# Evaluation of Different Frequency Bands Regarding their Qualification for Inhouse Powerline Communication

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## Abstract

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The frequency bands below AM-radio and above AM-radio are compared for PLC-usage. Besides a slightly higher interference level and a much smaller overall bandwidth the lower frequency range has only positive features: near fields are lower, far fields are extremely low, modem-costs are lower, transmission properties of the powerline-channel are much better and the chances to coexist with existing broadcasting services are given. All these positive aspects can be utilized by Inhouse-PLC-systems, as they can deliver sufficient performance for the tasks to be solved today and in the near future with medium speed bit rates in the order of 1.5 Mbit/s. The currently ongoing regulatory actions regarding PLC-systems are critically discussed.

## 1. Introduction

When we look at PLC-systems, using the low-voltage-energy-distribution grid for modern digital data transmission, we have to distinguish between two totally different applications: Inhouse-PLC-systems, that are distributing data inside private houses or apartments [1], and Access- or Last-Mile-PLC-systems, that are trying to compete with telecom companies in distributing information (voice and/or data) from the medium voltage transformer station to the connected private households. The high installation costs of an access-system require, that a high number of households that are connected to the same transformer station, are customers of this service. As the powerline is a shared medium, the data rate that a single user gets, is the data rate of the access system divided by the number of users, being active at the same time. Therefore we can conclude, if an Inhouse-PLC-system is successful with a data rate DR, than an access-PLC-system must guarantee a data rate in excess of 10 x DR, in order to be accepted on the market.

To estimate this data rate DR, we can look at currently available fast data services for private users, like ISDN, DSL, TV-cable-modems and wireless solutions. This leads to the result that a data rate between 750 kbit/s and 1.3 Mbit/s is necessary for an Inhouse-PLC-network and will be accepted by the customers.

## 2. Comparison of the frequency range below 525 kHz with the range above 1.6 MHz

When we consider the frequency range from 0 to 30 MHz, where PLC-systems today are technically feasible, we can distinguish four different bands (Fig. 1). The lower frequencies, below approximately 50 kHz, are dominated by man made noise and interference and therefore not very useful for powerline communication. Between 525 kHz and 1.6 MHz the public AM-radio-broadcasting services are located, worldwide. Only the band limits vary a little bit in different parts of the world. We will discuss neither the future necessity of these services in the internet age, nor question their widespread usage compared to the popular FM-radio-bands, but will accept this as a given fact for today and the near future.

According to this there are two frequency bands left for PLC-usage: The band from 50 kHz up to 525 kHz, for Low-Frequency-PLC-systems (LF-PLC) and the band from 1.6 MHz to 30 MHz for High-Frequency-PLC-systems (HF-PLC).

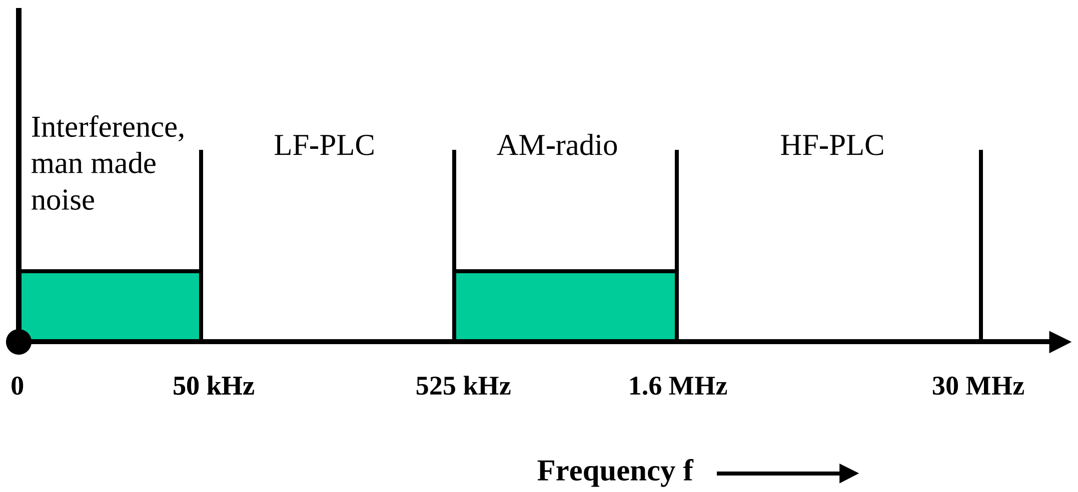


**Fig. 1: Frequency band from 0 to 30 MHz**

## 2.1 Electromagnetic fields of the guided wave

The electromagnetic fields exited by a PLC-system can be divided into two different types, the field of the guided wave and the radiated field [2]. Both fields are exited by the even mode current (Fig. 2). The fields resulting from the odd mode currents are several orders of magnitude smaller and can therefore always be neglected.

Figure 2 illustrates the origin of the even mode currents. Those currents, that leave the three-wire-line with phase, neutral and protective earth, flow through stray capacitive couplings to the surrounding earth. At the Watt-Hour-Meter, where neutral and protective earth are connected to ground, the even mode currents enter the original circuit again. In this way current loops with quite large diameters are introduced.

Because the origin of the even mode currents is the capacitive coupling, their amplitude is growing proportional to frequency.

$$I_{even} \sim f \qquad (1)$$

Consequently the fields of the guided wave are also growing proportional to frequency.

$$E_{guided\ wave} \sim f \qquad (2)$$

Measurements have shown, that the even mode suppression $a_{even}$ for typical Inhouse powerlines reaches 0 dB in a frequency range between 5 and 10 MHz [4]. Therefore $a_{even}$ can be roughly estimated for lower frequencies by

$$a_{even} \approx 20 \log (f / f_g) \qquad \text{with } f_g = 10 \text{ MHz and } f < f_g. \qquad (3)$$

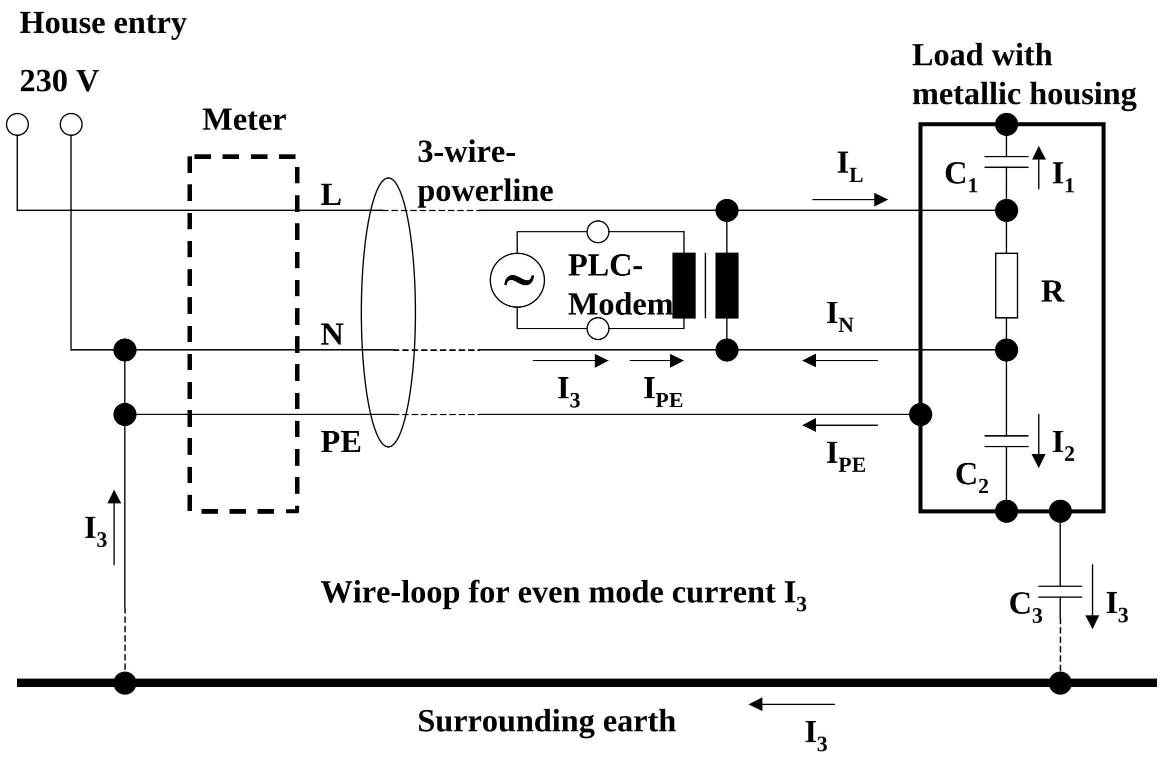


**Fig. 2: PLC-installation with even mode current $I_3$**

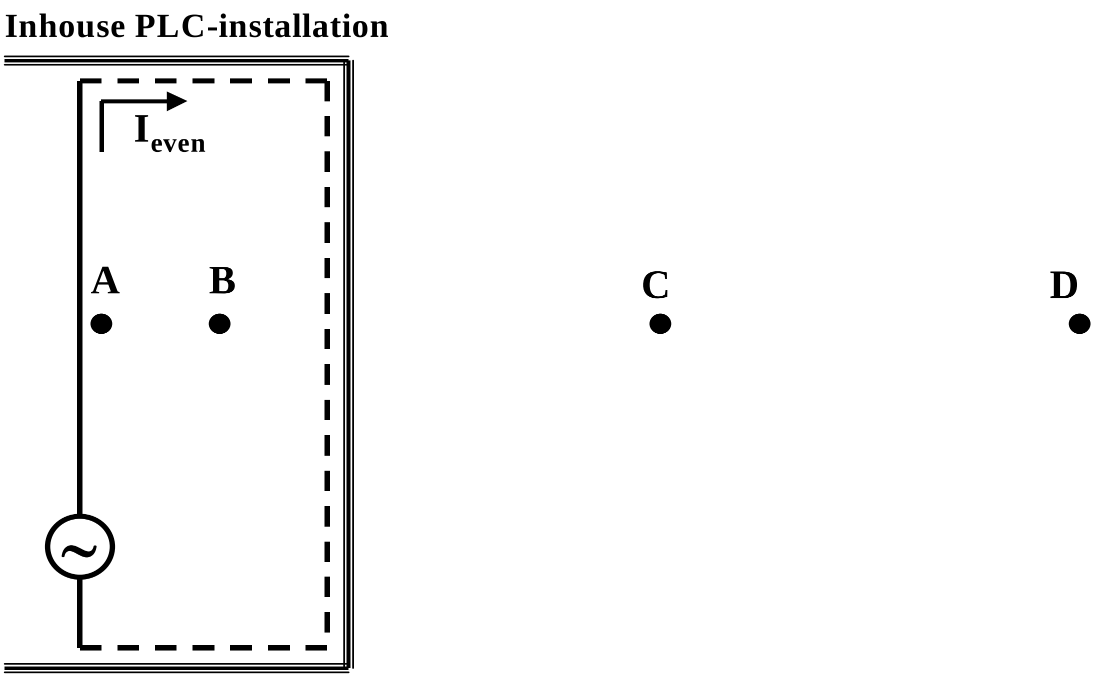


**Fig. 3: Locations with different type of field decay**

In Fig. 3 an Inhouse PLC-system feeding the powerline and the current loop of the even mode current is drafted. With respect to the distance from the wire, respectively the loop, four areas can be defined, where the electromagnetic field produced by the guided wave obeys differing laws.

**Point A:** In close vicinity to the wire (lateral distance e.g. 1 m) the magnetic field of the even mode current in this wire is the major component. This field decays with 1/r (20 dB per decade).

**Point B:** In the middle of the room all current carrying wires add to the resulting field. There is little or no systematic variation with respect to the room coordinates. Fields at low frequencies will show little variation. At high frequencies, above some MHz, uncorrelated maxima and minima, being a quarter of a wavelength apart, will exist.

**Point C:** Outside the house, e.g. 10 m away, the whole current loop has to be considered. The magnetic field of a loop decays in this intermediate range with $1/r^{x}$, where x changes with distance from 1 (very close to the loop) to 3 (far away from the loop).

**Point D:** Outside the house, e.g. 100 m or more away, the far field of the loop is reached. In the farfield, where the distance is large compared to the loop diameter, the magnetic field of a loop decays with $1/r^{3}$ (60 dB per decade). This decay is so strong, that the field of a guided wave can always be neglected beyond a certain distance from the guiding structure.

There is no relation between the electric fieldstrength and the magnetic fieldstrength of a guided wave. It depends on the termination of the line. Fig. 4 shows a diagram with the calculated field of a model-PLC-system. This simplified model is based on a straight wire, 10 m long, with an odd mode current of 1 mA. The diagram starts in the near field with a decay of 1/r, has the intermediate range from 10 to 30 meters and ends with the far field decay following $1/r^{3}$. The field strength at 10 MHz differs from that at 100 kHz by a constant 40 dB, because the even mode current at 100 kHz is 40 dB lower (1).

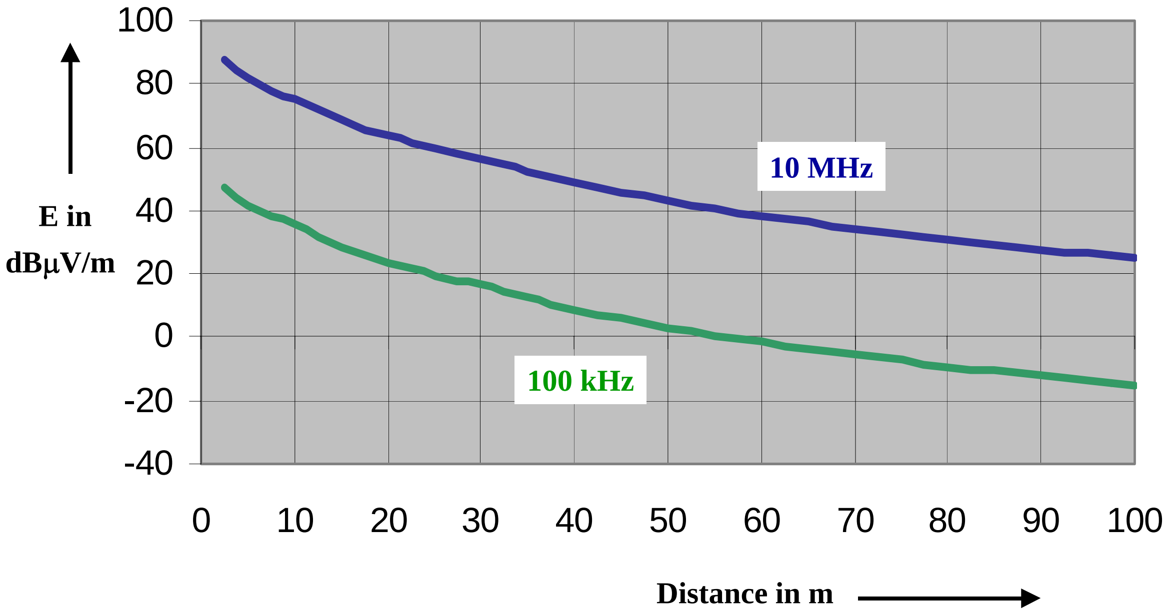


**Fig. 4: Fields of the guided wave**

## 2.2 Radiated electromagnetic fields

The fields belonging to the guided wave are transverse electromagnetic fields with a Poynting vector (direction of energy transport) parallel to the guiding wire structure. Such guided fields or quasistatic fields support energy transport only in direction of the wire, there is no radiation. Nevertheless there is a second type of field to be considered in conjunction with a wire that is fed by an even mode current: The radiated field. This field has a Poynting vector along radials of the emitting structure, which is therefore called "antenna". In contrast to the guided wave field that is bound to the conductors, the energy of this field leaves the emitting structure and radiates into the surrounding space. In the far field the quotient of the electric fieldstrength and the magnetic fieldstrength equals 377 Ω, the characteristic impedance of free space.

The radiated field of a model-Inhouse-PLC-system is calculated according to [3] and [4], based on the model of a straight wire antenna, 10 m long, with constant current distribution. Fig. 5 shows the results for 100 kHz and for 10 MHz. The odd mode current is again 1 mA. The radiated field has a radial decay with 1/r, independent of frequency. But because an antenna with a wire length being short compared to the wavelength, has a radiated field, that is increasing proportional with frequency, the fieldstrength at 10 MHz is 40 dB higher than that at 100 kHz. The even mode current, that is also increasing proportional with frequency, adds another 40 dB to this frequency dependence.

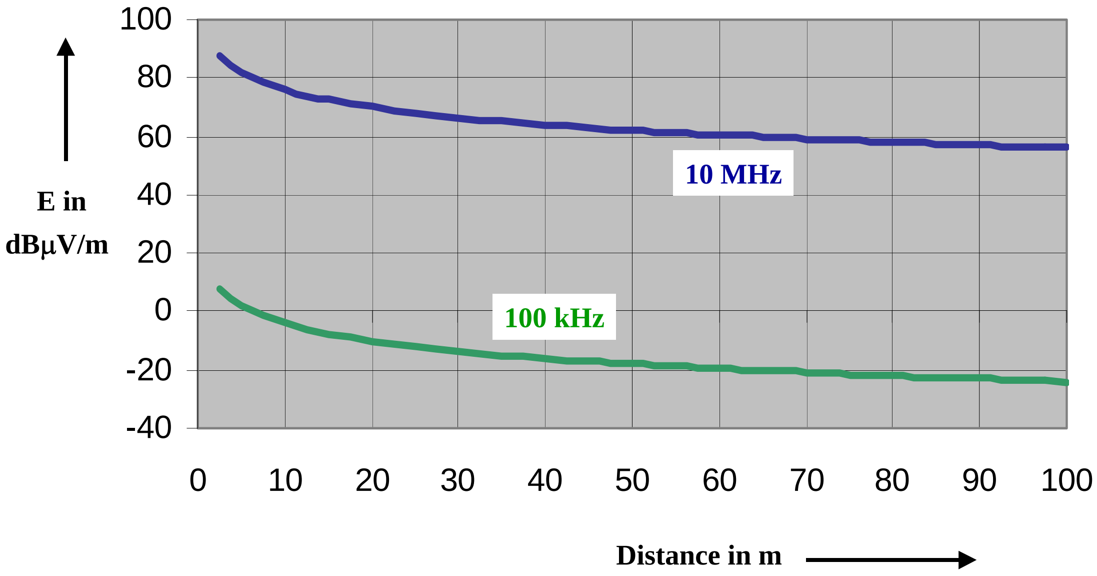


**Fig. 5: Fields of the radiated wave**

Comparing Fig. 4 and Fig. 5 leads to the following conclusions:

- At locations which are very close to the powerline (e.g. radial distance 10 m or less) the field of the guided wave is dominant. The fieldstrength at 10 MHz is 40 dB higher than at 100 kHz.
- With increasing distance from the powerline the field of the radiated wave becomes dominant, because the guided wave components decay very fast. The fieldstrength in a distance of 100 m at 10 MHz is 80 dB higher than at 100 kHz.

According to the radiation properties it is appropriate to divide the frequency range from 1.6 to 30 MHz into two different bands [4]. Starting from 1.6 MHz the even mode current increases and the radiation efficiency increases, each with 20 dB per decade. When a frequency limit of approximately 10 MHz is reached, the even mode suppression has reached 0 dB and the radiation efficiency has reached 100 %. Therefore the maximum values of the radiated fields are almost constant and remain at their optimum level in the frequency band above 10 MHz. Consequently this frequency range is not useful for Inhouse-PLC-applications. The PLC-systems of neighboring apartments will be electromagnetically coupled and disturb each other. There is no possibility to reduce this coupling. Also the installation of blocking filters at the house entrance point, which are very effective at lower frequencies, will have no effect.

## 2.3 Propagation effects

The short wave radio band, from 1.6 to 30 MHz, is the only frequency band that facilitates world wide radio connections. This is possible, because for frequencies in this range, the ionosphere, a partly conducting layer of the atmosphere, reflects electromagnetic waves back to the earth (Fig. 6). As the different layers of the ionosphere are between 60 and 300 km above the ground, distances between 500 km and 1.500 km are bridged with a single hop. This most welcome feature of the short wave radio band makes it very attractive for a lot of broadcasting services: military, police, secret service, embassies, airlines, maritime, public radio, radio amateurs etc. Because of the large distances, these services receive very weak signals. They can only be successfully demodulated, if the noise level in this frequency band is very low. Therefore the coexistence between radio services and PLC is an important issue.

Besides the skywave we have to look at the propagation characteristics of the groundwave. In the preceding chapters we assumed an ideal propagation medium, where radiated electromagnetic fields are attenuated with distance via the relationship 1/r. In reality we have to take into consideration, that the vertical components suffer additional attenuation because of ground losses. The horizontal components are attenuated very fast, because of ground conductivity, and can be neglected. For ground conditions like in central Europe and distances below 100 km the CCIR propagation tables [5] show that for the long wave frequencies the calculation of fields with 1/r is still correct. For the short wave frequencies, additional attenuation has to be considered. At 10 MHz this can be roughly approximated with $1/r^{3/2}$ up to distances of 1 km and with $1/r^{2}$ above 1 km.

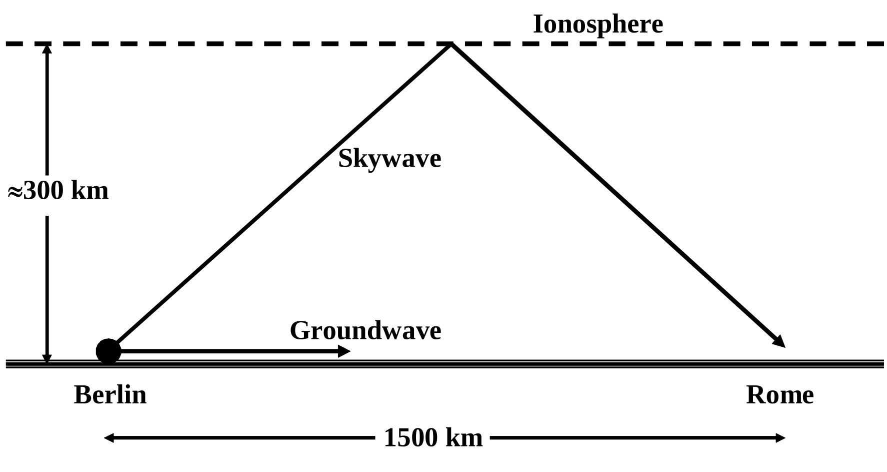


**Fig. 6: Skywave and groundwave**

Taking this into account, the radiated field in a distance of e.g. 1 km from a PLC-installation is 60 dB higher if the PLC-system uses carrier frequencies around 10 MHz instead of 100 kHz. This significant difference between the radiation properties of LF-PLC and HF-PLC may be illustrated by the following comparison: If we look at an urban area with many operating PLC-installations from above and the radiated electromagnetic fields were visible like light beams at night, than LF-PLC-systems would result in a multitude of isolated single light sources in an otherwise dark scenery. On the contrary the high radiation of HF-PLC-systems will accumulate and result in a completely floodlighted, bright area with only a few partly illuminated or dark spots.

### 2.4 Channel characteristics

The average noise level in the lower frequency band is typically decreasing with increasing frequency. Between 50 and 150 kHz by approximately 15 dB and between 150 and 500 kHz by another 10 dB. The noise floor in the MHz-frequency band is considered to be the same for all frequencies and something like 5 dB lower than at 500 kHz. Nevertheless does impulse and switching noise and the disturbance level of various interferers not obey the frequency dependence of the average noise level. Maximum possible interference levels are almost the same for all frequency bands.

The impedance levels in the powerline network will vary rapidly with frequency and time. The minimum values will be down to 1 Ω below 250 kHz and down to 10 Ω in the MHz range.

The transmission characteristics below 500 kHz do not experience negative influences by multipath propagation, reflections and signal delay time. As the wavelength of the signal is large compared to the length of the Inhouse powerlines, these effects may be neglected. These phenomena are totally different in the MHz region. Looking at the time domain, the impulse response is not ideal and varies depending on the time of day and the location in the powerline network. The signal is heavily degraded by reflections and resulting multipath effects. Selective amplitude fading and time delay distortion occurs.

Looking at the frequency domain, the amplitude response in the MHz region is characterized by periodical attenuation maxima, depending on the distance of the next reflection point. Also the amplitude distribution along the powerline will show these periodical variations. As a result of the radiation, a decrease of the signal level with increasing distance from the feeding point will occur.

### 2.5 Component costs

The component costs for an HF-PLC-modem with the same bit rate, that an LF-PLC-modem can achieve, will be higher: Because of higher sampling rates the A/D- and D/A-converters are more expensive. Also the DSP core is more expensive, because data frames containing the same number of bits are getting shorter with increasing frequency.

Theoretically the much larger available bandwidth in the MHz range does make much higher bit rates possible. But with today’s technology a DSP for a modem with 1.5 Mbit/s in the kHz range costs below 10 $ in high volume quantities. On the other hand a DSP, that is able to handle e.g.20 Mbit/s in the MHz range, must contain several cores working in parallel. The cost of such a powerful component will be above 100 $. This means that it is currently not possible to produce low cost HF-PLC modems with such high bit rates.

## 3. Fields of application for high speed PLC-modems

**PLC-access-systems in Europe:**

In Europe up to 400 households are connected to a single transformer. If 100 of these households are customers of the power utility company, that delivers this service, and only 10 of these customers want to use the service at the same time, this implies the necessity to install a PLC-system with at least 10 Mbit/s full duplex capability, in order to offer the same performance as the existing competitive access-technologies.

**PC-networks and data communication for professional users:**

The powerlines in an industrial or large office environment are very long, with many loads and interferers connected to it. This leads to large attenuation and high disturbance levels. In addition professional users, or for instance multi channel, high quality video distribution systems, demand data rates in excess of 10 Mbit/s together with 100% availability and heavy QoS requirements. All this excludes PLC-solutions from these areas of application.

**Inhouse applications:**

Applications inside private homes are much more suited to the fundamental features and properties of PLC-systems. The extension of the powerline network is small, the number of noise sources and loads is limited, the number of PC's connected to the network is limited (e.g. ≤ 5), the number of applications connected is e.g. ≤ 20 and the data rates needed are in the order of 750 to 1.300 kbit/s, as stated at the beginning.

## 4. International standards and regulations for PLC-systems

There are no frequency restrictions in the United States for Inhouse PLC-systems (Carrier current systems). The only limits to be observed are the fieldstrength limits of FCC Part 15, which is for Radio Frequency Devices and there Subpart B, which is for Unintentional Radiators. Figure 7 shows these limits. In the frequency range below the AM radio band the fieldstrength is measured with an average detector in 300 m distance.

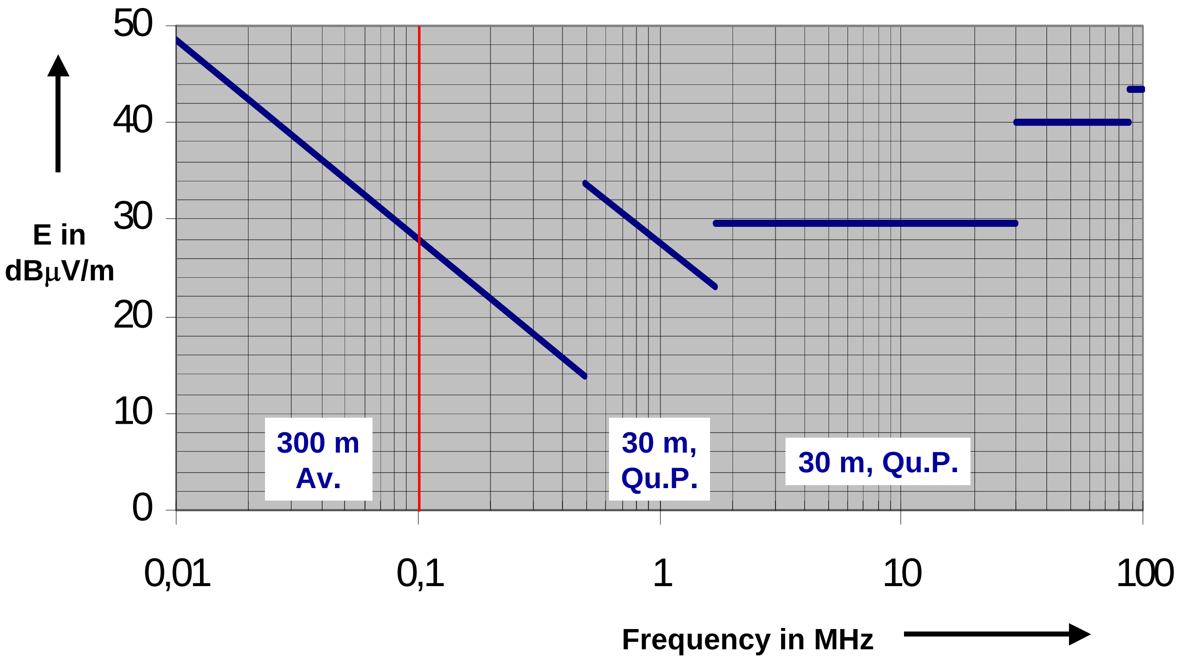


**Fig.7: Radiated emission limits, FCC part 15**

Outside the United States the international EMC fieldstrength limits have to be observed. However as PLC-systems are intended for very high volume usage, new, more stringent disturbance fieldstrength limits are under consideration in the United Kingdom and in Germany. Figure 8 shows the limits of the German NB30 and the MPT1570 from the UK. Both directives are discussed currently and not yet in effect. The limits of Fig. 8 are significantly lower than those of the FCC. Below 500 kHz the measurement distance is decreased from 300 m to 3 m respectively 1 m. As stated in chapter 2, the field of the guided wave is dominating in such close vicinity to the powerline. This fieldstrength will decrease by approximately 90 dB (Fig. 3) when the measurement distance is changed from 3 m to 3oo m. Only the radiated field (Fig. 4) has to be considered in 300 m distance. For the coexistence between broadcasting services and PLC-systems the radiated field is of much higher importance than the nearfield of the guided wave. Therefore it is necessary to establish measurement procedures for disturbance field strength limits that examine the radiated field and not the nearfield of the guided wave.

Figure 9 is an oscilloscope picture of a typical OFDM-signal during digital data transmission. Such signal contains very seldom very high amplitude peaks (Gaussian distribution). If a peak detector (UK limits) is used to measure this signal, the reading will be approximately by a factor of 3.5 higher (11 dB) compared to the reading of an average detector (US limits). An OFDM signal is similar to white noise (thermal noise). Nobody will describe a noise level, using a peak detector measurement. The result of a peak detector measurement does also not make sense to take into account the disturbance effect of a broadcast signal. For this purpose the quasipeak measurement has been successfully established.

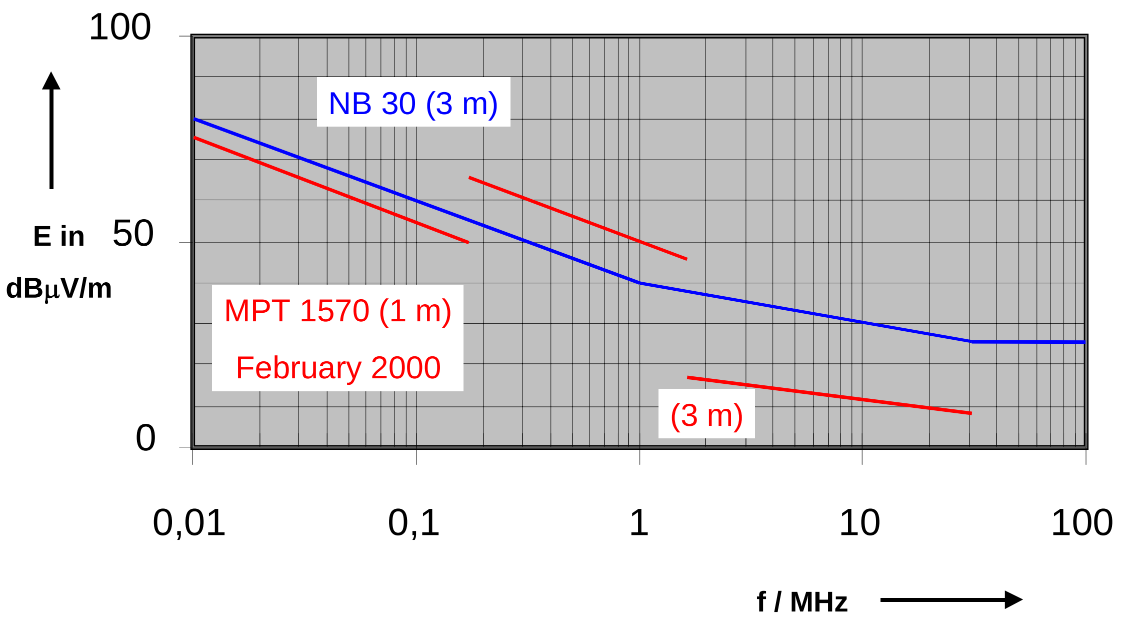


**Fig. 8: Proposed fieldstrength limits**

The field strength levels of Fig. 8 are so low, that they cannot be verified with standard broadband EMC measurement equipment. The internal noise level of this equipment is too close to these levels. Furthermore it is well known, that the actual man made noise level or interference level encountered in today's typical Inhouse environments, is 20 dB to 30 dB above those limits.

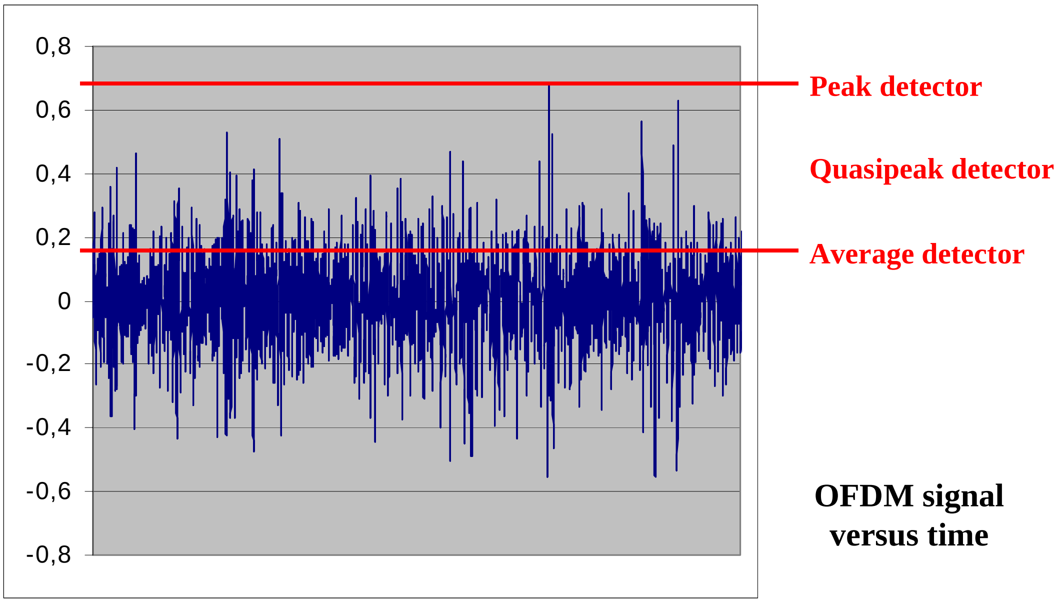


**Fig.9: Measured voltage for different types of detectors**

## 5. Conclusion

It has been shown, that the frequency range from 50 kHz up to 500 kHz (LF-PLC) has many advantages for Inhouse-PLC-systems, compared to the frequency range from 1.6 to 30 MHz (HF-PLC). Because of the extremely low radiation of LF-PLC-systems it is possible to deploy these systems in large volumes without disturbing existing broadcasting services. The limited data rates of LF-PLC are appropriate to the market demands of today.

HF-PLC-systems will enable higher data rates. However because of strong radiation problems in the MHz region, these systems need dedicated frequency bands, which are not used by broadcasting services. Broadband HF-PLC-systems, that use the whole band from 1.6 to 30 MHz, and stay below the disturbance fieldstrength of Fig. 8, have to exchange signal level against data rate. As another paper in this symposium will explain, this results in data rates below 400 kbit/s.

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