists effect

Telephone lines are twisted to decrease the interference that may affect the signal carried on these lines. However, the measurements showed that in MHz-region where the dominating field is the emission one, the twisting seems not to decrease the interference in significant values. This corresponds with the findings in [4] and suggests that twisting of the victim line is not that effective in reducing radiated interference. The first measurement campaign was conducted to evaluate the gain of using twisted pairs comparing to untwisted ones. Untwisted pairs were used and then replaced with twisted pairs telephone lines from a European incumbent operator. The second measurement campaign was dedicated to evaluate the gain of using high rate twists. The depicted results in figure 8 show that the gain of using high twist rate is small.

IV. Reducing the interference between PLC and telephone lines

The results of the electrical measurements show that high interference levels are present for the scenarios considered. Because the analog front end of the PLC and DSL modems may have different characteristics regarding common mode rejection, these results cannot be straightforwardly translated in effects on modem operations and performance. Nevertheless, it has to be taken into account that in the considered scenarios PLC devices may degrade the performance of DSL lines.

To reduce the interference between PLC and telephone line, the effects of radiated fields have to be minimized. This can be done by suppressing or reducing the levels of the common-mode currents, either on the power line or on the DSL line or both. Suppressing common mode currents is a viable option as these currents are not necessary for proper device operations. For DSL, such filters are readily available at low cost in the form of radio frequent interference filters that can be placed in series with the telephone loop. The use of suppression elements also called *common-mode choke* proves to be an effective and rather simple solution. Using such a device on the telephone line reduces significantly the interference by 20 to 30 dB as shown in figure 9. This figure shows the worst case scenario in which the power line and telephone line are located in the nearest vicinity (0 cm distance). Placing a common mode choke on the power line as well further reduces the interference levels by 10-15 dB (not shown).

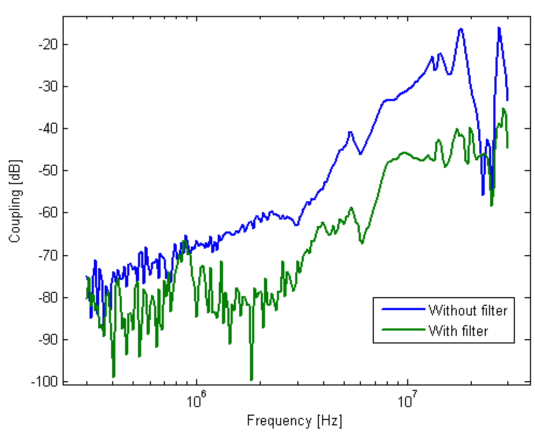


Fig. 9: A common-mode choke filter effectively reduces the interference between power lines and telephone lines

V. Conclusion

This paper has addressed the interference from PLC to telephone lines used as digital subscribers to access networks. The obtained results showed that in MHz-region, the dominating interference is generated by the radiated field of the common-mode current. Historically, one expected that the radiation region caused by electrical power distribution lines in house would be of importance for frequencies above 30 MHz, but this assumption seemed not valid in our case where the contribution of radiation, obviously, started at about 2 MHz and reached its maximum at a saturation frequency of about 10 MHz. This saturation frequency can be affected by line lengths, coupling geometry, load impedance, the position of the transmitter and the receiver, etc. The fact of having strong radiated fields has violated some assumptions which are proven to be valid for the conducting fields, e.g. that twisting the pairs would reduce substantially the coupling between the two conductor pairs. The overall results can be summarized as follows:

1) The dominating part of the interference above certain frequency is due to the electromagnetic emission (radiation);
2) The interference (or the coupling) will increase with frequency up to a certain cut-off frequency and a saturation region will start.
3) The conducting field interference is not that strong as would generally be perceived, but the radiated field has pushed the interference to higher values than expected.
4) The influence of the load of the power line (low impedance by heaters versus high load impedance of battery chargers e.g. for cell phones) is not very important to the overall interference level. For a given frequency, a load change has observed to cause a difference of 15dB in interference level, causing transient noise effects in DSL lines.
5) The influence of the separation distance between the two cables and of the coupling length is not very strong.
6) item Using twisted pairs will only mildly decrease the interference, even when high rate twists are used.

We have demonstrated that the commercial *common-mode choke* filters significantly reduce the interference between power lines and telephone lines.

This paper focused on electrical measurements. An analysis of the interference in real-live systems using PLT and DSL modems, and operational data provided by such modems is for further study.

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