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Considerations on Narrowband and Broadband Power Line Communication for Smart Grids

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***Abstract*—The high amount of applications to be implemented in the Smart Grid requires bi-directional connectivity between a multitude of nodes with a reliable, high speed, low latency, energy efficient and cost effective communication technology. Power line communication (PLC) has the potentiality to meet the requirements. Indeed, there exists space for PLC technology improvements and to overcome the challenges mostly due to a hostile communication medium. There are two considered frequency spectra: a narrowband (3-500 kHz) spectrum and a broad band (1.8-86 MHz) spectrum that are exploited by current technology. In this paper, we discuss the usage of these spectra both in LV and MV networks, highlighting pros and cons and advocating the realization of an adaptive technology that can cognitively make the best usage of available resources so that the requirements of reliability, latency and coverage can be met.**

I. Introduction

The realization of the Smart Grid requires the deployment of bidirectional communication links that interconnect the nodes of the grid. Power line communication (PLC) is a technology that is capable of doing so by exploiting the existing grid infrastructure and thus potentially reducing investment costs. A pervasive deployment of PLC is envisioned especially in the distribution network that comprises low voltage (LV) and medium voltage (MV) lines. In this scenario a large number of "smart" devices (i.e. active loads, sensors, actuators, etc.), will be present and generate an overall high amount of data.

Recently, industry has turned the attention towards the development of multipurpose PLC modems that can provide connectivity for: monitoring and protection (e.g., faults detection), monitoring of islanding effects, advanced metering, power management, home energy management, micro-grid control. Generally, the power supply generated from power plants is pervasively distributed to the end customers through a well planned network infrastructure that comprises high voltage (HV) overhead lines, medium voltage (MV) lines and low voltage (LV) lines that reach the final customer. A schematic representation of a typical power distribution grid is depicted in Fig. 1. Although the power lines can be used as a transmission medium, they have not been conceived for this use. Therefore, its exploitation typically faces several issues which depend on the specific application context, network topology and operating frequency band. They include: (i) channel attenuation and frequency selectivity due to multipath propagation, which depend on frequency and grid topology; (ii) channel time variations; (iii) low line impedance; (iv) high levels of background noise; (v) high interference coupled into the lines; (vi) radiation effects.

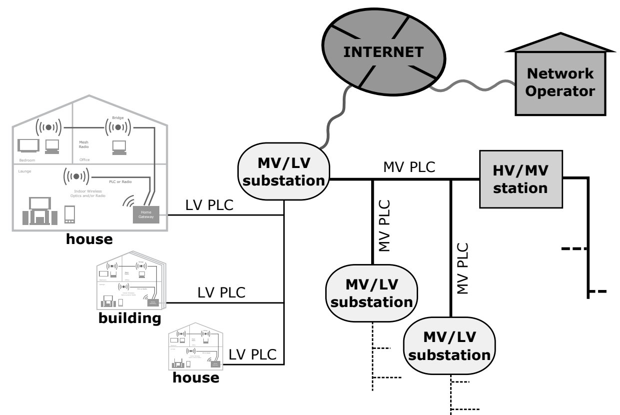

Fig. 1. Schematic of a typical power distribution grid.

A. Applications and Requirements

PLC can be used to offer a number of services in the grid. Monitoring and control enabled by PLC allows fault detection, monitoring of power quality and islanding effects. Energy management allows decentralized production and control of storage and electrical vehicles charge. Smart metering is the key component for demand side and demand response management, dynamic pricing and acquisition of user behavior. Smart building solutions can be realized with automation and control inside buildings.

All of these applications have different requirements in terms of data rate, latency, reliability. Although each single connection may have low data rate requirements, the overall traffic can be high, especially when fast real time services have to be granted. Furthermore, the data rate balance depends not only on the sensor/actuator needs but also on the redundancy introduced by the network protocol, including the need of implementing security/privacy mechanisms.

The amount of traffic to be carried by a link depends, finally, on the considered PLC network segment. For instance, the concentrator in a MV/LV substation has to collect the traffic from all LV nodes (houses) which can easily exceed 1 Mbps and much higher if fast demand side management has to be realized. Other applications, as control of islanding situations, fault detection and circuit breakers control, do not have high data rate requirements, but must be handled with extreme reliability and with fast response, below 100 ms.

It is therefore not obvious if a NB solution can handle all these applications or if a combination of NB and BB has to be deployed. For instance, with a NB solution for the LV network segment and a BB solution for the MV segment [1].

B. PLC: NB and BB Standards

Current technology uses the so called narrowband frequency spectrum (NB-FS) and the broadband frequency spectrum (BB-FS). In Europe, the standard EN 50065 (EN 50065-1:2011) was issued by CENELEC, and it specifies four frequency bands for PLC. Namely band A (3-95 kHz) is reserved exclusively to power utilities; band B (95-125 kHz) can be used for any application; band C (125-140 kHz) is dedicated to in-home networking systems; band D (140-148.5 kHz) is reserved to alarm and security systems. Instead, in the US and in Asia, the narrowband spectrum is regulated by FCC (Title 47, Part 15 (47 CFR 15)) (9-490 kHz) and ARIB (10-450 kHz), that allow PLC devices to work in the 3-500 kHz band.

In the NB-FS, so called NB-PLC technology has been standardized. The most popular standards are PRIME (ITU-T G.9904) and ERDF G3-PLC (ITU-T G.9903), which are specified for working over low voltage (LV) networks in the CENELEC-A frequency band. In order to provide a worldwide standard, the International Telecommunications Union (ITU) as well as the Institute of Electrical and Electronics Engineers (IEEE) work on defining next generation standards. For NB-PLC up to 500 kHz two standards, that incorporate the features of the previous ones, have been developed: the ITU-T G.hnem (ITU-T G.9902) and the IEEE P1901.2 (IEEE 1901.2-2013). They offer data rates in the order of hundreds kbps, reaching about 500 kbps in some special conditions and using orthogonal frequency division multiplexing (OFDM).

Contrariwise, in the BB-FS, the broadband PLC (BB-PLC) technologies operate at frequencies above 1.8 MHz and up to 86 MHz and can potentially reach rates of 1 Gbps in home networks. Also in this case two worldwide standards have been defined, namely ITU-T G.hn (ITU-T G.9960) and IEEE P1901 (IEEE 1901-2010). Furthermore, the HomePlug alliance has defined the HomePlug Green Phy specifications in the 2-30 MHz band for energy efficient transmission.

C. Paper Contributions

The aim of this paper is to provide an overview about the challenges that PLC for smart grid applications is facing. Emphasis is given to physical layer aspects, starting from the channel behavior analysis in the NB-FS and BB-FS. It has to be emphasized that the focus is not on the existing NB-PLC or BB-PLC solutions, but rather on the physical characteristics of the medium in the two considered frequency bands.

II. Network and Medium Aspects

The design of the PLC network depends on the application scenario and on the grid topology. Focusing on the distribution grid, it comprises both medium voltage (MV) and low voltage (LV) sections. Fig. 1 shows a schematic of the distribution grid. Bi-directional PLC services can be established between nodes of the network in a centralized or peer-to-peer fashion, covering different geographical areas.

The MV lines are used to provide power to large aggregations of customers, e.g., towns, neighborhoods, industrial sites. The MV lines with voltage in the order of tens of kilo volts are connected to the high voltage (HV) power supply network via a primary transformer substation [2]. The MV line can be deployed as underground or overhead lines and the underlying network structure is typically characterized by a tree structure with a low amount of branches. This, as described in Section II-A and in [3], translates into a lower channel attenuation and frequency selectivity w.r.t. both indoor and outdoor LV channels. Besides feeding the loads, the MV networks deploy a number of intelligent electronic devices, such as sectionalizers, capacitor banks and phasor measurement units, as well as large distributed energy generators from renewable sources. Depending on how the PLC network nodes are organized, it is desirable to cross the elements that create propagation discontinuity, as circuit breakers and transformers. The ability to cross such elements depends on the transmission band, as discussed in Section II-A and [4].

The LV lines, instead, cover the last part of the power distribution system, delivering the energy to the end customer premises (as houses and buildings). They are connected to the MV lines through secondary transformer substations and typically carry a voltage in the order of hundreds volts [2]. These transformers act as blocking filters. It may be desirable to partition the network into cells in order to increase system capacity. That is, the transformer splits the network and it creates two distinct physical cells with the use of a base station (concentrator). Usually, the LV lines are deployed as underground cables and their underlying network structure is comparable to a bus transmission line, namely a long backbone, with short branches connecting the utilities. However, significant differences are found among European and American outdoor LV networks. In Europe the 230/400 V 3-phase distribution system is divided in supply cells served by a MV/LV transformer station. Up to about 300 houses are connected via branches with say 30 houses/branch and a maximal branch length of $\sim$1 km. In the Asia and USA the power distribution is at 125/250 V with single or split phase. Each supply cell is small, serving less than 10 houses with branch lengths in the order of 100 m. This different network configuration must be taken into account since the number of repeaters/concentrators that has to be deployed in US networks is high, which can translate in higher deployment costs. Indeed, this depends on the solution adopted. In fact, the repeater can be a simple bypass coupler or an active PLC modem.

A. Channel Properties

The aim of this section is to highlight the main differences among the outdoor LV and MV communication media. The analysis of the PLC channel in outdoor distribution grids is less comprehensive in the literature compared to the indoor case. It is however very important to know such characteristics to design good PLC solutions [3], [5].

In reference to the LV channels, the measurements performed by the open PLC European research alliance (OPERA) project [6] are herein considered. From the collected measurements, an analytic model was derived providing eight different reference channel frequency responses (CFR). Each CFR has been selected and tabulated considering different length classes and attenuation levels (i.e. short, medium and high).

In reference to the MV channels, the measurement carried out during the measurement campaign described in [4] are discussed. The scenario is a three-phase 20 kV MV network that feeds a large number of users concentrated in a small area. In detail, the underlying network is tree structured with several MV/LV transformers connected to it. The measurements have been performed in time domain providing results that are valid up to 55 MHz. The CFR has then been computed through a

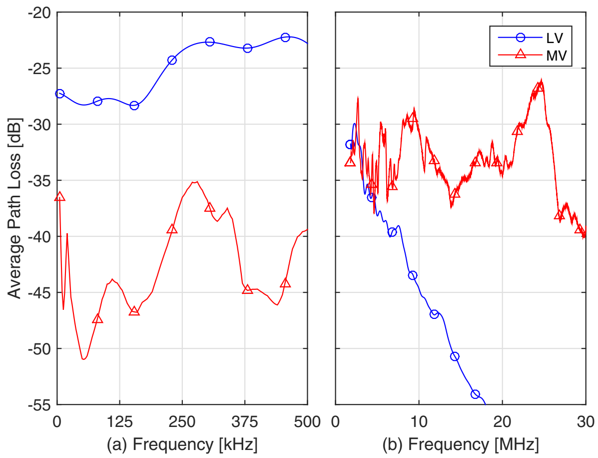

Fig. 2. Average path loss profile for outdoor LV and MV lines in both the NB (a) and BB (b) frequency range.

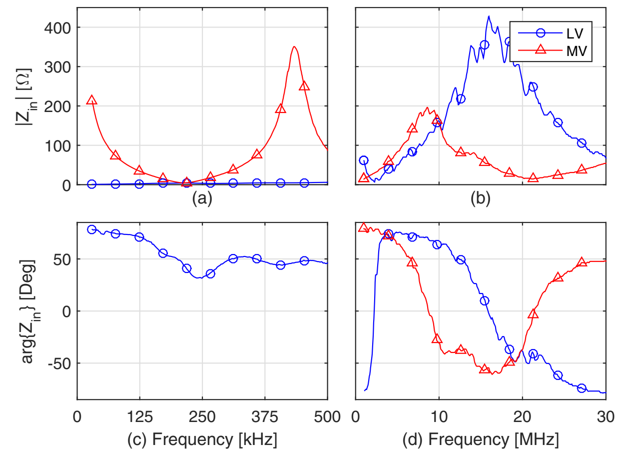

Fig. 3. Magnitude (on top) and phase (on bottom) of the input impedance for outdoor LV and MV lines in the NB (left side) and BB (right side) range.

fast Fourier transform. Other analysis of the MV channels can be found in [7].

The LV and MV average path loss (PL) profile, as a function of frequency, is shown in Fig. 2. It is defined as $\overline{PL}(f) = 10\log_{10}(E[|H(f)|^2])$, where $H(f)$ is the CFR at the f-th frequency, while $E(\cdot)$ denotes the expectation over the measurements. On the left side, in Fig. 2a, the narrowband case is considered, while on the right side the BB case is considered. In the NB-FS case (up to 500 kHz), the MV channels exhibit higher attenuation w.r.t. LV ones. This is mainly due tho the longer cable length deployed in MV networks, which translates into a larger signal degradation. Moreover, the MV PL shows a more pronounced frequency selective behavior compared to the smoother LV PL profile. This is since the underlying network topology is different: a tree structured for the MV case, while bus structured for LV scenario. The reduced number of branches and their lower length in LV networks, translates into less frequency selectivity.

The same selectivity behavior can be noted considering the BB case in Fig. 2b. Contrariwise the NB frequency range, the PL dominates the LV scenario for larger frequencies. In particular, beyond 5 MHz, the LV channels are affected by an attenuation higher than the MV ones. As before, this is mainly due to network structure and topology. Since the considered LV lines deploy short three-phase cables, in which each phase wire is close to each other, high resistance values at high frequency are introduced by the spread parallel resonance. This effect produces the prominent PL degradation. This is discussed in Section II-B considering the input line impedance.

B. Input Line Impedance Characteristics

In order to be able to couple and inject the PLC signal into the power network, the line impedance must have a suitable value. Very low values of the line impedance involve that the signal generator at the transmitter side must inject very high current values in order to transfer appreciable values of voltage to the load and therefore to the receiver port [8]. Thus, it is of fundamental importance to analyze the line impedance, named Z_{in}. Typical values of the magnitude and the phase of the line impedance are reported in Fig. 3. We consider both the MV and the LV scenario and the NB and BB case. The profiles have been obtained by averaging those reported in [9] (LV BB), [10] (LV NB), [9] (MV BB), and [11] (MV NB).

From Fig. 3 it can be firstly noted that the line impedance is significantly low in the NB case. The two peaks in correspondence of the edge frequencies of the MV case in Fig. 3a are mainly due to resonance effects induced by mismatches among the channel characteristic impedance and the line terminations (such as open-circuit and short-circuit). Nevertheless, as specified in [11], the characteristic impedance of the differential mode is very low, with values of few Ohms.

Contrariwise, the BB case exhibits much higher values of impedance, although it is frequency selective, which reflects into a more benign situation for the modem line driver. It is interesting to note that there is a serial resonance when the magnitude, or resistive part, (in Fig. 3b) approaches zero, while the phase (in Fig. 3d) is zero. Contrariwise, the magnitude drastically increases in correspondence of a parallel resonance, when the phase is zero. This is the reason of such high values of input impedance.

Another aspect that can be observed for the BB case is that the LV and MV networks exhibit almost a dual reactive behavior. Indeed, for lower (up to 2.2 MHz) and higher (over 15.5 MHz) frequencies, LV lines have a capacitive behavior, while MV lines for lower (up to 8.5 MHz) and higher (over 21.5 MHz) frequencies exhibit an inductive behavior. Contrariwise, in the middle frequency range. This effect is mainly due to the network configuration and structure, as well as to the specific loads of the network. For example, the transformers act as a high parallel inductance at low frequencies.

Finally, for long cables (typically deployed in MV networks) and high frequencies, the line impedance is dominated by the characteristic impedance of the cable.

C. Network Transformers and Discontinuities

As said, circuit breakers and transformers may act as discontinuity elements for the PLC signal propagation. While this is not necessarily a negative aspect since the overall network can be partitioned into cells and therefore increase the overall system capacity, in certain circumstances it is desirable to let the PLC signal propagate uninterruptedly through the circuit breaker and through the transformer. It has been claimed that transmission in the NB-FS has a better ability to bypass such elements. However, it should be observed that such an ability is actually increased at high frequencies where electromagnetic coupling effects are more pronounced. This is shown in Fig. 4,

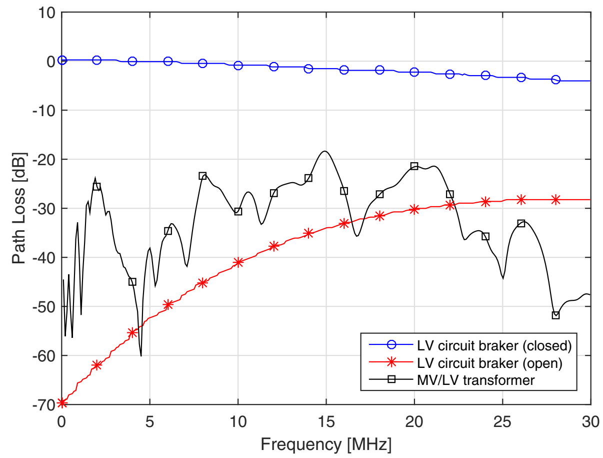

Fig. 4. Path loss of a LV circuit breaker, for both open and closed configurations, and of a bypass ML/LV transformer along frequency.

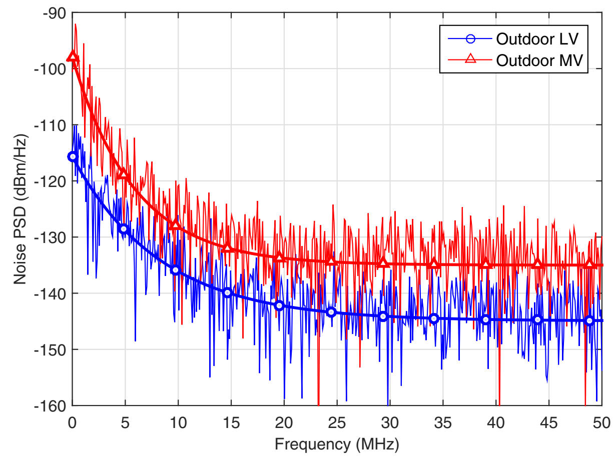

Fig. 5. LV and MV background noises. The exponential model is also shown.

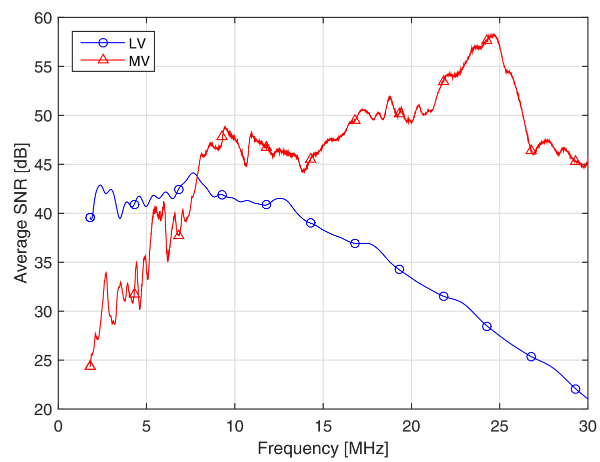

Fig. 6. SNR trend for LV and MV scenarios in the BB frequency range.

where the attenuation introduced by a circuit breaker in open and closed configuration, together with the attenuation between the primary and secondary ports of a MV/LV transformer, are depicted. When the circuit breaker is open, the attenuation is less than -40 dB for frequencies above 10 MHz, while it is significantly high at low frequencies. Also for the transformer the lower attenuation is located at lower frequencies.

Again, this shows that transmitting in the BB frequency range has higher potentiality to bypass circuit discontinuities.

D. Background Noise

PLC networks are affected by several noise components: background noise and impulsive noise with both periodic and aperiodic components introduced by noisy loads or switching devices [2]. That is, the noise is dominated by a mixture of active noise components injected in the network by the loads connected to it. Typically, an equivalent average (stationary) noise colored power spectral density profile is used to describe the overall noise experienced at the receiver. This is shown in Fig. 5 considering both the LV and the MV scenarios. Analytically, the PSD can be modeled as [12]

$$PSD_W(f) = a + be^{fc} \quad \text{[dBm/Hz]}. \tag{1}$$

As it can be noted in Fig. 5, MV channels experience a higher PSD level w.r.t. LV channels. This is probably related to the fact that MV lines deploy long cables which can capture RF interference. Moreover, load unbalances or device activities can directly inject great amounts of noise, with harmonics along the entire frequency range, more than in a LV network. Furthermore, the noise drastically increases at lower frequencies, thus having high impact in NB-PLC schemes.

E. Signal-to-noise ratio

Although we have seen that BB channels are more attenuated than NB channels, the noise level is higher in NB than in BB. In communications, what is relevant is the signal-to-noise ratio at the receiver [8]. Fig. 6 shows the SNR values as a function of frequency at the receiver side for both NB and BB. The values are computed relying on the average channels depicted in Fig. 2 and on the corresponding noise models displayed in Fig. 5. Indeed, despite they are sufficiently representative, other situations can be encountered. A transmitter PSD of -50 dBm/Hz has been considered.

The figure shows that for both scenarios the SNR has a concave trend due to the combination of an increasing channel attenuation and a decreasing noise PSD profile along frequency. The maximum values are centered around 7.5 MHz and 24.5 MHz for the LV and MV scenario, respectively.

It should be observed that the low line impedance exhibited in NB exacerbates the difference of SNR in NB w.r.t. BB. Thus, higher level of voltages at the source must be granted due to coupling losses, rendering the scheme less energy efficient.

F. Performance

It is of primary interest to evaluate the performance that a given transmission scheme can provide. In this respect, the achievable rate (capacity) is the most common and used metric. It is defined as

$$C = \int_{f_L}^{f_M} \log_2\left(1 + \frac{P_S(f)|H(f)|^2}{P_W(f)}\right) df \quad \text{[bps]}, \tag{2}$$

where f_L and f_M are the lower and upper frequencies of the considered bandwidth, respectively. While, $P_S(f)$, $|H(f)|^2$ and $P_W(f)$ are the transmitted power, the CFR and the noise power at the f-th frequency, respectively.

Since the channel capacity in (2) is directly connected to the SNR, the trend depicted in Fig. 6 motivates the study of the achievable performance when transmission is performed

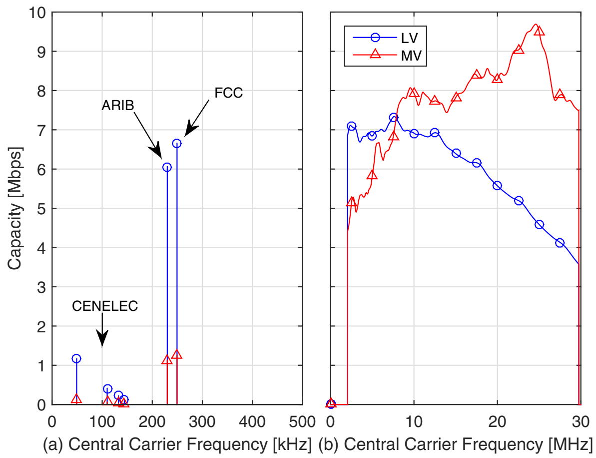

Fig. 7. Capacity for LV and MV scenarios in the NB (a) and BB (b) frequency range. For the BB case a bandwidth of 500 kHz is considered.

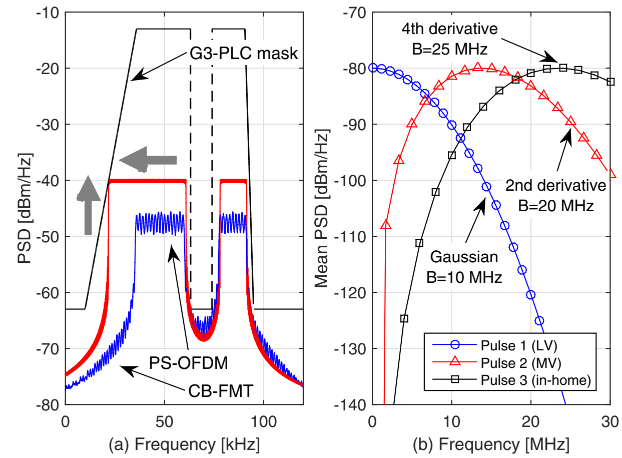

Fig. 8. PSD in CENELEC-A band for PS-OFDM and CB-FMT (a) and mean PSD of transmitted UWB pulses for LV, MV and in-home scenarios (b).

TABLE I. ACHIEVABLE CAPACITY AND TOTAL POWER REQUEST FOR LV AND MV SCENARIOS IN BOTH NB AND BB FREQUENCY RANGES.

	Bandwidth	**Capacity** (Mbps)	**Total power** @1Mbps (dBW)
LV	3–500 kHz	6.87	−64.13
	7.385–7.885 MHz	7.34	−66.20
	1.8–30 MHz	333.41	−68.13
MV	3–500 kHz	1.32	−29.95
	24.35–24.85 MHz	9.69	−80.29
	1.8–30 MHz	432.40	−82.11

in the NB-FS or in the BB-FS. In particular, we assume to keep the signal bandwidth equal to 500 kHz, but to adapt the central carrier so that the BB-FS can be occupied. This is a form of adaptive modulation that cognitively uses the available resources in an optimal manner. This is shown in Fig. 7b, together with the capacity offered by the individual CENELEC, ARIB and FCC band in Fig. 7a.

It can be noted as the capacity trend in Fig. 7b recalls the SNR curves shape, with the capacity maxima for the LV and MV scenarios located at the same frequencies of the SNR maxima. We do not consider transmission in the 500 kHz-1.8 MHz band since this is currently not possible for regulations. It is evident how the transmission in the BB spectrum can be beneficial. The individual CENELEC bands to do not offer high capacity. In general, this is due to the higher SNR that can be experienced in the BB region w.r.t. the NB case. Only in the low voltage case, the ARIB and FCC NB-FS offers capacity values close to the BB-FS case.

To aid the comparison, the capacity attainable in the NB-FS and BB-FS (when the central carrier is optimally chosen) are summarized in Table I for both the LV and MV scenarios. As a further term of comparison, the capacity achieved exploiting the entire BB-FS is displayed. It is from tens to hundreds times higher than that attainable in the NB-FS. Moreover, we report the total power (in dBW) needed in order to achieve a certain target rate (1 Mbps in this case). This power value has been computed applying the optimal solution provided by the margin adaptive water-filling algorithm, which minimizes the power required to achieve a given target rate. As it can be noted, the MV NB case is the most energy hungry environment (requiring 50 dB more than the BB-FS case), followed by the LV narrowband scenario. The differences grow, becoming more than twice, when comparing the NB-FS w.r.t. BB-FS at higher target rates (even of few Mbps).

The results show that transmission at higher frequencies as well as a bandwidth expansion can offer higher rates and higher energy efficiency. Consequently, BB transmission can also reduce significantly the transmission delay (latency).

III. Transmission Schemes

To efficiently exploit the available spectrum it is important to develop advanced transmission technologies. Current NB-PLC and BB-PLC systems use pulse shaped OFDM (PS-OFDM). This simplifies the equalization task, implementing notching and power/bit loading across the spectrum. More advanced schemes can be considered to enhance the spectrum management, as filter bank modulation or as impulsive PLC, to simplify the overall scheme, which is desirable in simple PLC sensor networks.

A. *Adaptive Cyclic Block FMT*

In PS-OFDM, the multicarrier scheme deploys a time confined window. This results in poor sub-channel spectrum confinement and therefore in poor notching capability and low spectral efficiency. In filter bank modulation, pulse shaping privileges the frequency confinement. This is for instance done in cyclic block filtered multitone modulation (CB-FMT) [13] which has the potentiality to offer a much higher notching capability and ability to fulfill EMS requirements. Furthermore, the linear convolutions are replaced with cyclic convolutions, rendering the implementation significantly less complex than in conventional filter bank modulation. Flexible adaptation of the spectrum can be realized in the frequency domain, allowing to meet EMC spectral masks constraints much easier [13]. This is shown in Fig. 8a where the CB-FMT spectrum is compared with the PS-OFDM spectrum in the CENELEC-A band. Sharp notches can be generated in CB-FMT so that either higher levels of maximum power can be transmitted or a higher number of active sub-channels (thus larger useful spectrum) can be used. This translates in higher data rates and reduced out-of-band emissions.

B. *Adaptive Impulsive PLC*

Another technique is impulsive modulation [14], which exploits the idea of transmitting short duration pulses over a large frequency spectrum enabling a simple base band implementation and spectrum expansion. Appropriate waveform can be designed so that adaptation is performed to occupy the right spectrum, exploit frequency diversity and transmit at an extreme low PSD level, below -80 dBm/Hz. This translates in the ability to coexist with other PLC systems as shown in [14]. An example of the mean PSD of different transmitted signal pulses is reported in Fig. 8b.

IV. Final Remarks

PLCs are a natural choice to deliver bi-directional connectivity in the power delivery grid and to enable several different applications for the smart control and management of the grid. Both the narrowband frequency spectrum (NB-FS, 3-500 kHz) and the broadband frequency spectrum (BB-FS, 1.8-100 MHz) can be exploited for the realization of PLC solutions. As a matter of fact, the market offers a choice of engineered solutions that are compliant with the NB standards (ITU-T G.hnem, IEEE P1901.2) or the BB standards (ITU-T G.hn, IEEE P1901, HPAV). Although both technologies are mature and ready for mass deployment, it is also true that technology has to evolve and to be able to offer increased levels of performance in terms of data rate, latency, robustness and coverage w.r.t. what is achieved today.

It is often said that most smart grid applications require low data rates and therefore narrowband solutions are the right choice. It should be recognized that broadband solutions offer higher flexibility and a better trade-off between data rate, latency, robustness and energy efficiency. Adaptive, scalable, flexible solutions that can smartly use the spectrum and operate in different spectrum portions (both in the NB-FS and in the BB-FS) are the right approach for the evolution of current PLC technology. It is a matter of fact that the low frequency bands, e.g., CENELEC-A, show a low channel attenuation but high noise due to the increasing number of emissions from active loads, a time variant behavior and a low impedance which challenges the realization of robust PLC modems and line drivers. On the other side, transmission in the BB-FS enjoys lower noise, much higher line impedance and it offers frequency diversity. However, transmission at high frequencies, at the moment, may be challenged by radiation limits, especially in overhead conductors and by coexistence problems which can be solved by following a cognitive approach and developing low power solutions. In this respect, filter bank modulation and impulsive PLC solutions are two promising approaches.

Complexity is also another point to consider and the associated requirements can be defined depending on the application and cost. NB solutions can be realized on re-configurable DSP architectures. BB solutions may require ASIC realizations, or mixed ASIC-DSP architectures. The cost difference vanishes as massive production and deployment takes place. Indeed, for certain applications, e.g., elementary sensor/actuator networks or extremely simple and embeddable solutions are desirable.

Maximum flexibility can be obtained by adopting advanced filter bank modulation techniques at the physical layer, such as filtered multitone modulation and cyclic filter bank modulation. These schemes allow to implement spectrum shaping, highly selective notching and adaptive time-frequency resource allocation. A very simple wideband solution can be realized with impulsive modulation which is appropriate for moderate data rates. It exploits frequency diversity, it is energy efficient using low PSD levels and it can coexist with other NB and BB solutions.

The overall system performance depends on layer 1, but also on layer 2. A key role is played by the media access scheme and in this respect a combination of TDMA and FDMA with adaptive scheduling, rather than simple CSMA, can offer benefits [15]. Routing mechanism implemented at layer 2 (or eventually at layer 3) is also fundamental to achieve the high coverage requirements in large grids. Overall, it is of paramount importance to design light protocols that allow fast responses and network configuration, especially in Smart Grids, where network recovery has to be immediate in the event of faults and blackouts.

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