EMC Aspects of Inhome-PLC: Crosstalk between Neighbouring Apartments and Increase of Disturbance Due to a Large Number of Simultaneously Transmitting PLC-Systems

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Abstract

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The physics of electromagnetic emissions from a single Inhome-PLC-system are reviewed. The physical relationships governing the emission of fields from one PLC-system and the coupling into another PLC-system are given. The coupling coefficient between two neighbouring PLC-LAN's is calculated and the frequency dependence of the interference is discussed. Results of measurements are given. The properties of external fields produced by PLC-systems are analysed. The disturbance resulting from the superposition of a very large number of simultaneously existing fieldstrength components is calculated, for the ground-wave as well as for the sky-wave, being reflected by the ionosphere. The estimated disturbance levels are compared to currently existing fieldstrength limits of national regulations about PLC-installations. Topics concerning the application of these regulations are discussed.

I. Introduction

The origin of external electromagnetic fields of a PLC-system is the even-mode-current [1]. As shown in Fig. 1 there are two types of external fields. The field of the guided wave, with a Poynting vector parallel to the guiding wire, and the field of the radiated wave, with a Poynting vector away from the wire. In the kHz-region, e.g. at 100 kHz, the wavelength of 3 km is large compared to the dimensions of the radiating structure. The radiated part of the field is very small and the guided field dominates in the immediate vicinity of the wires (Fig. 2). In the MHz-region, e.g. at 10 MHz, the wavelength is 3 m and the wires of an Inhome-LAN become very effective radiators (antennas). In addition to this the asymmetry of the network increases with frequency, resulting in higher even-mode-currents in the MHz-range. Therefore the radiated fields at 10 MHz are higher than at 100 kHz and they are the dominating part, even very close to the wire. As the guided wave-fields decrease with distance with $1/r^3$, compared to $1/r$ for the radiated fields, only the radiated fields remain beyond a certain distance from the Inhome-LAN (beyond 170 m in

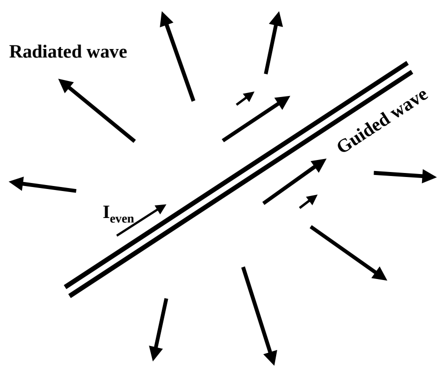

Fig. 1: Powerline with even mode current as the source of the guided wave and the radiated wave

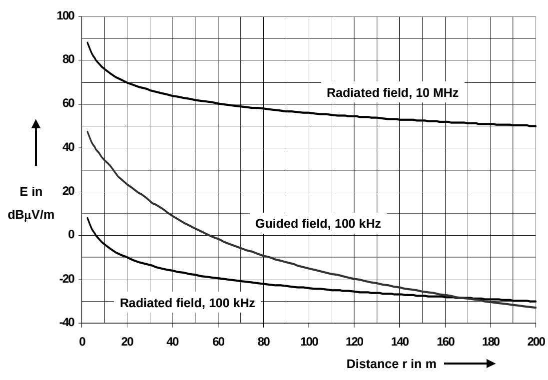

Fig. 2: External fields of a single PLC-LAN at 100 kHz and 10 MHz

the example in Fig. 2).

II. Interference between PLC-systems operating in adjacent apartments

With increasing market penetration of Inhome-PLC-LAN's it will occur more and more often, that two or more neighbouring apartments are equipped with PLC-systems. Therefore the interference potential between neighbouring LAN's has to be investigated. Two different cases are considered: conducted interference via the powerline and radiated interference through the air.

A. Conducted Interference

In Europe up to 400 households are connected to the same medium-voltage-transformer. All these are connected to the same powerline grid. In Fig. 3 two neighbouring apartments are sketched. Both are connected via their electricity-meter with the outside energy distribution line. Because of the low impedance of the outside line and because of additional attenuation of the PLC-signal passing through the connecting wires and the electricity-meter, there will be in most cases no interference between plug A1 and plug A2, those which are located close to the electricity-meter in each apartment. This will be true in the case of single houses. But for multi-dwelling-units and most probably for small apartments on the same floor, a signal from a PLC-transmitter connected to A1 will be detectable at A2.

As a result, the PLC-signals from apartment 1 will interfere with the PLC-signals in apartment 2 and vice versa in the shaded regions shown in Fig. 3. Outside the shaded regions the interference signals will be so much attenuated, that it cannot be detected e.g. at plugs A1 resp. A2, because of the limited dynamic range of the PLC-receivers. Another prerequisite is that both LAN's are transmitting simultaneously. For modern PLC-systems this overlap of signal coverage does of course not implicate, that there is a data connection between

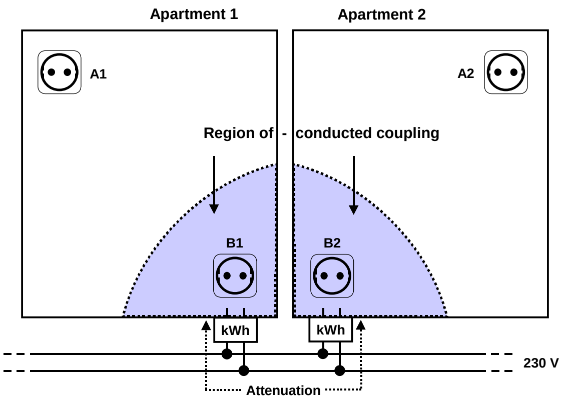

Fig. 3: Two PLC-LAN´s in adjacent apartments

both LAN's. Because of addressing, encryption and similar measures it is not possible to demodulate the data. The user will only suffer from a reduced performance (lower data rate, increased bit-error-rate and increased packet-loss-rate) because of inband interference. The privacy and data-security of each LAN is not at all endangered.

In case a user detects such interference from the neighbourhood and does accept the resulting part-time performance reduction of his LAN, there is an effective, simple and cheap way to prevent it. A blocking filter, installed by a professional electrician at the electricity-meter, will completely isolate his LAN. No private signals will leave the apartment and no disturbance from the outside can enter it.

B. Radiated Interference

In addition to the coupling by signal currents flowing through connecting powerline-wires there is the possibility of inductive coupling, capacitive coupling and antenna coupling. To estimate the amount of these coupling phenomena, the coupling factor a_k between the interference source U_S and the interfering signal U_I was calculated for typical geometries, using the basic laws of field theory [2].

$$a_k = 20 \log (U_I/U_S) \qquad (1)$$

The results are shown in Fig. 4. The dominating effect in the frequency range of interest is antenna coupling. Up to a certain cut-off-frequency of e.g. 10 MHz, like in this diagram, the coupling factor a_k increases with a slope of 80 dB/decade. This is because there are four factors, which are linear functions of frequency: the generation of an even mode current from the original odd mode PLC-signal U_S, the radiation from an electrically short antenna, the reception with an electrically short antenna and finally the conversion of the received even-mode-interference into an odd mode interfering signal U_I. For frequencies that are higher than the cut-off-frequency the even-odd-conversion and the radiation efficiency of the wires is at its optimum. In this saturation region the coupling factor reaches peak values between -15 and -30 dB. The exact value of the cut-off-frequency resp. the frequency band, where the saturation region begins, is dependent on the specific properties of the interacting networks (line lengths, coupling geometry, load impedances, position of receiver and transmitter etc.). Measurements have shown a range between 3 MHz and 10 MHz.

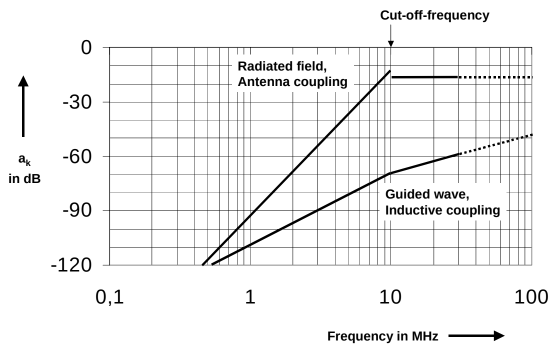

Fig. 4: Coupling factor of two LAN´s. Length of transmitting wire: 10 m, distance to the receiving wire: 10 m

Fig 5 shows the results of a typical measurement for two networks without conductive coupling. In this case the coupling factor is -100 dB at 800 kHz and increases to a first maximum of -28 dB at 3.8 MHz and a second maximum of -19 dB at 5 MHz. Beyond 5 MHz several minima and maxima exist, depending on constructive or destructive superposition of the various coupling signals. This is a common phenomenon in the short wave region.

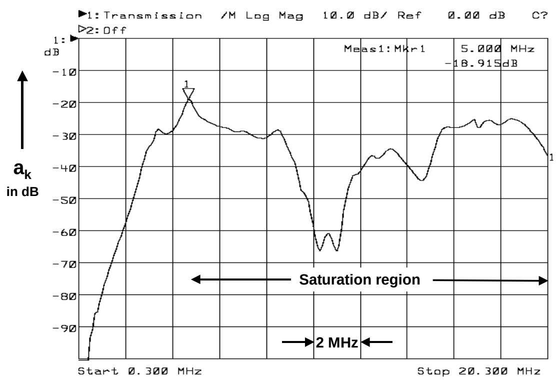

Fig. 5: Measured coupling factor between two Inhome-LAN´s

As the radiated fields decrease rather slowly with distance, the interference might spread out to more PLC-users than just the immediate neighbours. A countermeasure against this type of interference is not known. Even in case all users have the same system with the same multiple access protocol, the prior mere interference is turned into data rate sharing. The effect for the single user remains the same: His data rate is affected, whenever his neighbours are active. As a result of these calculations and measurements, the upper part of the MHz-range cannot be recommended for Inhome-PLC-applications.

III. Additive effects for the electromagnetic emissions of a large number of simultaneously operating PLC-systems

Since the end of 2001 PLC-modems that utilize the kHz-region are available in shops [3]. In current economical predictions of the Inhome-PLC-market a total number of 1 million Inhome-LAN´s is forecasted for a country like e.g. Germany. During times of maximum activity 50% of these LAN's are considered active. Because digital data transmissions like internet connections are usually bursty resp. packet-oriented, only 5% of these active LAN's are transmitting at the same time. This estimation leaves a total number of 25000 PLC-transmitters whose electromagnetic emissions have to be superimposed. In order to get simple analytical expressions, the transmitters are evenly distributed, as shown in Fig. 6. The highest fieldstrength is in the centre of the area. This centre, where the sum of all radiations is calculated, is surrounded by concentric circles. The PLC-transmitters are equidistantly spaced on these circles; their quantity is proportional to the radius of the circle. On the first circle with $r = \Delta r$ are 4 transmitters. The n-th circle with radius $n \cdot \Delta r$ has 4n transmitters. The total number M of transmitters on N circles is

$$M = 4 \sum_{n=1}^{N} n = 2 N^2. \qquad (2)$$

If the M = 25000 transmitters are in this way distributed on a circle with 350 km radius, N becomes 112 and Δr is 3.13 km.

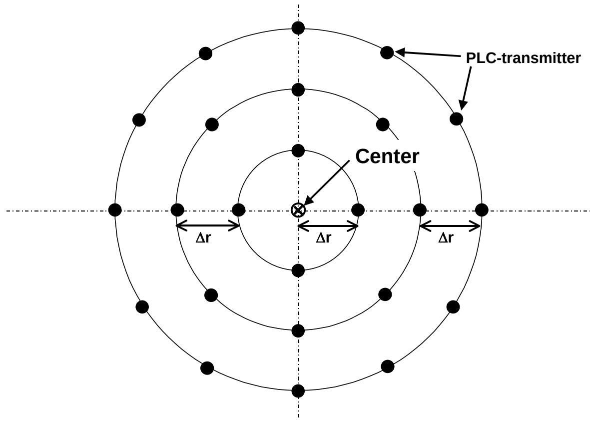

Fig. 6: Concentric rings with equidistant PLC-transmitters

A. Sum of groundwave interference

If we consider a fieldstrength limit E_0 in a distance r_0, which every single PLC-LAN is not allowed to exceed, then the fieldstrength E(r) in a distance r is

$$E(r) = E_0\, r_0 / r \qquad (3)$$

and the energy density at this point is

$$S(r) = E(r)^2/Z_0. \qquad (4)$$

As the signals from all transmitters are noncoherent, their energy densities are summed. The first circle generates the energy density

$$S_1 = 4\, (E_0\, r_0 / \Delta r)^2/Z_0 \qquad (5)$$

and the n-th circle

$$S_n = S_1 / n. \qquad (6)$$

When all terms S_n are added from n = 1 to N and the sum is converted into E_Σ, the resulting fieldstrength in the centre of the area compared to the fieldstrength limit E_0 is:

$$a_\Sigma = 20 \log (E_\Sigma / E_0) = 6\text{ dB} + a(r) + a(N) + G_M + a_{pol}. \qquad (7)$$

The first term is from the factor 4 in Eq. (5), $a(r) = 20 \log (r_0 / \Delta r)$ and $a(N) = 10 \log \sum_{n=1}^{N} 1/n$.

The last term a_{pol} = -3dB is added, because the horizontal component of the ground wave is lost, due to ground conductivity. G_M represents the average antenna gain of all PLC-transmitters. Obviously every single PLC-LAN has a different radiation characteristic. The superposition of all these results in an isotropic radiation characteristic. Nevertheless the individual rays, that reach the centre, are as often from a maximum as from a zero of the individual radiation characteristic. With G_M = -10 dB and r_0 = 3m Eq. (7) gives a_Σ = -60 dB. The accumulated emissions of 25000 PLC-transmitters result in a fieldstrength, which is 60 dB below the limit E_0.

All ground waves leave the surface of the earth, because of the curvature of the surface. Due to additional diffraction effects, the guidance properties of the conductive earth surface are dependent on frequency and location. For ground conductivities like in Europe the limit of the 1/r-law is reached at several 100 meters at 30 MHz and at 100 km at 100 kHz. Beyond these limits groundwave attenuation increases very fast [4]. Taking this into account, the term a(N) in the above calculation will not increase like it is shown in Fig. 7, but it will reach an asymptotic value of approximately 6 dB. This will result in a maximum value of a_Σ = -61 dB, independent of the size of the area, which is occupied with PLC-transmitters.

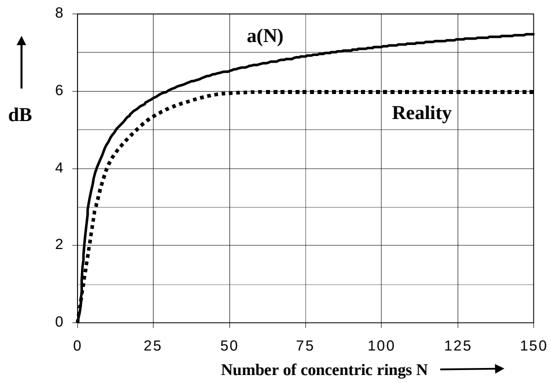

Fig. 7: Increase of sum disturbance due to the size of the area filled with transmitters

The uniform distribution of PLC-transmitters seems to be an illegal simplification in the above used model. A more detailed analysis shows, that urban surroundings are very good absorbers for disturbance emissions. Electromagnetic waves suffer an average attenuation of 3 dB at 50 kHz and 8 dB at 30 MHz when they have to pass through a house. This attenuation increases for higher houses with a steel skeleton. As a result it is only the outer surface, that radiates in densely populated areas and the attenuation of the ground wave is much higher than in the above calculation.

B. Sum of spacewave interference

If a plane is flying above the area of Fig. 5, it will also measure the highest fieldstrength in the centre of this area. Eq. (7) is used to calculate this fieldstrength. Both polarizations are existent in the space wave. Nevertheless a_{pol} = -3dB has to be kept in this equation, because the antenna, located at the airplane, will only be able to receive one polarization component. For a plane, that is in a height h above the centre of the area, the distances to the PLC-transmitters change from $n\cdot\Delta r$ to $s = \text{sqr}\,[(n\cdot\Delta r)^2 + h^2]$. This distance is increasing with height h. Because s is always greater than $n\cdot\Delta r$ the sum-amplitude of the disturbance fieldstrength for the space wave is always smaller than the sum-amplitude in the simple model that was used to estimate the effect for the ground wave.

With increasing height h the decrease in fieldstrength because of larger distances is reduced by the fact that the visible portion of the earth is increasing. More and more transmitters add to the sum-amplitude with increasing height. Nevertheless this effect can be neglected, because it happens in regions outside our atmosphere and for values of a_Σ < -60 dB. There is of course a limit for this increasing area of visibility given by the spherical shape of the earth.

C. Sum of skywave interference

Long distance radio connections utilizing skywave propagation with ionospheric reflections can be calculated resp. predicted with several readily available computer programs. These programs show that for the frequency range of interest the highest fieldstrength values will be found between 4 and 10 MHz. Fig. 8 shows the simplified results of such a calculation. A single transmitter with isotropic radiation characteristic produces after a single hop an illuminated area between an inner circle of 700 km radius and an outer circle of 1300 km radius. For 25000 transmitters, spread over an isotropically radiating circular area with 350 km diameter, the illuminated area will double (Fig. 9), to an annulus with an inner circle of 350 km radius and an outer circle of 1750 km radius.

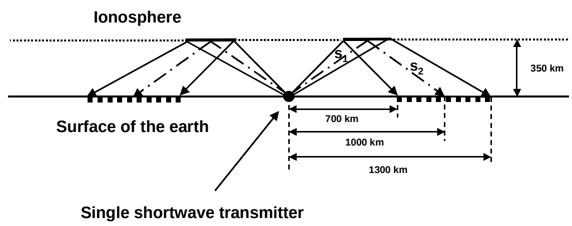

Fig. 8: Skywave propagation at 10 MHz. A single transmitter with isotropic radiation characteristic illuminates a region with the shape of an annulus

Independent of this, the highest fieldstrength amplitudes are found in the original annulus of Fig. 8. Their relative strength can be calculated by:

$$a_\Sigma = 20 \log (E_\Sigma / E_0) = a_{SA} + a(r) + a_{Ionos} + a(M) + G_M. \quad (8)$$

a_{SA} = -4.8 dB, if the spherical angle of that part of the transmitted energy, that is reflected by the ionosphere, is approximated by 1/3. a(r) is the attenuation due to the average distance of $s = s_1 + s_2$ = 1221 km. As the ionosphere is not a perfect reflector, the ionospheric loss a_{Ionos} is inserted as 6 dB, the minimum possible value. The number M of all transmitters is represented by a(M) = 10 log M. This results in a_{Σ} = -89 dB. The maximum fieldstrength generated by 25000 PLC-transmitters via ionospheric propagation is 89 dB lower than the original fieldstrength limit E_0. This is so low, that it is not necessary to improve the model used for this calculation. There is also no need to investigate multiple hops.

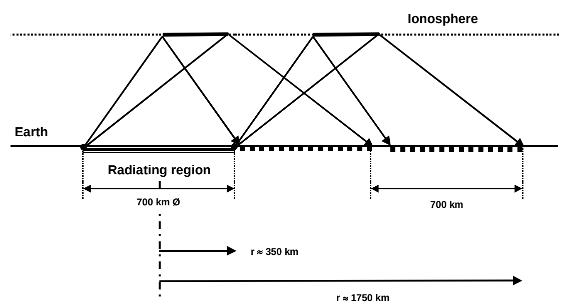

Fig. 9: The PLC-transmitters at the periphery of the area have illuminated areas that are not overlapping in this cross section

D. Interference limits for PLC-installations

Fig. 10 shows the fieldstrength limits of the German NB 30. The maximum external fields of a single Inhome-LAN with a spectral density of 50 dBµV/m is also included in the diagram as dotted line. The increasing distance with increasing frequency between current limits and external fields explains why several companies, that wanted to market PLC-access-systems in the MHz-region, stopped their business recently. The PLC-modems, which are currently sold in Germany [3], utilize frequencies below 500 kHz and are therefore NB-30-compliant.

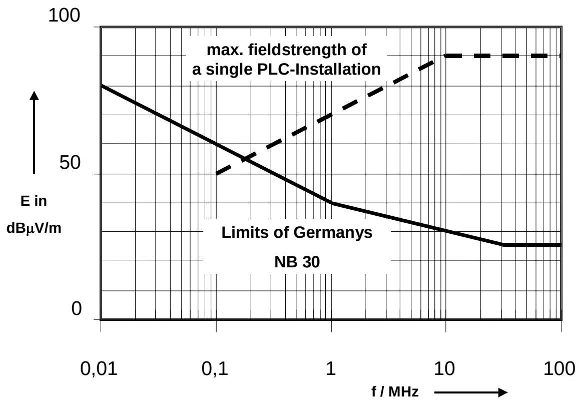

Fig. 10: External fields of a PLC-Inhome-LAN compared to the limits of the NB 30

In Fig. 11 the NB-30-limits are compared to internationally agreed disturbance levels in rural and urban environments. These values are based on measurements that have been made 35 years ago. The NB 30 limits are given for a fixed measurement bandwidth of 9 kHz. This results in 16.5 dB higher values below 150 kHz, compared to Fig. 10. (In accordance with CISPR 16 the measurement bandwidth down there is 200 Hz). The disturbance levels are taken from standard ITU/CCIR recommendations [5]. They are converted to fieldstrength in 9 kHz bandwidth measured with a peak detector. The conversion average-to-peak is done by adding 14 dB, which is typical for white noise, but by far not enough for e.g. atmospheric noise.

At first glance, the NB-30-limits appear to be extremely low, but correct, except for the region from 150 kHz to 4 MHz, where the limits are obviously 15 to 20 dB too low. A closer investigation reveals that the main problem is the measurement distance. According to Fig. 2 the external fields at 100 kHz decrease by 65 dB within the first 100 m distance from the powerline. The threat for radio services is not the amplitude of the nearfield, at 3 m distance from the wire, but only the radiated farfield. Therefore the limits in the USA, FCC part 15, use a measurement distance of 300 m in the kHz-range. The comparison of both limits, converted to the same distance and the same detector, lead to a grotesque difference of 60 dB.

Fig. 11 explains also, why NB-30-compliance measurements cannot be done in urban regions: The existing radio noise environment is continuously above the limit line.

IV. Conclusion

The above results for the attenuation of the sum interference signal compared to the limit E_0 in 3 m distance are so large, that the conclusion is, that the disturbances of all other Inhome-PLC-LAN's may be neglected. There is no cumulative effect. In case there is only a single PLC-transmitter located in the centre of the area, where the sum disturbance was calculated, then the original fieldstrength E_0 can be measured there. This amplitude is raised by 3 dB, when the sum-fieldstrength a_{Σ} from all other surrounding transmitters would have been 0 dB, and by 1 dB, when the sum-fieldstrength a_{Σ} would have been -6 dB. For any value of a_{Σ} below -6 dB, there is no degradation of the status quo detectable.

The limits of FCC part 15 were established with the intention to protect radio services and to allow innovative technologies to develop. The NB 30 was used as a political instrument, to make the large scale deployment of PLC-access-systems in the short-wave band impossible. In order to reach this objective, the limits of the NB 30 were set this low in combination with such a small measurement distance, far below any other comparable national or European EMC-standard. At 200 kHz for instance, the radiation limits for electric lighting equipment in EN 55015 are 40 dB above the NB-30-limits and those in EN 55011 are 43 dB above. For an objective, outside observer of this situation it is especially difficult to understand, that a mere disturbance (it is very easy to construct lighting equipment with much lower radiation, because light emission is possible without any radiation in the frequency bands under consideration here) gets tremendously higher emission limits than a telecommunication system, where the radiation is due to the wanted signal.

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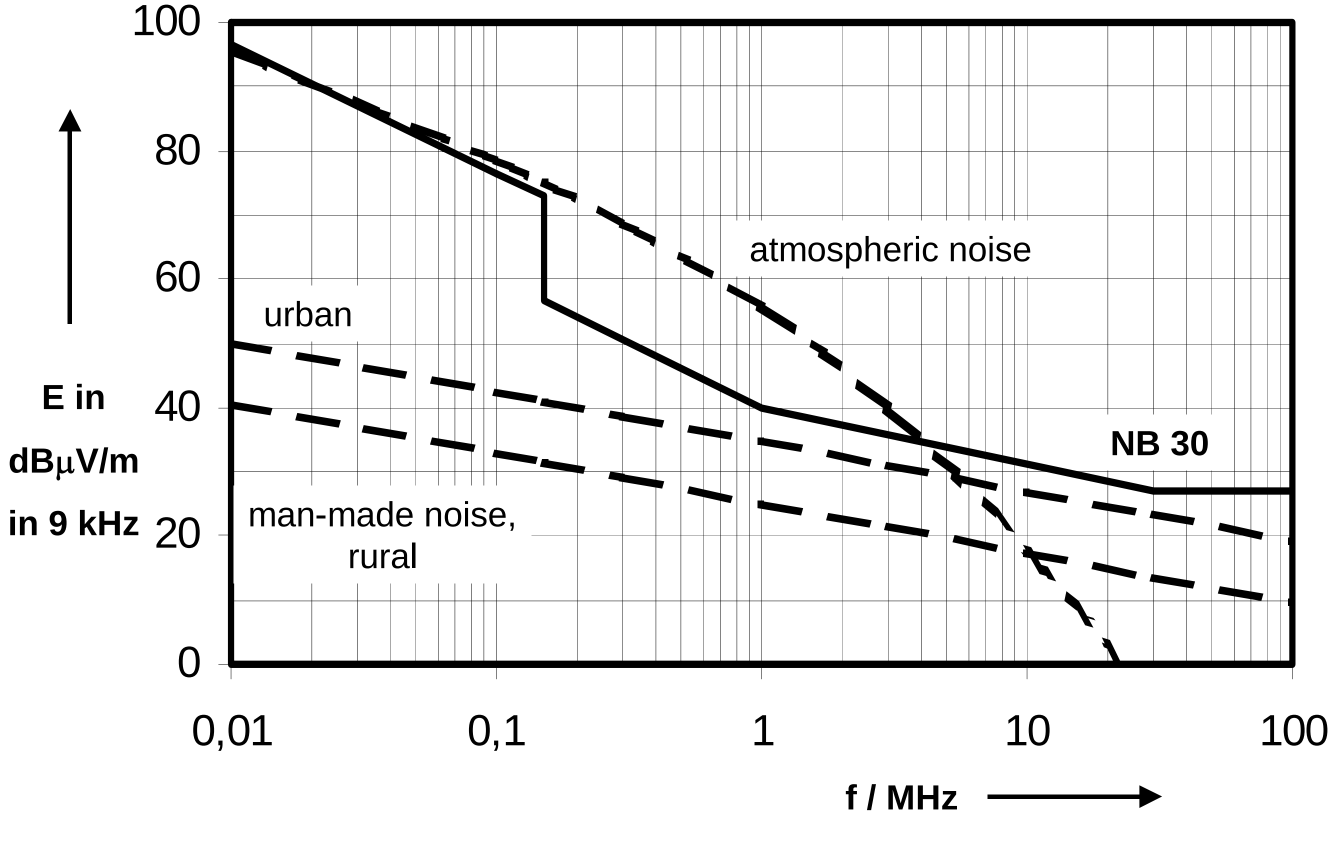

Fig. 11: Comparison of NB-30-limits with environmental disturbances (measured with a peak-detector in 9 kHz bandwidth)