Performance of NC-OFDM autocorrelation-based synchronization under narrowband interference

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Abstract—The NC-OFDM based cognitive radio can operate in a bandwidth partially occupied by licensed system, e.g. narrowband analog wireless microphone system. However, the benefit of using NC-OFDM for high spectral efficiency may not be achievable due to the NC-OFDM synchronization problem caused by interference originating from the narrowband transmission. In this paper, probability of correct NC-OFDM frame detection is analyzed for commonly used Schmidl&Cox synchronization algorithm under the mentioned interference condition. The results are obtained by the means of simulations while modeling interference in accordance with the proper wireless microphones standard. These results are compared to the ones obtained by simpler interference modeling as a complex sinusoid.

Index Terms—NC-OFDM, synchronization, Schmidl&Cox, PMSE, interference, wireless microphone.

I. INTRODUCTION

NON-CONTIGUOUS Orthogonal Frequency Division Multiplexing (NC-OFDM) is a modulation technique that focused much attention recently for advantages of its utilization in Cognitive Radio systems (CR) [1]. Worldwide measurements campaigns, e.g. [2], revealed that big part of electromagnetic spectrum is unused or partially used, even though licenses were already distributed among so called primary users (PUs). The CR, being secondary user (SU), aims at increased utilization of electromagnetic spectrum by transmitting its signal while keeping interference caused to the PUs at the limited (allowed) level. The NC-OFDM-based SU signal can use radio frequencies unused by a PU, while subcarriers actually used by a PU transmission are modulated by zeros. In order to further decrease interference caused to the PU, spectrum shaping algorithms can be applied, e.g. the ones described in [3]–[5]. Although the CR takes some actions to limit interference caused to the primary system, it is not reciprocated by the PU. In the worst case, when the PU transmission band lies within the SU receiver bandwidth, the whole PU signal can be treated as interference to SU link. In the CR receiver, some techniques must be applied to operate under strong PU-based interference. The first step for error-free data reception is correct synchronization in both the frequency and the time domain. As shown in [6], OFDM synchronization is very sensitive to frequency synchronization error and moderately sensitive to time synchronization error. The same conclusions can be derived for NC-OFDM systems. Incorrect time synchronization causes Inter Symbol Interference (ISI), i.e. part of an adjacent OFDM symbol is processed at the receiver as interfering with a currently received OFDM symbol. Moreover, Inter Carrier Interference (ICI) is caused by the loss of orthogonality between subcarriers. If the frequency synchronization error occurs, ICI is observed. In case when the frequency offset normalized to subcarriers frequency spacing is integer, the received symbols will be shifted at the output of the Fast Fourier Transform (FFT) by an integer number of frequency bins compared to the Inverse FFT (IFFT) allocation input bins at the transmitter.

Since the first proposals to use Fourier Transform for multicarrier transmission [7] many OFDM-based wireless communications standards came into existence. Over these years, many synchronization algorithms for OFDM have been proposed. The overview of these algorithms is provided in [6]. There are two main approaches. The first one is based on redundancy carried by a cyclic prefix (CP) e.g. [8] that can be used not only for initial synchronization but also for tracking after initial synchronization. The second approach is based on specially designed preamble transmitted at the beginning of OFDM symbols frame, e.g. the one presented in [9]. As preamble provides more redundancy than the CP it is more suitable for environments of low Signal-to-Noise (SNR) and Signal-to-Interference (SIR) Ratios, which is the case of our considerations.

The synchronization in OFDM- and NC-OFDM-based CR receivers has recently gained a lot of attention. In [10], the authors proposed to use pseudo noise (PN) sequence with excellent autocorrelation properties for the preamble-based synchronization. However, as this sequence is generated in the time domain, serious interference into a PU band is expected. In [11], an cross-correlation based synchronization was considered. There, narrow-band PU signal is strongly attenuated at the CR receiver thanks to specially design filter however, the system considered is a standard contiguous OFDM with single tap dispersive channel model, and no carrier frequency offset (CFO) taken into account. The solution based on autocorrelation in OFDM system, tested under non-zero CFO is presented in [12]. The interference is modeled as a noise added to subcarriers occupied by the SU signal in the frequency domain. In the first approach, preamble is prolonged to get better time synchronization performance, but as it does not provide sufficient synchronization quality improvement second stage is carried, based on cross-correlation and filtering. However, the second stage can be successful only if frequency offset is estimated correctly during the first phase. On the basis of literature study it can be observed that in the realistic test environment, i.e. in the presence of white noise, multipath propagation and non-zero CFO, autocorrelation-based synchronization is used the most commonly. In particular Schmidl&Cox synchronization algorithm [9] is usually refereed to. It inspired the analytical analysis of its performance in case of wideband interference.
Currently the most practical application of CR is in the so-called TV White Spaces (TVWS), which are vacant frequency channels in the UHF band of the digital terrestrial TV. The transmitters use PMSE devices, some of which are to be met: wideband digital television signals and narrowband signals of the Programme Making and Special Events (PMSE) equipment e.g. wireless microphones. This paper considers the performance of Schmidl&Cox synchronization method implemented in the NC-OFDM based CR receiver with the narrowband interference caused by analog PMSE transmitters. The PMSE equipment can be used without any preceding booking, at any location, and at any time what makes them harder to be avoided in comparison to the known and static configuration of DVB-T transmitters. As we will show, the narrowband interference can be detected as a useful signal in the CR receiver, so it is not treated as noise-like component. This paper models narrowband analog system that is an novelty in comparison to the analysis in [14] that was done for standard OFDM signal interfered with narrowband digital-modulated signal. In practice, many PMSE devices still use analog modulation. For the assessment of the PMSE impact on the synchronization quality a test signal defined for these devices in standard [16] was used.

The article is organized as follows. In Section II, the system model is presented with description of used PMSE interference model in subsection II-A. Section III describes synchronization algorithm whose performance is evaluated by the means of computer simulations in Section IV. The paper is concluded in Section V.

II. SYSTEM MODEL

The considered system consists of NC-OFDM based cognitive radio link: the NC-OFDM transmitter, radio channel and the receiver, that is disturbed by interference. The transmitter uses N-point IFFT as the multicarrier QAM modulator, while the receiver is based on N-point FFT. Each OFDM symbol consists of N samples generated with IFFT block that are preceded by NCP samples of cyclic prefix. Only α subcarriers out of N are modulated with QAM symbols. The indices of these subcarriers are elements of vector $I_{DC} = \{I_{DC1}, ..., I_{DCα}\}$. These values are taken from the set of possible indices, i.e. $\{-N/2, ..., N/2 - 1\}$. For the p-th OFDM symbol, complex value modulating k-th subcarrier is denoted $d_k^p$ (where $k \in I_{DC}$). An OFDM frame consists of $β$ consecutive OFDM symbols. For the subcarrier spacing of $Δf$ and the sampling period of $T_s = 1/(ΔfN)$, the transmitted signal, represented at complex baseband, is expressed as

$$y(nT_s) = \sum_{p=1}^{β} \tilde{y}(nT_s - (N + N_{CP})T_s(p-1),p)$$

where

$$\tilde{y}(nT_s,p) = \begin{cases} \sum_{k \in I_{DC}} d_k^p \exp(j2πkn/N) & \text{if } -N_{CP} \leq n \leq N - 1 \\ 0 & \text{otherwise} \end{cases}$$

is time domain representation of $p$-th OFDM symbol. Such a signal is transmitted over multipath radio channel whose impulse response is $h(lT_s)$ for $l = 0, ..., L - 1$ path. Apart from the multipath propagation effect, each $y(nT_s)$ sample is distorted by the CFO (denoted by $ν$, when it is normalized to subcarrier spacing frequency), white noise $w(nT_s)$ and the PU signal interference $i(nT_s)$. At the CR receiver antenna, the baseband signal can be expressed as:

$$r(nT_s) = \left( \sum_{l=0}^{L-1} h(lT_s)y((n-l)T_s) \right) \exp(j2πνn/N) + w(nT_s) + i(nT_s).$$

We are neglecting fractional time synchronization error, i.e. lower than $T_s$, as it can be removed by equalization [6]. While white noise is commonly modeled by the complex Gaussian random process, proper modeling of interference is a more challenging task.

A. Interference model

The interferer (the PU transmitter) under consideration is an analog wireless microphone. Although channel bandwidth for such a device is limited to 200kHz [16] like in a digital modulated version, the bandwidth of transmitted signal depends strongly on e.g. modulating signal characteristic and frequency deviation. In order to make the interfering signal model close to reality we have based it on a recent work [17] that was done in collaboration with well known wireless microphones manufacturer, i.e. Sennheiser. The interfering signal at the $n$-th received sample moment can be described as

$$i(nT_s) = a \exp\{j2π[f_{interf}nT_s + \int_0^{nT_s} (F_{interf}(τ) + F_\pi\cos(2πf_\piτ))dτ]\}$$

where $a$ describes amplitude that can be changed to achieve required SIR value, $f_{interf}$ is normalized carrier frequency of wireless microphone, $F_\pi$ is the frequency deviation, $F_\pi$ is the frequency deviation of pilot and $F_\pi$ is the frequency of pilot tone. The modulating signal $d_{interf}(τ)$ is colored noise defined as test signal in [16].

The other interference model considered in this paper is simple complex sinusoid defined as

$$i(nT_s) = a \exp(j2πf_{interf}nT_s).$$

III. SCHMIDL&Cox SYNCHRONIZATION ALGORITHM

The synchronization algorithm presented in [9] needs specially designed first two OFDM symbols in a frame. The first half of the first symbol is to be identical to the second half. Generation of such a preamble can be done by modulating only subcarriers of even indices out of all $I_{DC}$. In order to keep constant OFDM symbol power the resulting symbol samples should be multiplied by $\sqrt{2}$, because half of all available subcarriers is used. It can be observed that the influence of multipath channel on both halves is the same. Moreover, the CFO causes only relative phase rotation between the same
samples of two halves. It allows for the design of the timing metric:

\[ M(i) = \frac{|P(i)|^2}{(R(i))^2} \]

where

\[ P(i) = \sum_{m=0}^{N/2-1} r^*(i + m) T_s \left( i + m + \frac{N}{2} \right) T_s = P(i - 1) + r^*(i + N/2 - 1) T_s r((i + N - 1) T_s) - r^*(i - 1) T_s r((i + N/2 - 1) T_s) \]

\[ R(i) = \sum_{m=0}^{N/2-1} |r((i + m) T_s)|^2 = R(i - 1) + |r((i + N/2) T_s)|^2 - |r((i - 1) T_s)|^2 \]

and \( x^* \) denotes complex conjugate of \( x \). The nominator is a result of correlation of two \( N/2 \)-long received samples vectors, where the second vector is delayed by \( N/2 \) samples. The integer CFO estimation is important only in case of correct time synchronization, the differential method used in [9] will not be presented here.

\[ \hat{n}_{opt} = \arg \max M(i). \]

For the case of high SNR and no interference, the timing metric approaches 1. Moreover, \( P(\hat{n}_{opt}) \) can be used to estimate fractional frequency offset \( \hat{\nu}_{frac} \), i.e.

\[ \hat{\nu}_{frac} = \frac{\text{angle}(P(\hat{n}_{opt}))}{\pi}. \]

where \( \text{angle}(x) \) extracts the phase of complex number \( x \). As high values of CFO are less probable and the error of integer CFO estimation is important only in case of correct time synchronization, the differential method used in [9] will not be presented here.

IV. SIMULATION RESULTS

In the considered NC-OFDM system, \( N = 256 \) subcarriers and the cyclic prefix of \( N_{CP} = 16 \) samples are used. The vector of occupied subcarriers indices is: \( I_{DC} = -100, ..., -1, 1, ..., 16, 32, ..., 100 \). As the subcarrier spacing is \( \Delta f = 15 \) kHz, the notch of 210 kHz is wide enough to accommodate one PMSE channel. The simulated OFDM frame modulated with random QPSK symbols consists of \( \beta = 3 \) OFDM symbols. In the first symbol only subcarriers of even indices out of \( I_{DC} \) are modulated. Before each OFDM frame, two empty OFDM symbols (modulated by zeros) are transmitted that brings the scenario closer to a bursty signal transmission. The transmitted signal passes 9-path Rayleigh fading channel defined for LTE [18] whose instance is generated independently for each frame. Similarly, the CFO is the uniformly distributed random variable drawn from the interval \((-3, 3)\) for each frame independently.

Below, the probability of correct time synchronization is considered. We assume that a frame is detected correctly if the absolute value of timing error is lower or equal than \( N_{CP} T_s \) and the absolute value of frequency error is equal or lower than the half of the subcarrier spacing. In the Fig. 1, probability of correct synchronization estimated over 100000 frames is plotted for wide range of SNRs and SIRs. The interference is modeled as originating from a wireless microphone, modulated with test noise-like signal, operating on normalized frequency 24. As expected, for high SIR, it is observed that the probability of correct detection increases with an increase of an SNR. However, for moderate SIR, e.g. 10 dB, the probability of correct synchronization decreases rapidly as SNR increases. It is the effect of false synchronization at PMSE signal itself. As the SNR increases the interference-to-noise power ratio increases proportionally. This observation justifies the assumption that the PMSE-based interference cannot be treated simply as noise generated on unoccupied subcarriers as in [13].

In an analog PMSE device, the carrier signal is modulated with audio signal that does not change strongly over the time of an OFDM symbol duration, i.e. 67 \( \mu \)s. Taking this into account, as well as the fact that the computational complexity of noise filtering is quite high, it seems reasonable to compare it against simple interference model of complex sinusoid. In Fig. 2, probability of correct synchronization is shown against SNR and SIR for both interference models. It is visible that both interference sources disturb NC-OFDM transmission similarly, especially in low SNR region. The higher the SNR, the bigger
The strongest degradation is observed when the interference occupies an uneven subcarrier. The peak of the timing metric is degraded at optimal correlation index, i.e. correlation index for which autocorrelation windows in (6) is perfectly aligned with two halves of received preamble. In no-interference, no-noise case maximum of timing metric is observed at optimal correlation index. For the simulated system correlation index equals 561.

The effect of complex sinusoid carrier frequency can be observed in the resulting timing-metric values too. In Fig. 4A mean timing metric (solid line) is shown in no-noise, no-interference environment. Region, in which 68% of all samples appear is found between the dashed lines. The maximum of the timing metric is achieved for the correlation index value equal to 561. The other three subplots of Fig. 4 are presented for SIR of 0dB. In all of them timing metric achieves the maximum value of 1 (with very small variance) for the correlation indices characteristic for the time before the frame start. It is possible that the maximum of timing metric is found in this region, and the false frame synchronization occurs. For the interference frequency of 24, the mean timing metric at optimal correlation index is close to 0.8. As the variance of timing metric at optimal correlation index is quite high, correct frame synchronization is possible. As the interference frequency is closer to the odd frequency 25, the mean timing metric at optimal correlation index decreases strongly. The probability of correct frame synchronization decreases, as was previously shown in Fig. 3.

V. Conclusion

The paper has presented highly destructive influence of a narrowband interference on the synchronization performance in NC-OFDM system. The most commonly used Schmidl&Cox synchronization algorithm has been examined. It has been shown that a complex sinusoid is quite simple source of interference that models influence of a practical PMSE system quite well. It is clear that the NC-OFDM based cognitive radio receiver needs new synchronization algorithms to be developed. One of the conclusions drawn from the simulation results is that a proper synchronization algorithm for the considered scenario should not be based on the autocorrelation.

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Fig. 4. Plots of mean timing metric (solid line) and 68% confidence interval (dashed line) over 10000 random frames versus correlation index. Four cases: A-without interference and noise, B-with complex sinusoid interference on normalized frequency 24, C-with complex sinusoid interference on normalized frequency 24.5, D-with complex sinusoid interference on normalized frequency 25. Optimal correlation index is 561.


