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On the Optimization of the Physical Layer Frame Lengths of Narrowband Power-Line Communications

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Abstract—Low Voltage Narrowband Power-Line Communications for future smart grid networks are considered in this article. The impact of the physical layer frame lengths (or durations) as a determinant factor of the performance of the Narrowband Power-Line Communications is discussed. A simulation-based evaluation of the optimal frame lengths of Narrowband Power-Line Communications in terms of the effective data rate is provided. This approach and the obtained results can be used, amongst other things, for the proper selection of the parameters of the error correction codes and retransmission schemes for the Narrowband Power-Line Communications systems.

Index Terms—Narrowband (NB) Power-Line Communications (PLC), Cyclostationary Noise, Frames Lengths, Outage Probability, ARQ.

I. INTRODUCTION

A smart grid is an electricity network that integrates the information and communication technologies (ICT) to allow for an improvement of its management [1]. This update of the power grid will have to answer at the same time new challenges. First there is adaptation with respect to energy transition, which requires the proper integration of the renewable energy produced in an intermittent and decentralized way. Then there is mastery of mobile consumption with the large-scale introduction of hybrid and electric cars. The smart grid will be enabled by a set of diverse physical transmission mediums as no solution is suitable for all communication scenarios [2]. An example of such technologies is NB PLC based on multi-carrier modulations like OFDM (Orthogonal Frequency Division Multiplexing) which operate in the frequency range 3 – 500 kHz. These are viable mediums of communication for the smart grid at the access network, as evidenced by the multitude of technologies and standards for NB PLC: PRIME [3], G3 [4], IEEE 1901.2 [5], ITU-T G.hnem [6].

However, the NB PLC channels have hostile and unfavourable characteristics due to the fact that they were not designed to propagate signals beyond 1 kHz [7]. Indeed NB PLC channels are affected by several impairments such as high attenuation, time and frequency selectivity, and non-Gaussian strong noise dominated by its periodic impulsive component [7]–[9]. The attenuation increases with frequency, distance, and even more so by the charge density on the electrical network [10]. However, the attenuation only has a minor

impact upon error-free communications as long as it is known and an appropriate amplifier module ensures a good level of signal strength at the receiver.

Different measurement campaigns have shown that the dominant component of the noise on NB PLC channels is the impulsive noise synchronous to the mains voltage. The period of the variations of the variance $\sigma^2(t)$ of the impulsive noise is the same as the half of the duration of the AC voltage cycle:

$$\sigma^2(t) = \sigma^2(t + k \cdot T_{AC}/2), \quad (1)$$

where $1/T_{AC}$ is the frequency of the alternating current and $k \in \mathbb{Z}$. Given the low rate, less than 800 kbps [11], of the next generation NB PLC compared to the noise variations frequency, the periodic properties of the impulsive noise cannot be ignored. The NB PLC noise have been characterized recently by the cyclostationary models of Nassar [12] and Katayama [9].

This impulsive noise is one of the major factors limiting the performance of the NB PLC systems, and also the most difficult to mitigate. Current NB PLC systems are using Forward Error Correction (FEC) coding (e.g. repetition coding, convolutional coding, Reed-Solomon coding) along with interleaving to ensure reliable transmissions [11].

There is a probability of decoding failure, P_{out} , which is a function of the received frames Bit Error Rate (BER). During decoder failure events, the ARQ (Automatic Repeat reQuest) protocol allows for the detection and the retransmission of the data that have been incorrectly received. In NB PLC, the ARQ protocol is implemented based on acknowledged and unacknowledged retransmissions. The principle is simple: during an exchange of data, the transmitter sends one data frame at a time. Then it waits to receive an ACK message, which acknowledges the correct transmission of the sent frame before sending an additional frame. If the sender does not receive the ACK before the expiry of a pre-set time (called time-out), it retransmits the frame previously sent. This protocol called stop-and-wait ARQ is usually used for NB PLC [13]. Since a given frame length corresponds to a certain duration, the terms frame lengths and frame durations are used interchangeably throughout this article.

For the additive white Gaussian noise, the $\text{BER} = f(F_l)$ is an invariant function of the physical frame lengths F_l . For the NB PLC channels, the behaviour of the BER according to the frame durations is no longer evident because of the statistical and temporal characteristics of the noise. We propose to analyse the BER as a function of the lengths of the transmitted frames. This is important because some frame lengths will cause a more important BER and thus will lead to greater probability of outage.

In this article, we assume that the Channel State Information (CSI) is available at the receiver thanks to channel state estimation techniques. It is also assumed that each frame is independent of the other frames; in the sense that its processing in the physical layer (modulation, error correction coding, ect) is done independently of the other frames.

Usually, short frame durations result in better latencies. On the other hand, long frame durations (which often provide better protection from the channel impairments) tend to cause additional treatment period. Long frame durations are often associated with longer interleaving depths. When done intelligently, as advocated in [14], the interleaving mechanism can help bring diversity in transmissions and separate the error bursts encountered in the NB PLC channels. The best performance is usually obtained for large sizes of the interleaver depths. It is necessary to find a compromise between the durations of the sent frames and the level of protection ensured in the MAC and the PHY layers. According to the technologies used, strategies are different. For example, Prime lightens the error protection mechanisms on the physical layer and counts on a retransmission scheme to ensure reliable transmissions. ARQ is preferred over FEC for error control in Prime. In contrast, G3 uses a strong error correction on the PHY layer. Knowledge of BER behaviour depending on the frame durations allows for a better understanding of the benefit of an optimal frame duration selection. In fact, from a certain frame size, increasing the frame lengths no longer improves the performance in terms of effective throughput.

The main contribution of this article is in showing firstly that, in specific situations, the extension of the size of the frames increases the average BER. And secondly, we provide a simulation-based approach in order to determine the optimal lengths of the NB PLC frames in terms of the effective throughput given the characteristics of the impulsive noise. To the best of our knowledge, this approach has barely been addressed in the literature so far. The rest of this article is organized as follows: in section II, we present the NB PLC channel characteristics. In section III, we describe the method of calculation of the optimal frame durations. Simulation results confirming the relevance of the analysis are provided in this section. Finally, Section IV concludes the article.

II. NB PLC CHANNEL CHARACTERISTICS

A. Channel model

First proposed by Phillips in [15] and later improved and validated by Zimmermann and Dostert in [16], the multipath model provides a parametric function that describes all aspects

of the behaviour of the PLC channels: the low-pass characteristics, the attenuation, the frequency selectivity. The parametric transfer function is given as follows:

$$H(f) = \sum_{i=1}^N g_i(f) e^{-\alpha(f)l_i} \cdot e^{-j2\pi f\tau_i} \quad (2)$$

where: N is the number of significant paths, g_i is the complex gain of each path, $\alpha(f)$ represents the attenuation in function of the frequency, l_i is the length of the i^{th} path, τ_i the delay of the i^{th} path.

$$\alpha(f) = a_0 + a_1 \cdot f^k,$$

where a_0 , a_1 and k are the attenuation parameters. This model requires measurement campaigns of the channel response in order to determine the parameters N , $\alpha(f)$ and $(g_i, l_i, \tau_i)_{1 \leq i \leq N}$.

B. NB PLC noise: the Katayama model

We present below sufficiently accurate noise models in order to assess the real impact of the impulsive noise on the communications performance. The Katayama noise model proposed in [9] models the NB PLC noise as a real passband zero-mean coloured cyclostationary Gaussian process. The instantaneous variance (σ^2) of the noise is a periodic function of time, which period equals half the A.C. current cycle.

For the sake of simplicity, this model assumes that the shape of the power spectral density (PSD) of the noise is decoupled from time, as can be seen in Eq. 4. The spectral coloration is introduced by passing the noise through an invariant linear filter $\beta(f)$ whose spectral density decreases exponentially with the frequency (see Eq. 5).

$$n_t \sim \mathcal{N}(0, \sigma^2(t, f)), \quad (3)$$

$$\sigma^2(t, f) = \hat{\sigma}^2(t) \cdot \beta(f), \quad (4)$$

$$\beta(f) = \frac{a}{2} \exp(a \cdot f), \quad (5)$$

$$\hat{\sigma}^2(t) = \sum_{l=0}^{L-1} A_l \left| \sin\left(\frac{2\pi t}{T_{AC}} + \theta_l\right) \right|^{n_l}, \quad (6)$$

(where f is the frequency in Hz. $\mathcal{N}(0, \sigma^2(t, f))$ follows a Gaussian distribution with a mean of zero and a variance of $\sigma^2(t, f)$.)

As can be seen from Eq. 6, the various components of the NB PLC noise are described by the sum of L sinusoids:

- i) The invariant continuous noise is described by the sinusoid corresponding to $l = 0$ in the sum. For this component of the noise, the parameters θ_1 and n_1 are irrelevant because this component of the noise does not depend on time. θ_1 takes an arbitrary value and n_1 is set to zero.
- ii) The slowly changing cyclic continuous noise component corresponds to the sinusoid with $l = 1$.
- iii) And the cyclic impulsive noise component corresponds to the sinusoid with $l = 2$.

This model is calibrated with field measurement data. The values of the parameters $\{A_l, \Theta_l, n_l\}_{l=0,1,2}$ are given in Table

l	A_l	$\Theta_l [deg]$	n_l
0	0.13	-	-
1	2.8	128	9.3
2	16	161	5.3×10^5

(a) Parameters for environment A

l	A_l	$\Theta_l [deg]$	n_l
0	0.23	-	-
1	1.38	-6	1.91
2	7.17	-35	1.57×10^5

(b) Parameters for environment B

TABLE I: Parameters of the Katayama model for different environments

Frequency of AC source $f = 1/T_{AC} = 50$ Hz
Frequency range 34.4 – 478.1 kHz
Sampling rate $f_s = 1.2$ MHz
data rate $R_b = 500$ kbps
FFT size 256
Used modulation : BPSK and QPSK

TABLE II: Assumptions for the simulations [5]

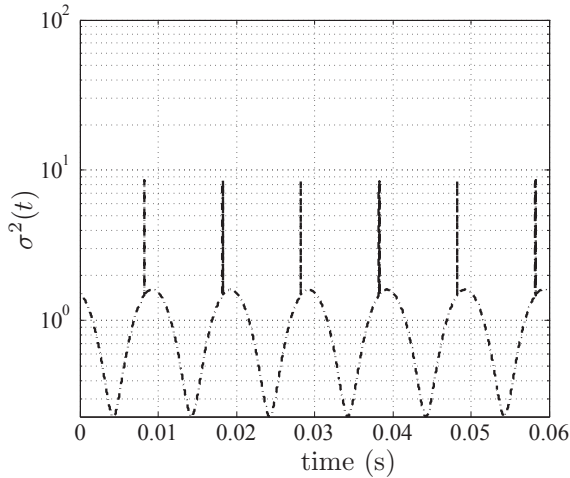


Fig. 1: Variance of noise in environment A

I and correspond to two different environments, A and B, where the Katayama noise model was calibrated [17].

Figs. 1 and 2 shows the variations of the variance of the noise in function of time, and the Figs. 3 and 4 shows a realization of the noise for the parameters defined in table I.

III. SYSTEM SET-UP AND SIMULATION RESULTS

The variations of the transmitter and/or the receiver positions are usually the main causes of the outage events in wireless communications. For a certain data rate R_b , a minimum threshold Signal to Noise Ratio (SNR) level is needed to ensure acceptable communication performance. An outage occurs if the signal drops below a predefined power level (corresponding to a predefined $SNR = SNR_0$). Since the BER is a decreasing function of the SNR, the outage events can be defined relative to the BER,

$$P_{out} = \Pr(SNR < SNR_0) = \Pr(BER > BER_0).$$

When using the stop-and-wait ARQ protocol, the effective data rate R which takes into account the data rate R_b in the

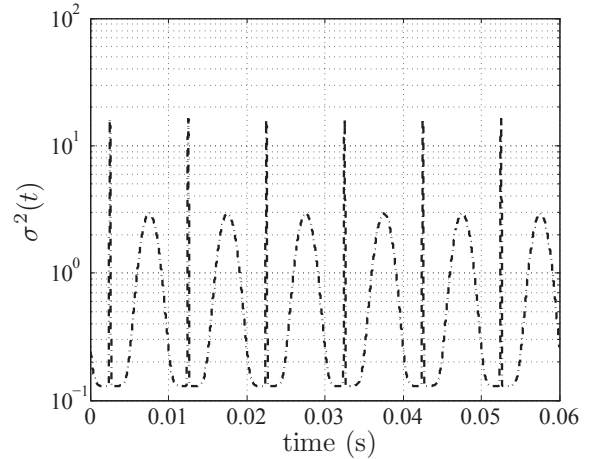


Fig. 2: Variance of noise in environment B

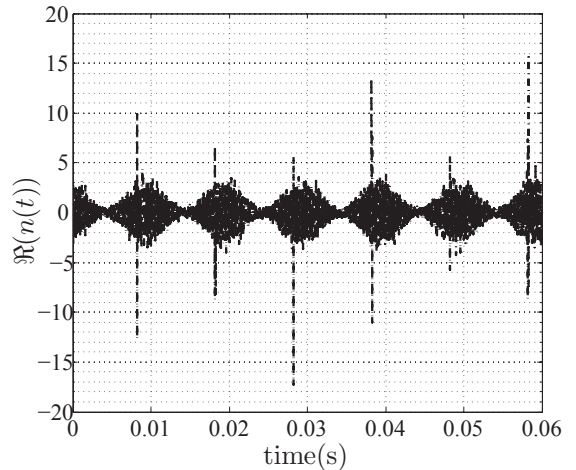


Fig. 3: Examples of noise realization in environment A

physical layer and the ARQ retransmission mechanism of the upper layers is given in [18], and computed as follows:

$$R = \frac{(1 - P_{out})R_b}{(1 - P_{out}) + c \cdot P_{out}}, \quad (7)$$

where c is the ratio of the time-out and the round-trip time (RTT) of the connection between the transmitter and the receiver. Simulation parameters in Tab. II are selected to be close to the parameters used in the IEEE 1901.2 standard for the FFC band [5].

The starting time of the frame t_0 is a uniformly distributed random variable that falls within 0 and $T_{AC}/2$. The frame

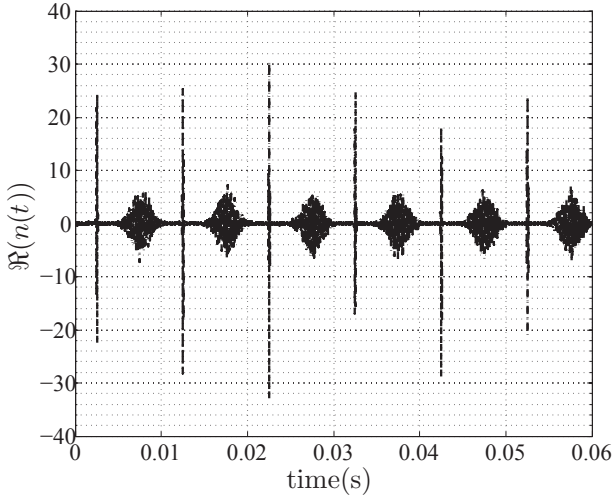


Fig. 4: Examples of noise realization in environment B

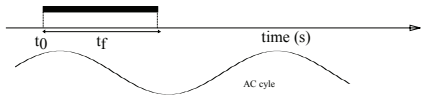


Fig. 5: Frame duration and sending time

duration is chosen to be $t_f = F_l/f_s$ as shown in Figure 5. Where F_l is the number of symbols that make up the frame. For any transmitted frame, the BER is a function of t_0 and t_f . Averaging all the possible transmission times t_0 , we get

$$\mathbb{E}(\text{BER}(t_0, t_f)) = f(t_f).$$

For each fixed frame length F_l , using Monte Carlo methods, the BER of the transmitted frames is computed for a fixed SNR (SNR= 10 dB). Thereafter the outage probability is computed for this fixed frame length and finally the effective data rate is computed by using the equation 7. The results of the effective data rate versus frame lengths have been plotted in Fig. 7, for a given $\text{BER}_0 = 10^{-6}$.

The BER depends on the length of the transmitted frames; all frame sizes (durations) do not experience the channel in the same way. The analysis of the shapes of the curves in Fig. 6 highlights two parts. The BER decreases to its minimum as the lengths (durations) of the transmitted frames increases, which is reached for 5,000 transmitted symbols. Then the BER slightly increases with the size of the transmitted frames.

This is due to the fact that, for small frame lengths, either the frames cover periods during which the noise is low (minima of the variance function of the noise) in which case the BER is good; or the frames cover periods during which the noise is high (maxima of the variance function of the noise). For longer frame sizes, the effect of the presence of samples of the noise with high power is weighted by the following noise samples with low power. From a certain size, when we extend the frame lengths, the average BER increases because the signal is likely to meet successive maxima of the noise. It is therefore

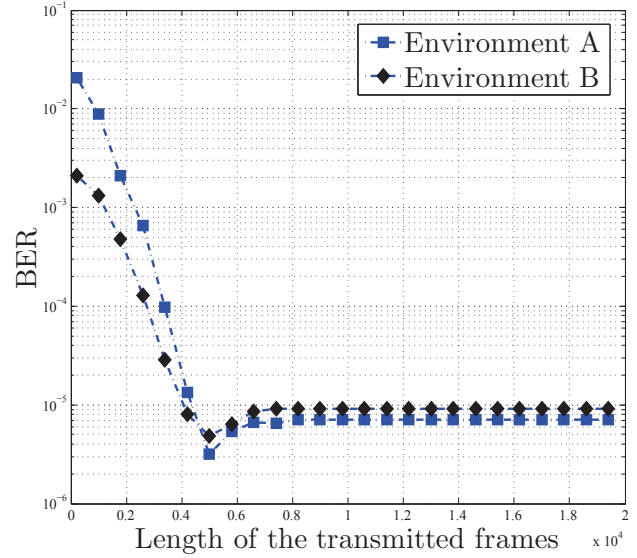


Fig. 6: BER curves depending on the lengths of the transmitted frames for environment A and B

necessary to find optimal frame lengths that minimize the BER.

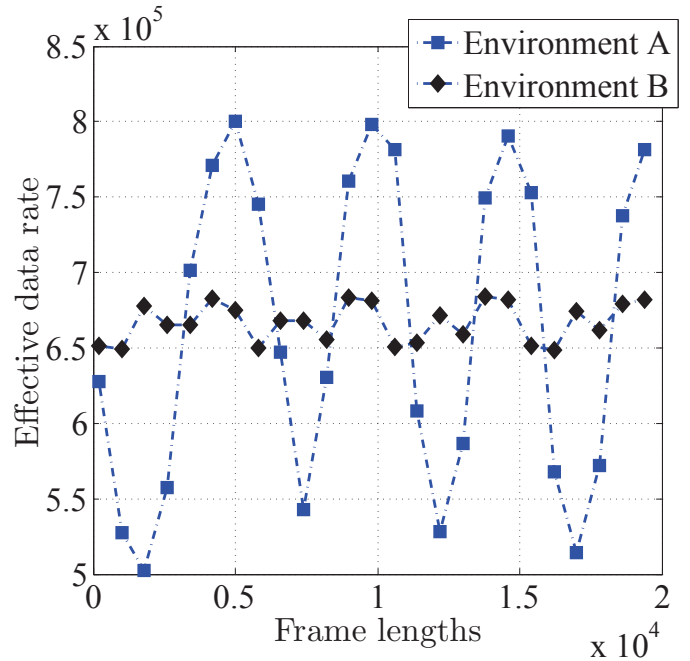


Fig. 7: Effective data rate depending on the lengths of the transmitted frames for environments A and B

We realize that, just as the BER, the effective data rate R depends on the transmitted frame length. Apart from the fact that this behaviour is periodic just as the noise and is different for each environment A and B; it may be noted that there are optimum frame sizes for transmitting across the network;

which correspond to lengths which are multiples of 5000 as shown in Fig. 7.

As expected, the effective data rate increases with the decrease of the BER to a minimum and increases as the BER begins to increase.

IV. CONCLUSION

Through simulations this article accounts for the correlation between the effective data rate and the length of the frames transmitted on the NB PLC channel. It is thus observed that there are optimal frames lengths, that maximize the effective data rate assuming the presence of noise described by the Katayama model. The interest of such results is to assist in the design of error correcting codes and retransmission schemes for the NB PLC channels. The same approach can be adopted for a different noise model e.g. Nassar noise model.

Finally, the approach and the results presented in this article pave the way for future research on the optimal frame lengths for NB PLC. More specifically it opens the door for analytical calculation of the dependency between the BER and the frame lengths, since the exact formula of the variance of the noise is provided.

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