An Interconnection Approach and Performance Tests for In-home PLC Networks

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Abstract—The concept of the electrical grid conceived as an infrastructure that only delivers power to the end users is going to disappear. In the next years, the electrical grid will be viewed as a smart grid (SG), namely, a distributed complex large scale system that needs to smartly manage flows of electricity produced by big or small plants. To fully exploit the SG potentialities, we think that it is mandatory to extend the SG concept to the home. In our vision the smart home (SH) network has to be developed to offer a broad variety of heterogeneous services that will improve the quality of life, yet addressing energy consumption challenges, and in parallel providing the delivery of information and entertainment services.

In this paper, we describe a SH network architecture characterized by a tree like topology, where the communication among the nodes belonging to different levels of the tree is based on the internet protocol (IP). Some of the functionalities of this solution have been implemented in a network testbed where broadband (BB) power line communication (PLC) devices are used to provide (i) an IP backbone to allow interconnection between heterogeneous devices belonging to different subnetworks, and (ii) an increase of the performances of narrow band (NB) PLC technologies.

I. INTRODUCTION

In the last years, we have assisted to an increased interest of the utility companies towards the development of communication technologies that allow for the remote automatic meter management (AMM).

Besides the need of AMM technologies, nowadays the utility companies are facing with new challenges such as [1]: the safe integration and the management of renewable energy sources; the management of plug-in electric vehicles that may cause a large load increase on sections of the grid; the management of demand side and demand response allowing the customers to collaborate in order to adapt the production and the delivery of electricity to achieve energy efficiency and saving.

In the next years, the electrical grid will be viewed as a smart grid (SG), namely, a distributed complex large scale system that needs to smartly manage flows of electricity produced by big or small plants. Therefore, the management of the SG will require a pervasive telecommunication infrastructure to allow the entire supply chain of electricity, to benefit from a bidirectional, reliable, short and long distance communication.

Industries and standardization organizations have proposed the use of narrow band (NB) power line communications

(PLCs) to support the requirements of the outdoor (bulk generation, transmission and distribution domains) SG applications. On the other hand, broadband (BB) PLCs solutions are spreading to the in-home network market. This happens because the PLC infrastructure is indeed pervasively deployed and its exploitation for communication purposes does not require any additional cost.

To fully exploit the SG potentialities, we think that it is mandatory to extend the SG concept to the home, namely, the customers domain. In our vision the smart home (SH) network has to be developed to offer a broad variety of heterogeneous services that will improve the quality of life, yet addressing energy consumption challenges, and in parallel providing the delivery of information and entertainment services. Nevertheless, the full deployment and exploitation of a broad variety of electronic appliances and devices, e.g., TVs, HVACs, PCs as well as sensors, detectors and actuators, is nowadays limited by coexistence and interconnection problems, i.e., interoperability. In fact, a large number of vendors has put on the market devices for in-home applications that use different standard, protocols, and even different media to communicate. In our opinion this is the main obstacle to the growth of the SH market.

We think that, in order to exploit the huge potential of a smart home, the full interoperability among different types of standard and protocols has to be offered seamlessly. With this aim in mind, we can easily liken a SH to Internet, i.e., a global system made of independent networks of devices based on the internet protocol (IP).

In this paper, we describe a SH network architecture. It is characterized by a tree like topology, where the communication among the nodes belonging to different levels of the tree is based on IP. To integrate devices, which are not IP based, in our IP network, we introduce the Bridge nodes. These nodes translate IP packets into proprietary communication protocols and vice versa.

The idea of using IP technology to ensure connectivity between devices within an in-home network has been presented in several works in the literature. The differences brought by this SH solution w.r.t. the ones presented in [2], [3], [4] can be summarized as follows.

- The network can be divided in Areas. Each Area is managed by an area gateway (AG). This allows for

offering different services to different areas without the need to know the services provided by the other AGs. Further, it overcomes the single point of failure problem.

- The root node, which we refer to smart home gateway (SHG), can request some services to the AGs. This allows for applying complex scenarios in which one or more areas are involved.

In this paper, we show some of the functionalities of the presented SH solution through an implementation of a network testbed. More precisely, we first show the performance - in terms of throughput and frame error rate - obtained testing in a single and in a multi floor house two representative NB-PLC solutions, i.e., one based on orthogonal frequency division multiplexing (OFDM), and the other based on frequency shift keying (FSK). The test results show that the performance of the OFDM-based solution are very poor when working in the multi floor scenario where channels exhibit higher attenuation. To solve this problem, we implement a network prototype where BB-PLC devices are used to provide an IP backbone that leads to a significant improvement of the performances of the OFDM-based solution, and further it offers connectivity between heterogeneous devices belonging to different subnetworks.

The reminder of the paper is as follows. In Section II, we glance at the state-of-the-art of PLC technologies. Then, in Section III, we describe the network architecture. The test campaign results are reported in Section IV, and finally, the conclusions follow in Section V.

II. STATE-OF-THE-ART OF PLC TECHNOLOGIES

Power line communications make use of the existing power line grid to transmit data signals. There is a broad range of applications for which PLCs have been or are being used, e.g., remote metering, command and control of domotic systems, small office-home office (SOHO), and recently, smart grid applications. Essentially, the PLC devices can be grouped into two categories, i.e., narrow band and broadband devices, according to the bit-rate that they can achieve.

Narrow Band PLC Technologies. They have been developed with the scope of offering indoor (home automation) and outdoor (smart grid) command and control services. These technologies are cheap and offer low bit-rates. The frequency bands dedicated from standardization organizations to NB-PLC devices vary among the continents. In the EU, the CENELEC issued the standard EN 50065 that specifies four frequency bands for communications over PL networks [5]. The band A (3–95 kHz) is reserved exclusively to power utilities. The band B (95–125 kHz) can be used for any application. The band C (125–140 kHz) is dedicated to in-home networking systems. The band D (140–148.5 kHz) is reserved to alarm and security systems. In the US and Asia, the regulation is different. FCC and ARIB allow PLC devices to work in the band 3–500 kHz.

In Table I, we report the NB-PLC technologies developed for home automation applications. For the interested reader, more details can be found in [5, Chapter 7]. From

TABLE I
NB-PLC TECHNOLOGIES.

NB-PLC			
	Insteon	Konnex	X10
Spectrum	CENELEC C	CENELEC B CENELEC C	CENELEC B
Modulation	BFSK	BFSK Spread FSK	PPM
Bit-rate ($kbit/s$)	2.4	1.2 to 2.4	0.05
MAC	-	CSMA	CSMA/CD
IP	YES	YES	NO
NB-PLC			
	CEBus	UPB	HomePlug CC
Spectrum	CENELEC C/ FCC/ARIB	50 Hz 60 Hz	CENELEC A-C/ FCC/ARIB
Modulation	Spread spectrum	PPM	DCSK
Bit-rate ($kbit/s$)	8.5	0.48	0.6–7.5
MAC	CSMA/CD	-	CSMA/CA
IP	-	-	YES

Table I, we only notice that the listed technologies work in different frequency bands and adopt different physical (PHY) and medium access control (MAC) layers. Therefore, these technologies are not interoperable. Furthermore, we note that even coexistence of those devices whose MAC layer is based on carrier sense multiple access (CSMA) is not assured since this would require sharing some specific protocol structure and parameters.

Besides the technologies listed in Table I, we notice that there are other NB-PLC technologies that have been developed for smart grids applications. The most important are the PRIME [6], and the ERDF G3-PLC [7] solutions. The PRIME solution offers data rate up to 128 $kbit/s$, whereas G3-PLC offers data rate up to 34 or 240 $kbit/s$ when working on the CENELEC A or FCC band, respectively. Both the previous solutions have the physical layer based on orthogonal frequency division multiplexing (OFDM), and the MAC layer based on CSMA.

Regarding the standardization aspect, currently, two working groups, the IEEE P1901.2 and the ITU-T G.hnem, are specifying the PHY and the MAC layers of NB-PLC solutions for communication below 500 kHz.

TABLE II
BB-PLC TECHNOLOGIES.

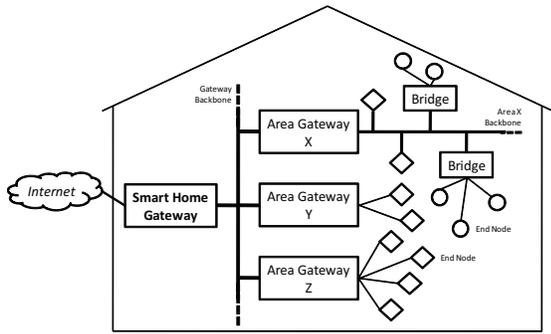| BB-PLC			
	HomePlug AV	HomePlug GP	HD-PLC
Spectrum (MHz)	2–30	2–30	4–30
Modulation	OFDM Bit loading	OFDM/ QPSK	W-OFDM Bit loading
Bit-rate ($Mbit/s$)	200	3.8–9.8	190
MAC	TDMA CSMA/CA	CSMA/CA	TDMA CSMA/CA
IP	YES	YES	YES

Broadband PLC Technologies. They have been developed

Fig. 1. Logical scheme of a generic smart home network.

with the aim of offering SOHO and multimedia services. Essentially, BB-PLC devices work on the frequency band 2–30 MHz, and make use of advanced modulation techniques such as OFDM and bit-loading to offer bit-rates in the order hundreds of $Mbit/s$. The most relevant examples of commercial devices are the ones compliant with the HomePlug AV (HPAV) [8] and the HD-PLC [5, Chapter 7] industry standard. Their MAC layer is based on time division multiple access (TDMA) for high quality of service traffic, and to CSMA/CA for best effort traffic. Furthermore, their network layer is based on IP. In Table II, we summarize the characteristics of BB-PLC devices. It is interesting to note that both solutions, i.e., HPAV and HD-PLC, have been used as baseline for the PHY layer specification of the IEEE P1901 standard, released in December 2010 [9]. Finally, we note that also ITU is delivering the ITU-T G.hn standard for in-home communications over power lines, coax, and phone lines [10]. G.hn PLC devices will work on the frequency band up to 100 MHz, will adopt OFDM, and will offer bit-rates up to 1 $Gbit/s$.

III. GLOBAL NETWORK ARCHITECTURE

As we have seen, there are several PLC devices that can be used within the home to offer certain network services. Clearly, also wireless systems can be used. Unfortunately, in general, these devices cannot communicate. Therefore, we describe a network architecture that allows for an easy integration of the different communication systems overcoming the lack of connectivity between devices. The general SH network architecture is depicted in Fig. 1, where the root, represented by the Smart Home Gateway (SHG), plays the role of interface between the home and the outdoor environment. In one hand, the SHG is connected to Internet and thus it is also reachable by energy service providers while on the other hand, it is connected to the second level of the SH network, represented by a certain number of Area Gateways (AGs), through a backbone. These AGs are associated to the topology of the home and manage the lower level that is represented by End Devices (EDs) and End Nodes (ENs), grouped into subsystems/subnetworks.

In the following we describe in detail the components of the SH network.

End Device. At the bottom layer of the network, we find the End Devices (EDs). They represent the devices of the network

that provide the functionalities to the end-user. We note that the EDs can be either physical nodes, e.g., TVs, PCs, sensors and actuators, or virtual nodes grouped into a device that we name as Bridge. The difference between a physical node and a virtual node is that the first is IP addressable, while the second represents a device that uses a proprietary network protocol (not IP based).

Bridge Since we can have devices that operate using different standard and/or protocols, we decide to gather those compliant to a given standard, not IP based, in a subnetwork. Each subnetwork is addressable through a Bridge. It is worth noting that the Bridge can be also used to extend the coverage. To be more precise, a subnetwork can be split in more subnetworks in the case that some of its nodes are not in visibility.

The main role of the Bridge is to virtualize each node of its subnetwork in order to be reachable by other IP based devices and vice versa.

Area Gateway The next level of SH architecture is represented by the Area Gateways (AGs). Taking into account the topology of the house, we assume to divide it into areas, where each area can represent one or more rooms. The AGs are logical or physical entities that manage a given area of the house (see Fig. 1).

As anticipated above, under request, an AG gets the information regarding the EDs and their corresponding subnetworks, thus it will contain a data base with all the information regarding its area.

The AG is also responsible for building routing tables within its area. In particular, routing paths are selected taking into account the energy efficiency, i.e., the selected paths are the ones that need the lowest energy consumption to satisfy the QoS constraints, e.g., bit-rate, latency, delay.

It is worth noting that the assumption of dividing the house in areas allows for offering in a simple way a specific set of services to a given area of the house. This characteristic renders this network different from the solutions presented in the literature, e.g., [2], [3], [4].

Smart Home Gateway On top of SH network there is the Smart Home Gateway (SHG) that plays the role of coordinator and supervisor for the whole network.

Area and Gateway Backbones As we have seen, the SH network is pervasively deployed within the home. The choice of the physical medium that acts as backbone is therefore fundamental to reduce the set-up costs and make the SH network solution attractive.

We think that the power line is the most convenient solution to act as backbone. However, we note that this network is media independent, and thus the backbone can be realized using any media combination.

IV. NETWORK ARCHITECTURE TESTBED

In order to test some of the functionalities of the network architecture - in particular, the interconnection between NB and BB PLC devices and the range extension - we have

developed a network testbed consisting of different areas connected through an IP backbone based on HPAV [8] BB-PLC technology. Each area represents a given floor of the house and comprises an Area Gateway (AG), a NB-PLC/IP Bridge, and a NB-PLC modem (end-node). The AGs have been implemented by a network software running on a PC connected to the IP backbone through an ethernet cable. Note that, in the specific scenario, the absence of a SHG is not restrictive at all. In fact, the communication among SHG and AGs or EDs (directly connected to the IP backbone) can be later implemented using client-server softwares - e.g., middleware solutions - as a result of the underlaying IP technology.

To set the performances of this network solution, in Section IV-A, we define two metrics. Then, in Sections IV-B, and IV-C, describe two representative NB-PLC solutions whose PHY layer is respectively based on OFDM and FSK. The two technologies are compared through a test campaign in Section IV-D. Finally, in Section IV-E, we show the improvement of the performance that are brought by the use of this network solution.

A. Throughput and FER Definition

The first test that we will consider is meant to compare FSK and OFDM based NB-PLC solutions. To this end, we define two representative metrics, namely, the throughput and the frame error rate (FER). The throughput can be evaluated both at PHY and MAC layers as

$$THR_{PHY} = mN_g \quad [bit/s], \quad (1)$$

$$THR_{MAC} = nN_g \quad [bit/s], \quad (2)$$

where N_g represents the number of correct received frames per second detected exploiting either the knowledge of the transmitted frame, or the cyclic redundancy check (CRC) code where redundant bits are stored in the frame check sequence (FCS). Furthermore, m and n respectively represent the payload length (data encapsulated at the PHY layer) and the MAC layer data expressed in bits. As it will be clarified in the following, for each system under test, we can set the total number of transmitted frames N. Therefore, the FER can be obtained as

$$FER = \left(N - N_g^{tot}\right)/N, \quad (3)$$

where N_g^{tot} is the total number of correct received frames in a complete transmission. It is worth noting that FER takes into account corrupted frames as well as missed frames.

B. FSK-based System Details

To test a FSK NB-PLC solution, we use the hardware platform developed by ADD [11]. A general PHY frame encapsulation has the structure depicted in Fig. 2 where the 6

Fig. 2. PHY frame format of a FSK-based system.

bytes long preamble is used for synchronization, whereas the

2 bytes long header is used to define the type of frame. The following field is represented by the payload. As shown in Fig. 3, three different types of payload are available according to the error correction mechanism, namely, low, medium and high protection. Low protection drops any kind of error correction. Medium protection introduces 6 bits of forward error correction (FEC) every data byte making the system capable of correcting 3 bit error burst in a 14 bit block. High protection exploits a convolutional code with bit interleaving. The two bits of postamble terminate the frame. It is worth

(a) Low protection: $m = 8\,(n+2)$ bits.

(b) Medium protection: $m = 14\,(n+2)$ bits.

(c) High protection: $m = 16\,(n+2)$ bits.

Fig. 3. Payload structure for n data bytes.

noting that each data byte in the payload is part of the higher layer frame, i.e., the MAC frame.

When showing numerical results, we set the FSK hardware platform with the following parameters. The central frequency is set to 72 kHz with a working baud rate of 4800 bps. The two FSK tones are at frequency 69.6 kHz, and 74.4 kHz. Therefore, the system works in the CENELEC A band. Finally, we choose to transmit the maximum amount of data bytes, i.e., $n = 64$. Consequently, the payload length is set to $m = \{528, 1056\}$ bits for low, and high protection.

It is worth noting that FSK is also implemented in the KNX-PL132 standard [12] that is derived by the European Home Systems (EHS) protocol specs [13].

C. OFDM-based System Details

To test an OFDM NB-PLC solution, we use the hardware platform developed by Maxim [14]. It implements the PHY and the MAC layers of an OFDM system compliant with the G3-PLC standard [7]. According to [14], in Fig. 4 we show
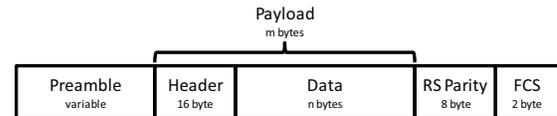
Fig. 4. PHY frame format of an OFDM-based system.

a general PHY frame. The preamble is a multi symbol field used to perform carrier sense operations, to enable control functions and to synchronize the receiver and the transmitter. The next two fields, namely, header and data, represent the payload whose length depends on the transmission mode, i.e., *normal* and *robust*. In normal mode, the error correction is performed through a Reed Solomon (RS) encoder, whereas the error check is done with a FCS. In robust mode, each bit

following the preamble is repeated 4 times. The FCS and RS fields length are 2 and 8 bytes, whereas the data length are set to $n = 113$ bytes for the normal mode, and $n = 8$ bytes for the robust one. Consequently the frame duration is the same for the two modalities.

The system works in the frequency band 32-95 kHz (CENELEC A) and its specification are detailed in Table III, where the frame control header (FCH) denotes a part of the preamble field that brings control information required for data demodulation.

TABLE III
OFDM-BASED SYSTEM SPECIFICATIONS

Number of symbols	$N_{sym} = 40$
Number of FFT points	$N_{FFT} = 256$
Number of overlapped samples	$N_o = 8$
Number of cyclic prefix samples	$N_{CP} = 30$
Modulation	DBPSK, DQPSK
Number of FCH symbols	$N_{FCH} = 13$
Sampling frequency [MHz]	$f_s = 0.4$
Number of preamble symbols (without FCH)	$N_{pre} = 9.5$

D. FSK vs. OFDM

In order to compare the NB-PLC solutions above described, we performed two trial campaigns connecting, at each time, a couple of modems to two power sockets within a house.

The first campaign took place in a single floor house. Whereas, the second took place in a three-floor house, whose electricity is distributed from the main panel (MP) to each floor through a floor circuit breaker (CB) located at the MP. In the latter case, we considered either the transmission between outlets belonging to the same floor or between outlets belonging to different floors. Appliances have been plugged and unplugged, e.g., television, washing machine, battery charger, fluorescent lamps, fridge, and so on.

During the test campaign, we considered different types of communication modes. More in details, for the FSK-based system we used low and high robust transmission, while for the OFDM-based system, we used normal and robust transmission modes.

Fig. 5(a) and Fig. 5(b) respectively show the complementary cumulative distribution function (CCDF) of the throughput, and the cumulative distribution function (CDF) of the FER for the FSK-based solution. Although not shown, we notice that no corrupted or lost frames have been observed using the FSK solution in the single floor house. Therefore, the throughput only depends on the modality by which the frames have been transmitted. The behavior changes when considering the multi-floor house. In this case, in fact, the FER increases and consequently the throughput decreases. This is simply explainable observing that channels associated to multi-floor houses, and in particular those associated to different floors, experience higher attenuation than those belonging to a given floor. We note the same behavior for OFDM (Figs. 6(a), and (b)).

TABLE IV
AVERAGE THROUGHPUT AND FER VALUES.

	MAC THR [$kbit/s$]		FER	
	Single Floor	Multi Floor	Single Floor	Multi Floor
FSK low	2.3098	2.2659	0	0.0190
FSK high	1.5208	1.5117	0	0.0060
OFDM normal	18.909	3.4345	0.0033	0.7856
OFDM robust	1.3198	0.3992	0.0010	0.6646

Now, in Table IV, we report the average throughput and FER values. From this table and Figs. 5, and 6, we note that, in general, OFDM allows for higher peak or average throughput than FSK. However, it has also to be said that, FSK offers better robustness, where with robustness we mean the highest probable throughput value. For example, considering the multi-floor case and FSK low/OFDM normal transmission modes, with probability equal to 0.9, FSK and OFDM respectively achieve a throughput of 2.079 $kbit/s$, and 0.055 $kbit/s$. Nevertheless, the choice between FSK and OFDM has to be done in conjunction with the required service.
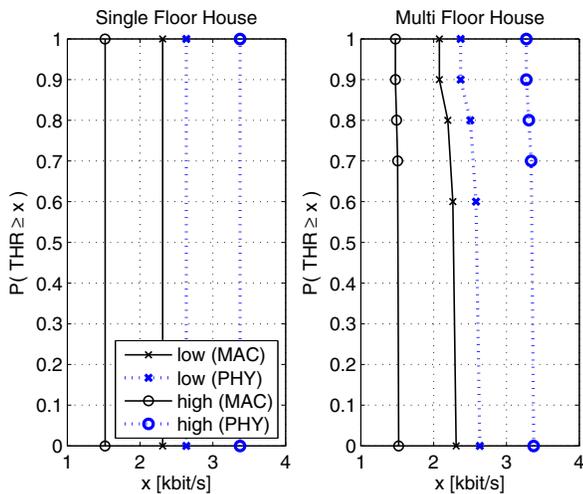
E. Connectivity and Range Extension

We now focus on the interconnection between NB and BB PLC devices. Looking at Fig. 6(b)-right, we see that OFDM shows very poor performance in terms of FER. Analyzing the data, we notice that the highest performance degradation occurs during communication across different floors due to the attenuation of PL channels. However, the use of the HPAV backbone combined with the Bridge functionalities allow for increasing performances of the OFDM-based system. In details, the HPAV modems are used to extend the IP backbone through different floors, and the Bridges provide the connectivity between OFDM and HPAV. In this perspective, the communications between OFDM modems (end node and Bridge) is performed on the same floor, while the communication across different floors is performed by the HPAV.
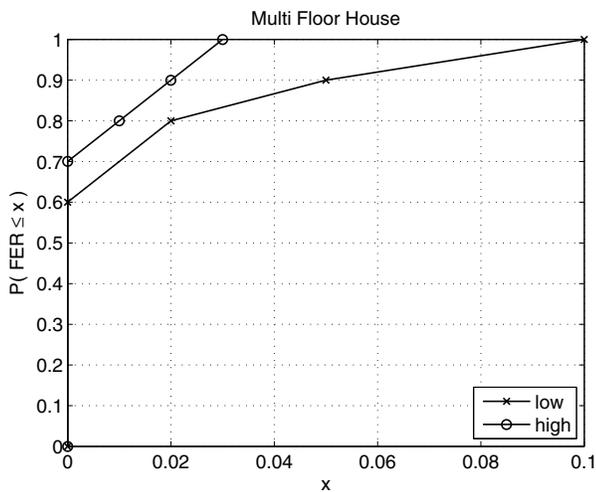
In Fig. 6(b)-right is depicted the CDF of the FER obtained using the HPAV extension. It is worth noting that there is a huge improvement in term of FER.

V. CONCLUSION

Nowadays, several communication devices are available for home networking and automation. Nevertheless, in general, these are not interoperable. To solve this problem, we have presented a network architecture characterized by a tree like topology, where the communication is based on IP. Furthermore, we have tested, in single and multi floor houses, two representative NB-PLC devices, i.e., one based on FSK and the other based on OFDM. Test results have shown that, although OFDM, in general, allows for higher peak throughput than FSK, it shows poor performance in terms of FER, thus throughput, when working in the multi-floor house. This issue has been solved developing a network testbed where BB-PLC devices are used to provide an IP backbone that allows for (i) connectivity between NB and BB PLC devices, and (ii) range extension.

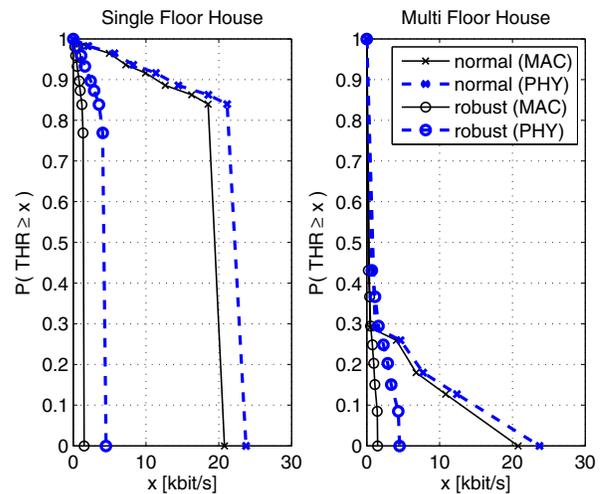(a) PHY and MAC throughput for low and high robustness.

(a) PHY and MAC throughput for normal and robust mode transmission.

(b) FER for low and high robustness.

(b) FER for normal and robust mode transmission.

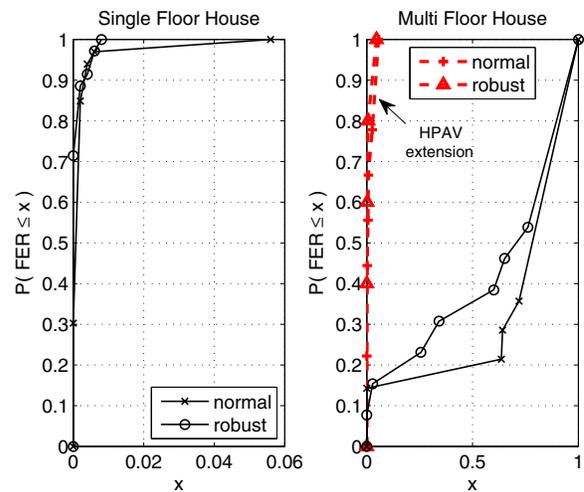Fig. 5. FSK-based system performances within single and multi floor houses.

Fig. 6. OFDM-based system performances within single and multi floor houses.

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