Interoperability of Carrier–Modulated OFDM Systems with PRIME

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Abstract—**A consortium of several companies is currently working on the so called PRIME Project, a system for communication in a powerline grid. The new technology intends to use CENELEC A band, where some communication systems are already operating. As OFDM is specified as transmission method for PRIME, existing devices using OFDM might be adapted easily to interoperate with PRIME. Here, a brief "how–to" is presented and some problems concerning interoperability are addressed. At last, we state PRIME compatibility of iAd's DLC-2B® device.**

I. Introduction

PRIME is a recently developed powerline technology for SmartGrids. The abbreviation stands for Powerline-Related Intelligent Metering Evolution, as one main application is managing metering instruments via Powerline Communication (PLC) [1]. A larger consortium is working on this technology since 2007 and wants to present first products using it in 2010. In the presence, there are specification efforts of this PRIME system, regarding its physical and medium access layer according to IEEE conventions. The new communication system is based on non-modulated OFDM (Orthogonal Frequency Division Multiplexing) [2] and will allocate a frequency range 41 kHz − 89 kHz in CENELEC A band.

By now, some PLC systems working in this band are available which use carrier–modulates OFDM as transmission technique. Consequently, the question arises whether existing systems will be able to interoperate with PRIME devices. Here, we want to illustrate the conditions that have to be met and the problems which might occur. As DLC-2B® devices provided by iAd GmbH Großhabersdorf meet those conditions, we proofed that DLC-2B® chip is compatible with PRIME by trial.

The paper is organized as follows: Section II gives a brief introduction to the specification of the PRIME physical layer. An interoperable carrier–modulated OFDM system is described in Section III. Section IV investigates the effects of sampling frequency mismatch and synchronization is addressed in Section V. In section VI we report on the interoperability of iAd's device DLC-2B® with PRIME. Finally, Section VII draws some conclusions.

II. PRIME

The physical layer of PRIME is specified in [3]. A typical PRIME signal consists of a preamble for synchronization followed by two OFDM symbols with header information and up to 63 data OFDM symbols. As a sampling frequency of 250 kHz and a number of OFDM carriers of 512 is chosen, the sub-carrier spacing is

$$\Delta f = \frac{250\,\text{kHz}}{512} = 488.28125\,\text{Hz}. \qquad (1)$$

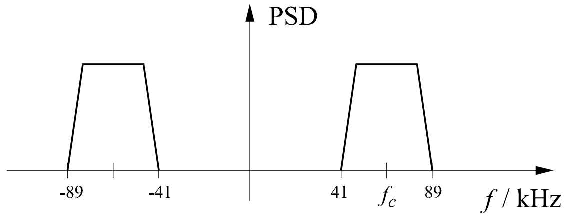

Fig. 1. Typical PSD of PRIME

Additionally, a cyclic prefix of length 48 (samples) shall guaranty interference free transmission. To occupy the desired frequency range, only carriers no. 87 to 183 are used for data transmission (with no. 331 to 427 complemented complex conjugated). Therefore, the center frequency of the transmission band calculates to $f_\text{c} = 134\Delta f = 65{,}429.6875\,\text{Hz}$. The typical power spectral density is sketched in fig. 1.

Data transmission can be performed in six different modes using either DBPSK, DQPSK or D8PSK, each of them optionally combined with forward error correction (FEC). The generation of data OFDM symbols in a PRIME transmitter is illustrated in fig. 2. The single blocks before the IFFT will not be described in detail here, for they are not the point of interest and an exhaustive description can be found in [3].

III. Interoperable Carrier–Modulated OFDM System

Clearly, an interoperable carrier–modulated OFDM system has to follow the PRIME specification in generating the 97 differentially modulated symbols per OFDM symbol from the input data. Further signal processing to generate the discrete time transmit signal is shown in fig. 3. and described as follows.

From the modulated data, an IFFT (Inverse Fast Fourier Transform) of length $N_\text{FFT} > 97$ produces a time domain signal in Equivalent Complex Baseband (ECB) representation. Hereby, the differentially encoded symbols are mapped on carriers no. $(N_\text{FFT} - 47)$ to N_FFT and 1 to 49. This signal is then passed to a rate converter, which performs oversampling with some factor R. After that, the discrete time transmit signal is generated by an inverse ECB transformation with transformation frequency f_0.

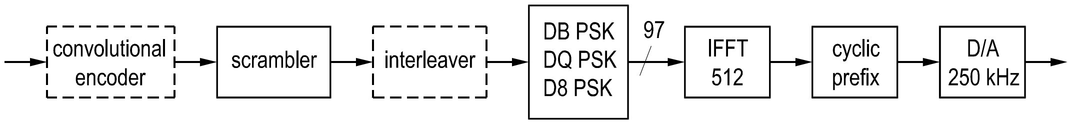

Fig. 2. PRIME Transmitter

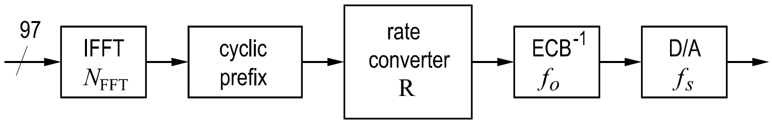

Fig. 3. Carrier–Modulated OFDM Transmitter

The considered carrier–modulated OFDM system might use an arbitrary sampling frequency $f_s \geq 250\,\mathrm{kHz}$. Therefore, its sub-carrier spacing calculates to

$$\widetilde{\Delta f} = \frac{f_s}{N_{\mathrm{FFT}} R}. \tag{2}$$

As PRIME uses 97 carriers, $N_{\mathrm{FFT}} = 128$ is a sufficient size of the IFFT. Hence follows, that the modulated data have to be mapped on carriers no. 81–128 and 1–49. For compatibility, the length of cyclic prefix is $48 \frac{N_{\mathrm{FFT}}}{512} = 12$. To assure a sub-carrier spacing of $\widetilde{\Delta f} = \Delta f$, the oversampling factor has to be set to

$$R = \frac{512}{N_{\mathrm{FFT}}} \frac{f_s}{250\,\mathrm{kHz}} = 4 \cdot \frac{f_s}{250\,\mathrm{kHz}}. \tag{3}$$

Finally, the ECB transformation frequency f_0 is the center frequency of the transmission band

$$f_0 = f_c = 65{,}429.6875\,\mathrm{Hz} \tag{4}$$

Thus, the modulated OFDM system will be able to send and receive signals interoperable to PRIME.

IV. Sampling Frequency Mismatch

In practice, an already existing system will have same limitations in choosing the parameters: Assuming f_s to be fixed and R to be restricted to a set of values, the system might not meet the sub-carrier spacing Δf. The resulting deviation can be measured by

$$\zeta = \frac{\widetilde{\Delta f} - \Delta f}{\Delta f}. \tag{5}$$

Regarding a pair of transmitter and receiver according to PRIME specification, this would lead to absolute frequency offsets $\mu \zeta \Delta f$ for each used carrier $\mu \in \{85, \ldots, 182\}$. However, due to ECB transformation with correct center frequency f_c, the frequency offsets are $\mu \zeta \Delta f$ with $\mu \in \{-48, \ldots, 48\}$ for the modulated OFDM system.

The performance degradation due to a mismatch in sampling frequency has been investigated by means of simulation. Under test is a PRIME compatible carrier–modulated OFDM system with $N_{\mathrm{FFT}} = 128$, $R = 4$ and $f_s = 250\,\mathrm{kHz}$. As "uncoded D8PSK" is the most sensitive transmission protocol used in PRIME, we consider transmission over an

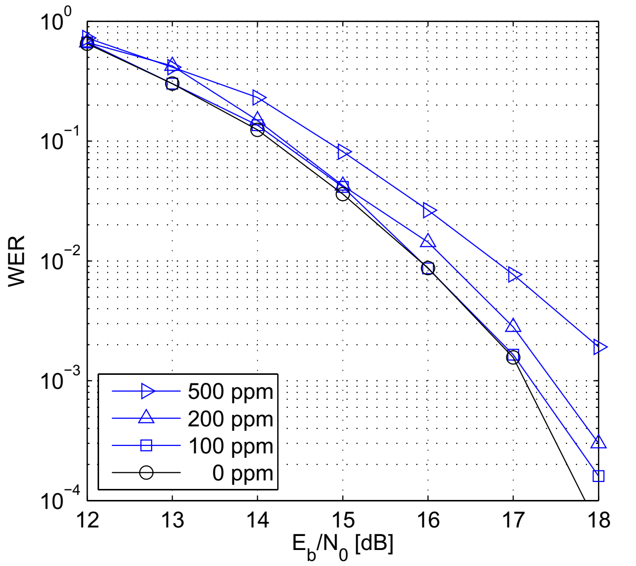

Fig. 4. Word Error Rate for Different Sampling Frequency Offsets

AWGN channel (Additive White Gaussian Noise) for this scheme. Fig. 4 presents the Word Error Rates (WER) obtained for different sampling frequency offsets, whereby a "word error" is defined such that at least one bit error occurs in an OFDM symbol (= word). As the ECB transform frequency f_0 retains its correct value, we observe only moderate loss in performance for offsets up to 200 ppm.

V. Synchronization

PRIME uses a linear chirp signal as a preamble for synchronization. Its waveform reads

$$p(t) = \cos\left(2\pi \left(f_{\mathrm{st}} t + \frac{1}{2} \frac{f_{\mathrm{fi}} - f_{\mathrm{st}}}{T} t^2\right)\right) \tag{6}$$

with start and final frequencies $f_{\mathrm{st}} = 41{,}992\,\mathrm{Hz}$ and $f_{\mathrm{fi}} = 88{,}867\,\mathrm{Hz}$ and a duration $T = 2{,}048\,\mu\mathrm{s}$, i.e. $t \in [0, T]$ [3]. So the preamble has a bandwidth of about 47 kHz and allocates the same frequency range as the OFDM symbols. Furthermore, a discrete time representation can be given as $p[n] = p\left(\frac{n}{250\,\mathrm{kHz}}\right)$ $(n \in \{0, \ldots, 511\})$.

Consequently, the preamble can be ECB transformed and sampled just like the data signal without violating the sampling theorem. This means that the carrier–modulated

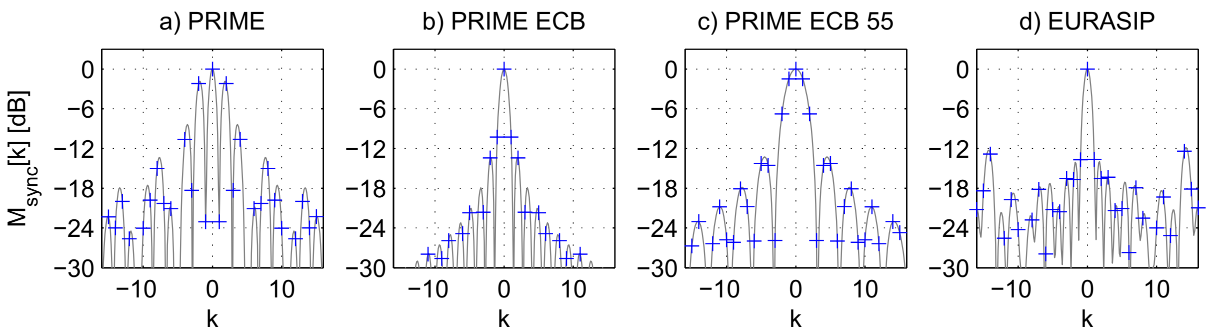

Fig. 5. Synchronization Metric with $L = 1$ in Noise- and Distortion-Free Environment for Various Preambles: "PRIME" – Preamble $p[n]$, "PRIME ECB" – Preamble $p_{\mathrm{ECB}}[n]$, "PRIME ECB 55" – Part of 55 Samples of $p_{\mathrm{ECB}}[n]$, "EURASIP" – Preamble of [4].

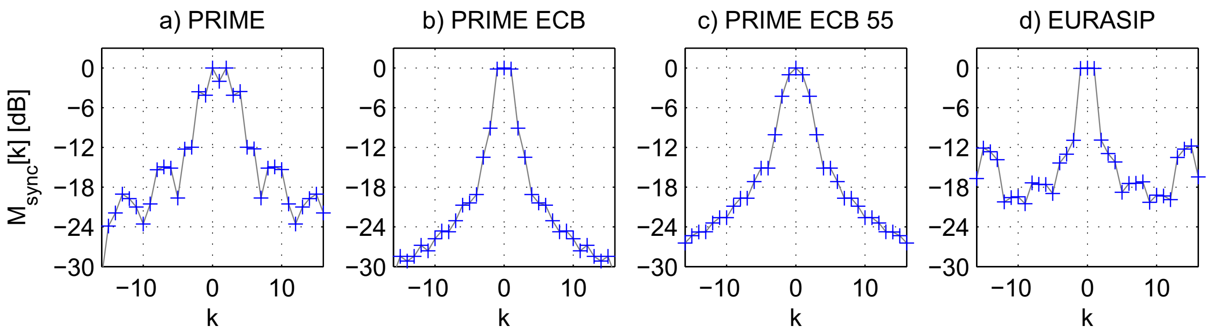

Fig. 6. Synchronization Metric with $L = 3$ in Noise- and Distortion-Free Environment for Various Preambles: "PRIME" – Preamble $p[n]$, "PRIME ECB" – Preamble $p_{\mathrm{ECB}}[n]$, "PRIME ECB 55" – Part of 55 Samples of $p_{\mathrm{ECB}}[n]$, "EURASIP" – Preamble of [4].

OFDM system introduced in sec. III can use a discrete time preamble of length 128 according to

$$p_{\mathrm{ECB}}[n] = \exp\left[j2\pi\left(-\frac{f_{\mathrm{fi}}-f_{\mathrm{st}}}{2}\frac{R}{f_{\mathrm{s}}}n + \frac{1}{2}\frac{f_{\mathrm{fi}}-f_{\mathrm{st}}}{T}\left(\frac{R}{f_{\mathrm{s}}}n\right)^2\right)\right], \tag{7}$$

where $n \in \{0, \dots, 127\}$.

In order to compare synchronization with $p[n]$ and $p_{\mathrm{ECB}}[n]$, we consider the synchronization metric introduced in [4], which reads

$$M_{\mathrm{sync}}[k] = \frac{\sqrt{\sum_{l=0}^{L-1}\left|\sum_{\kappa=0}^{N-1} y[n-l-\kappa]p^*[N-\kappa]\right|^2}}{\sqrt{\sum_{\kappa=0}^{N+L-2}\left|y[n-\kappa]\right|^2}}, \tag{8}$$

where $r[k]$ is the received signal in discrete time domain, N the length of the preamble and L the correlation window length. If L is set to 1, (8) calculates the correlation of the received signal $y[k]$ and the preamble $p[n]$ normalized by the short time energy of the correlation interval. For $L > 1$, the correlator output is averaged over L samples, what is advisable if the transmission channel is time dispersive (with discrete time impulse response of length L).

In fig. 5, $M_{\mathrm{sync}}[k]$ is plotted for various preambles in the case of $L = 1$, when the signal $y[n]$ is the respective preamble, i.e. $M_{\mathrm{sync}}[k]$ is the energy normalized autocorrelation function (ACF). We consider a) the "PRIME" preamble $p[n]$ and b) the "PRIME ECB" preamble $p_{\mathrm{ECB}}[n]$. A preamble c) "PRIME ECB 55", which is a subsequence of $p_{\mathrm{ECB}}[n]$ of length 55, is investigated additionally, as a yet existing device using ECB might have a restriction to $N < 128$. Fourthly, the preamble presented in [4] is included in the analysis as d) "EURASIP", which has got a length of 44. For each preamble, the autocorrelation function of an oversampled version is plotted as a gray line, while their values at time instances $n \in \{-16, \dots, 16\}$ are marked with '+'. The PRIME preamble a) shows sidepeaks at $n = \pm 2$ with a level of -2 dB, unfortunately. However, the ECB transformed preamble b) has got a more narrow correlation peak, as it can be interpreted to be the original PRIME preamble decimated by 4, and the values that are closest to the maximum read -10 dB. If one decreases the length of a chirp signal, the sharpness of the ACF declines—this is illustrated by case c). Note that the position where the 55 samples are taken form p_{ECB} is irrelevant with respect to the correlation properties. Finally, we see from d) that the well designed preamble from [4] shows a maximum sidelobe level of -12 dB, although it is the shortest sequence considered here.

Due to the PLC channel being time dispersive, one should employ a larger value of L to calculate M_{sync}, e.g. $L = 3$, see fig. 6. The choice $L = 3$ results in a broader maximum of M_{sync} for all preambles a) – d). Anyway, the relations between these sequences regarding the sharpness do not change compared to $L = 1$. Therefore, synchronization in the ECB domain seems to be more robust than synchronization in the real-valued baseband and, from the

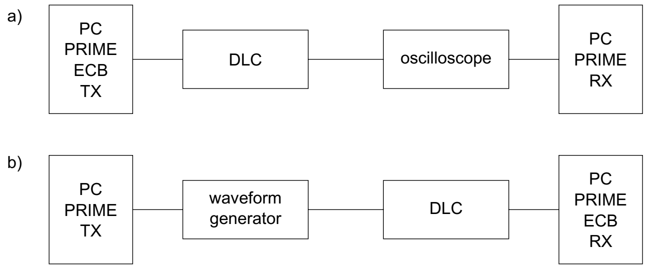

Fig. 7. Trial Setup: a) Transmission DLC to PRIME, b) PRIME to DLC

point of view of synchronization, a better preamble than a chirp signal could have been chosen in PRIME. As a differentially modulated OFDM system is not very sensitive to synchronization time offsets, PRIME devices might not suffer from that. However, one has to point out, that the sequence d) not only exhibits a sharper correlation peak, but also a shorter length, i.e. leads to a higher transmit efficiency, as less energy is wasted in the signal part that carries no information.

VI. Verification of Interoperability for iAd's DLC-2B®

iAd GmbH, Großhabersdorf, is providing a carrier–modulated OFDM PLC device called DLC-2B®, which is operating in CENELEC A band and hence is a competitor to PRIME. Its building blocks are well described by fig. 3, whereby the input symbols are generated by a programmable DSP. With an appropriate parameter setup and firmware update according to the conditions presented in sec. III, DLC-2B® can interoperate with PRIME devices that use non–modulated OFDM as intended by the PRIME project.

To verify this, we used the trial setup sketched in fig. 7. Firstly, PRIME ECB transmit signals were generated by PC software and sent by DLC-2B® with suitable rate conversion R and transform frequency $f_0 = 65{,}429\,\mathrm{Hz}$. An oscilloscope recorded these signals, which then were detected by a software defined PRIME receiver using a PC. Secondly, software generated PRIME signals were sent using a waveform generator and recorded by DLC. Afterwards, we processed the received ECB signals with a PC emulating a PRIME compatible firmware. Both trials a) and b) included burst synchronization.

In our tests, we investigated all six possible transmission protocols, i.e. uncoded/coded DBPSK, DQPSK and D8PSK, and transmission succeeded with zero bit errors for all schemes and for both scenario a) and b). Consequently, DLC-2B® devices can be stated to be compatible with PRIME.

VII. Conclusions

In this paper, we have outlined how existing carrier–modulated technologies operating in CENELEC A band are interoperable with the PRIME specification. Restrictions to the system's parameters have been derived and mismatch of sampling frequency has been investigated.

Additionally, a carrier–modulated OFDM system can perform synchronization with the PRIME preamble in ECB domain. Therefore, these existing powerline technologies—like the DLC-2B® devices produced by iAd GmbH Großhabersdorf—are compatible with PRIME in principal if the firmware is updated appropriately. For DLC-2B®, this has been proofed by trial.

References

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