EMC ASPECTS OF POWER LINE COMMUNICATIONS

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INTRODUCTION

With the growing deployment of PLC, cumulative effects of far field radiation are of great interest. The existing background noise level should not be enhanced by extensive use of PLC systems especially concerning sensitive short wave radio services like amateur radio or various wireless security services operating within the frequency range from 1 to 30 MHz. Earlier studies carried out e.g. by BBC [1] and York University [2] led to the conclusion that by extended deployment of PLC the background noise level would considerably increase, interfering these services.
The main propagation paths known as ground wave and sky wave, as well as the space wave are investigated theoretically in the relevant frequency range up to 30 MHz. Afterwards, a model for the radiation characteristics of widespread PLC deployment will be proposed. Assumptions on the number and the distribution of possible radiation sources will be introduced. Using an isotropic antenna model will turn out as a highly useful approach to describe the behaviour of power supply networks, typically consisting of various randomly distributed cables. After presenting simulation and measurement results for the different propagation paths, they will be compared with limits specified by the German NB30 regulation issue which had been in force until summer 2001, but still is considered a guideline for upcoming standards. Finally, assuming that all radiation sources comply with NB30 radiation limits, it is shown that both the ground wave and the sky wave are sufficiently attenuated not to enhance the "natural" background noise.

THEORY OF PROPAGATION PATHS

In order to study a possible impact of the cumulative radiation of widespread PLC applications, all typical propagation paths for short wave radio have to be examined. Thereby, the most important paths are the ground wave and the sky wave as there is generally no line-of-sight connection between transmitter and receiver location in the far field. The ground wave can be assumed as the main propagation path at distances of up to some hundreds of kilometres as has been shown in earlier studies [1][2], whereas the sky wave provides the main contribution for greater distances. Both ground and sky wave will only be briefly outlined as further information is easily accessible in literature [3]. In addition, the space wave has to be considered, possibly having an impact on sensitive systems of aircraft passing cities supplied with PLC [1]. Possibly higher field levels have to be expected as in this case a line-of-sight connection exists.

Ground Wave

Short wave radio services and amateur radio transmit signals over small or medium distances using ground wave propagation. In presence of humid soil, low frequencies can be received without significant attenuation in the vicinity of a radiation source with almost a *1/r* behaviour of the electromagnetic field. Theoretical aspects of ground wave propagation can be found in [4]. In general, it can be stated that ground waves show increased attenuation at higher frequencies and lower ground conductivity σ. Due to the higher attenuation, ground wave propagation can be neglected in the frequency range above 30 MHz. In this approach, existing models of ground wave propagation are applied. Plenty of data about the behaviour of the ground wave can be found in [5].

Sky Wave

The sky wave enables short wave radio to transmit data over thousands of kilometres via multiple ionosphere reflections. Hence, radiation limits for PLC must be kept low enough, so that the cumulative far field stays below the background noise. Due to high energetic radiation from the sun, the electron concentration N in the ionosphere increases. The dielectric constant of the ionised gas can be written as

$$\varepsilon = 1 - \frac{Ne^2}{\omega^2 m\varepsilon_0} = 1 - \frac{\omega_p^2}{\omega^2} \qquad \text{with} \qquad \omega_p = \sqrt{\frac{Ne^2}{m\varepsilon_0}} \tag{1}$$

being the plasma frequency. The dielectric constant becomes less than zero for $\omega<\omega_p$, indicating that the wave can no longer propagate in the medium. Thus, it is reflected to the earth's surface. The wave changes its direction continuously, depending on frequency, electron concentration and angle of incidence. Even waves with $\omega>\omega_p$ can turn back to earth if they reach the ionosphere at certain angles. Generally, it can be stated that waves at lower frequencies are reflected at normal incidence, whereas waves at higher frequencies are reflected only if the angle of incidence is sufficiently large, forming a "dead zone" around the radiation source. In simulations, the complex behaviour of the sky wave was reduced to a worst case scenario. The reflection was assumed to occur at an effective height h'. The ionospheres´ attenuation was regarded with a reflection loss of 10 dB [1]. More theoretical aspects about sky waves can be found in [3].

Space Wave

Space wave propagation is equivalent to free space propagation. The simulation of this propagation path is very elementary. Assuming an aircraft flying at a certain level above ground, the visible sources can be determined. Thus, knowing the distance between aircraft and each radiation source, the corresponding field strength can be calculated. Obviously, the worst case scenario to be considered will be a flight over an area being densely supplied with PLC.

MODELLING OF SOURCES

Number and Distribution of Sources

Radiation sources, e.g. PLC systems in a city, are assumed to be statistically distributed Hertzian dipoles, instead of being replaced by a single equivalent source [2]. Calculations with such a single equivalent would only be valid at a certain distance outside the city limits, whereas distributed sources allow simulations even within the city limits. Concerning a real world scenario, the number of radiation sources in the access domain is calculated based on the area of the city. According to [1], an area of about 600 m in diameter is supplied by a transformer substation, which leads to

$$N = A \cdot 3.537 \frac{1}{\mathrm{km}^2} \tag{2}$$

radiation sources within a city of area A. In the in-house domain, the number of sources is calculated by the number of households and a special utilization factor.

Radiation Characteristics

Generally, the network structure of a PLC system is far too complex to be described exactly. Hence, simplified statistical models have to be applied. Considering that most power supply networks consist of randomly distributed cables, an isotropic antenna is an adequate model [2]. Thereby, it is assumed that all radiation sources comply with NB30. The maximum allowed field strength in the frequency range from 1 to 30 MHz at a distance of 3 m from the network is calculated according to

$$\frac{E_{NB30}}{\mathrm{dB}\mu\mathrm{V/m}} = 40 - 8.8 \log \frac{f}{\mathrm{MHz}} \tag{3}$$

Thus, an evaluation of the radiation field limits is possible. In the next step, the attenuation factor D is introduced, describing the field of a point source at a distance r relative to 3 m.

$$D(r) = E(r) - E_{NB30} \tag{4}$$

In free space, where $E \sim 1/r$, D is calculated according to (5).

$$D(r) = 20 \log\left(\frac{3\mathrm{m}}{r}\right) \tag{5}$$

As the NB30 is only applicable in the extreme near field, the according measurements have to take place at a location with maximum field strength. Thus a decrease with $1/r$ at least, or even faster, can be expected. The faster decrease for the transition to the far field can be included by an additional attenuation D_0, resulting in

$$D(r) = E(r) - E_{NB30} - D_0 \tag{6}$$

in the far field. Own measurements showed that $D_0 \approx$ -10 dB might be a good approximation in many cases. However, this value is still very uncertain, which was the reason to set D_0 = 0 dB for worst case conditions in this paper. In summary, there may be simulation uncertainties concerning the behaviour of the field strength. However, due to the *1/r* approach, the calculated field strength is expected to exceed the real field strength, thus the simulations show the worst case from the point of view of EMC.

Simulation Results

The Ruhr area in Germany, a group of cities with A = 3.507 km^2 and approx. 5.4 million inhabitants, was chosen to perform worst case simulations representative for large cities. PLC applications were modelled as statistically distributed radiation sources within a circle having a radius R = 33.41 km. For the access domain, N = 12.520 radiation sources and an operating frequency of f = 5 MHz had been chosen. The number of households was roughly estimated to be 2.5 million, so that the number of radiation sources equals 50.000 for the in-house domain, where the operating frequency was chosen to be 20 MHz. Simulation results are introduced for each propagation path in the following.

Ground Wave Propagation
Apparently, the average of the ground wave field is constant within the city limits and shows peaks if the observation point is in close neighbourhood of a radiation source (Fig. 1).

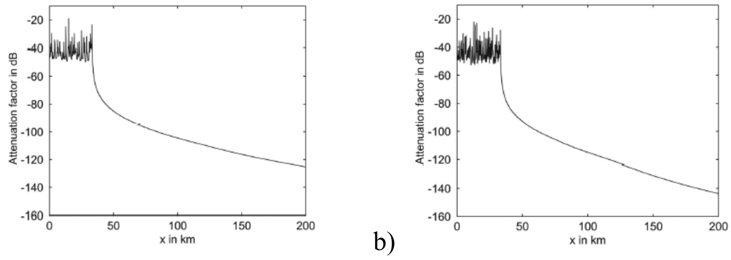

Figure 1: Widespread application of PLC in the a) access domain, b) in-house domain

It is evident that the average field strength within the city depends only on the density of sources, which could be proved by comparison with other simulation scenarios. Outside the city limits, field strength decreases surprisingly fast, both for the cases of access and in-house domain. In the case of the in-house domain, the expected higher field strengths, due to an increased number of radiation sources, do not appear, as can be seen in Fig. 1b, mainly because of increased attenuation at higher frequencies.

Sky Wave Propagation
Concerning sky wave propagation, the minimum path length is $2h'$ in contrast to the ground wave. Consequently, higher attenuation is expected in the vicinity of a city. As the path length only varies little with the distance, also attenuation varies only slowly over distance.

Space Wave Propagation
Due to the propagation in free space, higher field levels are expected for the space wave. Simulations show definitely lower attenuation compared to ground wave and sky wave. Interestingly, there is only a slightly higher attenuation affecting aircraft flying at higher altitudes. This is due to the fact that at low altitudes, the main contribution results from only few sources located directly beneath the observation point, while more sources contribute at higher altitudes.

EVALUATION OF RESULTS

Comparison to Background Noise

In order to study a possible impact of cumulative emission from widespread PLC systems, the radiated field strength in the far field must be compared with the background noise. Even at locations far away from urban areas, where man-made noise is expected to be almost zero, an electromagnetic field can be measured with sensitive receiving antennas. The origin of this background noise can be traced back to processes in the atmosphere and cosmic radiation. Further information on this topic can be obtained from [6].
At first, the radiation limits of NB30 have to be recalled to evaluate the simulation results. At f = 5 MHz, the limit is at 33.8 dBμV/m, decreasing with a log-linear course to 28.6 dBμV/m at 20 MHz. Attenuation factors of at least -39 dB have to be reached in order to prevent a significant increase of background noise. As the simulations showed, this condition is already met at a few kilometres outside the city limits, concerning the ground wave. The sky wave is attenuated even much more than required. Simulations with radiation sources distributed over the whole country of Germany showed that there seems to be no threat by sky waves even with very extensive use of PLC. Noticeable field enhancement is only to be expected for the space wave due to lower attenuation. However, there is no threat to the proper operation of aircraft as the field strength will generally stay below 0 dBμV/m. An aircraft has to provide much higher immunity against “self-made” interference than against field strengths produced by widespread use of PLC.

Verification by Measuring Study

Background Noise and Man-Made Noise

In order to characterise this radiation, measurements at different locations and times, starting from densely populated areas and expanding to rural sites, were performed. It became obvious that the highest sensitivity could be reached using a rod antenna and running the spectrum analyser in the receiver mode. The results show that the field strengths exceed the data of [6] if the point of observation is located in the vicinity of radiation sources, e.g. office buildings. At greater distances to these sources, especially in rural environment, a general increase of noise level could not be approved. Consequently, the noise level at electromagnetically quiet locations is still expected to match the data of [6].

Radiation Measurements with PLC Operation

According to the simulation results of this paper, it is expected that a sky wave arising from PLC can not be detected at all, while the ground wave can only be observed in the vicinity of PLC installations. This assumption is validated by the measurements, where the radiation of a single residential building is perceptible only in rather small distances.

However, due to the broadband character of typical PLC systems, studies were only possible at some selected carriers and up to a maximum distance of about 100 m. Therefore, further measurements with injection of narrow-band signals into the power supply network were performed. Thus, time-invariant signals with adjustable amplitudes are used, so that even at greater distances corresponding field strengths can still be detected.

The radiated field strengths at each object were measured according to measurement instruction MV05, using a loop antenna at r_0 = 3 m. At greater distances, the field strengths were measured with a rod antenna and evaluated with respect to the attenuation factor D_0. In all measurements the total magnetic field at r_0 = 3 m was chosen as a reference.

The measurement results do not show a particular dependency on the type of building. The behaviour of the field strength proportional to *1/r* is a good estimate in most cases, despite the fact that - following instruction MV05 - the reference value was measured in the near field. In the frequency range from 10 to 20 MHz field strengths show a slight increase of up to 10 dB, whereas at frequencies below 6 MHz the results are 5 to 10 dB lower than the *1/r* estimate.

Comparing the measurement results at r_0 = 3 m, it can be seen that the far field capability of the radiation is clearly underestimated in almost all cases if a rod antenna is used for the reference measurement in the near field. Thus, the loop antenna seems to be more appropriate for measurements at small distances. However, difficulties using the measurement instruction MV05 became obvious. If the point of injection is not situated in the ground floor of a building, the far field radiation is underestimated because the main radiation emanates from the point of injection. As a consequence, the use of point sources for modelling the radiation - like in the described own simulations - is justified.

CONCLUSION

In this paper, a new approach for modelling the cumulative far field radiation from widespread PLC applications is presented. Instead of one equivalent source in the centre of a city, distributed sources were applied in the simulations. Assuming that all radiation sources comply with the former German NB30 radiation limits, there is obviously no threat by electromagnetic emissions from PLC. Both ground wave and sky wave are sufficiently attenuated, so that they will not enhance the background noise level. Only the space wave might produce a slightly increased noise level but the simulations show that it will in no case be harmful to the proper operation of aircraft. Even under worst case assumptions made in our investigations, PLC, with an average radiation according to NB30, will not produce interference by sky waves nor will it produce widespread interference to sensitive short wave services by ground waves.

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