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Improved Spectrum Agility in Narrow-Band PLC with Cyclic Block FMT Modulation

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***Abstract*—Narrow-Band power line communications (NB-PLC) operate in portions of the 3-500 kHz spectrum and have to obey certain spectral masks for EMC and coexistence issues. Although orthogonal frequency division multiplexing (OFDM) allows simple spectrum management by switching on-off the sub-channels, its poor sub-channel frequency selectivity translates into a poor spectrum usage. An agile use of the spectrum and higher spectral efficiency can be obtained with filter bank modulation. In particular, in this paper, we investigate the use of cyclic block filtered multitone (CB-FMT) modulation and compare it to pulse shaped OFDM (PS-OFDM) deployed in the G3-PLC and IEEE P1901.2 standards. The comparison shows that higher spectral efficiency and improved spectrum management can be achieved with CB-FMT.**

I. Introduction

The interest on Power Line Communications (PLC) have grown in recent years. One of the most important application scenario is the Smart Grid. The need of modernizing the electric grid infrastructure, integrating renewable energy sources, controlling and optimizing electricity flows, requires a smart management of the grid with the adoption of a communication infrastructure. Not only wireless and traditional wired technologies, but also PLC are valid candidates. The rationale for PLC is that the infrastructure is already widely deployed and can be exploited for communication purposes, which may reduce costs.

Recently, standard organizations have regulated the frequency bands dedicated to PLC with particular application in the smart grid context. The band plan is not universal and varies among continents. In Europe (EU), the standard EN 50065 [1] defines four bands in the 3-148.5 kHz frequency range. In the United States (US), FCC allows the use of the 9-490 kHz band [2]. In Japan, ARIB allows the use of the 10-450 kHz band. Communications in these frequency bands are referred to as Narrow-Band PLC (NB-PLC). PLC is also regulated for communications above 500 kHz, i.e., in the 2-30 MHz frequency range. These communication services are denoted as Broad-Band PLC (BB-PLC) and they are intended for high-data rate applications, e.g., for home networking.

Typically, the PLC channel exhibits a low-pass frequency selective response. Consequently, the channel impulse response introduces time dispersion to the transmitted signal. This translates into significant inter-symbol interference (ISI) if single carrier modulation is deployed. To simplify the equalization task, multi-carrier modulation (MCM) has been proposed. In MCM, a high date rate signal is split in a series of low data rate signals, transmitted over narrow band sub-channels. If the sub-channel number is sufficiently high, each sub-channel exhibits a flat frequency response so that the equalization stage can be significantly simplified. Furthermore, MCM allows to manage the spectrum allocation and notching in a simple way by switching on/off the sub-channels.

The most popular MCM scheme is orthogonal frequency division multiplexing (OFDM) [3]. A form of OFDM was adopted in NB-PLC: in the standards PRIME [4] and G3-PLC [5]. These standards have been the base to develop the ITU-T G.hnem [6] and the IEEE P1901.2 [7] standards for PLC below 500 kHz. OFDM was also adopted for BB-PLC, e.g., in IEEE P1901 [8] and in HomePlug [9]. Since baseline OFDM uses a rectangular window as sub-channel pulse, it exhibits poor sub-channel frequency confinement and therefore poor notching capability. In an attempt to lower this drawback PS-OFDM [10], [11, Chapter 5] is actually used in the system above cited. In PS-OFDM a more relaxed time window is used, e.g., a raised cosine window in the time domain. Nevertheless, the spectral efficiency is not optimal when selective notching and spectral masks have to be fulfilled since a high number of sub-channels need to be switched off which introduces a significant loss in data rate.

In order to offer improved spectrum agility and higher spectral efficiency, in this paper we investigate the use of filter bank modulation (FBM). In particular, we focus on Cyclic Block Filtered Multitone Modulation (CB-FMT) [12]. In this FBM scheme, the sub-channel frequency confinement is privileged w.r.t. OFDM which reduces the out-of-band interference compared to OFDM. Good sub-channel frequency confinement can be obtained also with conventional FMT [13]. However, FMT requires longer pulses and it does not enjoy the efficient frequency domain implementation of CB-FMT [12], [14]. This is made possible in CB-FMT by the use of cyclic convolutions instead of linear convolutions in the filter bank.

Now, in this paper we consider CB-FMT for NB-PLC and study whether it allows a better usage of the NB spectrum than PS-OFDM when the spectral masks specified by the standards have to be fulfilled. The spectral masks are imposed to satisfy the electromagnetic compatibility (EMC) regulations and to allow the coexistence with other systems. In particular, we perform a comparison with PS-OFDM used in the G3-PLC and the recent IEEE P1901.2 standards in terms of maximum achievable rate and out-of-band emissions. An analysis for the BB-PLC application and a comparison in the framework of the HomePlug standard was reported in [15].

This paper is organized as follows. In Section II, we briefly describe a conventional FBM scheme, the PS-OFDM scheme and the CB-FMT scheme. In Section III, we describe the band plan for NB-PLC and the EMC limits in EU (CENELEC bands) and US (FCC band). Then, we describe the main parameters of the G3-PLC and IEEE P1901.2 standards. The considered channel and noise models are reported in Section IV with reference to the Outdoor-Low Voltage (O-LV) scenario. The numerical results and comparisons are reported in Section V.

II. Filter Bank Modulation

In a general FBM scheme, the high rate information sequence is converted into K sub-sequences, denoted as $a^{(k)}(\ell NT)$, $k \in \{0, \ldots, K-1\}$, where T in the sampling period. The overall data rate is equal to $K/(NT)$. In the following, the sampling period is assumed to be normalized, i.e. $T = 1$. Each sub-sequence is interpolated by a factor N and, then, filtered with a prototype pulse, equal for all the sub-channels. Then, the K filtered signals are modulated with a complex exponential function to occupy a certain sub-band. Thus, the sub-bands are obtained partitioning the available bandwidth in K equal parts. Finally, the K signals are summed together, yielding the transmitted signal

$$x(n) = \sum_{k=0}^{K-1} \sum_{\ell \in \mathbb{Z}} a^{(k)}(\ell N) g(n - \ell N) W_K^{-nk}, \quad (1)$$

where $g(n)$ is the prototype pulse and $W_K^{-nk} = e^{i2\pi nk/K}$ is the complex exponential function.

The transmitted signal in (1) is digital-to-analog converted and transmitted over a power line (PL) channel. At the receiver, after analog-to-digital conversion, we have

$$y(n) = x * g_{ch}(n) + \eta(n), \quad (2)$$

where $*$, $g_{ch}(n)$ and $\eta(n)$ are the linear convolution operation, the discrete-time impulse response of the PL channel and the background noise, respectively. To demodulate the received signal, (2) is modulated with a bank of complex exponential functions, then filtered with a prototype pulse and sampled by a factor N to obtain $z^{(k)}(mN)$. In detail, $z^{(k)}(mN)$ can be expressed as

$$z^{(k)}(mN) = \sum_{n \in \mathbb{Z}} y(n) W_K^{nk} h(mN - n), \quad (3)$$

where $h(n)$ is the receiver prototype pulse.

A. PS-OFDM

The PS-OFDM system can be obtained by deploying as prototype pulse a time confined window, e.g., a raised cosine window in the time domain. This is slightly different to conventional OFDM, where a rectangular window is used. As in OFDM a cyclic prefix (CP) is added. The system remains orthogonal in the presence of a dispersive channel if the CP is sufficiently long. PS-OFDM can be implemented (at the transmitter) using an inverse discrete Fourier transform (IDFT). The output samples are extended by the CP, weighted by the window coefficients and, finally, an overlap and add operation is performed. Details can be found in [10], [11, Chapter 5].

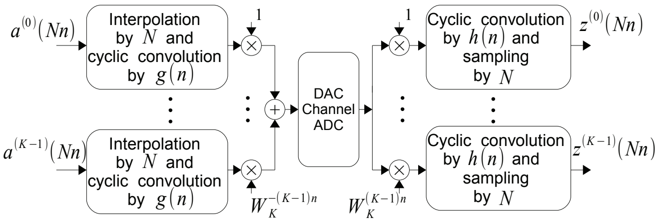

Fig. 1. Block diagram of the CB-FMT transceiver.

B. Cyclic Block FMT

The block diagram of the CB-FMT transceiver is shown in Fig. 1. CB-FMT is still a FBM technique, where however the linear convolutions in (1) are replaced with circular convolutions. In detail, the transmitted signal can be rewritten as

$$\begin{aligned} x(n) &= \sum_{k=0}^{K-1} \left[a^{(k)} \otimes g \right](n) \\ &= \sum_{k=0}^{K-1} \sum_{\ell=0}^{L-1} a^{(k)}(\ell N) g((n - \ell N)_M) W_K^{-nk}, \quad (4) \\ & n \in \{0, \cdots, M-1\}, \end{aligned}$$

where $\otimes$ is the circular convolution operator and $g((n)_M)$ is the periodic repetition of the prototype pulse, i.e. $g((n + aM)_M) = g(n), \forall a \in \mathbb{Z}$. The prototype pulse $g(n)$ is a casual FIR filter with impulse response length equal to M. More in general, if the filter length is less than M, zero-padding can be used. We note that the transmitted signal in (4) involves LK symbols and the transmission is block wise.

At the receiver, the circular convolution is also adopted, as done at the transmitter. The k-th receiver output sub-sequence can be obtained as

$$\begin{aligned} z^{(k)}(mN) &= \sum_{n=0}^{M-1} y(n) W_K^{\ell k} h((mN - \ell)_M), \quad (5) \\ & k \in \{0, \ldots, K-1\}, \quad m \in \{0, \ldots, L-1\}, \end{aligned}$$

where $h((m)_M)$ is the periodic repetition of the prototype analysis pulse.

To maximize the signal-to-noise ratio (SNR) at the receiver output, synthesis and analysis prototype pulses should be matched, i.e. $g(n) = h^*(-n)$, where $(\cdot)^*$ is the complex conjugate operator. An obvious choice is the root-raised-cosine pulse. Nevertheless, other pulse shapes can be used. In particular, in CB-FMT, a simple orthogonal prototype pulse

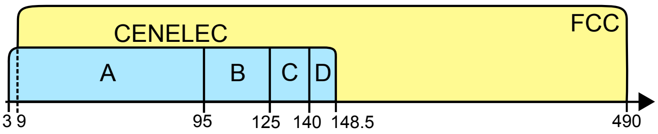

Fig. 2. Band plan for NB-PLC in EU (CENELEC bands) and US (FCC band). Frequencies are expressed in kHz.

design can be devised as described in [16]. This is much simpler than designing an orthogonal FMT system [17], [18].

CB-FMT has an efficient frequency domain implementation that reduces significantly the complexity w.r.t. FMT. This is because the circular convolutions can be realized in the frequency domain exploiting the Discrete Fourier Transform (DFT). The detailed complexity analysis is reported in [14]. As well, equalization can be easily performed in frequency domain [12].

III. Narrow-Band PLC

A. Band Plan and EMC Limits

PLC systems are partitioned in two classes. PLC in the 2-30 MHz frequency range is referred to as broad-band. These communications are intended for high data rate applications, e.g. internet access or multimedia services. Below 500 kHz, the communications are referred to as narrow-band. In this frequency range, existing systems offer low data rates, in the order of tens of kbps. NB-PLC is suited for command, control and monitoring, e.g. for Automatic Meter Reading (AMR). The frequency bands used by NB-PLC are not universal but vary as a function of the continent. In this paper, we focus on Europe and North America.

In EU, the European Committee for Electrotechnical Standardization (CENELEC) has regulated NB-PLC in the frequency range 3-148.5 kHz in the standard EN 50065. This band has been partitioned in four sub-bands. CENELEC A (3-95 kHz) is reserved for electric distribution companies. Band B (95-125 kHz) can be used without restriction for any application. Band C (125-140 kHz) is used for home automation systems and the devices must use a CSMA/CA protocol. Band D (140-148.5 kHz) is reserved to alarm and security systems. Concerning the transmission level, devices must fulfill the EMC regulation defined in EN 50065. The EMC measurements are performed according the CISPR 16-1 norm (quasi-peak detector with 200 Hz of resolution bandwidth). The limits are expressed in dBμV. For CENELEC A, the limit decreases with the logarithm of the frequency, from 134 dBμV at 3 kHz to 120 dBμV at 95 kHz. For B, C and D bands the limit is set to 116 dBμV.

In the US, the Federal Communications Commission (FCC) has regulated NB-PLC in the frequency range 9-490 kHz in [2]. The norms set both radiated and conducted limits. The radiated limit is set to 2400 μV/m at $f = 1$ kHz and decreases with the inverse of the frequency, i.e. $E_{lim} = 2400/f$, where f in the frequency expressed in kHz. The measurement is performed at a 300 m distance. Concerning conducted emissions, the limits are set for the frequencies above 150 kHz. In the 150-500 kHz frequency range, the limit decreases with the logarithm of the frequency, from 66 dBμV at 150 kHz to 56 dBμV at 500 kHz for the quasi-peak measure, and from 56 dBμV at 150 kHz to 46 dBμV at 500 kHz for the average measure. Measurement follows the CISPR 16-1 norm.

Fig. 2 summarizes the band plan in EU and the US.

PLC employs differential mode signals. Ideally, PLC does not produce emissions, i.e., the currents should flow with opposite directions in the conductors and the resultant emission in negligible. However, the asymmetries of the wiring structure produce a conversion from differential mode signals into common mode signals, referred to as transverse conversion transfer loss (TCTL). For the In-Home scenario, a TCTL analysis is reported in [11]. To derive the limits in dBm/Hz, a conservative approach is followed. A common mode transmission is assumed. Consequently, the PSD limit can be derived as follows

$$P_{lim} = V_{lim} - 10\log_{10}(B_{if}) - \nu \quad \left[\frac{\text{dBm}}{\text{Hz}}\right], \tag{6}$$

where V_{lim} is the limit expressed in dBμV, B_{if} is the intermediate frequency bandwidth of the spectrum analyzer that is used in EMC measurements and $\nu = 110$ is a coefficient for the conversion from dBμV to dBm. B_{if} is equal to 200 Hz for frequency below 150 kHz and is equal to 9 kHz for frequencies above 150 kHz. In Tab. I, the EMC limits are reported expressed in dBm/Hz.

B. NB-PLC Standards: G3-PLC and P1901.2

The first FBM relevant standards for NB-PLC were G3-PLC and PRIME. Both standards are based on PS-OFDM to provide higher data rate w.r.t. the single carrier FSK, standardized in IEC 61334. Recently, two new standards have been ratified, based on G3-PLC and PRIME: ITU G.9902 (known as G.hnem) in 2012 and IEEE P1901.2 in 2013. They also use PS-OFDM at the physical layer.

In this paper, we focus on G3-PLC and IEEE P1901.2.

1) G3-PLC: G3-PLC was initially released for operating in the CENELEC A band. Later, Maxim - member of the G3 Alliance - has proposed to extend G3-PLC to the other CENELEC bands [19] and to the FCC band [20]. In base band, the sampling frequency is set to $1/T = 200$ kHz for CENELEC bands and to $1/T = 600$ kHz for the FCC band. The sub-carrier number is set to $M = 128$ and the cyclic prefix length is set to 30 samples. In Table II(a), we report

TABLE I
Conducted Emissions Limits for NB-PLC.

Band [kHz]	dBm/Hz limit from (6)	
	Quasi-Peak	Average
$3 - 95$ [1]	$1.0/-13.0$	
$95 - 148.5$ [1]	-17.0	
$150 - 500$ [1,2]	$-83.5/-93.5$	$-93.5/-103.5$

[1] Valid only in EU and defined in EN 50065.
[2] Valid in both EU and US and defined in CISPR 22.

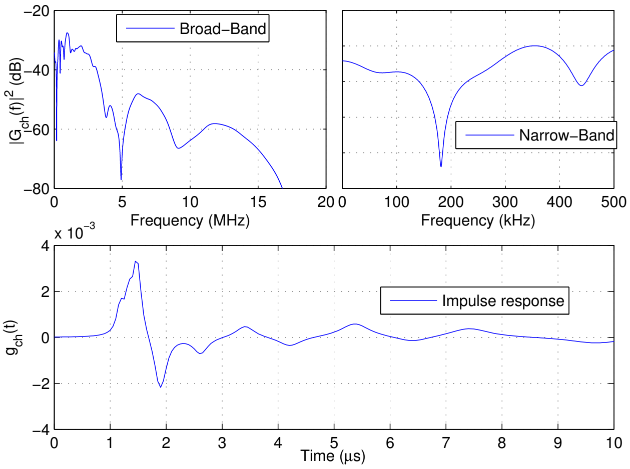

Fig. 3. Frequency and impulse response of the bad Opera channel belong to the 150 m class. On the top-left, the full frequency response in the 20 MHz band. On the top-right, a detail of the full frequency response in the narrow-band frequencies, i.e. below 500 kHz. On the bottom, the broad-band impulse response.

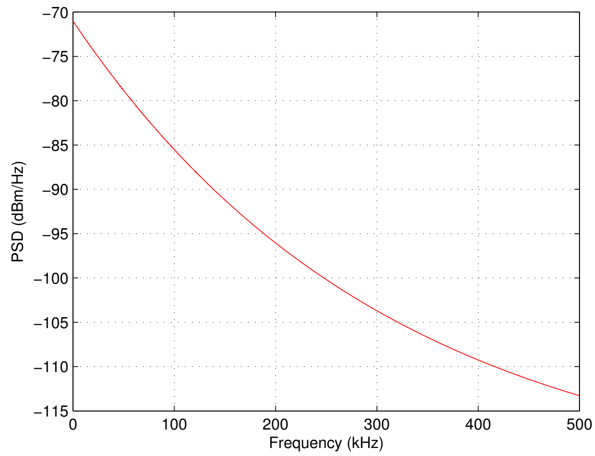

Fig. 4. Power Spectral Density of the background noise model.

the active sub-carries for each band. G3-PLC can operate in multiple CENELEC bands to increase the rate. In detail, it can operate in these bands: A, B, C, D, BC, BCD and BD.

To fulfill the EMC regulation, a PSD mask is specified. The transmitted signal spectrum must not exceed the limit of 120 dBμV. To ensure the coexistence with the single-carrier solution IEC 61334, a notch has been introduced between 63.3 kHz and 73.8 kHz. In the spectral notch, the limit is set to 70 dBμV. Finally, the PSD dynamic range in the notch and outside the notch has to be larger than 25 dB.

2) IEEE P1901.2: The new IEEE P1901.2 standard joins the previous NB-PLC standards to obtain a universal communication specification. At the physical layer, PS-OFDM is used. In CENELEC bands, IEEE P1901.2 can operate only in bands A and B. The full FCC band is partitioned in two parts, below 150 kHz (FCC-low band) and above 150 kHz (FCC-above-CENELEC band). The band above 150 kHz has be partitioned in 2 or 4 sub-bands. In this work, we consider the FCC-above-CENELEC partition reported in Tab. II(b). In the following, we denote the FCC-low band as LOW.

The PSD mask specifies a limit of 120 dBμV. If a notch is present, the limit is set to 100 dBμV. The minimum PSD dynamic range in the notch and outside the notch has to be larger than 20 dB.

TABLE II
ACTIVE CARRIERS FOR G3-PLC AND IEEE P1901.2 STANDARDS.

(a) Active carriers in CENELEC and FCC bands.

Band	Start freq.	Stop freq.	Cardinality
CENELEC A[1,2]	35.9	90.6	36
CENELEC B[1,2]	98.4	121.8	16
CENELEC C[1]	128.1	137.5	7
CENELEC D[1]	142.1	146.8	4
G3-FCC[1]	145.3	478.1	72
FCC-above-CENELEC[2]	154.6	487.5	72
FCC-low (LOW)[2]	37.5	117.2	18

[1] Used in the G3-PLC standard
[2] Used in the IEEE P1901.2 standard

(b) Partition of the FCC-above-CENELEC band.

	Start freq.	Stop freq.	Cardinality
$HIGH_0$	154.7	487.5	72
$HIGH_1$	154.7	318.8	36
$HIGH_2$	323.4	487.5	36

IV. Outdoor-Low Voltage Channels and Noise

For the performance analysis that follows in the next section, we consider the outdoor low voltage (O-LV) application scenario. This scenario considers the communication between the transformer sub-stations and the houses. To model the O-LV channels, we consider the OPERA model [21]. This model was derived from a measurement campaign. Three classes of channels were measured and modeled. The first class takes into account short distances (about 150 m), the second class medium distances (about 250 m) and the third class long distances (about 350 m). For the 150 m and the 350 m classes, three channel responses are provided and further classified into good, medium and bad quality. For the 250 m class, only good and medium quality channels are provided. The model is valid in the 0-20 MHz frequency range and exhibits a low-pass frequency response. The attenuation at 20 MHz exceeds 50 dB. The channel response dispersion is generally high, between 2 μs and 10 μs. In Fig. 3 an example of OPERA channels is shown.

The background noise can be modeled as described in [22]. Noise is assumed to be stationary colored Gaussian. Its power spectral density (PSD) exhibits high values at low frequencies and it decreases when the frequency increases according to an exponential profile. This behaviour is common to all scenarios, i.e. the In-Home, the O-LV and the Outdoor-Medium Voltage.

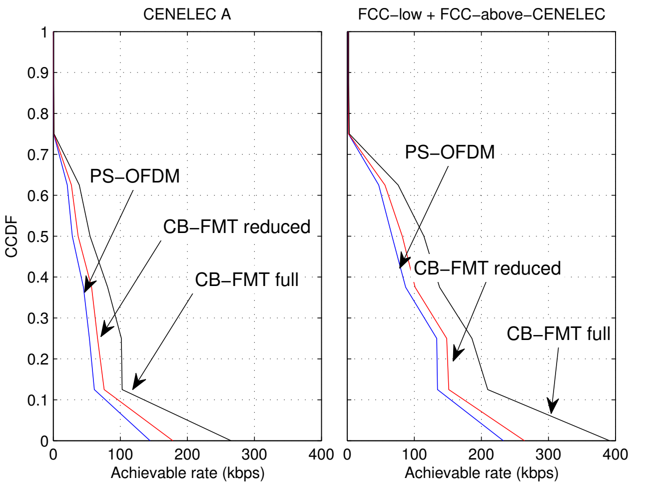

Fig. 5. CCDF examples of the achievable rate for the eight OPERA channels. On the left, CCDF related to CENELEC A band (EU). On the right, CCDF related to full FCC (IEEE P1901.2 FCC-low + FCC-above-CENENEC).

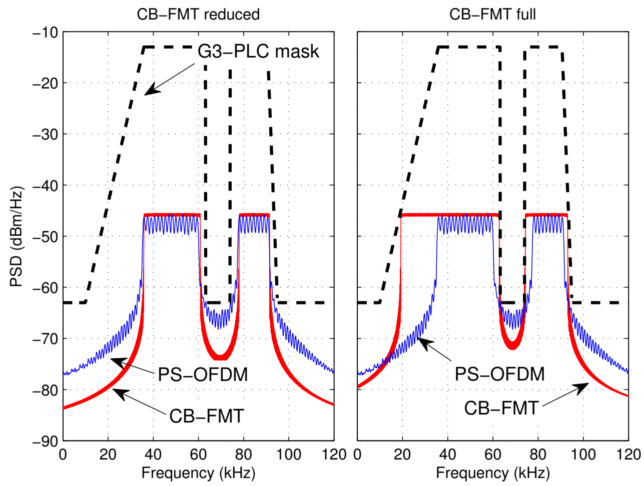

Fig. 6. PSD example in CENELEC A band for PS-OFDM, CB-FMT reduced and CB-FMT full.

In particular, we adopt the following model

$$\mathrm{PSD}(f) = a + be^{fc} \qquad \left[\frac{\mathrm{dBm}}{\mathrm{Hz}}\right], \tag{7}$$

where $a = -124$, $b = 52.98$ and $c = -0.0032$. The frequency f is expressed in kHz. In Fig. 4 the PSD of the background noise is shown.

In addition to the background noise, impulsive noise is also present [23]. This noise exhibits a series of short bursts. The burst amplitude is significantly higher w.r.t. the background noise. The CB-FMT analysis in the presence of impulse noise and the mitigation techniques will be the object of further studies.

V. Performance Comparison

We perform a performance comparison when CB-FMT is deployed in the G3-PLC and P1901.2 standards instead of PS-OFDM in terms of maximum achievable rate. The PL channel and the noise are modeled as described in Section IV. For PS-OFDM, we adopted the parameters described in the G3-PLC and IEEE P1901.2 standards and reported in Section III-B.

For CB-FMT, we set the same sampling frequency and maximum sub-channel number as for PS-OFDM. The CB-FMT prototype pulse length is equal to $M = KQ = LN$ [14], where Q is an integer number. In the following results, we set $K = N$ and $Q = L = 8$. The CB-FMT prototype pulse has a rectangular shape in frequency domain, i.e. $G(i) = 1$ for $i \in \{0, \ldots, Q-1\}$ and 0 otherwise; $G(i)$ denotes the M-point DFT of the prototype pulse [15].

With a such a choice, it should be noted that CB-FMT becomes the dual of OFDM where the rectangular pulse shape is chosen in the time-domain. Concerning the transmission power, we set the PSD of the transmitted signals so that we fulfill the EMC regulations and the PSD mask as shown in Fig. 6. In detail, we set a PSD limit to -45 dBm/Hz for frequencies below 150 kHz and -105 dBm/Hz for frequencies above 150 kHz. The limits are set equal for both systems. We have computed the achievable rate for all the eight OPERA channels for different CENELEC and FCC bands. The achievable rate is computed according to the Shannon capacity formula. In detail, for each band, we have computed the complementary cumulative distribution function (CCDF). Two CCDF examples are shown in Fig. 5. Then, we compute the mean achievable rate among the eight OPERA channels. The achievable rate is evaluated for two different CB-FMT configurations. Firstly, we set the CB-FMT active sub-channels to be equal to those used in OFDM. We denote this configuration as *CB-FMT reduced*. Then, we increase the number of active sub-channels so that the available bandwidth is better occupied. We denote this configuration as *CB-FMT full*. This is made possible because CB-FMT has a significant lower out-of-band PSD which allows to better fulfill the norms and to increase the possible number of active sub-channels. An example of these two configurations is reported in Fig. 6.

The achievable rate values are reported in Tab. III. CB-FMT outperforms OFDM because it is capable of exploiting the sub-channel energy with matched filtering in the frequency domain [12]. For the FCC band, we note that when the transmission involves only the high part of the band (above 150 kHz), the achievable rate is significantly low. This is due to the low PSD level (-105 dBm/Hz) that has to be used to satisfy the EMC regulation.

To evaluate the spectrum confinement properties of PS-OFDM and CB-FMT, we compute the power ratio between the useful signal in a sub-band and the interference generated by the signals in the adjacent sub-bands. In detail, we focus on the CENELEC band. We compute such ratio as

$$\begin{aligned} R_{ab} = &\frac{P_a}{P_b}, \\ &a \in \{A, B, C, D\}, b \in \{Z - a\}, \\ &Z = \{A, B, C, D, \mathrm{FSK}_{notch}\}, \end{aligned} \tag{8}$$

TABLE III
MEAN ACHIEVABLE RATE FOR SEVERAL BANDS IN EU AND US.

		Mean achievable rate [kbps]		
Band		PS-OFDM	CB-FMT reduced	CB-FMT full
CENELEC	A	44.38	55.45	80.88
	B	53.96	67.52	76.48
	C	25.48	31.77	42.39
	D	13.81	17.20	22.83
	BC	95.57	119.45	128.95
	BCD	122.80	153.35	157.34
	BD	67.77	79.03	99.30
FCC	G3-FCC	2.28	3.25	3.63
	$HIGH_0$	2.53	3.63	3.63
	$HIGH_1$	0.23	0.31	0.31
	$HIGH_2$	2.28	3.22	3.25
	$LOW+HIGH_0$	88.37	101.27	140.34
	$LOW+HIGH_1$	86.07	97.96	137.02
	$LOW+HIGH_2$	88.12	100.87	139.97

TABLE IV
POWER RATIOS BETWEEN USEFUL SIGNAL AND INTERFERENCE IN CENELEC BANDS FOR PS-OFDM AND CB-FMT.

	Power Ratio (PS-OFDM/CB-FMT reduced) [dB]				
Band	A	B	C	D	FSK notch
A	-	25.5/34.2	35.0/42.8	38.3/46.1	24.0/31.7
B	21.7/30.5	-	23.1/32.1	31.8/40.4	33.1/41.3
C	27.2/35.5	19.2/28.8	-	20.6/29.4	36.3/44.5
D	28.6/36.1	26.3/34.8	18.0/26.6	-	37.8/45.4

where P_a is the power of the transmitted signal in the CENELEC a band and P_b is the interference power generated by the signal transmitted in the b band. FSK_{notch} denotes the range of frequencies that need to be notched to have coexistence with single-carrier S-FSK. In Tab. IV, we report these power ratios. It can be observed that CB-FMT generates less interference in adjacent bands than PS-OFDM. For CB-FMT, the power ratios are about 9 dB higher than the OFDM ratios showing again that we can have better coexistence with systems operating in distinct bands.

VI. CONCLUSIONS

In this paper, we have investigated the use of an alternative FBM scheme for NB-PLC. We have considered CB-FMT, an FBM scheme where linear convolutions are replaced with circular convolutions. We have briefly described the band plan and EMC norms for NB-PLC in EU and US. Then, we have focused on two NB-PLC standards, namely G3-PLC and the recent IEEE P1901.2 standard. A numerical analysis has been performed in the Outdoor Low-Voltage scenario. Numerical results have shown that CB-FMT has higher achievable rate w.r.t. OFDM which is due to the ability to better exploit the channel energy and to provide better spectrum confinement which allows to fulfill the PSD norms with a higher number of active sub-channels than PS-OFDM. The better spectrum notching capability allows also to generate lower interference to adjacent bands, e.g., CENELEC bands, which in turn allows to have better coexistence between PLC systems operating in different bands.

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