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Challenges for 1 Gbps Power Line Communications in Home Networks

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Abstract—**We address the challenges related to the development of very high speed power line communication (PLC) systems in the home environment. The development of such a technology is fundamental to realize the objective of reliably delivering new high speed services in the home environment in a network that integrates in a coordinated fashion also wireless systems. That is, an in-house network with the need of "no new wires". We start with an overview of the state of the art PLC technology, and then we describe our vision on application scenarios, and requirements. We address the problem related to transmission bandwidth, channel modeling, capacity evaluation as well as we describe novel advanced transmission technologies that enable reliable high speed transmission. We show that by enhancing current technology bandwidth up to 100 MHz, Gbps transmission is achievable.**

Keywords—home networks, power line communications (PLC).

I. INTRODUCTION

The broadband services penetration can be enhanced by extending the access network quality of services (QoS) in the home network up to the end devices. A fully connected digital home will be a seamless extension of the access network which will enable new services and potential benefits to the end-users in terms of information access, security, health, quality of life. The required performance has to be high since the in-home network has to provide several services simultaneously, each with different requirements. Further, devices have to be low cost, and should be easy to install to allow for mass penetration. To this respect, the paradigm "no new wires" motivates the development of wireless and power line communication systems. The latter can benefit from the existing largely deployed in home-power line network. Our view is that wireless and PLC communication systems shall not only coexist but converge and interoperate in order to achieve the ambitious goal of broad band Gbps penetration into the home. The FP7 OMEGA (Home Gigabit Networks) project [1]-[2] targets this goal and is devoted to develop innovations in transmission technology and convergence layer for wireless i.e., wireless local area networks (WLAN), ultra-wide band (UWB) and 60 GHz radio systems, wireless optics (visible light and infra-red) communication system, and PLC systems.

In this paper we address the challenges related to the development of very high speed power line communication systems in the home environment. We describe our vision on application scenarios, and requirements, then we give an overview of state of the art PLC technology. We address the problem related to transmission bandwidth, channel modeling, capacity evaluation as well as we describe novel advanced transmission technologies that enable reliable high speed transmission. Taking into account the electromagnetic compatibility issues, we show that by enhancing current technology bandwidth up to 100 MHz, Gbps transmission is achievable.

II. VISION AND APPLICATION SCENARIOS

In our vision, the OMEGA home network will support Gbps transmission with low latency, and high coverage within the home, in continuity of the access network. The network concept is depicted in Fig. 1.

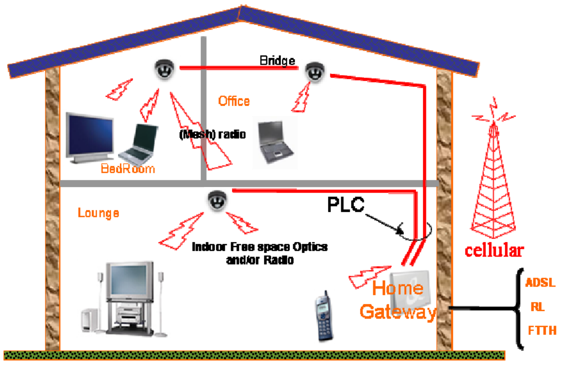


Fig. 1: Ultra-broadband home area network – OMEGA.

The idea is based on a collaborative mesh network that deploys wireless, and PLC systems connected to a home gateway to reach the outdoor access network. The PLC network will be used not only to link the devices to the gateway but also to connect the bridges within the OMEGA network [3]. This will allow room-to-room connectivity for the channels constrained to a single 'space', e.g., UWB, and it will increase the available data rate to 'wired' nodes of the network. The targeted applications for in-home PLC are Audio/Video, Voice, Internet, Interactive multimedia (video conf, etc.), Home control, Security and Surveillance. Envisioned application scenarios, although not limited to, are:

Family Scenario: it requires two HDTV streaming flows, plus one music streaming, one video streaming and one VoIP connection. The expected throughput is equal to 90 Mbps.

Home-networking: it requires one video-conference plus one HDTV connection, high speed (1 Gbps) file downloading, VoIP connections, game and NAS safeguard. The expected peak throughput will be in the order of 1 Gbps.

High Rate SOHO (Small Office - Home Office) 1 video-conf + 1 HDTV (on-line demo) + 5 continuous files downloading + 3 VoIP = 320 Mbps; 1000 Mbps peak.

The Home-networking and SOHO scenarios are similar in terms of flows, but SOHO requires much wider coverage areas.

III. REQUIREMENTS

The innovative solutions developed may be classified as solutions towards coexistence, interoperability, compatibility, and compliance with existing PLC standards, e.g., HomePlug AV (HPAV) [4]. We further emphasize that the OMEGA PLC system will be integrated in home networks where high speed services are provided not only by other PLC devices, but also by wireless systems. Below, we first report a definition of such terms, and then we discuss our vision.

Coexistence is the state of two or more systems or components to exist together with or without mutual interaction.

Interoperability is the ability of two or more systems or components to exchange information and to use the information that has been exchanged.

Compatibility is the ability of a system or components to exchange information with existing systems and/or standards in a backward sense, i.e., use interfaces and data from earlier versions of the system.

Compliance is a state of being in accordance with established systems and/or standards. Equivalently, compliance refers to full compatibility.

The goal is the development of a PLC system that is capable of achieving increased performance compared to existing technology so that high speed reliable transmission in the order of Gbps is provided in in-house environments. The OMEGA PLC technology will be integrated with radio and free optics communication systems and as such shall not only coexist with them but shall also be interoperable. Coexistence will be allowed by means of electromagnetic compatibility, while interoperability will be allowed through the use of an optimized inter-MAC. Furthermore, coexistence with other technologies, for instance, radio amateur systems, radio broadcast systems, and even DSL technology shall be supported.

At the same time the OMEGA PLC system shall coexist with current PLC standards, in particular HomePlug AV. We recall that increased throughput is achievable by means of the usage of wide bandwidth transmission. The technical approach followed by OMEGA PLC technology consists in increasing the bandwidth up to 100 MHz and taking into account the electromagnetic compatibility issue (as it will be described in Section III). As such the coexistence with existing technology (whose spectrum is below 30 MHz) will be made possible by PHY and MAC algorithms targeting spectrum sharing with a detect and avoid approach.

Interoperability, and more importantly compatibility, with existing standards, namely HomePlug AV, will in principle be allowed by defining PHY mechanisms that enhance HPAV bandwidth and that allow communication both with existing devices and new (OMEGA) devices. To this respect at the PHY layer compatible transmission techniques in the lower band with the existing ones, e.g., windowed OFDM, shall be developed. For the upper band, existing or novel transmission techniques can be developed.

A. Services and QoS

For each supported service the specified QoS parameters are: coverage, throughput, latency (i.e. delay), jitter (i.e. delay variation), bit error rate. The key QoS requirements are hereafter listed.

The targeted maximum bit rate (PHY layer) is 1 Gbps. A mix of multiple simultaneous QoS and best effort services has to be sustained without noticeable degradation such as HD TV channels @ 6-12Mb/s, SD TV channels @ 4Mb/s, Internet access @ 2Mb/s, Security cameras @ 500kb/s, Voice calls @ 120kb/s.

Coverage criterion. Reliable and robust bandwidth must be available across 95% of socket pairs in the home in both single and multiple phase homes. Typically, IP rate of 30-50 Mbps must be guaranteed over 95% of socket pairs.

Latency. Real time services such as Gaming & VoIP require low latency. The maximum latency between nodes, in each direction, shall be <5 ms. We note that the latency of the flows is particularly impacted by the packet retransmission scheme, the scheduling scheme, and the presence of overheads in the transmitted data frames.

IV. STATE-OF-THE ART

A very large panel of standardisation activities is focusing on PLC. The three main bodies dominating the PLC standardisation for transmission aspects are ETSI PLT, IEEE P1901, ITU G.hn. Furthermore, consortiums such as HomePlug Powerline Alliance, UPA (Universal PowerLine Association), CEPCA (Consumers Electronics Powerline Communication Alliance) play an important role in the definition and proposal of PLC systems.

IEEE P1901 "Standard for Broadband over Power Line Networks" (BPL) is currently developing specifications for high speed (>100 Mbps at the physical layer) PLC devices. The standard will use transmission frequencies below 100 MHz. The aim is to define MAC and PHY layer specifications for all classes of BPL devices. Many companies and standard bodies are participating in the developing IEEE P1901 standard including HomePlug Powerline Alliance, UPA and CEPCA. HomePlug Powerline Alliance and Panasonic (CEPCA member) have proposed within the IEEE P1901 working group to converge towards a common MAC layer supporting both HPAV and Panasonic (i.e. HD-PLC) PLC PHYs. HomePlug – Panasonic proposals have been selected as “Technology Baseline” in the Access, In-Home and Coexistence clusters of P1901 workgroup, all other proposals (among them UPA, which includes DS2, proposal) being rejected. This proposal would ensure at least the coexistence between HomePlug and Panasonic technologies; and in the end make possible interoperability. Nevertheless, the inter-PHY protocol that would allow the coexistence between HPAV version (OFDM) and Panasonic version (wavelet OFDM) is yet to be finalised.

In Table I we summarize the main differences between Panasonic [5], HPAV [4], UPA systems [6].

	Panasonic	HPAV	UPA
Modulation	wavelet OFDM	windowed OFDM	windowed OFDM
Channel coding	Reed Solomon (RS) - convolutional code (CC); LDPC	Parallel-concatenated turbo convolutional code	RS + 4D-TCM concatenation
Mapping	PAM 2-32	QAM 2, 4, 8, 16, 64, 256, 1024	ADPSK 2-1024
FFT/FB size	512 (extendable to 2048)	3072	NC
Max number of carriers	NC	1536	1536
Sample frequency	62.5 MHz	75 MHz	NC
Frequency band	4-28 MHz 2-28 MHz optional	1.8-30 MHz	0-30 MHz 0-20 MHz optional
PHY Rate	190 Mbps	200 Mbps	240 Mbps
Information Rate	NC	150 Mbps	158 Mbps
Programmable notches	Yes	Yes	Yes
Power Spectral Density	NC	-56 dBm/Hz	-56 dBm/Hz
Media Access Method	TDMA-CSMA/CA	TDMA-CSMA/CA	ADTDM
Hidden Node Avoidance	NC	Yes	Yes
Duration MAC frame	NC	Variable	Variable
MAX number of nodes	64[*3]	NC	64
Network identifier	Yes	Yes	Yes

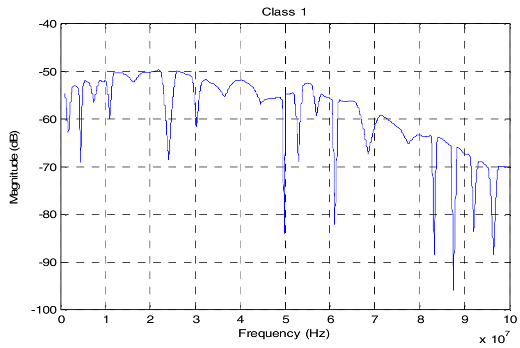
Table I: Comparison of the PHY and MAC characteristics of P1901 proposals.

Site number	Site information	Number of transfer functions
1	House - Urban	19
2	New house - Urban	13
3	Recently restored apartment – Urban	12
4	Recent house – Urban	28
5	Recent house – Urban	34
6	Recent house – country	22
7	Old House - country	16

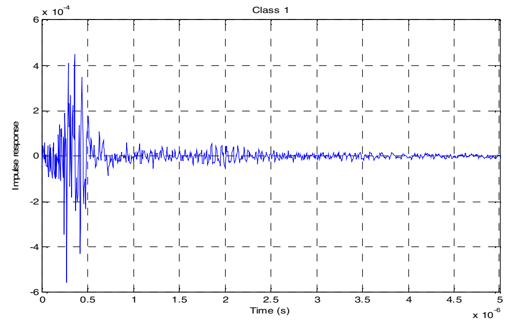
Table II. Distribution of transfer functions by site.

V. TECHNICAL CHALLENGES

To achieve the goal of delivering very high speed in-home PLC services, significant improvements have to be made both at the physical layer and at the MAC layer. The technical approach followed starts with increasing the bandwidth from current 30 MHz up to 100 MHz having in mind the electromagnetic compatibility constraints. The usage of new bandwidth requires the characterization of the channel and background disturbances as well as the development of physical layer and MAC layer algorithms that are matched to such a channel.



a) Magnitude



b) Impulse response

Fig. 2. Illustration of a frequency and time response for a class 1 channel.

A. Channel Characterization

Broadband PLC channels are characterized by high frequency selectivity. Further, background disturbances as colored Gaussian noise, impulse noise, and narrow band interference from broadcasting stations and radio amateur signals are present.

The channel transfer function, amplitude and phase, varies in time and frequency. A common feature to in-door and out-door networks is the reflection phenomenon. Thus in both cases this leads to multi-path transmission which comes together with a frequency selective channel.

In the context of the OMEGA project it is expected that the measurements resulting from the experiments carried out will help to find the appropriate parameter values of these theoretical models of channel and noise. For this purpose noise and wideband propagation measurements were undertaken in the 30 KHz – 100 MHz band in various indoor channel environments (country and urban, new and old, apartments and houses).

The PLC transfer functions study presented hereby relates to seven measurement sites and a total of 144 transfer functions. For each site, the transfer function is measured between a principal outlet (most probable to receive a PLC module) and the whole other outlets (except improbable outlets such as refrigerator outlets...). The distribution of the transfer functions by site and the characteristics of each site are given in Table II. A deterministic model describing magnitude and phase of complex transfer functions of PLC networks up to 100 MHz has been developed. Also in the proposed model, channels of same electrical circuit are treated separately from channel of different electrical circuits, as they have different statistical properties.

As described in [7]-[8], a PLC channel classification is realized, and an average magnitude and phase channel model by class is proposed. The multipath characteristic of PLC channels is then introduced by a statistical-based approach.

PLC channels were classified into 9 classes per ascending order of their capacities according to the Shannon's capacity formula. For this classification we always use a same reference noise and we refer to an upper limit of -50 dBm/Hz for the Power Spectral Density (PSD) emission mask. The transfer functions of class 1 are those which convey the smallest bit rate, the transfer functions of class 2 are those which convey rates higher than those of class 1, etc. As an example for the class 1, Fig. 2 represents the supplied transfer function magnitudes in dB, and the impulse response as a function of the time in seconds.

Currently, modeling of noise is undergoing on the basis of the undertaken measurements.

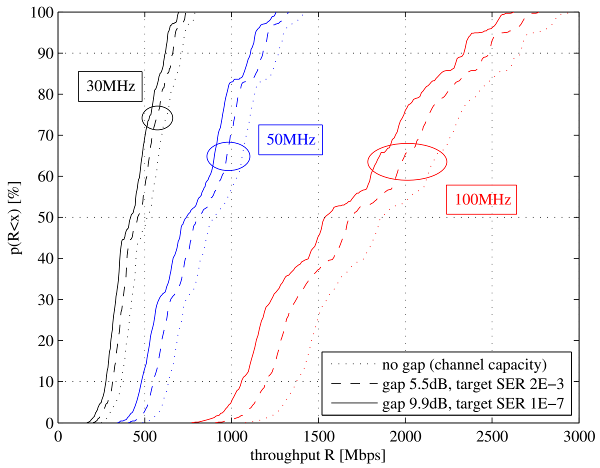


Fig. 3: Theoretical capacities of power line channels for various bandwidths.

B. Capacity Evaluation

In PLC, the determination of the capacity is mainly dependent on the representation of the channel. This representation can be established from statistical models or from measured channels and this with different levels of complexity. The capacity as well as maximal data rate computations are fulfilled using previous channel measurements.

The transfer function and a stationary noise serve for determining the signal to noise ratio (SNR) from which the capacity or the maximum data rate can be calculated using Shannon's formula. This only provides an upper bound of the channel capacity. In order to determine a more realistic maximum data rate a gap, usually denoted Γ, can be introduced to take into account the fact that the transmitted symbols will lead to a given symbol error probability. In order to evaluate the influence of the gap choice on PLC transmission data rates, the cumulative distribution function (CDF) of the computed data rates over the 7 different sites transfer functions and stationary noise measurements are computed. As an example, the curves of Fig. 3 are related to the channel capacity using three different spectra 30 MHz, 50 MHz and 100 MHz [9]. The capacity increases with the spectrum width. It is almost proportional to the spectrum width as a consequence the CDF function steepness decreases with the widening of the spectrum.

For instance, the curves for 50 MHz show that in the 50% of the cases, the channel capacity will be at most equal to 903 Mbps, whereas the data rate with Γ=5.5 dB will at most of 813 Mbps and with Γ=9.9 dB will be at most of 740 Mbps. Note that Γ=5.5 dB and 9.9 dB correspond to uncoded M-QAM symbol error rate of $2\text{x}10^{-3}$ and 10^{-7}, respectively.

Moreover, the wider the used frequency spectrum is, the higher the loss related to the value of used gap is. This difference is due to the fact that there are more frequency bands for larger spectra where there is a fall in the allocated bits [9].

An important issue is the consideration of the EMC constraints for the determination of the capacity. That is, in order to assess the real throughputs of the whole measured PLC channels, the optimal Power Spectral density of the PLC modem has to be determined in order to be compliant with the electromagnetic emission requirements [10].

VI. PHYSICAL LAYER AND MAC IMPROVEMENTS

Wideband PLC channels exhibit long time dispersion that is responsible for intersymbol interference (ISI) in digital communications. To simplify the equalization task multicarrier modulation is becoming the *de facto* transmission technology. In particular orthogonal frequency division multiplexing (OFDM) has been adopted in the HPAV and UPA solutions. OFDM is an elegant and simple solution to orthogonalize frequency selective channels provided that a cyclic prefix (CP) is added. Two weak points are first that the CP may reduce transmission rate, and most importantly OFDM sub-channels have a sinc frequency response. This translates into poor spectral confinement that makes the system vulnerable to narrow band interference, and multiple access interference in FDMA approaches where devices are multiplexed by partitioning the tones among active users. Further, OFDM is affected by channel time selectivity, i.e., time variation, which becomes more detrimental as the OFDM symbol duration (number of tones) increases [11]. PLC channels exhibit a periodic time variant behavior that is due to appliances that exhibit a time variant impedance related to the mains frequency. Several strategies can be followed to increase OFDM performance. Signal processing algorithms as time-domain equalization to shorten the channel length, or pulse shaping and windowing techniques.

Another approach is to develop advanced multicarrier schemes that retain the good properties of OFDM and possibly provide enhanced performance. We refer to these schemes as filter bank modulation. Among them,, Filtered Multitone Modulation (FMT), and Offset QAM/OFDM are gaining some interest and are described in the following.

Clearly, to achieve high throughput, efficient filter bank modulation schemes have to be combined with high order modulation (up to 4096 levels QAM) and powerful channel coding schemes. We also emphasize that impulse noise is another significant impairment in PLC channels. Filter bank schemes combined with channel coding and signal processing algorithms can provide significant gains in the presence of impulse noise.

An important aspect is how to develop a 100 MHz physical layer solution that can coexist or even interoperate with existing technology, e.g., HPAV. A possible approach is to develop a filter bank based system that is capable of detecting and communicating, for instance, with an existing HPAV device in the low portion of the spectrum below 30 MHz, while using the high portion of the spectrum 30-100 MHz to communicate with a new technology device. At the same time if no low bandwidth devices are detected, then the whole spectrum can be allocated to the new technology devices. This approach leads to a kind of cognitive PLC system that can be managed by the MAC layer. This MAC will, therefore, be significantly innovative compared to the existing single technology CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) scheme adopted in current systems (HPAV and CEPCA). It will allow enhancement of cooperative techniques towards seamless handover between heterogeneous technologies.

Regarding the cross layer mechanisms, advanced management and optimisation of resources and QoS in a context of multi-cell deployment have to be developed. In particular, single user but also multiple user resource allocations (bits, sub-channels, codes) in a multi-user environment will be developed in order to maximize the throughput of each user.

A. FMT Modulation

FMT is a discrete time implementation of a multicarrier system where sub-carriers are uniformly spaced and the sub-channel pulses are identical. FMT modulation has been proposed for transmission over broadband frequency selective channels both in very high speed digital subscriber lines (VDSL) [12], and more recently in wireless scenarios [11], [14]. The design of the sub-channel filters, and the choice of the sub-carrier spacing in an FMT system, aims at subdividing the spectrum in a number of sub-channels that do not overlap in the frequency domain, such that we can avoid the ICI and get low ISI contributions. In FMT the sub-channel ISI is handled with sub-channel equalization. Provided that equalization is performed, FMT achieves higher spectral efficiency than OFDM because it does not require the cyclic prefix.

The FMT system can support user multiplexing in a FDMA fashion through the partition of the available tones across the users similarly to OFDMA [14]. FDMA can be combined with TDMA, which allows good transmission granularity to be obtained and system resources to be allocated in an efficient manner. FMT has superior performance than OFDMA because of the sub-channel spectral containment that allows sub-channel orthogonality to be maintained when deployed in a network with non-synchronized users.
Further benefits are the sub-channel spectral containment that allows deep spectral notches to be fulfilled and guarantees robustness to narrow band interference [13].

One important aspect is the implementation complexity of the scheme. We have recently proposed low complexity multiuser FMT architectures that are based on FFT and low rate filtering [13]. A block diagram of such implementation is depicted in Fig. 4.

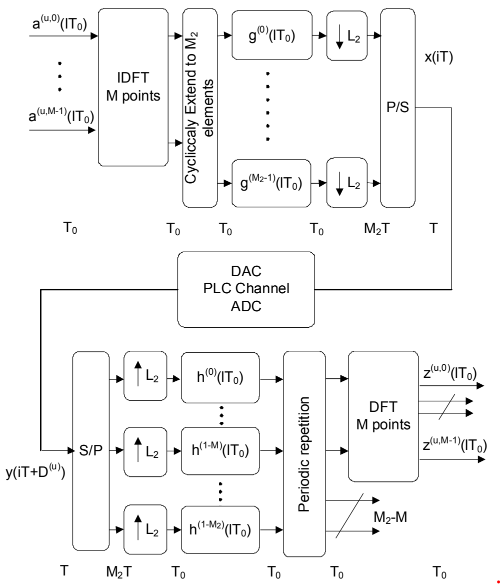


Fig. 4. Efficient implementation of FMT with *M* sub-channels.

B. Offset QAM/OFDM

Another filter bank based approach we envision for high speed PLC is known as OFDM/OQAM, where OQAM stands for Offset-QAM. Indeed for each sub-carrier a time-offset is introduced between the real and imaginary part of the complex data symbols, e.g. QAM, that have to be transmitted. At the end this leads to orthogonality conditions that are defined in the real field for the PAM symbols resulting from the initial QAM constellations. Similarly to FMT, OFDM/OQAM is based on an exponential modulation of a prototype filter and does not require any CP. Furthermore for OFDM/OQAM the frequency spacing between sub-carriers is strictly equal to the inverse of the duration of the QAM symbols, so it attains the maximum theoretical spectral efficiency. A detailed description of the filter bank structure of OFDM/OQAM is provided in [15]. It can be seen that the orthogonality conditions for the prototype filter are equivalent to the ones required for Wavelet OFDM (WOFDM), i.e. the modulation scheme proposed by Panasonic for PLC. WOFDM and the windowed OFDM proposal of HPAV are also the two possible modulation schemes for the in-home PHY layer inside IEEE P.1901.

As all these filter bank based multicarrier modulation schemes allow us to get better frequency properties, they are of a particular interest with respect to the stringent frequency masks imposed for PLC links. This is illustrated in Fig. 5 where it can be clearly seen, for the US HPAV frequency mask , that OFDM/OQAM provides a higher attenuation in the notches for the 3 different prototype filters we have simulated. These results have been obtained using the windowed OFDM of the HPAV specification, i.e. with an FFT size M=3072. For OFDM/OQAM the three prototypes we have tested are: IOTA4 a prototype optimized in continuous-time w.r.t. to time-frequency localization (TFL) and then truncated and discretized leading to a filter of length 4M, OptlocT0 of length M directly optimized in discrete-time w.r.t. TFL and, finally OptSelect4T40, of length 4M, also optimized in discrete-time but w.r.t. the minimization of the out-of-band energy [16].

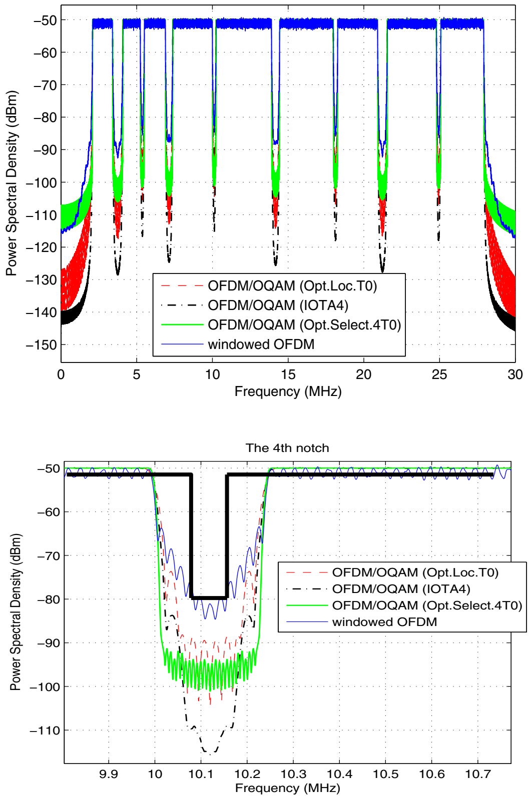


Fig. 5. PSD, satisfying HPAV specifications, with windowed OFDM and OFDM/OQAM using three different prototype filters : general view at the top and zoom at the bottom.

The zoom view of the fourth notch in Fig. 5 also shows that with OFDM/OQAM the number of unmasked sub-carriers could be higher than 1155 which is the upper limit for HPAV in the [1.8-30 MHz] band.

Although these results are similar to the ones that can also be obtained with WOFDM, on the other hand we have also recently shown [17] that thanks to specific channel estimation techniques OFDM/OQAM may also provide better performance than CP-OFDM.

VII. CONCLUSIONS

We have addressed state-of-the art and challenges for the development of high speed in-home PLC systems. Increased bandwidth (up to 100 MHz) combined with advanced filter bank modulation techniques, channel coding, resource allocation algorithms and cognitive MAC can allow reaching the ambitious goal of achieving Gbps data rate as well as allow for coexistence and possibly interoperability with existing PLC technology.

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