Research Areas for Efficient Power Line Communication Modems

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Abstract

The power line communication (PLC) is a new technology open to improvements in some key aspects. Some companies in the world provide broad band PLC devices and an increasing number of utility companies have already gone through field trials and commercial deployment of PLC services. From this experience it is necessary to decrease costs, and to improve the bandwidth and liability, and ease the installation procedures and access to technical support. This paper provides a review of the main problems that the PLC modem technology faces, problems representing the research areas for PLC where more studies are still necessary. It also enumerates some of the most interesting ideas proposed in the last years to solve these problems, finally describing our current research works in PLC modems.

1. Introduction

Customers of telecommunication companies demand new services with higher bandwidth, but the physical medium that new applications require has to cover the so called ``last mile'' without incurring in high costs. This is the main reason why the usage of the power grid for communication purposes is being regarded as an expanding field with important market perspectives. In the last years, many electrical companies have quickly developed functional prototypes in order to discourage potential competitors, but the actual performance needs to be improved. Current PLC devices are not hardware efficient, what makes the technology too expensive for a mass market.

This technology offers a great variety of research areas, in which many investigators are already working. However, there are still many fields that are not fully covered, and many works that overlap. This situation is in most cases due to a weak regulation [1] and the lack of an international standard, which should be one of the first objectives for PLC commercialization.

The design of PLC modems is a challenging task, as it covers several layers of the Open System Interconnection (OSI) standard (see Figure 1) in which there are still crucial problems to solve. A PLC broadband modem is a large digital design including base band DSP, equalization, and MAC tasks [2]. Most investigations evaluate different methods by simulations or cosimulations, but the results may not be easily implemented in hardware efficient solutions. Some efforts have been made in this area [3] and there is still much to be done.

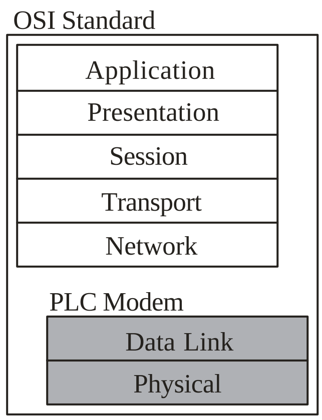


Figure 1- OSI Layers implemented in our modem

The Data Link layer comprises the security related investigations and the MAC layer problems, while the Physical layer has to deal with all the modulation and hardware implementation problems.

This paper offers a deep review of the current researches and future needs of the power line communications. Being a hostile environment, PLC physical layer features must be chosen carefully. We take a concerned look to international regulations and their impact on power limits or network security. Finally, the specific problems of MAC layer and modem design in which we are currently working are discussed, and several feasible solutions suggested.

In addition, some remarkable international initiatives are reviewed in order to provide a wider scope of the trends of Power Line Communications.

2. Modulation

As electrical distribution circuits were not built for communication purposes, transmission of high frequency signals is severely hampered. Each appliance and switch in a house can be considered as a changing load in the transmission line between two appliances, what makes the adaptation of the line a very difficult task. Several investigations have been conducted searching a suitable model for the house power grid as a communication channel [4]. Furthermore, the lack of adaptation, and the attenuation it implies, is strongly dependent on the frequency. This problem is also the source of the multiple reflections that occur in such a branched network. To solve this problem and achieve high transmission rates, the modulation technique should be carefully chosen. The most popular solutions are modulation schemes such as frequency shift keying (FSK), orthogonal frequency division multiplexing (OFDM), or code-division multiple access (CDMA).

The FSK modulation has only proved valuable in a reduced set of applications, mainly in narrow band, low cost modem design.

Industry alliances, such as European Home Systems Association (EHSA) [5] or HomePlug [6], have gradually modified their standards, increasing the architecture complexity. The simplest architecture for PLC devices uses the CDMA modulation, as its hardware implementation has not the size nor the complexity of those required by the OFDM modulation. However, the CDMA modulation is more affected by the multi-path problem characteristic of the power line medium. The OFDM technique can achieve higher bandwidth, what is an important feature if communication companies want to offer high-definition digital television services. Companies developing narrowband modems, intended for small integrated systems, need an easy and inexpensive way to implement a PLC network in order to gain as many customers as possible, and the CDMA modulation may fit their needs, providing fast communications and less complex hardware architectures. But a stronger effort should be made to develop PLC devices, taking advantage of the yearly improvement of technology, and trying to find hardware-efficient OFDM solutions.

2.1. OFDM Modulation Scheme

OFDM can be seen as either a modulation technique or a frequency multiplexing technique.

In an OFDM system, data is carried on narrowband subcarriers modulated with different possible techniques, such as binary phase shift keying (BFSK) or quadrature amplitude modulation (QAM). Each subchannel is modulated with a separate symbol and then all the subchannels are frequency-multiplexed, using orthogonal frequencies to increase the channel efficiency. Data is transformed into time-domain using IFFT at the transmitter and transformed back to frequency-domain using FFT at the receiver. The total number of sub-carriers is equivalent to the number of points of the IFFT/FFT.

Suppose the data set to be transmitted is

$$U(-\frac{N}{2}),U(-\frac{N}{2}+1),...,U(\frac{N}{2}-1) \qquad (1)$$

where N is the total number of subcarriers. The discrete-time representation of the signal after applying the IFFT is

$$u(n)=\frac{1}{\sqrt{N}}\sum_{k=-N/2}^{N/2-1}U(k)\cdot e^{j2p\frac{k}{N}n} \qquad (2)$$

where $n \in [-N/2,N/2)$. At the receiver side, data is recovered by performing the FFT on the received signal.

As a single fade or interfering signal affects only a small percentage of the subcarriers, OFDM increases the robustness against frequency selective fading or narrowband interferences.

Several researches have been conducted to find the most suitable modulation for PLC [7], and it seems most investigators choose OFDM as the most versatile and robust scheme, although the hardware required is also more complex, as it has to implement complex mathematical operators (FFT, IFFT, and typical modulation hardware). A PLC modem has to be a small device, so the most hardware demanding parts of the modem, such as both the OFDM transmitter and the OFDM receiver, should be carefully designed.

3. Power Limits

The PLC medium is a very noisy environment and the electromagnetic compatibility (EMC) requirements set a limit for the radiation emission of any communication line. This fact limits the signal power, and makes the signal-to-noise ratio an important feature for reliable communications through power lines. EMC constraints for power line communications devices are inadequately regulated, although a high effort is being conducted.

Typical power lines are unshielded, so electromagnetic radiation will surely propagate out of the wires. Many international associations, such as the International Amateur Radio Union (IARU), are complaining because they claim that the communications through the power lines, particularly those operating in the range 1.6 MHz – 30 MHz, challenge the fundamental purpose of EMC standards [8]. Not only will they interfere with existing HF radio applications, but the PLC systems may also suffer interruption or degradation of service by the operation of local transmitting stations.

It is not feasible to shield every wire in every house before using power line communications. The only solution is to reduce the emitted power to comply with international standards and to implement robust communications systems that may share the HF band without problems.

4. Network Security

The CDMA modulation adds a minimum level of encryption, as the pseudo-random codes it uses to spread the spectrum could be regarded as a secret key. However, more complex and robust encryption methods are needed for PLC networks, as the privacy of the users should be ensured.

Standard algorithms as DES, ICE, or AES are block ciphers that usually demand too many resources. A block cipher is a reversible function

$$f(k,b) : K \times B \rightarrow C \quad (3)$$

which maps a key in K and a block in B into a block in C. Usually B and C are the same set, so the block cipher permutes B in a key-specific way. There should be no way to deduce the key given any number of pairs *(b, f(k,b))* in *(B, C)*, and no efficient way to deduce *f(k, b)* from *b*, or *b* from *f(k, b)*, without the key.

All the algorithms mentioned above have been implemented in hardware solutions. However, adding this hardware to the inherent complexity of a PLC device may not be reasonable in a low-cost solution. The reversible functions *f(k, b)* that most algorithms use are not linear and usually need permutation tables, what makes encryption and decryption slow procedures. Leaving the strongest algorithms for upper layers of the OSI standard, a higher effort should be made in order to adapt known algorithms to the specific characteristics of PLC.

Most encryption systems do not fit in the OSI layers that a PLC modem implements. It is important to remember that the power line inside a house is a private environment and conducted emission limits (from EMC regulations) partially avoid signal sniffing, so it may not be necessary to implement an advanced encryption system. Most of commercial software applications already include encryption algorithms. Only the headers of MAC frames may be susceptible to attacks.

There are at least two security related problems inherent to the PLC network topology.

- The electric distribution wiring fed with a high frequency signal produces enough electromagnetic radiation to be detected several meters away.

  This fact means that MAC frames may be listenned by a near receiver without much effort, what is not too relevant, as far as internet traffic is concerned, because upper OSI layers provide enough protection to the data they give to the Data Link layer, just as it happens in Ethernet or ADSL networks.

- Unfortunately, if the electric distribution wiring acts as an antenna for emitting purposes, it also receives all the interferences radiated by near emitters. In many domestic old power lines, the wires are inadequately shielded for high frequency signals.

  The first consequence of this last problem is that PLC communications may be easily jammed with a low-power noise generator [8]. Moreover, a PLC device equipped with an antenna and enough power may link with a home PLC network as if it was another ordinary appliance if some basic security cautions are not considered.

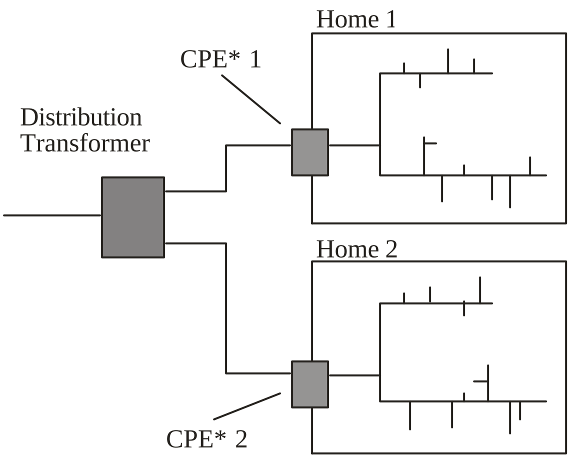
International standards and researchers have to look for a balanced solution, taking into account EMC regulations, security needs, and current technology.

5. MAC Layer

Well-known error handling mechanisms can be applied to PLC systems to solve the problem of transmission errors caused by the disturbances. However, the use of these mechanisms consumes a part of the transmission capacity and therefore decreases the data rate of the PLC systems. PLC networks have to provide very good network utilization, keeping also a sufficient quality of service (QoS), which can be reached by usage of Medium Access Control (MAC) protocols for sharing the network capacity. Various MAC protocols for PLC, such as ALOHA, CSMA, or the polling protocol are being investigated to adapt its characteristics to PLC networks [9].

The MAC protocol to be implemented in a PLC network must provide support for the transmission of different kinds of services: TV, telephone and data transmission services. In addition, the PLC MAC layer should include features to make the system able to support more sophisticated services (e.g. Variable Bit Rate services with higher data rates, standard services with higher QoS requirements) and specific PLC services.

Every appliance inside a home, with a PLC modem included in it, is a network station. In Figure 2, each home network (Home 1 and Home 2) is shared by all its appliances so collisions will certainly occur. The appliances may try to establish communication with another appliance or with the Customer Premise Equipment (CPE), which links the home network with the internet.



* CPE - Customer Premise Equipment

Figure 2. PLC Network

Due to the large number of network stations, collisions are too frequent in dynamic contention protocols. These collisions introduce a long delay in the system, what makes these protocols not suitable for time-critical services. On the other hand, reservation protocols can carry hybrid traffic with variable transmission rates, but they require more logic control to be implemented. Improving the ALOHA or polling protocols may be an efficient solution [9] and add an important contribution to PLC-oriented solutions.

Appliances and switches are most common source of impulsive noise. The noise power ranges according to the distance between the noise source and the receiver. An important effort has been made by many investigators to develop channel coding techniques [10] in order to reduce the effect of impulsive noise in the bit error rate (BER). To improve OFDM modulation, the best suiting coding technique is the bit-interleaved coded modulation (BICM). This coding scheme uses a channel code followed by a bit-interleaver and a bit-to-symbol mapper. Several researches have already been conducted to find a low complexity implementation [11], but the overall complexity is still too high in a PLC modem.

6. Modem Design

The design of PLC modems should be oriented to attain low complexity and low power-consumption devices.

Modem design suffers from all the problems mentioned in the sections above. In addition, more research should be made to fully integrate in the same chip the analog and digital side of a PLC broadband modem using advanced digital technologies. A HF-PLC broadband modem is a large digital design including base band DSP, equalization, and MAC tasks. Including a non-optimum advanced digital technology in the integration of a System on Chip (SoC) increases the final cost of the system.

Some of the previous investigations have focused on the hardware problems impulsive noise generates, as inexpensive electronic components cannot work properly under these circumstances. We have focused on analog-to-digital and digital-to-analog converters, trying to improve their performance for power line communications [12].

6.1. Converters

The analog-to-digital converters (ADC) remain one of the most expensive parts of a PLC modem. The most critical criteria in choosing such data converters are that they shall not degrade the signal-to-noise ration (SNR) and that the data converters shall not introduce any spurs or distortions.

We developed a new technology to implement low cost AD and DA converters using FPGAs and a few external components [12]. The FPGA digital output pins are used as voltage or current sources, and a passive RLC network implements a continuous time multi-bit Delta-Sigma converter. This architecture drastically reduces the cost and size of the PLC modem.

Delta-Sigma converters take the best of analog and digital worlds, combining a fast analog network to shape the noise, and a high precision low-pass digital filter. Our objective is to reduce the analog side of the converters as much as possible.

But the problem of impulsive noise still remains, as converters with broad bandwidth are required to process the high dynamic range of the ADC input (the signal and the impulsive noise). The usual approach is using a coarse converter followed by a fine converter (Figure 3), both based on the *flash* architecture.

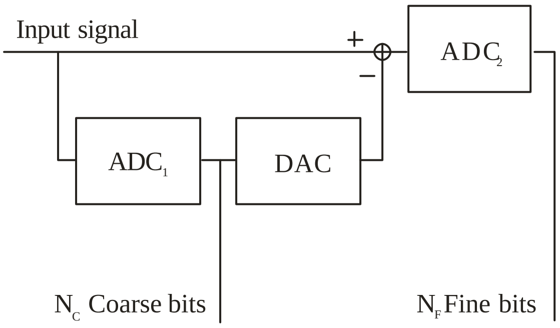


Figure 3. Pipelined converters

We are working to reduce the cost and size of these converters, trying to pipeline two Delta-Sigma converters; a high-dynamic-range converter without much precision, followed by a precise converter that focuses on the signal dynamic range. This solution will also decrease the complexity of the analog design, as Delta-Sigma converters require more signal digital processing reducing the analog side of the converter, what is a great advantage comparing them with flash converters. It is important to understand that mixed technologies which integrate digital and analog circuits in the same chip are too expensive and restrict the size of the final chip.

The design of a completely digital architecture, with just a few very simple external components, is the final goal of our research. This self-imposed restriction makes many useful analog circuits, such as automatic gain control or analog filters, not suitable for our design. Without gain controls, the possible variation in amplitude of the received signal increase the required dynamic range of the analog-to-digital converters. Moreover, state of the art technologies aim towards smaller gate lengths, what also restricts the dynamic range.

7. International Initiatives

There are two kinds of initiatives related to PLC, which should be encouraged by researchers worldwide, added to the obvious applications in domotic environments. Standardization efforts will allow us to offer PLC devices to the market, and new applications which demand distributed networks appear as perfectly suitable services for PLC networks.

An example of the first kind of initiatives is the integrated project "Open PLC European Research Alliance (OPERA)" included in the sixth European research frame. This project aims to develop a uniform European Power Line Communications standard, what will surely encourage competition in the broadband market. Universities, energy companies, telecommunication equipment manufacturers, and consultancies, all of them part of the OPERA project, plan to develop a European standard in two years.

The MOSAIC-HS project intends to promote a common standard development, that will provide inter-operability between relevant systems, as well as integrated applications, which will cover the whole range of elderly and disabled users and application fields. These applications include many home automation systems, which will surely take advantage of PLC networks, providing a wide market for PLC devices.

8. Conclusions

Communications through power lines offer a broad field for investigation. We have provided a review of the main problems that the PLC modem technology faces, problems representing the research areas for PLC where more studies are still necessary.

The modulation techniques, suitable MAC protocols or advanced digital designs will surely be fruitful fields of investigation.

We have also enumerated some of the most interesting ideas proposed in the last years to solve these problems, and described our current research dealing with PLC modems. Particularly, some ideas from our work with converters have been suggested.

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