Electromagnetic Fields of Powerline-Systems

Part 4: Superposition of the fields of a large number of powerline-systems

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Powerline-modems, that enable the user to utilize the low voltage powerline network in a private home for digital data communication (keyword: Inhome powerline networking), are currently introduced into the European market [1]. In part 1 and 2 of this series [2, 3] estimations have been derived for the external electromagnetic fields that are generated by such kind of utilization. Fig. 1 shows a summary of these results. The basic assumption for the calculation of the field strength is a PLC-modem with 100 μW in 9 kHz bandwidth respectively -50 dBm/Hz. From a large number of field tests it is known, that a transmitter-power of this magnitude is necessary, in order to guarantee a reliable data connection with approximately 99% coverage of all outlets in a private household.

The maximum values of the external field strength, resulting from this model calculation, are included in Fig. 1 as a red line. Up to a cut-off-frequency at 10 MHz there is a linear increase with 20 dB per decade (factor of 10 for the frequency) in a logarithmic scale. Above 10 MHz the expected maxima of the electric field strength in a distance of 3 m from the powerline remain constant. There are two physical reasons for the increase with frequency: First the asymmetry of the two-wire-powerline increases with frequency and second the radiation efficiency of the powerline is improving as the wavelength is decreasing. Beyond a certain cut-off-frequency, which was set to 10 MHz in this diagram (in reality, depending on the individual characteristics of each installation, this will vary between 3 and 10 MHz), there is a saturation effect: asymmetry and radiation efficiency have reached their maximum values.

The blue line in Fig. 1 gives the limits of disturbance field strength for powerline installations, which are in effect in Germany since the first of July 2001. These limits are defined in the utilization directive (**N**utzungs **B**estimmung) No. 30 of a federal ordinance, effective from

4/26/2001, called frequencyband-allocationplan-ordinance (FreqBZPV), that comprises of the frequencyband-allocationplan and the utilization directives 1 to 30 [4]. Because of this it has the commonly adopted abbreviation NB 30. A comparison of the red line, giving the external field strength of a reasonably dimensioned PLC-installation, with the blue limits, that shall not be breached, explains why PLC-systems, which comply with the NB 30, are only technically feasible below 500 kHz. This is the reason, why several companies, that planned to put PLC-systems working in the MHz-range to the market, have withdrawn their intention.

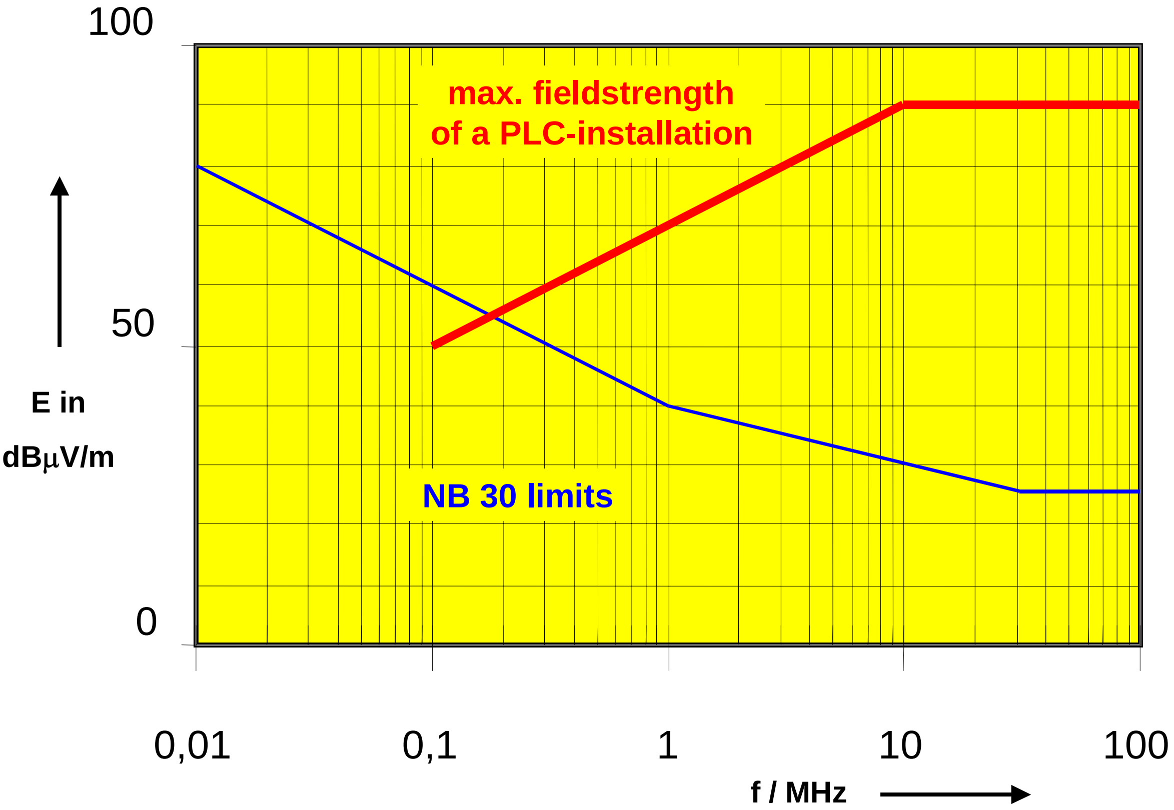

Fig. 1: External fields of a PLC-installation compared to the limits of the NB 30

Whereas part 1 and 2 of this series [1, 2], as well as the NB 30, deal with the external fields of single PLC-installations, it is the topic of this paper to examine the total field strength from a large number of PLC-installations, being active simultaneously. Opponents of PLC-technology use the term "cumulative" effects of disturbance emissions for this scenario. However this term does not really make sense in this specific context. Cumulative effects occur for instance when capital assets increase by interest and compound interest or when biologic tissue is damaged by ionizing radiation (e.g. x-rays), where the amount of damage is proportional to the number of exposures respectively to the accumulated duration of exposure.

In contrast to this we have a simple superposition in the case of the electromagnetic waves that are discussed here: If two transmitters illuminate the same region, the intensities of both have to be superimposed there, and when both transmitters are switched off, the intensities are gone.

Disturbance-scenario

In order to get real numerical estimates for the expectable sum field strength, it is assumed, according to actual market forecasts, that around 1 million PLC-systems are installed in Germany, when the market reaches saturation. In the majority of applications these PLC-systems are used for PC-networking in private households (Inhome-LAN´s) and for internet connection of these PC's via an analog telephone line respectively via ISDN or ADSL. This type of digital data communication is characterized by data packets of limited duration that are transmitted one after the other with quiet intervals of varying duration between them. As continuous downloads of large amounts of data are rather seldom, the typical traffic is bursty, with long times of inactivity interrupted once in a while by the transmission of a limited number of data packets. Therefore the assumption is made for the following, that 50% of all PLC-systems are active during times of maximum traffic, and an average of 5% of these systems are transmitting data at the same time. Taking into consideration that a 5-%-usage means 1.26 MByte per hour for an analog telephone connection with 56 kbit/s and 17.3 MByte per hour for an ADSL-connection with 768 kbit/s for the single user shows that these basic assumptions are relatively high. As a result of this, 25,000 PLC-installations are actively transmitting data at the same time during rush-hours. The fields of 25,000 PLC-transmitters have to be superimposed in the center of Germany during such a rush-hour.

The above derived assumption can obviously be discussed controversially. Nevertheless it is necessary to bear in mind that in the area of disturbance of broadcasting services, which is addressed here, it is tolerated that these disturbances are exceeding the limits for short periods of time, according to the laws of statistics.

Disturbance signal

OFDM (Orthogonal Frequency Division Multiplex) is especially suited as modulation method for PLC-communication. Therefore it is used by the majority of PLC-manufacturers worldwide. Fig. 2 shows an OFDM-signal as a function of time. It is created by superimposing a large number of sine wave carriers. Because of this the resulting amplitude distribution is very close to that of Gaussian white noise. This type of signal is with respect to the disturbance of broadcasting signals almost ideal; this means it produces almost the least disturbances possible.

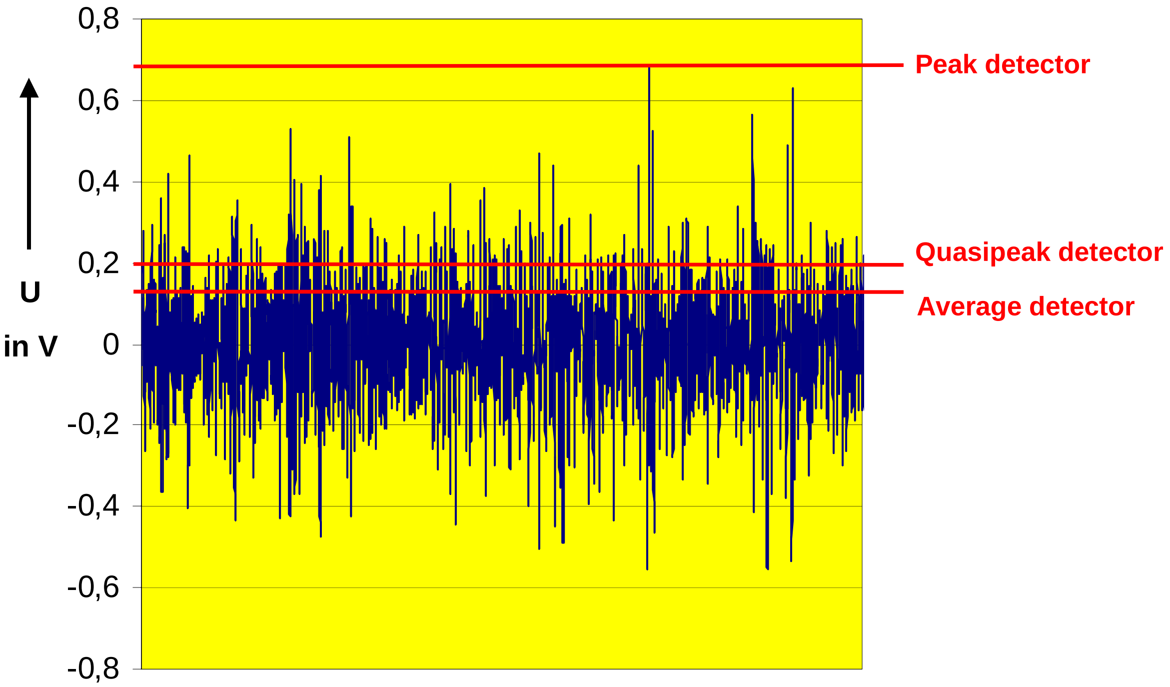

Fig. 2: OFDM signal as a function of time

The diagram shows the measurement results, if this signal is measured with different detectors. In the field of electromagnetic compatibility (EMC) mainly three types of detectors are used: The average-detector, the quasipeak-detector and the peak-detector. Noise is measured with an average-detector. The measurement result with this detector (here 0.13 V) means, that a dc-voltage of the same amplitude produces the same heating of a resistor as the shown OFDM-signal. In the past most disturbance signals were amplitude or frequency modulated. These types of modulation produce a higher subjective annoyance effect for someone listening to a broadcasting station than a noise disturbance signal. To take this into account the quasipeak detector was introduced (measurement result in the diagram: 0.2 V). Consequentially it is compulsory in EMC-standards to use the quasipeak detector when disturbance-limits are measured, in order to get an adequate evaluation of the disturbance effect. In contrast to this the limits in the NB 30 refer to the use of a peak detector. For the given OFDM-signal a peak value of 0.7 V is taken from the diagram. The actual reading of a peak-detector would be 0.7 V / sqr(2) = 0.5 V. This is based on the fact that all three detectors (peak, quasipeak and average) are calibrated in that way, that all of them give the same reading for a sine wave input. This reading is set to be the root-mean-square value, which is amplitude / sqr(2) in case of the sine wave.

In a logarithmic scale the quasipeak value of an OFDM-signal is around 8 dB below the peak value and the average value is approximately another 4 dB smaller. In contrast to a real stochastic signal like white Gaussian noise, the multitude of carriers in an OFDM-signal is synchronized. Therefore the corresponding values for white noise are slightly different: the quasipeak value is roughly 7 dB below the peak value and the average value another 7 dB lower.

Radiation characteristic of a single Inhome-PLC-installation

From the point of view as a radiation source for electromagnetic waves, emanating from an installed Inhouse-PLC-system, a single occupancy house for instance can be reduced to a three-dimensional star-net-configuration of copper wires with right angle bends at varying places. The wiring is found in the outer surfaces and inside a cuboid with an edge length of approximately 10 m. In the frequency range which is under consideration here, plaster, brick walls, wooden lockers, carpeting, paper and fabrics do not produce noteworthy amounts of attenuation and can be neglected accordingly. Whereas all metal parts like water and heating pipes, radiators, CATV-cables, metal cabinets, large electric appliances, aluminum-windows, aluminum-foil for thermal insulation and concrete-reinforcement strongly influence the radiation. But for the wavelengths under consideration here, between 6,000 m (50 kHz) and 10 m (30 MHz), this influence is not an attenuation of the radiated wave but mainly a modification of the radiation pattern: the metal parts are in the near field of the antenna structure, they are electromagnetically coupled. All metal surfaces that carry RF-currents act as radiating antennas themselves.

The highest radiation emanates from those parts of this complicated, three-dimensional antenna structure, that carries the highest RF-current. These are primarily those sections of wire, which lead away from that outlet, to which the currently transmitting PLC-modem is connected. In principal the RF-current will decrease with increasing distance from the feeding point. Also the radiation-coupled metal surfaces will normally not carry higher currents than their primary source. It has to be born in mind, that the RF-currents are considered to be the sources of the radiated farfield. As explained in part 1 of this series [2] there is also the guided field, which clings to the wire, in the nearfield of the antenna. The fields of the guided wave decay very fast with increasing distance and can therefore always be neglected in the farfield. Due to this, measurement results in a distance of 3 m from the current-carrying structure, as enforced by the NB 30, do not give any suitable information about the farfield of the installation.

The radiation pattern of a straight wire carrying an RF-current has a null in the direction of the wire and a maximum with circular characteristic in the cross section perpendicular to the wire axis. It is possible to calculate the radiation pattern of an Inhome-PLC-installation by approximating the real structure by a large number of straight segments, each of these carrying a constant current. The field strengths of all these elementary antennas are added by magnitude and phase in every point of the farfield. As a result of this, the radiation pattern of a complicated structure can be estimated by the following: If you look upon a wire antenna and there are current carrying metal parts visible in the flat projection plane, then RF-energy is radiated in this direction. Knowing this, it is evident, that an Inhome-PLC-system will radiate into all directions. Depending on the place of the feed point and on the loading of the network, the radiated amplitudes in each direction will vary significantly. With increasing frequency (or more precise: when the dimensions of the radiating structure become greater than half a wavelength) the number of nulls in the radiation pattern will increase, because there will be more and more directions, where field components are in antiphase and their sum vanishes. Nevertheless the envelope of the radiation pattern will not be changed by this effect.

Radiation characteristic of a large number of Inhome-PLC-installations

Just because the radiation pattern of each individual PLC-installation is different from all others, it is possible to estimate the superposition of all of them very accurately: the larger the number of PLC-installations is, the more precise the total pattern equals an isotropic radiator, who radiates the same field intensity in every direction of the upper half space (the region above the surface of the earth). Because all installations are different, the variation of the intensities in different directions is averaged by the summation over a large number of these. But it has to be considered, that the resulting average value is not the summation of the maximum values of all installations. If just one single installation is examined, there is a high degree of probability that at least one direction exists, where an exceedingly high field strength amplitude is radiated. Because of this, it was assumed in the first two parts of this series, that a single Inhome-PLC-installation has the same radiation efficiency as a straight wire antenna with a length of 10 m. This results in rather high values of disturbance field strength. Indeed the main objective had been to find an estimate for the expected maxima of radiation.

In case of the superposition of the radiated fields of a large number of PLC-installations it has to be taken into account that the main beam of every installation points into a different direction. A fixed point in the farfield will as often be in a radiation minimum (a null) of a single installation as in a maximum (the main beam) of another one. Thus for the superposition of all single components an averaging over the radiation pattern is necessary. For the following calculations the antenna gain due to averaging is set to G_M = -10 dB (the average radiation intensity is 1/10 of the maximum intensity). From many unpublished measurement results on this topic, which is internationally a sensitive issue, it is well known, that this is a very conservative assumption. A straight wire antenna (a dipole) for instance, that is optimized for the radiation of waves, has already a value of G_M = -2.1 dB. Other authors are using values down to G_M = -60 dB for the radiation efficiency of PLC-installations.

Disturbance signal of a large number of Inhome-PLC-installations

Fig. 3 shows the summation of two sine waves of equal amplitude and differing frequency. This is called a beat signal. It is characterized by periodic maximum values having double the amplitude of the single sine waves. The superposition of n sine waves of equal amplitude results in a signal with periodic maximum values of n-times the single amplitude. In logarithmic scale 10 coherent (phase synchronized) radiation sources produce field strength maxima which are 20 dB (20 log n) higher than the field strength of a single source.

In the case of a large number of Inhome-PLC-systems with OFDM-modulation the signals from the radiation sources are neither sine waves nor coherent. Therefore not the field strength amplitudes of all single radiation sources have to be added but their power values respectively their intensities. In logarithmic scale than 10 non-coherent radiation sources produce field strength maxima which are 10 dB (10 log n) higher than the field strength of a single source. This type of superposition may be illustrated for instance by 10 electric bulbs of 100 W each, being arranged at the circumference of a circle. The light intensity in the center of this circle is proportional to the number of bulbs that are switched on in each case.

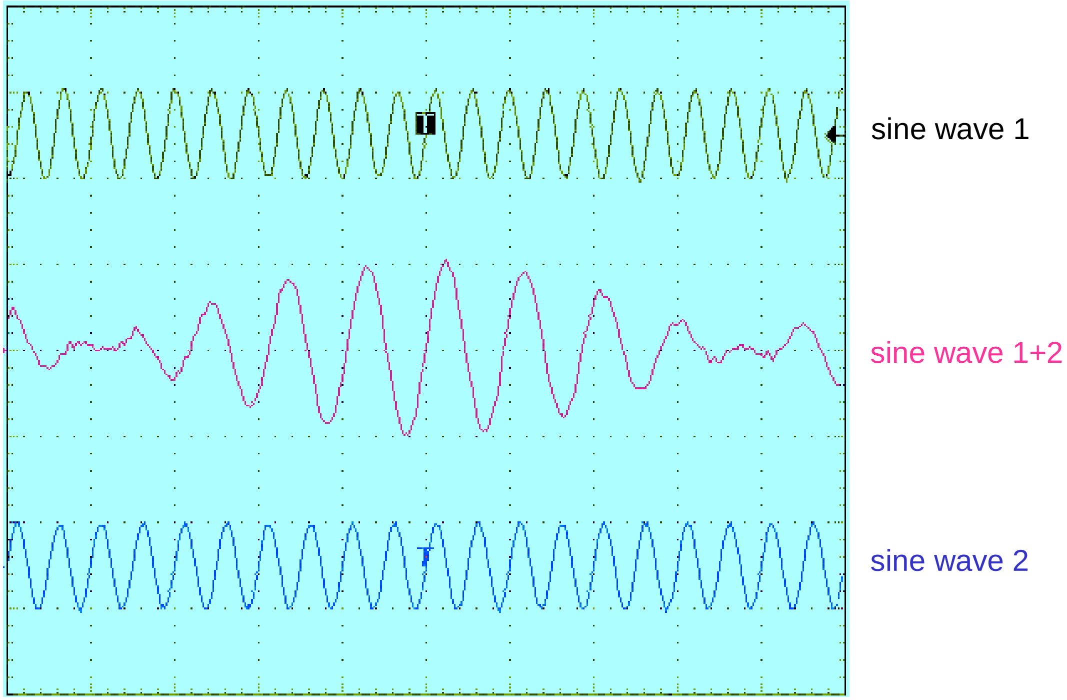

Fig. 3: Superposition of two sine waves to a beat note with double amplitude

In both cases described above, for the superposition of coherent and non-coherent waves, the basic physical laws are the same: the sine waves are added and the sum lies between the two extremes: mutual cancellation to zero and multiplication to n-times the single amplitude. The difference between both cases comes from the probability of the existence of very small and very large sum-amplitudes. For coherent waves the maximum values are generated periodically, at regular intervals. In the case of stochastic, non-coherent waves, the probability that a large number of these interfere constructively (add in amplitude), decreases with increasing number of waves. Eventually this is the reason behind the amplitude distribution in Fig. 2: the maximum value e.g. is formed by the fact, that at this moment an exceptionally large number of waves with a similar phase are added. If this law is applied to thermal noise it means: the immense number of free moving electrons in a conductor results in a real stochastic (random) amplitude distribution of the voltage that can be measured at the ends of a conductor resp. of a resistor. The higher the measured amplitude, the more electrons have moved in the same direction at this moment.

Total field strength of the groundwave

That part of a radiated wave, that propagates parallel to the surface of the earth, is called groundwave. In the frequency range of interest the effective ground conductivity is rather high (in Europe). In a first, rough approximation this may even be assumed as metallic conductivity. A more detailed examination, according to [5], leads to a specific conductivity $\sigma = 0.01$ S/m and a permittivity $\varepsilon_r = 30$. Between the extremes desert = 1 and sea (salt) water = 10 this is rank 7 in [5].

A vertical rod antenna creates in the farfield a vertically polarized field. This means the electric field strength has only a vertical component, normal to the ground. This type of wave is not or almost not influenced by the presence of the ground. The field intensity decays with $1/r^2$ with increasing distance r from the antenna. A horizontally oriented rod antenna creates in the farfield a horizontally polarized field. The electric field strength is parallel to the ground. Because of the ground conductivity these electric fields are shortened at the surface of the earth. Therefore this type of wave is not able to propagate as groundwave. Even with lower ground conductivity the attenuation is so high, that this horizontally polarized wave cannot be detected any more after a short distance.

All waves that are radiated from antennas having a random orientation with respect to ground can be decomposed into a horizontal and a vertical component. The horizontal component is detracted from the groundwave. As for a large number of randomly oriented radiators one half of the radiated power belongs to the vertical polarization and the other half to the horizontal polarization, the combined groundwave, generated by PLC-installations, loses one half of the originally radiated power. This effect produces an attenuation of the far- field by $a_{Pol} = -3$ dB.

If we look at a large area, where PLC-transmitters are active, the maximum value of the combined field strengths will be found in the center of this area. With a total area of 357,000

km^2 Germany is approximated by a circle with equal size and the radius $r_D = 337$ km. If it is furthermore assumed, that those 25,000 PLC-systems, that transmit simultaneously, are evenly distributed on the circumference of N concentric rings (Fig. 4), than the total number M of all PLC-transmitters can be calculated to be:

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

This gives N = 112 rings for a total of M = 25,000 PLC-transmitters arranged in such order. With r_D/N the shortest distance between two adjacent transmitters is $\Delta r = 3.01$ km. There is no PLC-transmitter in the center, where the combined field strength $E_{\Sigma N}(r)$ will be calculated. In a distance of Δr from the center are the most closely spaced 4 PLC-transmitters. In a distance $r = 2 \cdot \Delta r$ are the next $2 \cdot 4 = 8$ PLC-transmitters, in a distance $r = 3 \cdot \Delta r$ the next $3 \cdot 4 = 12$ etc. The number of simultaneously radiating PLC-systems increases proportional to the radial distance r. A ring with radius $r = n \cdot \Delta r$ contains $n \cdot 4$ PLC-transmitter.

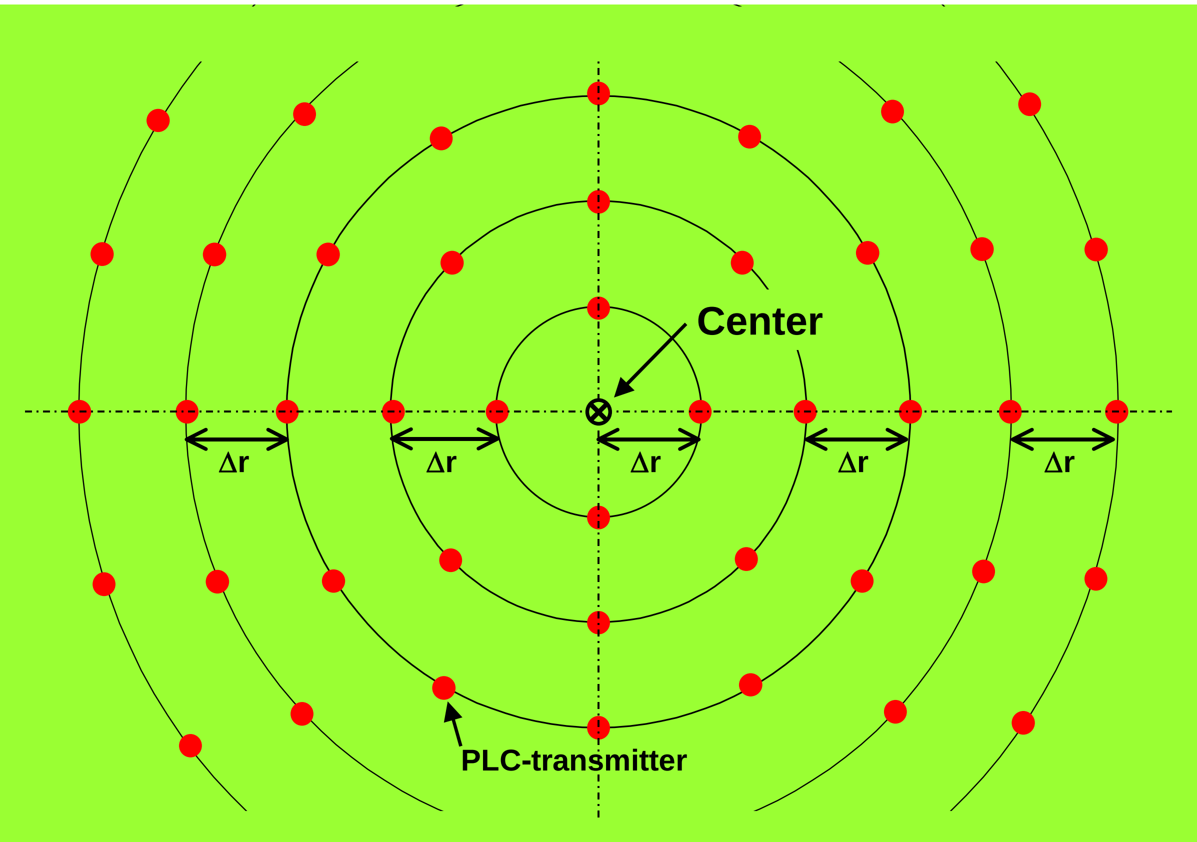

Fig. 4: Circular arrangement of PLC-transmitters in Germany

If E is the RMS-value of the electric field strength, as it is customary in the field of EMC, than the radiation intensity S in a distance r from the transmitter is given by:

$$S(r) = E(r)^2/Z_{0}, \tag{2}$$

with Z_0 = 377 Ω, the wave impedance of free space. The NB 30 defines the maximum tolerable electrical field strength E_0 in a distance r_0 = 3 m. The field strength of an NB-30-compliant PLC-installation in an arbitrary distance r is:

$$E(r) = E_0\, r_0 / r. \tag{3}$$

At this distance the field intensity resp. the magnitude of the Poynting vector is

$$S(r) = (E_0\, r_0 / r)^2/Z_0. \tag{4}$$

The nearest 4 PLC-transmitters deliver in the center a contribution of

$$S_1(r) = 4\, S(r) = 4\, (E_0\, r_0 / \Delta r)^2/Z_0 \tag{5}$$

and the n-th ring with 4·n transmitters in the distance n·Δr delivers a contribution of

$$S_n(r) = 4n\, \{E_0\, r_0 / (n\, \Delta r)\}^2/Z_0 = S_1(r) / n. \tag{6}$$

All radiation intensities have to be attenuated by G_M = -10 dB and by a_{Pol} = -3 dB according to the results derived above. In linear scale this is the factor 1/20. This leads to

$$S_n(r) = S_1(r) / (20n). \tag{7}$$

For the calculation of the total energy density $S_{\Sigma N}(r)$ all single components $S_n(r)$ are added. The summation over all N rings is:

$$S_{\Sigma N}(r) = S_1(r) / 20 \sum_{n=1}^{N} 1/n\,. \tag{8}$$

With Eq. (2) and Eq. (5) and (8) the sum field strength $E_{\Sigma N}(r)$ is:

$$E_{\Sigma N}(r) = \text{sqr}\,\{S_{\Sigma N}(r)\,Z_0\} = 2\,E_0\,r_0\,/\,\Delta r\ \text{sqr}\,(\,1/20\sum_{n=1}^{N} 1/n\,). \qquad (9)$$

In logarithmic scale the attenuation $a_{\Sigma N}(r)$ of the sum field strength $E_{\Sigma N}(r)$ in the center of Germany with respect to the field strength limit E_0 of the NB 30 is:

$$a_{\Sigma N}(r) = 20\log\,(E_{\Sigma N}(r)\,/\,E_0) = 6\text{ dB} + a(r) + a(N) + G_M + a_{pol}, \qquad (10)$$

with a first term of +6 dB, caused by the fact that the first ring contains 4 transmitters {20 log(2) = 6 dB}. Next is the regular propagation attenuation term a(r), produced by the path length Δr,

$$a(r) = 20\log\,(r_0\,/\,\Delta r) \qquad (11)$$

and then the attenuation term a(N), that is caused by the superposition of the fields of N rings in total,

$$a(N) = 20\log\,(\text{sqr}\sum_{n=1}^{N} 1/n\,) = 10\log\sum_{n=1}^{N} 1/n \qquad (12)$$

In this example calculation for a circular area with radius r = 337 km and N = 112 the series Σ 1/n has the sum 5.3. With the assumptions made at the beginning $a_{\Sigma N}(r)$ is -60 dB. The compiled field strength in the center of Germany is 60 dB, resp. by a factor of 1/1,000 below the limit of the NB 30. In the following Table 1 the values of the individual terms of this equation and the value of the sum is given once again in logarithmic scale.

$a_{\Sigma N}(r)$	6 dB	a(r)	a(N)	G_M	a_{pol}
-59.8 dB	6 dB	-60 dB	7.24 dB	-10 dB	-3 dB

Table 1: Attenuation terms for 25,000 PLC-transmitters

Throughout this paper the following nomenclature is used: If the value of the expression a = 20 log (E_1 / E_0) is negative, than the absolute value of a is called attenuation. In case of a large attenuation E_1 is very much smaller than E_0. In the opposite case a is a positive number and called gain. A negative gain, as it is used for G_M, is an attenuation, because antenna gain is a fixed technical expression.

It is apparent, that the largest attenuation term is caused by the distance between the point where the field strength is calculated and the point, where the nearest PLC-transmitter is located. The existence of the other 24,999 PLC-transmitters results in an increase of altogether 13 dB (6 dB because of the 3 others with the same distance and 7.24 dB because of the remaining 24,996 in the other rings). This increase is reversed by the attenuation due to averaging of the antenna gains and by the loss of the horizontal polarization.

Increased PLC-transmitter density

With the above derived Eq. (10) for the sum field strength it is now possible, to calculate the results for any desired scenario. Here only the results for a fivefold PLC-transmitter-density are given. 125,000 simultaneously transmitting PLC-modems means, that each of the 500,000 active users downloads an average of 6.3 MByte/h with an analogue telephone connection and 86.5 MByte/h with an ADSL-connection. In this case the distance between the rings is Δr = 1.35 km and their total number N = 250. The results are given in Table 2:

$a_{\Sigma N}(r)$	6 dB	a(r)	a(N)	G_M	a_{pol}
-52 dB	6 dB	-53 dB	7.85 dB	-10 dB	-3 dB

Table 2: Attenuation terms for 125,000 PLC-transmitters

Even with this increased density of PLC-systems there is no deterioration of broadcast reception detectable. A disturbance signal, that is 52 dB below the limits of the NB 30, is several orders of magnitude below the normal disturbance level found in urban areas. Fig. 5 shows some of these ambient noise levels: the red line gives the maximum values of atmospheric noise [6, 7, 8]. These field strength values are exceeded only during 0.5 % of time. Atmospheric noise is mainly generated by the more than 100 lightning strokes per second worldwide. The pink line gives the internationally accepted values for "man-made radio noise" in urban areas and the green line for rural areas [7, 8, 9]. These values have been found by numerous measurements. But since these measurements were carried out between 1966 and 1971 they are not representative for today's noise levels. Commonly such noise levels are given as average values (RMS values). In order to be comparable to the NB 30 limits, the noise levels shown in Fig. 5 were converted into peak values measured in 9 kHz bandwidth. The conversion into a different measurement bandwidth for noise signals is done by:

$$\text{E in dB}\mu\text{V/m in bandwidth B} = \text{E in dB}\mu\text{V/m in bw. } B_0 + 10 \log (B / B_0). \qquad (13)$$

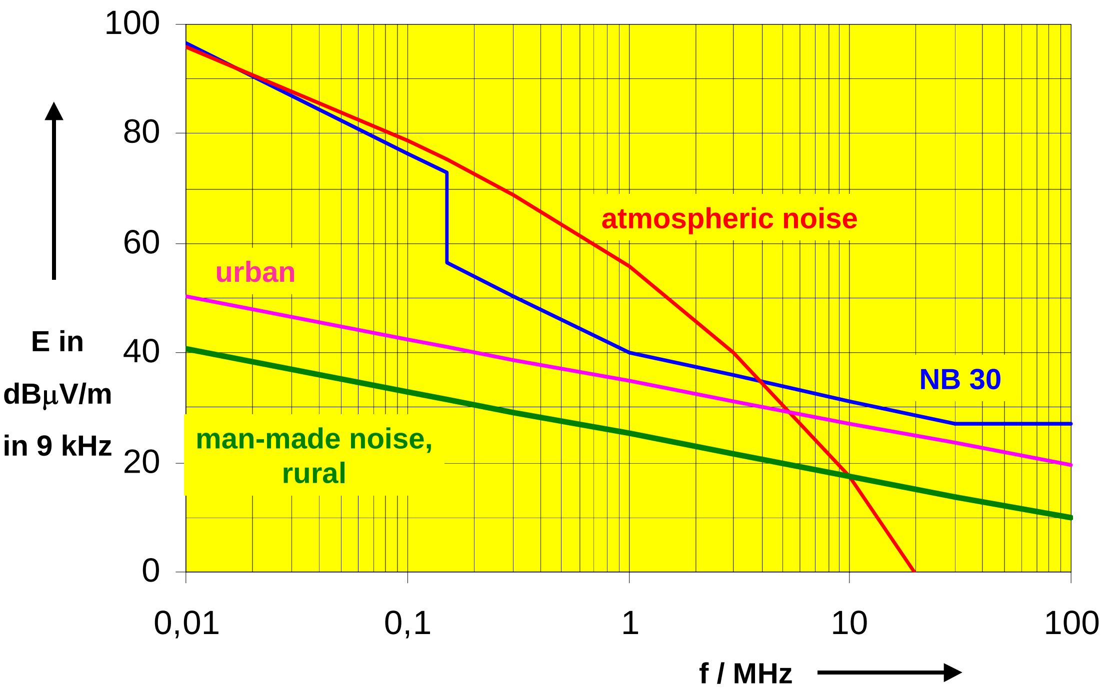

Fig. 5: Comparison of the NB-30-limits with different, environmentally generated disturbance emissions (peak values in 9 kHz bandwidth)

There is a discontinuity in the NB-30-limitline in Fig. 5 due to the fact that the NB 30 defines a measurement bandwidth of 200 Hz below 150 kHz. Because of this the limit increases by 16.5 dB. The conversion of a noise signal from average to peak is done, as mentioned earlier, by adding 14 dB:

$$\text{E in dB}\mu\text{/m (peak)} = \text{E in dB}\mu\text{/m (average)} + 14 \text{ dB}. \qquad (14)$$

For the environmentally caused disturbance signals that are given in Fig. 5 this increase because of the change to a peak detector will in reality be more than 14 dB. Atmospheric noise and man-made-noise have a completely different amplitude distribution compared to white noise. Very high amplitudes occur very often. Peak values up to 40 dB above the average are quite usual. Besides this it is obvious from Fig. 5 and it has also been proven in the past by all people who tried to apply the NB 30, that it is not possible to measure NB-30-limits in urban areas. The ambient noise is noticeably higher than the limit.

Special case: densely populated areas

The assumption of evenly distributed PLC-installations in Germany is an approximation which does not apply in reality. The PLC-density will of course be much higher in conurbations like for instance the Ruhr area and in large cities like Berlin and Munich compared to less densely populated areas. But in this context the following has to be considered: The above calculation was based on a plain surface of the earth without buildings and woods. In high-density areas this assumption cannot be maintained any more. The groundwave has to penetrate very many buildings along its propagation path. Whereas the attenuation due to walls etc. could be neglected for the calculation of the external fields of a single PLC-installation, which of course led to rather high estimates, this is not possible any more if a wave pervades neighboring houses. Building attenuation increases with frequency and is around an average of 3 dB per building at 50 kHz and 8 dB and above per building at 30 MHz. This results, for an average distance between buildings of 30 m, in an additional attenuation for densely populated areas of 100 dB/km at 50 kHz and 267 dB/km at 30 MHz. The groundwave is so heavily attenuated by this effect that the sum field strength in urban areas is distinctly below the calculation results given above, even though the PLC-density is much higher there. The estimated values above are based on two and three story residential houses. City like conditions with multi-story-houses and canyon like roads cause a multiple of these attenuation values. Insofar conurbations are not the source of intensified disturbance emissions but on the contrary they act more as an absorber for electromagnetic waves. Only the outer surfaces produce radiated farfields.

PLC-installations outside Germany

The calculations made above are based on the assumption, that the total number of transmitting PLC-installations is located on a limited space, with an area equivalent to the total area of Germany. This assumption seems to be invalid at first glance, because there will be of course also active Inhome-PLC-LAN's in the surrounding countries like Denmark, Holland, Belgium, Poland etc.

The series in Eq. (8) and (12) is called harmonic series. This is a divergent series, which means that the sum over an infinite number of elements is infinite. If the earth would be a flat disk with infinite diameter, the disturbance fields of all PLC-installations would combine to an infinitely high amplitude of disturbance field strength, as long as the above described simplified propagation model is used. Luckily the earth has a spherical shape with a radius of 7,800 km. As a consequence of this, the groundwave, whose direction of propagation is principally along a straight line, loses contact to the curved surface of the earth and disappears in the universe. A ray of light, being tangential to the surface of the earth in the center of the area under investigation, is already 7.3 km above ground after a path length of 337 km. In the frequency range of interest the guidance of the groundwave by the surface of the earth is the more pronounced, the higher the ground conductivity and the lower the frequency. According to this, the attenuation of the fields of the groundwave that can be measured along the earth’s surface increases after a certain distance from the transmitter not any more with 1/r but with an increasingly higher rate. The end of the region with a decay with 1/r is frequency dependent, due to diffraction effects. According to [10] the propagation law changes in central Europe for 500 kHz approximately at a distance of 50 km from the transmitter and for 10 MHz already below 1 km. Taking this into account the term a(N) has to be revised once again. One important consequence of the groundwave losing contact to the surface is that disturbance emissions from sources outside Germany do not increase the local noise level. Furthermore because this increase of attenuation beyond the 1/r-law happens already after a very short distance of travel and because the initial calculation was based on a total radius of 337 km, the estimation can be refined some more.

Beyond the first propagation range with the law 1/r, the propagation in the succeeding annulus can be mathematically described by $1/r^{3/2}$. After this it changes to $1/r^2$, and so on. If, for the sake of simplicity, the propagation law is fixed to be $1/r^{3/2}$ for all distances, which is a tolerable assumption for e.g. 10 MHz and distances up to 100 km, Eq. (3) changes to

$$E(r) = E_0 \, (r_0 / r)^{3/2}, \tag{15}$$

and the sum field strength $E_{\Sigma N}(r)$ results to:

$$E_{\Sigma N}(r) = 2\, E_0\, (r_0 / \Delta r)^{3/2}\ \mathrm{sqr}(\,1/20)\sqrt{\sum_{n=1}^{N} 1/n^2}\ ). \qquad (16)$$

This sum over $1/n^2$ is convergent and has the sum value $\pi^2/6 = 1.64$ resp. $\pi/\mathrm{sqr}(6) = 1.28$ for the square root of the series. These relations are graphically depicted in Fig. 6. The red line shows the increase of the square root of the harmonic series sqr(Σ1/n) with increasing N. The green line shows the increase of the value of the sum sqr($\Sigma 1/n^2$). A mixture of both characteristics is found in real life. The sum field strength increases at the beginning with 1/n and afterwards changes to $1/n^2$. This is approximated by the blue line. The consequence of this for the groundwave is, that a large number of PLC-transmitters respectively an earth totally covered by PLC-transmitters, leads to a combined field strength that is by a factor of 2 higher than the field strength produced by the 4 nearest PLC-transmitters.

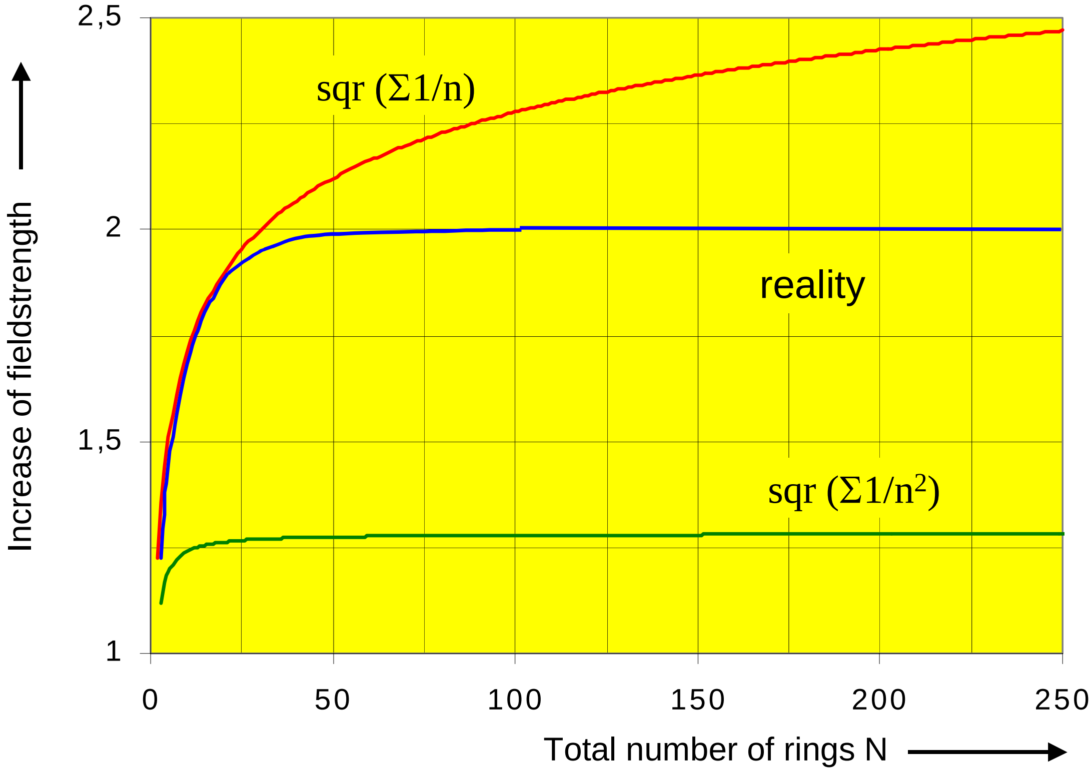

Fig. 6: Increase of fieldstrength as a function of the area covered by PLC-installations, expressed by the total number of rings N

Thus at 10 MHz a more exact value of the sum field strength is

$$a_{\Sigma N}(r) = 20 \log (E_{\Sigma N}(r) / E_0) = 6 \text{ dB} + a(r) + a(N) + G_M + a_{pol}, \qquad (17)$$

where a(N) = 6 dB, this means independent from N for large N (as shown in Fig. 6), and

$$a(r) = 20 \log (r_0 / \Delta r)^{3/2} = 30 \log (r_0 / \Delta r). \qquad (18)$$

$a_{\Sigma N}(r)$	6 dB	a(r)	a(N)	G_M	a_{pol}
-91 dB	6 dB	-90 dB	6 dB	-10 dB	-3 dB

Table 3: Attenuation terms for 25,000 PLC-transmitter, if the increase in attenuation of the groundwave with increasing distance is included in the calculation.

Total field strength of the spacewave

As the airplanes in the sky above Germany are also using the RF-band for broadcasting purposes (e.g. voice services in several channels between 2.85 MHz and 23.35 MHz), it is necessary to examine the effects of the summation of disturbance emissions there. The equations used for this remain the same as those used in the chapter about the sum field strength of the groundwave. Here as well the maximum value is found according to Fig. 4 above the center of Germany. Even though the spacewave contains the horizontal polarization as well as the vertical polarization, the term a_{pol} nevertheless has to be kept in Table 4. The reason for this is, that the receiving antenna onboard the airplane will only be able to extract one type of polarization from the incident wave.

With the geometry as in Fig. 7 the resulting sum field strength can be derived:

$$E_{\Sigma N}(r) = 2 E_0 (r_0 / \Delta r) \operatorname{sqr}\left(\sum_{n=1}^{N} \frac{1}{n + (h / \Delta r)^2 / n}\right) / 20. \qquad (19)$$

This equation is converted and given in logarithmic scale as an attenuation with respect to the limit E_0 of the NB 30:

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

with only one change compared to Eq. (10), which is valid for the groundwave, namely

$$a(N) = 10 \log \sum_{n=1}^{N} \frac{1}{n + (h/\Delta r)^2 / n} \,. \tag{21}$$

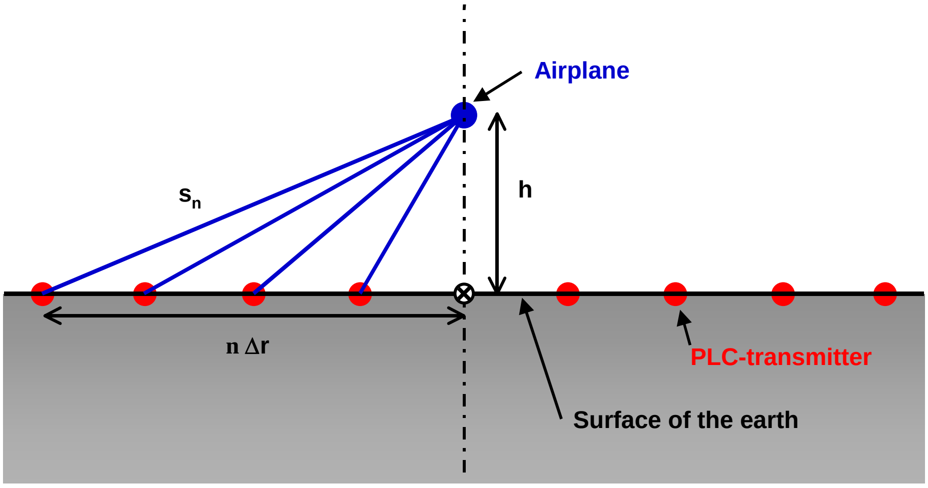

Fig. 7: Airplane above the center of Germany

The sum field strength decreases slowly with increasing height h, because the distance $s_n = \text{sqr}[(n\ \Delta r)^2 + h^2]$ between the PLC-transmitters and the location of the airplane, where the field strength is calculated, increases with increasing h. Within the simplified model which is used here, where the fact, that the groundwave attenuation increases with distance faster than with 1/r is neglected, the maximum value of the field strength is found at the surface of the earth at h = 0 (In reality the field strength at h = 0 is equal to the value in Table 3 and approaches with increasing height the value in Table 4).

As the path length s to the nearest PLC-transmitters, that deliver the largest contribution to the total field strength, becomes longer with increasing height, the sum field strength decreases slowly in the beginning, with h = 0 as starting point. The path length for the more distant transmitters remains almost unchanged. Therefore the decrease of the sum field strength is rather small. The limiting effect, which is true in case of the groundwave, where the PLC-transmitters with large distances do not contribute any more because there is no line-of-sight-connection with the receiving antenna due to the curvature of the earth, does not exist in case of the spacewave. This additional effect with the opposite direction leads to the fact that the decrease of the field strength becomes smaller and smaller with increasing height. The area of the earth, which can be seen from the airplane, grows with increasing altitude. But because of the spherical shape of the earth, this effect has a theoretical limit. In practice all this can be neglected. On the one side there is no air traffic with RF-broadcasting connections in altitudes beyond 10 to 20 km and on the other side all path lengths are so long at these altitudes, that the resulting field strength values are well below the ambient noise level and can be neglected. Eq. (20) gives for instance for the example used in the beginning with N = 112 and h = Δr = 3 km an attenuation of the total field strength with respect to the limit of the NB 30 of 60.3 dB. The field strength at an altitude of 3 km is 0.6 dB smaller than the field strength on the ground. Table 4 contains the individual attenuation contributions.

$a_{\Sigma N}(r)$	6 dB	a(r)	a(N)	G_M	a_{pol}
-60.3 dB	6 dB	-60 dB	6.66 dB	-10 dB	-3 dB

Table 4: Attenuation terms of the spacewave for 25,000 PLC-transmitters

Field strength of the skywave after reflection at the ionosphere

The short-wave band from 1.6 to 30 MHz is the only frequency range, where worldwide radio connections are possible. The reason for this are single (or multiple) reflexions of these radio waves at the ionosphere (and the ground). This is a part of our atmosphere, consisting of several layers in altitudes from 60 to 1,000 km, where the ultraviolet part and other spectral parts of the sunlight with even shorter wavelengths, generate a significant amount of ions (electrically charged atoms and molecules). These ionized layers have the property to reflect electromagnetic waves of a certain frequency band, if their angle of incidence is within a certain range. Higher frequencies and those waves with the wrong elevation angle can penetrate the ionosphere and leave the earth.

The transmission properties for those radio connections that utilize the skywave (the ionospheric reflection) are strongly dependent on the time of the day, the time of the year, the sun spot activity, the electron density, the magnetic field of the earth and the location of the transmitter and the receiver. For the disturbance emissions, that are discussed here, it is sufficient to investigate the frequency range between 2 and 14 MHz, with possible maxima from 4 to 10 MHz. Worldwide radio connections via ionospheric reflection are very cheap (no satellites needed) and easily installed. But these connections have greatly reduced reliability and a very low transmission quality. The field strength levels at the receiving antenna are very low, according to the large distances that have to be bridged. Therefore short wave radio connections rely on low disturbance levels at the location of the receiver, in order to be able to successfully demodulate the incoming signal.

Several software packages are available which are specialized on the calculation of long distance radio connections with a single or several successive reflections at the ionosphere (hops). Actually these software packages do not deliver a fixed link calculation but only a prediction for a link with a certain probability. With the help of these the worst case was found for the disturbance investigation under consideration here. Fig. 8 shows a greatly simplified example for 10 MHz. A point source as isotropic transmitter radiates waves into all directions of the upper hemisphere. A specific portion of these is reflected back to earth from the ionosphere. Thus the transmitter reaches an annulus-shaped region with distances from 700 km up to 1,300 km from the transmitter (Fig. 9).

To calculate the field strength at the location of the receiver, the path length $s = s_1 + s_2$, the solid angle of the reflected radiation and the ionospheric loss a_{io} must be known. Of course the ionosphere is not a perfect reflector like a conductive surface but a semitransparent reflector. The ionospheric loss a_{io} is a minimum of 6 dB (once a year for one hour) and an average of 17 to 20 dB. To estimate the field strength $E_E(r)$ at the ground after a single reflection at the ionosphere the following equation in logarithmic scale is used:

$$a_{SW}(r) = 20 \log (E_E(r) / E_0) = a_{RW} + a(r) + a_{io}, \qquad (22)$$

with the propagation attenuation $a(r) = 20 \log (r_0 / s)$. If the solid angle of the reflected wave is assumed to be 1/3 ($a_{SA} = 10 \log (1/3) = -4.8$ dB), than the attenuation for the dashed ray in Fig. 8 (s = 1,221 km) has the following value (For the outer rays, that are also included in Fig. 8, the value for a(r) is in one case 2 dB lower and in the other case 2 dB higher.):

$a_{SW}(r)$	a_{SA}	$a(r)$	a_{io}
-123 dB	-4.8 dB	-112.2 dB	-6 dB

Table 5: Attenuation terms for ionospheric reflection and a single PLC-transmitter

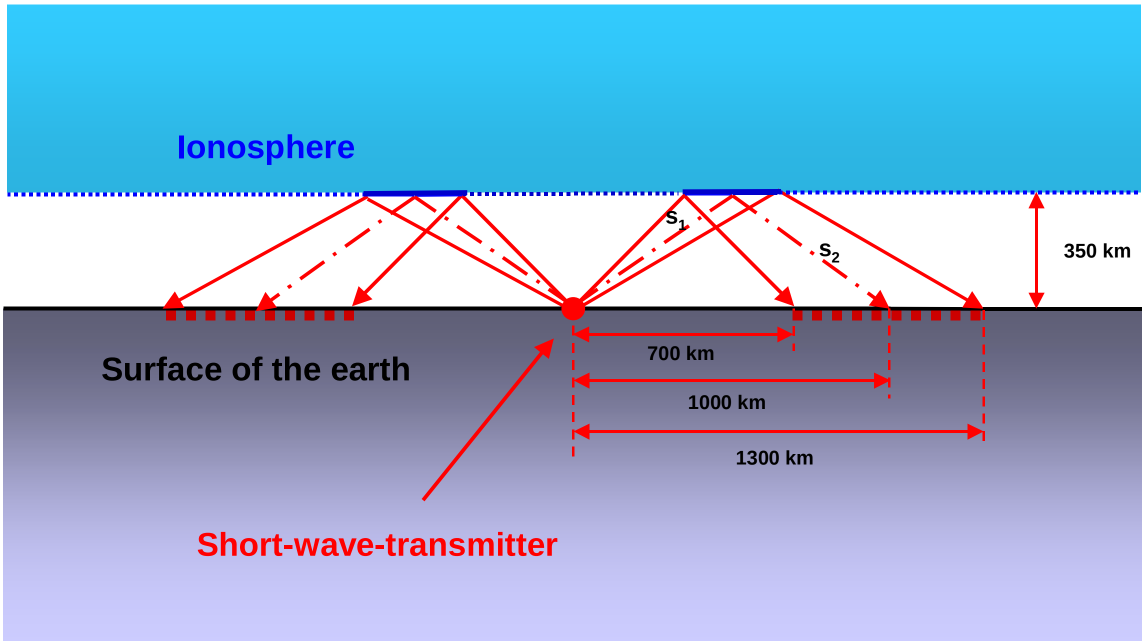

Fig. 8: Propagation of the sky wave at 10 MHz, point source at the center of Germany

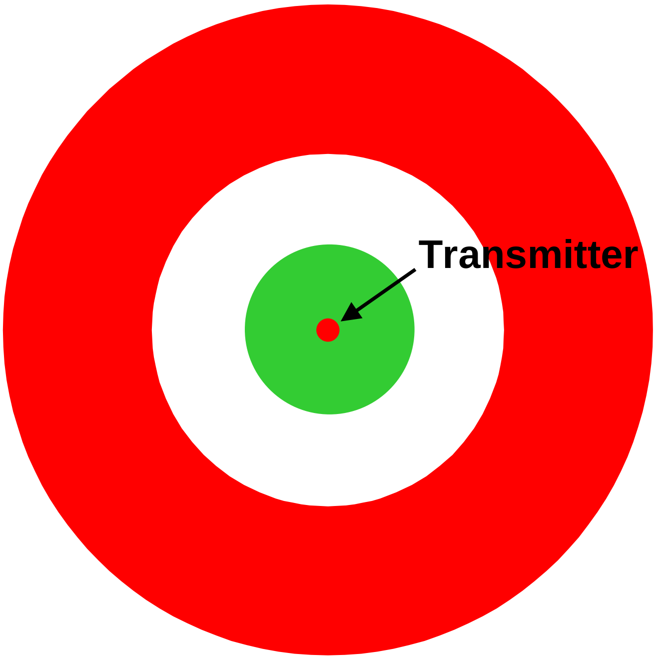

Fig. 9: Coverage pattern of the skywave (red annulus, illuminated area) in case of a single transmitter in the center of Germany (green circle), f = 10MHz (view from above at Fig. 8)

For the example given, with a frequency f = 10 MHz, the field strength at the location of the receiver in a distance of 1,000 km is about 123 dB below the limit of the NB 30.

Total field strength of the skywave

For an estimation of the sum field strength after a single reflection at the ionosphere, it has to be taken into account that the large number of PC-transmitters is spread out evenly over a large area. As sketched in Fig. 10, the areas, that the PLC-transmitters at the edge of Germany are feeding, do not overlap, referring to the cross-section shown. Compared to Fig. 9, where the area covered by a single transmitter (point source) is shown, this area is approximately doubled, if the source is changed to a circular area with evenly spread transmitters. The illuminated area is an annulus with an inner diameter of 680 km and an outer diameter of 2,000 km (Fig. 11).

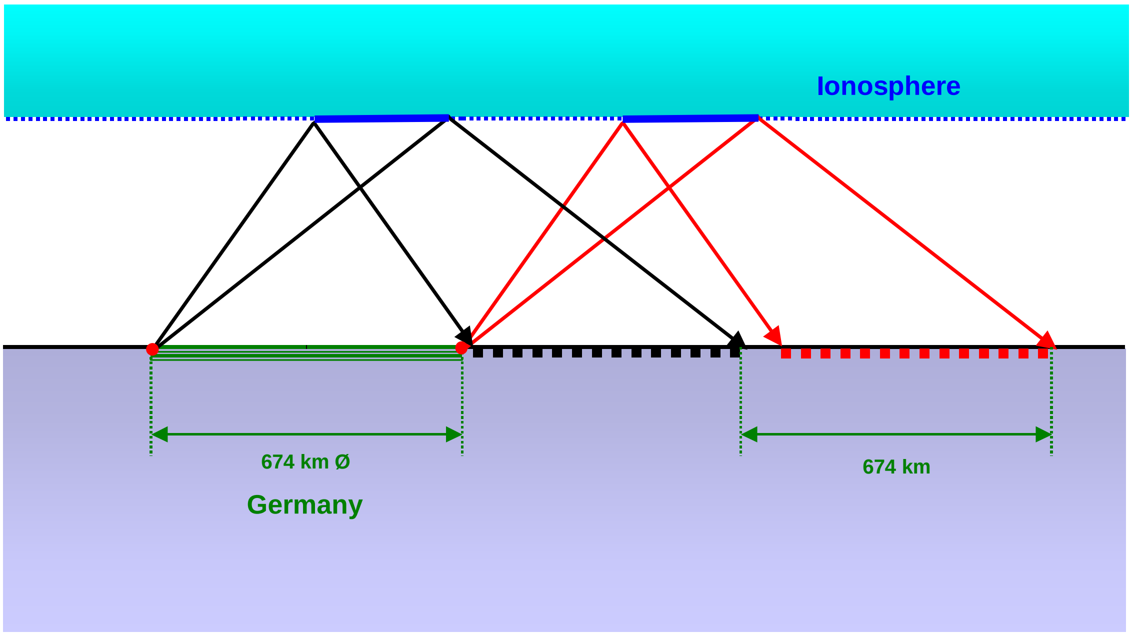

Fig. 10: The PLC-transmitters at the fringe of Germany have coverage areas, that do not overlap, partly

The total number M of all simultaneously active PLC-transmitters is accounted for by a multiplication of the energy density with M. Therefore the field strength must be multiplied by sqr(M). In logarithmic scale this results in an additional term a(M) = 10 log (M). With this the total field strength after a single reflection at the ionosphere is:

$$a_{\Sigma MSW}(r) = 20 \log (E_{E\Sigma io}(r) / E_0) = a_{SA} + a(r) + a_{io} + a(M) + G_M, \quad (23)$$

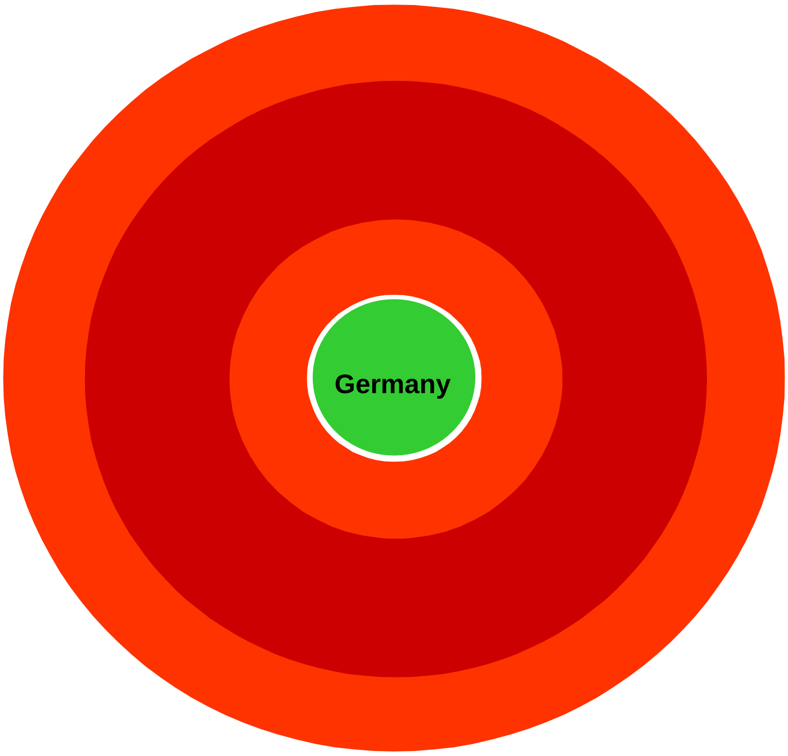

Fig. 11: Increase of the coverage area (red) due to the spread of the PLC-transmitters over total Germany (green)

The values of the individual attenuation terms for M = 25,000 PLC-transmitters are given in Table 6.

$a_{\Sigma MSW}$ (r)	a_{SA}	a(r)	a_{io}	a(M)	G_M
-89 dB	-4.8 dB	-112.2 dB	-6 dB	44 dB	-10 dB

Table 6: Attenuation terms for the skywave with 25,000 PLC-transmitters

The maximum value of the field strength after ionospheric reflection is 89 dB below the limit of the NB 30.

The corresponding values for M = 125,000 PLC-transmitters are given in Table 7.

$a_{\Sigma MSW}(r)$	a_{RW}	a(r)	a_{io}	a(M)	G_M
-82 dB	-4.8 dB	-112.2 dB	-6 dB	51 dB	-10 dB

Table 7: Attenuation terms for the skywave with 125,000 PLC-transmitters

The maximum value of the field strength after ionospheric reflection is 82 dB below the limit of the NB 30. The attenuation values above, that were obtained with a very simple model for the propagation of waves and their reflection at the ionosphere (this means making use of very conservative assumptions), are so extraordinarily high, that there is no need to refine the model in order to obtain more precise results.

Summary of results

The above derived numerical results are based on the one hand on fixed physical interrelations (e.g. the propagation attenuation of a radiated wave) and on the other hand on specific predictions (e.g. the number of simultaneously active PLC-transmitters) and assumptions (e.g. the value of the ionospheric loss). The task was to estimate the maximum possible total disturbance field strength. Therefore the predictions and assumptions used in this text were strictly chosen in such a way, that the resulting field strength would be as high as possible (conservative assumptions). Nevertheless the results derived in this way are so low, that there is no necessity to refine the estimation process.

The above calculated values $a_\Sigma(r)$ for the attenuation of the total field strength as compared with the limit of the NB 30 are 60 dB, 52 dB, 91 dB, 60dB, 89 dB and 82 dB. These attenuation values are so large, that the conclusion can be drawn, that the influence of the multitude of PLC-transmitters may be completely neglected. Supposed there is a PLC-transmitter at the location, where $a_\Sigma(r)$ was calculated, and this transmitter produces the field strength E_0 of the NB 30. Than there will be an increase of the local field strength of 3 dB, if $a_\Sigma(r)$ = 0 dB, and of 1 dB, if $a_\Sigma(r)$ = 6 dB. All attenuation values larger than 6 dB do not lead to an increase of the existing field strength which can be verified in whatsoever way.

For RF-engineers it is well known, for instance from the worldwide frequency reuse at base stations for cellular phones, that there are no cumulative effects in conjunction with radiated electromagnetic waves. Regardless of this, the NB 30 was created with the anxiety, that the large number of possible installations of modern telecommunication systems using wires (ADSL, VDSL, PLC, Ethernet und CATV) would generate a threat for our society with a totally new EMC-scenario (cumulative effects!), which could not be compared with anything else known until now. From the previous chapters it can be concluded that these fears are unsubstantial. Nevertheless a directive was put into effect by German authorities, either because of lack of technical background or in bad faith, which massively overshoots the former target, the protection of broadcasting services. The other objective of the NB 30, which has at least been announced in the past, to encourage newly emerging, innovative technologies, has been reversed into the opposite.

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