Proposal for MAC frame parameter design based on OFDM signaling and synchronization error criteria

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***Abstract*— Nowadays, communication systems are usually implemented by digital modulated waveforms. Such is the case of OFDM, where the spectrum efficiency and the robustness against undesirable channel effects are the main reported advantages to improve the quality and data rate of transmission. However, OFDM demands for accurate synchronization methods, otherwise intersymbol and intercarrier interference will degrade the achievable capacity of the transmission. The impact of synchronization errors must be considered while designing a system based on OFDM waveforms for the performance guarantee. In this direction, this work addresses a selection strategy of main MAC frame parameters regarding preamble and payload length under OFDM signal transmission with synchronization errors. This selection strategy is proposed to assist designers in the choice of proper MAC frame parameters that best fits into their own restrictions.**

Keywords: MAC frame, OFDM, synchronization.

I. Introduction

Nowadays, digital communication schemes, by means of OFDM transmitting waveforms, are widely used in a variety of scenarios for wireless and wired mediums provided the benefits on quality and performance transmission. This is the case of mobile communications by LTE standard, wireless access by WiMAX or WLAN, wired access by power lines in case of G.hn and PLC, and terrestrial television broadcasting DVB-T [1].

For the implementation of above mentioned digital communication systems, synchronization schemes represent an essential component block. The proper recovery of symbols and binary data depends on the synchronized detection of incoming received signal, otherwise, the misalignment of received packets will degrade performance of the communication link.

In particular, OFDM is a digital waveform which demands accurate synchronization methods. In spite of OFDM provided advantages regarding robustness against inter-symbol interference (ISI), low implementation complexity and high spectral efficiency, a main disadvantage is given by the sensitivity to synchronization errors. In this regard, the current applications on the use of OFDM transmitting waveforms demand to implementing accurate synchronization methods on the receiver side to adjust time and frequency offsets.

Techniques to implement the synchronization of OFDM symbols between pair of nodes are referred to three major features [2]: the symbol timing, the carrier frequency, and the sampling clock synchronization. Any of these three concerns will produce system degradation performance in terms of signal to noise ratio at the receiver side, which in turn will reduce the allowable transmission rate.

In this direction, a variety of solution have been reported to synchronize the receiver to the transmitted OFDM symbol based on inserted training symbols or the cyclic prefix (blind). Basically, these methods compute the less difference between repetitive patterns on the transmitted symbol [3], [4]. Methods based on training symbols offer further opportunities not only to estimate the time-offset but also to estimate the carrier and sampling clock offsets [5], [6], [7].

These training patterns to synchronize the transmitter and the receiver result in additional overhead to the communication system. Since these patterns are not useful to convey information, the communication scheme have to assign additional resource facilities with the corresponding reduced transmission efficiency.

Additionally, some studies consider the impact of synchronization errors on performance [8], [9], [10], [1]. From a theoretical standpoint, closed-form expressions have been derived to establish the lower bound on the symbol error rate (SER) based on the introduced interference from synchronization error signals.

Reports above provide solutions to synchronize the received OFDM symbols and the theoretical lower bounds on SER performance. However, from a designer perspective, it is needed to balance the introduced overhead and the achieved performance to select the most suitable MAC frame parameters: preamble and payload length. Current paper discusses a methodology to select these parameters based on the effect of synchronization errors on the system performance.

The rest of the paper is organized as follows: Section II introduces the effect of synchronization errors and summarizes the analytic expressions to describe impact on performance. A proposed methodology is presented in Section III to select the most suitable MAC frame parameters. Section IV presents a case of study by a numerical example to illustrate the application of the proposed strategy. Finally, Section V concludes the paper.

II. Effect of synchronization errors

Synchronization errors can be categorized by three different effects [1]:

- Symbol timing offset: This is produced when the starting point of the OFDM symbol is not properly identified. This implies a misalignment between the received and decoded samples in the time domain as depicted in Fig. 1 a). This misalignment will produce time-shifted decoded samples as represented in Fig. 1 b).

- Carrier frequency offset: This is produced by the difference between the transmitter and receiver oscillators. These oscillators implement the upper and down conversion of the signal at the transmitter and the receiver sides, respectively, as depicted in Fig. 2 a). This carrier frequency offset produces a shifted recovered spectrum from the input signal as depicted in Fig. 2 b).
- Sampling clock frequency offset: This is given by the mismatch between the clock oscillators from the transmitter and the receiver, which in turn will produce an increasing or decreasing shifted sampling at the receiver side, as depicted in Fig. 3 a). This is mainly produced by the tolerances of quartz oscillators. The influence on the time-frequency domain is depicted in Fig. 3 b), in this case an increasing shifting on the decoded samples in time and frequency is produced.

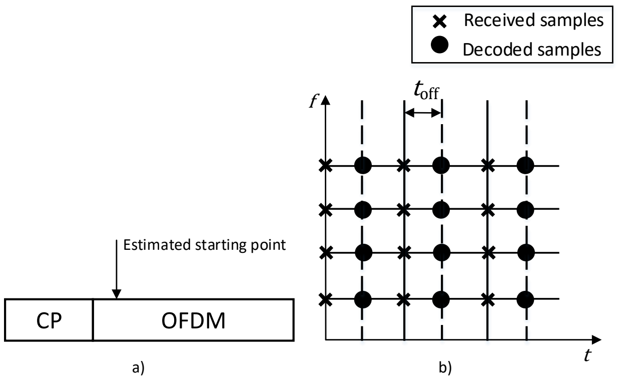

Fig. 1: Example of symbol timing offset effect. a) Received OFDM symbol. b) Effect on the time-frequency domain.

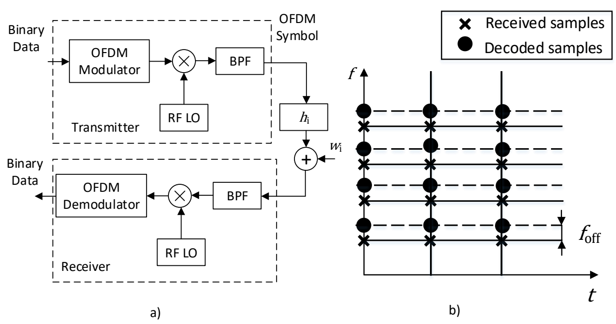

Fig. 2: Example of carrier frequency offset effect. a) Transmitter and receiver schemes. b) Effect on the time-frequency domain.

The impact of these three different offsets are described by the introduced inter-symbol interference (ISI) and inter-carrier interference (ICI). For instance, ISI is produced when

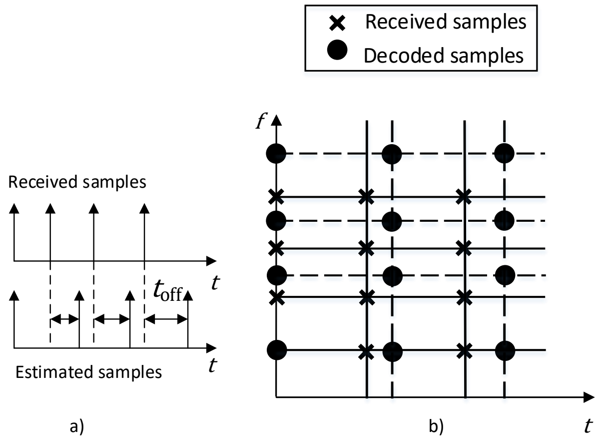

Fig. 3: Example of clock frequency offset effect. a) Time representation of sampling clock frequency offset. b) Effect on the time-frequency domain.

decoded samples from the current symbol are mixed with decoded samples from the previous or next transmitted symbol. This effect happens in case of symbol time offset, when estimated starting point is located at any point before or after the beginning of a given symbol, and in case of sampling clock frequency offset. On the other hand, ICI is produced by the interference components from neighbor subcarriers into the current demodulated subcarrier (orthogonality is lost). ICI interference happens when a carrier or clock frequency offsets produce shifted samples in the frequency domain, as depicted in Figures 2 b) and 3 b).

A. Analytic description of the impact of synchronization errors

The analytical description on the impact of these three offset errors are described as follows. We consider that transmitted symbols are conformed as depicted in Fig. 4. The OFDM symbols of length duration $T_{\rm OFDM}$ (N_C samples) are prepended with a cyclic prefix (CP) of duration $T_{\rm CP}$ (N_{CP} samples), this to avoid the effects of channel dispersion. The complex envelope of the transmitted OFDM symbol, without considering the cyclic prefix (CP) portion, will be given by [11]:

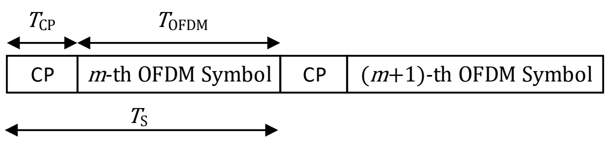

Fig. 4: Estructure of transmitted OFDM symbols.

$$s_{\text{OFDM}}^{m}(t) = \sum_{k=0}^{N_c-1} d_k^m \cdot e^{j2\pi \frac{k}{T_{\text{OFDM}}}(t-T_{\text{CP}}-mT_S)}, \quad (1)$$
$$k = 0, ..., N_c - 1, \quad t \in [0, T_{\text{OFDM}}],$$

where d_k^m is the transmitted constellation point at subcarrier k during the m-th OFDM symbol, and N_c is the total number of subcarriers for each OFDM symbol. The symbols will be transmitted by a multi-path frequency selective channel. This channel is described by several impulse response functions for each path as follows [11]:

$$h(t,\tau) = \sum_i h_i(t) \cdot \delta(\tau - \tau_i). \quad (2)$$

The received sampling interval $T = \frac{T_{\text{OFDM}}}{N_c}$, without considering the CP, will be given by [11]:

$$z[n] = \sum_i h_i(nT) \cdot s_{\text{OFDM}}^{m}(nT - \tau_i) + w[n] \quad (3)$$

For each i-th path, the transmitted signal $s_{\text{OFDM}}^{m}(t)$ will be filtered by the channel impulse response $h_i(t)$ and delayed by τ_i.

Then, considering the effects of the time sampling at the receiver side $T' \neq T$, the symbol timing offset Δn samples, and the frequency offset Δk, the resulting received signal model will be [11]:

$$z'[n] = e^{j2\pi\Delta kn} \sum_i h_i(nT') s_{\text{OFDM}}^{m}((n-\Delta n)T' - \tau_i) + \quad (4)$$
$$+ w[n]$$

Based on this model, the offset errors have the following general expression to describe the impact on a decoded subcarrier k and for the m-th OFDM symbol block:

$$Z_k^m = A_k^m H_k^m e^{j2\pi\phi_k^m} \cdot d_k^m + w_{\text{error}}[n] + w[n]. \quad (5)$$

where $H_k^m = \sum_i h[i] e^{j2\pi \frac{ki}{N_c}}$ is the frequency response of the channel [12], and $h[n] = \sum_i h_i(nT)$. Based on (5), the offset errors will introduce three different effects at the DFT output for each subcarrier amplitude d_k^m:

1) Attenuation factor given by $A_k^m H_k^m$.
2) Rotation of the transmitted constellation by the angle φ_k^m.
3) Interference noise by the sequence $w_{\text{error}}[n]$.

These factors are analytically described in the following Table I [11], [8]. In this table, $\sigma_{X_k}^2$ is the transmitted power on the subcarrier X_k, $d = \max\{C - (N_G + \Delta n), 0\}$, where $\sigma_H^2 = \sum_{i=0}^{C} \sigma_{h_i}^2$, $\sigma_{h_i}^2$ is the power or the i-th channel tap, and C represents the length of the channel delay spread normalized by the sampling period. Additionally, ε represents the relative sampling-clock offset given by $\varepsilon = \frac{T'-T}{T}$.

B. Analysis

The impact of synchronization errors (Δn, Δk, ε) have three different effects on the received subcarrier: amplitude attenuation, phase rotation, and introduction of interference. These three different effects, summarized by the analytic expressions in Table I, influence the subcarrier amplitude depending on the carrier frequency k and the OFDM symbol block m.

Considering the introduced attenuation factor (second column, Table I), the frequency and clock offset errors will introduce the most significant attenuation provided by the sinc$(\cdot)$ function relation with the offset errors Δk and ε. The symbol time offset will only have a linear relation with the offset error Δn, which in turn degrades less compared to the similar cases for frequency and clock offset errors.

Regarding the rotation produced by these three different synchronization errors (third column on Table I), only the clock offset error will be dependent on the OFDM symbol block m. The rotation produced have a linear relation with the OFDM symbol block index m, and with the subcarrier index k. Besides, the phase rotation produced by the symbol time offset will be also dependent on the subcarrier index k, whereas the angle rotation produced by the frequency offset will be independent of the subcarrier index k.

Considering noise power (last column in Table I), only the clock offset error will be a function of the carrier index k. This is due to the fact that time and frequency offsets will be constant for each processed OFDM symbol.

For all these cases, the worst case scenario is obtained for the larger subcarrier index; i.e. $k = N_c - 1$. In this case, the impact of synchronization errors on the DFT output will be more accentuated.

C. Total synchronization error -power

Based on the interference noise introduced by the synchronization errors, the total interference power produced by the synchronization errors may be upper bounded by [11]:

$$P_{k,\text{synch}}^m = P_{k,\Delta n}^m + P_{k,\Delta k}^m + P_{k,\varepsilon}^m. \quad (6)$$

In addition to this introduced noise, the extreme effect, on the rotated constellation angle, can be considered by superposing the three different cases as follows:

$$\phi_{k,\text{synch}}^m = \phi_{k,\Delta n}^m + \phi_{k,\Delta k}^m + \phi_{k,\varepsilon}^m. \quad (7)$$

In a similar case, the amplitude of the received signal will be attenuated by:

$$A_{k,\text{synch}}^m = A_{k,\Delta n}^m \cdot A_{k,\Delta k}^m \cdot A_{k,\varepsilon}^m, \quad (8)$$

when considering the higher attenuation case. Then, given this rotated angle and the produced attenuation on the received signal amplitude, the SNR metric will be reduced to $\text{SNR} \cdot (A_{k,max}^m)^2 \cos^2(\phi_{\max})$, which is similar to increasing the channel power noise by $P_N \cdot \frac{1-(A_{k,\text{synch}}^m)^2 \cos^2 \phi_{k,\text{synch}}^m}{(A_{k,\text{synch}}^m)^2 \cos^2 \phi_{k,\text{synch}}^m}$. Additionally, considering negligible impact of term, i.e.

TABLE I: Summary of noisy term factors introduced by synchronization errors [12], [8].

Offset	Attenuation A_k^m	Rotation ϕ_k^m	Interference Power P_k^m
Symbol	$A_{k,\Delta n}^m = \frac{N_c-\Delta n}{N_c}$	$\phi_{k,\Delta n}^m = 2\pi \frac{k\Delta n}{N_c}$	$P_{k,\Delta n}^m = \sum_{i=0}^{\Delta n-1} \lvert h[i]\rvert^2 \sigma_{X_k}^2 \frac{2N_c-(\Delta n-i)}{N_c^2}(\Delta n - i)$
Frequency	$A_{k,\Delta k}^m = \text{sinc}\,(\pi \Delta k N_c)$	$\phi_{k,\Delta k}^m = 2\pi\Delta k N_c$	$P_{k,\Delta k}^m = \frac{\pi^2}{3}(\Delta k N_c)^2$
Clock	$A_{k,\varepsilon}^m = \text{sinc}\left(\pi \frac{Nmk\varepsilon}{N_c}\right)$	$\phi_{k,\varepsilon}^m = 2\pi \frac{Nmk\varepsilon}{N_c}$	$P_{k,\varepsilon}^m = \frac{\pi^2}{3}(k\varepsilon)^2$

$(A_{k,\text{synch}}^m)^2 \cos^2 \phi_{k,\text{synch}}^m \to 1$, then the included noise may be simplified to $P_N(1-(A_{k,\text{synch}}^m)^2 \cos^2 \phi_{k,\text{synch}}^m)$.

Based on these considerations, an upper bound of the total noise power, produced by synchronization errors, yields:

$$P_{\max,\text{synch}}^m = P_{k,\text{synch}}^m + + P_N[1-(A_{k,\text{synch}}^m)^2 \cos^2 \phi_{k,\text{synch}}^m]\big|_{k=N_c-1}, \tag{9}$$

on each m-th OFDM symbol after considering the worst case scenario for $k = N_c$.

D. Approximation for small offset error values

The expression in (9) represents the total introduced noise on each subcarrier k for each OFDM symbol block m. The cosine function may be simplified considering small values of $\phi_{\max}^m$ when $\cos(\phi_{\max}^m) \approx 1 - \frac{(\phi_{\max}^m)^2}{2}$. Additionally, the sinc$(\cdot)$ function (second and third rows on second column in Table I) may be approximated to be unity for small values of the argument. For this case, the expression in (9) may be simplified by:

$$\begin{aligned} P_{\max}^m = &\left[P_N\left(1-\left(\frac{N_c-\Delta n}{N_c}\right)^2\left(1-\frac{(2\pi\Delta n)^2}{2}\right)^2\right)+\right. \\ &\left.+\sum_{i=0}^{\Delta n-1}|h[i]|^2\sigma_{X_k}^2\frac{2N_c-(\Delta n-i)}{N_c^2}(\Delta n-i)\right] \\ &+\left[\frac{\pi^2}{3}(\Delta k N_c)^2+P_N\left(1-\frac{1}{2}(2\pi\Delta k N_c)^2\right)\right]+ \\ &+\left[\frac{\pi^2}{3}(N_c\varepsilon)^2+P_N\left(1-\frac{(2\pi N m\varepsilon)^2}{2}\right)\right], \end{aligned} \tag{10}$$

where each term inside brackets represent the introduced noise by symbol, frequency and clock offset errors, respectively.

III. Proposed selection strategy

MAC frames, composed of a preamble and a payload (PDU), as depicted in Fig. 5, are typically used to transmit burst packets. The preamble sequence is transmitted to detect the starting point of OFDM symbols and to synchronize the local frequency oscillator. Training symbols, placed on the preamble, support data-aided algorithms to implement synchronization techniques. The preamble and the PDU sections are comprised of several OFDM symbols.

Based on the impact of synchronization errors, the MAC frame design should consider the relative length of the preamble to the PDU. The larger the preamble, the reduced the synchronization errors, but the higher the introduced overhead.

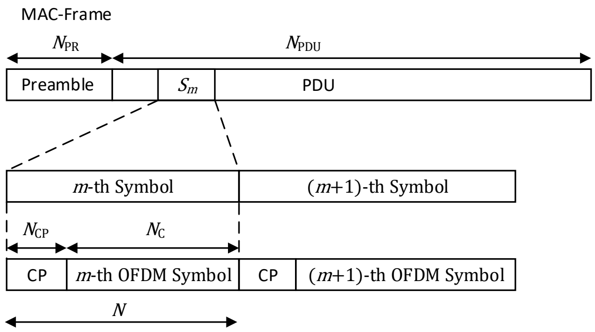

Fig. 5: Structure of transmitted MAC frames symbols.

On the other hand, we consider that the duration of the OFDM symbol is related to the allowable delay on the system. Given the OFDM symbol duration N_c, the delay introduced will be given by the waiting time to generate and receive the OFDM symbol plus the time spent to decode it, which results in a minimum delay of $2N_c$. We also assume the minimum length for the CP sequence given by the channel's spreading value (in samples), to reduce its undesirable effects.

A strategy to select the proper lengths of preamble and the PDU is to consider the introduction of negligible noise from the synchronization errors compared to that already introduced by the channel. This is expressed by [11]:

$$P_{\max,\text{synch}}^m \leq \frac{1}{K} P_N. \tag{11}$$

Considering the approximation derived in (10), each introduced noise error may be weighted separately to jointly have the same order of $\frac{1}{K}P_N$ in (11). That is, we may consider the following three cases:

$$\begin{aligned} &P_N\left(1-\left(\frac{N_c-\Delta n}{N_c}\right)^2\left(1-(2\pi\Delta n)^2\right)^2\right)+ \\ &+\sum_{i=0}^{\Delta n-1}|h[i]|^2\sigma_{X_k}^2\frac{2N_c-(\Delta n-i)}{N_c^2}(\Delta n-i) \leq \frac{1}{3}\frac{1}{K}P_N, \end{aligned} \tag{12}$$

in case of the symbol time offset error,

$$\frac{\pi^2}{3}(\Delta k N_c)^2 + P_N\left(1 - (2\pi\Delta k N_c)^2\right) \leq \frac{1}{3}\frac{1}{K}P_N, \qquad (13)$$

in case of the clock frequency error, and:

$$\frac{\pi^2}{3}(N_c\varepsilon)^2 + P_N\left(1 - (2\pi N m\varepsilon)^2\right) \leq \frac{1}{3}\frac{1}{K}P_N, \qquad (14)$$

for the frequency offset error.

Given the channel noise power P_N and the total number of carriers N_c, then expressions in (12) and (13) will determine the maximum accuracy for the symbol and the frequency offsets, given by Δn and Δf, respectively. This accuracy will determine the minimum length of the preamble (needed by the synchronization method) to guarantee the system performance.

On the other hand, the PDU length will be determined by the maximum number of symbol blocks allowable to support the system performance. In this case, relation in (14) will specify the maximum value of m for the given N_c, N, ε, and P_N. In this case, the sampling clock offset, given by ε (clock synchronizer accuracy), will determine the maximum length of the PDU.

Fig. 6 depicts the proposed strategy on five steps. Given the system and channel parameters and required performance criteria, steps in one and two evaluate the maximum allowable symbol time and frequency offset errors. Subsequently, we may implement a synchronization method, which in turn will demand a minimum training-sequence length. This will establish a minimum length for the preamble in step three. Finally, considering a value of ε (based on clock synchronization method), we may compute the maximum PDU length in step 5.

IV. Case of Study: Numerical Example

To illustrate the obtaining of the MAC frame parameters, we must define (see Fig. 5):

- OFDM symbol length (N_c),
- Cyclic prefix length (N_{CP}),
- Preamble length (N_P),
- PDU length (N_{PDU}),

based on the channel characteristics given by the noise power P_N, the channel impulse response $h_i(t)$, the performance metric given by K, the total number of subcarriers N_c, and the energy of each subcarrier $\sigma^2_{X_k}$.

We assume a wired medium (similar to twisted-pair cables in G.hn [13]), where multi-path effects are negligible. We consider the use of an ideal channel equalizer, such that no attenuation is introduced, i.e. $H_k^m = 1$. We also assume a guard interval of $1/4$ the OFDM symbol duration, i.e. $N_{CP} = \frac{1}{4}N_C$. We consider $\text{SNR} = 10$ dB for each subcarrier frequency, and assuming a noise power of 10^{-1} W, then $\sigma^2_{X_k} = 1$ W. Finally, we consider a performance metric of $K = 10$.

Considering this scenario, we illustrate the MAC frame parameter by evaluating the five step from the diagram in

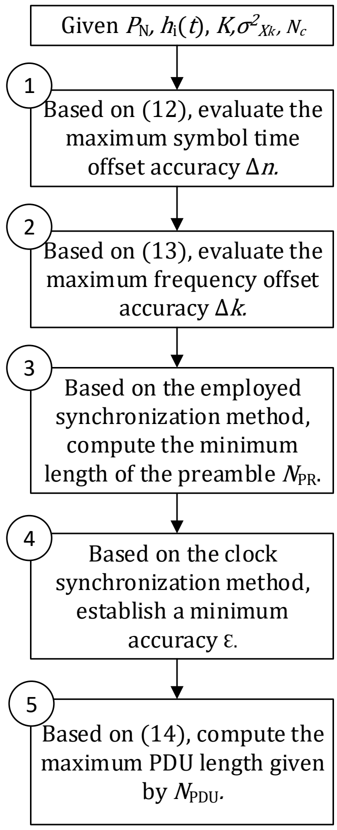

Fig. 6: Block diagram of the proposed strategy.

Fig. 6 design using $N_C = 2048$, and $N_{CP} = 512$. We obtain $\Delta n = 0.003$ on the second step after clearing:

$$P_N\left(1 - \left(\frac{N_c - \Delta n}{N_c}\right)^2\left(1 - (2\pi\Delta n)^2\right)^2\right) \leq \frac{1}{3}\frac{1}{K}P_N \qquad (15)$$

considering the effect of the second term only in (12) (assuming negligible effects from the equalized channel).

Following the second step on the diagram from Fig. 6, we use (13) to evaluate the maximum frequency offset, which yields $\Delta k N_c \approx 0.02$, i.e. the normalized frequency offset must represents 2% of the total number of used sub-carriers. In other words, the frequency offset must be 2% of the subcarrier spacing.

To compute the length of the preamble sequence we implement the method of Schmidt and Cox in [14] to adjust symbol time and offset frequency. By using this method, the symbol time offset is given by $(\Delta n)^2 \approx \frac{4}{L \cdot \text{SNR}}$, meanwhile the frequency offset is given by $(\Delta k N_c)^2 = \frac{1}{\pi^2 \cdot L \cdot \text{SNR}}$, where L represents the total number of samples from the training symbols. Clearing L in both expressions and taking the maximum value we obtain that only half of an OFDM symbol is needed on this scenario to accomplish with the frequency and time symbol accuracy.

Finally, to compute the maximum PDU length, we consider a typical clock offset error of 10^{-5} [15]. By clearing the total number of consecutive OFDM symbols m from (14), then we get $N_{\text{PDU}} = 13$.

The methodology illustrated here is a novel proposal to account for the impact of synchronization errors while obtaining the MAC parameters. This is important to ensure proper performance regarding OFDM transceivers. Reported literature in providing the MAC frame parameters is only from the related standards (WLAN 802.11, DTV, G.hn). However, a methodology departing from the available synchronization methods is not provided. This study illustrates a methodology to assist designers on the choice of the MAC frame parameters for generic applications taking into account the accuracy of the given synchronization techniques.

V. Conclusions

Current paper addresses a selection strategy to establish the MAC frame structure in OFDM system. The design of preamble length and the PDU will have an impact on the error performance and the overhead introduced in the communication system. The larger the preamble, the better the system performance in terms of the SNR, but the larger the introduced overhead. In this direction, the proposed strategy is intended to assist to communication system designers to have a balance between system performance and the introduced overhead.

Acknowledgment

Current research project is part of the Elektromobilität mit Redundanter Intelligenter Kommunikations-Architektur (ERIKA) Project, supported by the Bundesministerium für Wirtschaft und Energie, Germany.

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