Telecommunications over the Power Distribution Grid - Possibilities and Limitations

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1. Introduction and Historical Review

The use of the electrical power distribution grid for communication purposes is not a new approach at all. But recently, with the announcement of the expiring telecommunications monopoly of the German „Telekom" the field of high speed power line communications received new and strong impulses. Basically, power line communications started with the beginning of wide-spread electrical power supply in Europe about 75 years ago. Around the year 1922 the first carrier frequency systems (CFS) began to operate at high-tension lines in the frequency range 15...500kHz. As we only find open-wire equipment with very few cross connections here, high-tension lines represent excellent carriers for RF energy. A transmission power of about 10W is often sufficient to overcome distances of more than 500km. During the past and even nowadays the main purpose of CFS for the utility corporations (UCs) was to maintain operability of the power supply system. While in former times speech transmission was dominant, today we have more and more digital data communications, due to the rapid progress of overall automation. Through the application of modern digital modulation and coding schemes, a significant enhancement of bandwidth efficiency could be achieved for CFS.

From the beginning utility corporations preferred the construction of their own communication links. The use of existing „usual" telecommunication networks was rejected, especially for remote measuring and control tasks, as they are neither ubiquitous nor able to guarantee real-time operation. The UCs generally regarded the power distribution wiring as a „natural" medium for their communication needs, as all important stations are connected.

On the medium- and low-tension level we find different requirements as for the high-tension side. In the past, load management was one of the most important tasks. The flow of information needed for such purposes was small and one-way from the UC to the consumer's premises. Around the year 1930 ripple carrier signaling (RCS) became ready for operation. In contrast to CFS, RCS was designed for different voltage levels, i.e. the medium level (15-20kV) and the low-tension level (230/400V). Due to a high number of cross connections and different conductor types (e.g. open-wire and cable) transmission techniques such as CFS are ruled out. Long distance RF signal propagation can be expected to be extremely bad in this environment, because of high attenuation and impedance matching problems. The RF transmission power needed to overcome the impairments would certainly evoke numerous problems of electromagnetic compatibility (EMC). Therefore the frequency range in use for RCS is normally below 3kHz, down to 125Hz. As the loaded distribution network represents a very low impedance for such signals, transmission powers must be in the range from 10kW up to 1MW. For RCS transmitters are a major factor of cost, and for this reason RCS definitely is a one-way technique. Modulation within RCS is performed through amplitude shift keying (ASK). A typical telegram consists of 10 to 60 packets with intervals, and has a total length in the range of 1/2 up to 3 minutes, containing 20 to 120 bits of information. Although RCS proved its high reliability over decades, further extension or enhancement of this technique does not make sense under aspects of future requirements.

2. Dedicated Resources and Actual Applications

The typical European distribution grid topology is star-shaped. Several lines (5-10) originate from a transformer and connect some hundreds of households. The availability of an appropriate bi-directional signaling technology would open completely new fields of applications, such as „enhanced value services“ (EVS), an item which calls for closer definition in future. At the moment EVS includes for example tasks such as load management, tariff switching, remote meter reading, control and supervision of customer's premises, up to possibilities for ordering Pay-TV. With current European norms and regulations in mind, especially CENELEC EN 50065, techniques are available for bi-directional signaling at data rates up to several thousand bits per second. EN 50065 specifies three frequency bands A, B and C with maximum transmission amplitudes and user dedication as shown below:

band	frequency range	max. transm. amplitude	user dedication
A	9 - 95 kHz	10 V	utilities
B	95 -125 kHz	1,2 V	home
C	125 - 140 kHz	1,2 V	home

EN 50065 significantly differs from American or Japanese norms, where the frequency range is generally open up to approximately 500kHz. Furthermore transmission over the protection earth line is allowed, where much lower levels of interference are found. Due to the different norms it will normally be impossible to operate US or Japanese equipment unchanged in Europe.

2.1 „Indoor“ Applications for Building Automation

Different kinds of buildings may be upgraded, e.g. into „smart homes“, by using their power wiring for communications in the CENELEC bands B or C. A smart home can be defined as a building equipped with numerous sensors and actuators, where e.g. heating, air-conditioning or illumination are automatically and remotely controlled and supervised. Furthermore safety systems such as burglar or fire alarms may be included. Additional wiring for communication purposes is cost-effective only in buildings under construction, whereas retrofitting normally will be ruled out by its costs.

In spite of obvious advantages and numerous attempts for communications over power supply networks, no significant progress became evident until now. The main reasons for this can be found in a lack of understanding the basic physical properties of the medium. At the university of Karlsruhe significant work towards modeling power supply networks as data channels has been done during the past six years. Based on these results prototypes of communications equipment were designed an constructed. Further development for series production was initiated in industry, leading to systems which have reached maturity for market now. At Hannover Fair '96 a building automation system named „Powernet-EIB“ was presented to the public. Powernet-EIB is for example applicable to networking with „intelligent“ appliances and the complete electrically powered building equipment such as air-conditioning, shading or illumination. EIB stands for „European Installation Bus“, which is distributed by almost 70 European companies at the moment. The EIB system includes all of the 7 OSI/ISO layers and can be connected to a variety of components such as switches, sensors or actuators. The essential drawback of the standard EIB system, however, is the need for a separate two-wire bus. The step to Powernet-EIB allows to use the existing power supply wiring and will in any case be able to fill a significant market gap.

2.2 „Outdoor“ Applications ⇒ „Enhanced Value Services“ (EVS).

Of course the power supply wiring of a building does not end at the limits of the building's real estate, but from an electrical point of view is in direct connection with hundreds of other households and at least with one transformer station. This extended network will obviously offer additional opportunities for communication purposes. Comparing the transmission of RF signals and electrical power at 50Hz, there is no general difference in physics. Considering the properties of the wiring at the different frequencies, however, reveals major differences. With growing frequency, on the one hand losses are growing along the lines, and on the other hand effects of electromagnetic field propagation must be considered, as distances may be up to 1km now. Fortunately knowledge and experience gained at indoor networks are to a great extend also applicable to the outdoor environment. Furthermore system concepts which led to success for indoor applications can - modified appropriately - be brought into operation also in the outdoor environment. A great deal of research work in this direction has been recently completed at the university of Karlsruhe. Ongoing development according to the model „Powernet-EIB“ is under way in industry. Field trials have been started over distribution networks selected by utilities and brought a series of generally positive results until now.

3. Systematic „Outdoor“ Measurements

In parallel with system development extended measurements with special emphasis on „difficult“ links were carried out for channel analysis and modeling. Unfortunately large portions of the necessary measuring equipment could not be obtained from market; so costly and time consuming in-house developments were unavoidable. At the university of Karlsruhe these activities led to the construction of AUMEDAS (Automatisches Meßsystem für Datenübertragungsparameter in Stromnetzen). AUMEDAS is in operation since summer 1996 and has already recorded attenuation, interference scenarios and access impedance for various power distribution systems.

3.1 Network Access Impedance

At conventional communication links normally impedance matching is attempted. For a typical antenna or a coaxial cable matching is generally no problem, as the characteristic impedance values are well defined and in a wide range independent of frequency. The power supply network, however, represents a completely different environment. Within the A-band, for example, input impedance may vary in such a way, that several hundred watts of transmission power would be needed to put the allowed signal amplitude into the network at 10kHz, whereas some watts were sufficient for the same task at 90kHz. Generally access impedance will increase with growing frequency. Besides frequency dependence also significant time variance of the access impedance must be encountered. Furthermore also location is of major importance. In a typical transformer station, e.g. directly at the busbar, impedance values are 10...20 times below those of a normal outlet of a building.

3.2 Attenuation

Generally every transmitted signal will experience more or less attenuation on the way over the power supply wiring to a receiver. The attenuation values strongly depend on individual properties of a link and may be as large as 90dB. Besides the total length of a link, frequency, time and location play major roles. Typical fluctuations with time are around 20dB. Concerning frequency dependence most links between transformer station and household exhibit some kind of signature with almost invariant shape. The signature of nearly every link, however, is individual and different from others. This fact will call for transmission methods which, for example, are able to overcome local notches in the transmission band.

3.3 Interference Scenario

Attenuation normally is of minor impact on error-free communications, as long as appropriate receiver signal amplification is possible. At the power distribution grid, however, various kinds of strong interference overlap the desired signal. Analysis of the spectral amplitudes of typical interference, e.g. within a greater building, reveals that normally three different kinds of noise can be identified: Colored Gaussian noise, single-tones and impulse noise. Colored Gaussian noise is characterized by its frequency dependent spectral power density. At power lines a typical run starts with very high power density at low frequencies up to 20kHz. Above 20kHz we find a steady decrease of power density with growing frequency. At 150kHz e.g., a decay of almost 60dB can be registered in comparison with 20kHz.

Whenever narrow peaks appear in the frequency domain, the presence of single-tone interference is supposed. Such narrow-band interference may be caused by switched power supplies, static power converters, fluorescent lamps, TV sets or computer monitors.

A characteristic feature of impulse noise are short peaks of 10...100µs with amplitudes up to 2kV. Generally there are two different classes of impulse noise:

- rare single events, e.g. caused by on- or off-switching of appliances
- periodic events, e.g. caused by phase angle control devices such as light dimmers, occurring at twice the power line frequency (100Hz)

In presence of interference and strong attenuation receiver signal processing is obviously prone to errors. For colored Gaussian noise we will have statistically distributed errors with typical bit errors rates in the range of 10^{-6} ... 10^{-5} for well designed systems.

The impact of single-tone interference extremely depends on the used modulation scheme - even total system blocking cannot be excluded.

Dependent on the energy of individual impulses, the typical effect of impulse noise is destruction of one or several coincident bits. Whenever such events occur, e.g. with twice the powerline frequency, the bit error rate may take on tremendous figures. Appropriate coding will be the only effective means to ensure reliable communications in such situations.

4. Modulation Schemes

Generally modulation schemes can be subdivided in narrow-band and broadband. Narrow-band schemes are advantageous in „well-behaved" channels, as they guarantee optimal spectral efficiency, e.g. line-of-sight radios, TV and audio broadcasting.

4.1 Narrow-band Modulation Schemes

Typical narrow-band modulation schemes taken into account for power line communications are amplitude shift keying (ASK), frequency shift keying (FSK) or binary phase shift keying (BPSK). As already mentioned, ASK is used for ripple carrier signaling. Furthermore some attempts were made in the past to build ASK-modems for CENELEC bands A-C, e.g. based on a NE5050 chip made by Philips/Valvo. Today ASK does not play a significant role in power line communications, except for ripple carrier signaling of course.

FSK turned out to be a much better candidate for reliable data transmission over power lines. The presented Powernet-EIB system essentially relies on a modified „spread-carrier“ FSK version. One major reason for certain robustness of FSK is the fact, that added interference is not able to directly influence the frequency of a carrier and therefore no degradation is visible unless the signal to noise ratio falls below certain levels. In contrast, for ASK, even small interference is noticeable, because amplitudes carry the information. On the other hand, FSK is far from being immune in the powerline environment. Whenever one of the carriers is heavily attenuated or superimposed by strong narrow-band interference, errors are unavoidable. Various practical investigations in indoor environments, however, revealed that such cases are extremely rare. For typical building automation systems the higher costs for enhanced robustness, e.g. through implementation of frequency hopping (FH) schemes, cannot be justified.

BPSK would generally offer the best performance of narrow-band schemes, due to the largest Euclidean distance of the vectors in signal space. The theoretically expected figures can, however, only be observed in a Gaussian noise environment. At powerlines BPSK may be severely affected by phase noise introduced through interference of various kinds. Furthermore BPSK calls for coherent detection, based on precise phase estimation. The typical corrupted signal received over powerlines generally will pose high load on receiver circuitry to achieve sufficiently precise phase estimation. BPSK is used occasionally for power line communications. A noticeable superiority, e.g. in comparison with FSK, could not be demonstrated until now.

4.2 Spread Spectrum Modulation

Originally spread spectrum systems were designed exclusively for military applications. Through extreme spectral redundancy these systems exhibit excellent robustness against various kinds of interference. In the past, spread spectrum techniques were characterized by tremendous effort and costs. The rapid progress in the field of microelectronics, however, led to dramatic changes, so that today spread spectrum techniques (SST) are open for almost any application. Due to the inherent immunity of SST against all kinds of narrow-band interference or selective attenuation, such techniques would generally be ideal candidates for communications over power lines. Moreover, the norm EN 50065 even favors broadband modulation. Three major classes of spread spectrum schemes are of technical importance:

- pseudonoise direct sequencing (PN-DS)
- frequency hopping (FH)
- chirp

Generally the processing gain (PG), denoting the ratio of the bandwidth of the transmitted signal versus the pure information bandwidth, is a measure of performance. In military systems typical PG values are above 1000. Within the CENELEC A-band at powerlines the PG would be limited to about 18, assuming a data rate of 2400bits/s in a maximum bandwidth of 85kHz. Practice has clearly demonstrated, that for such small figures of PG, spread spectrum techniques loose most of their attractive features. Due to general realization losses, which are unavoidable in every technical system, finally no noticeable advantages in comparison with narrow-band techniques remain. For brevity only two representative effects are mentioned:

1.) Receiver synchronization generally is not possible without timing errors. Especially in situations where the received signal suffers from severe corruption, and thus full exploitation of the PG would be paramount, acquisition and tracking procedures to achieve and maintain synchronism are most critical and prone to errors.

2.) Appliances and various noise sources generally have more or less impact on the carrier phase. Furthermore nonlinear phase response or group delay distortion are common effects in the powerline environment. Then, in spite of acceptable synchronization, despreading at the receiver will be far from ideal.

Frequency hopping (FH) can be regarded as an extension of FSK. Instead of two carriers for FSK, FH uses many, often several thousands in military applications. Portions of a data bit will then be present at many more or less distant locations within the transmission band. The advantages are quite obvious: Local interference and notches in the spectrum will not severely affect data transmission. FH offers wide spreading of carriers without the need of a contiguous spectrum, and even without „fast“ spreading codes, which generally make synchronization a crucial task. These and more advantages of FH which, for brevity, cannot be entirely listed here made FH a favorable candidate for „wide area“ communications over the outdoor distribution grid. In cooperation with industry the design of modems in form of mixed-signal ASICs, based on a modified FH scheme with four carriers per bit named MFH is under way [1]. The first single-chip solutions are scheduled for summer 1997.

Chirp modulation is of almost no importance for applications in European power supply systems regarding the norm EN50065. The US company Intellon is a major provider of chips for chirp modulation. Significant performance, however, can only be demonstrated at channels with at least 500kHz of bandwidth.

5. Error Control Coding

Whenever high energy noise impulses hit a data carrier, the probability of an error is generally 50%. On the signal processing levels, such as modulation, amplification, filtering or demodulation, there is no way to avoid such errors. The intervention must take place in the digital domain by appropriate coding. For forward error correction (FEC) elementary block codes, such as modified Hamming codes, demonstrated excellent performance in the powerline environment. Block codes are easily implemented on low-cost standard microcontrollers. Hamming codes are generally able to correct a single error and detect two or more within a block. In practice, code rates below 80% are normally not accepted, which imposes major restrictions on powerful FEC, i.e. normally no more than one error per block is corrected. Field trials with a (31,25,4) modified Hamming code showed excellent FEC performance. Currently this coding scheme enters industrial series production. For general remote control applications the residual error rate provided by the mentioned (31,25,4) code turned out to be insufficient. Therefore a standard cyclic redundancy check (CRC) was added, to meet the requirements concerning „integrity levels“ IP1...IP3, which are defined by remote control standardization. IP3 for example requires a residual error rate as low as 10^{-12}, which would mean the occurrence of an undetected error every 31 years for a continuous data stream of 1000bit/s. CRC schemes are easily implemented on low-cost microcontroller platforms with minor impact on the effective data rate.

6. State of the Art in System Development

Currently several companies offer various chip sets or even complete systems for applications within the CENELEC bands A-C. Until now there was no concept with significant success. Besides US companies such as Echelon, Intellon, Adaptive Networks or National Semiconductor in Europe only Thomson (France) is selling powerline communications hardware. With the beginning of 1997 the German ABB company Busch-Jaeger Elektro GmbH offers the mentioned Powernet-EIB building automation system in Europe. In comparison with the US competitors Powernet-EIB has the advantage of having been developed and tested in and for the European power wiring system in strict accordance with EN50065 from the very beginning. Whereas none of the US products, for example, can be operated in Europe without major modification, which as experience has shown, generally leads to more or less severe performance degradation.

As already mentioned above in the spread spectrum modulation section, currently the integration of a complete powerline modem in form of a mixed-signal ASIC is under way in cooperation with ABB Load Management GmbH and ABB Corporate Research Center. Besides the mentioned modified frequency hopping scheme (MFH) analog signal conditioning as well as precision of synchronization have been significantly improved in comparison with foregoing prototypes. First samples of the new chip are scheduled for the beginning of summer 1997. Currently a hardware emulation system as well as system software for the new chip are under development at the university of Karlsruhe. Complete modems based on the new chip are planned for autumn 1997.

7. Current and Future Research Activities

The cessation of German Telekom's telecommunications monopoly with the beginning of 1998 has initiated to various activities in many major utility companies. Especially German utilities are owners of long-distance high-speed communication channels in form of optical fibers mounted along the high- and medium-tension power supply lines. Until now, due to the existing monopoly, this capacity could only be partially exploited. After cessation of the monopoly, the UCs are able to offer telecommunication services not only for mobile phones, but also in fixed networks. The latter, however, calls for communication links over the so-called „last mile“ between the medium tension level and the customer's premises.

Reflections towards this aim start with the basic question, whether the existing distribution grid generally exhibits the necessary physical properties for telecommunication purposes. A second question would be, how such properties could be provided with reasonable effort. Obviously the rules of EN 50065 have to be given up, as data rates in the range 2..5Mbits/s must be taken into account now, calling for carriers and bandwidths in the Mhz-range. In a first step the examination of the complete distribution grid's bandwidth, which is likely to allow RF signal transmission, seems to make sense. The effort for measuring the relevant quantities is rather high, starting with the need for special coupling equipment to feed RF signals into power lines, up to gathering and evaluating large portions of data automatically. Each distribution cable appears as an individual at first glance. Numerous investigations in different places are necessary to get an overview in order to be able to extract the essential information. Also here large portions of the measuring equipment will have to be developed and build individually.

At the moment, based on theoretical analysis, simulations and some distinctive measurements the following statements can be given:

Data transmission at rates up to several megabits per second appears realistic at typical European power distribution grids. It could be proved that possibilities for telecommunication purposes exist up to frequencies of about 20MHz. Even overhead lines do not present crucial obstacles for RF signaling. Also different types of cables do not exhibit completely different behavior; the most important properties can be captured by a few parameters.

Measurements revealed that reliable data transmission at some megabits per second can be performed with transmission powers significantly below 1W over distances of several hundred meters. Also within buildings reliable transmission of signals up to 20MHz over a distance up to 100m could be demonstrated.

Normally interference at higher frequencies can be modeled as colored background noise with relatively low power density. In some places of the spectrum broadcast transmitters appear as distinctive interferers. Between the occupied frequency bands, however, large gaps can be found, which could be easily used for our purposes. Above all, appropriate measures for RF isolation of transmission links from other parts of the supply system appear to make sense. On one hand this would be an effective means against electromagnetic compatibility problems, and on the other hand transmission power obviously could be lowered in a conditioned network. In any case the benefits of network conditioning will be valuable contributions to better acceptance of new services, adaptation of norms and setting up of new admission regulations.

7.1 Systems for Telecommunications

At this time globally no systems or hardware are available for telecommunications over the power distribution grid. On the other hand, undoubtedly, there are technical and economical solutions which, however, will still have to be developed. In order to achieve applicable results rapidly various cooperations, e.g. of utilities, industrial companies and research institutions are paramount. The recent development of mobile radios clearly has demonstrated how even under severe conditions cost-effective solutions can be found. With the actual state of the art in mind, telecommunicating over the power grid appears not more complex than e.g. the management of urban mobile radio channels. However, none of the proven modulation techniques or media access procedures, which are in effect in other fields of telecommunications, are directly applicable without change or adaptation. For a final statement in which direction to operate, evidence of significant channel properties is still missing, such as detailed figures of amplitude and phase response or group delay. Furthermore it is important to find out whether „large" frequency bands can be used contiguously or should be separated into appropriate „narrow-band" portions. An answer to this question would allow general decisions towards wideband modulation techniques with one or very few carriers on one hand, or multicarrier techniques such as OFDM (orthogonal frequency division multiplexing) on the other. In case of wideband techniques some kind of channel equalization should be feasible.

Another important question concerning amplitude sensitive modulation such as QAM (quadrature amplitude modulation) is expected to be answered by channel analysis. QAM is an interesting candidate with respect towards bandwidth efficiency - 16QAM will e.g. offer 4bits/Hz. As resources of the power line channel are generally never too redundant, the possibility to apply QAM would be valuable.

After an appropriate modulation scheme is found, the next step will look out for media access methods. Here generally multiple access schemes such as FDMA (frequency division multiplexing), CDMA (code division multiplexing) and TDMA (time division multiplexing) as well as mixed versions must be taken into consideration. The benefits and drawbacks of the schemes listed above are well-known from various applications, e.g. in mobile radio channels.

When modulation and media access schemes have been successfully defined, reflections towards system design will be a final step. Generally a digital approach is preferred for a variety of well-known reasons. It is expected that for highly functional and economic solutions, certain key components will have to be realized in ASICs (application specific integrated circuits). Furthermore the verification of newly designed prototypes in field trials is unavoidable. Modern FPGA (field programmable gate array) technology enables such a strategy in very early stages of development, as the necessary chips can be produced in a normal laboratory without the need to contact a silicon foundry. Furthermore FPGAs offer tremendous flexibility: Changes are made rapidly at no hardware costs and are even possible without removing an FPGA chip from the system under test. The IIIT at the university of Karlsruhe is equipped with the necessary tools and man-power to bring system ideas to silicon according to the outlined philosophy. In practice this means that various system ideas can be prosecuted and evaluated with limited effort and in reasonable time, in order to select an optimum solution for further development in industry.

8. References

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