Extended Cyclostationary Signatures for OFDM-Based Cognitive Radio

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Abstract— **Cyclostationary signatures have been shown to be an effective method for OFDM network synchronization and Cognitive Radio coordination. In this work, an extended method that utilizes cyclostationary signatures for signal parameter identification of OFDM-based Cognitive Radio nodes is presented. The scenario, implemented on a GNU Radio based evaluation platform, shows how different signal parameters, e.g. carrier frequency, occupied bandwidth and the used modulation scheme can be identified at the receiver side using the described approach. Corresponding performance details, simulation results and implementation issues are presented and evaluated.**

Index Terms—**Cognitive Radio, Cyclostationary Signal Analysis, OFDM, GNU Radio**

I. INTRODUCTION

A POSSIBLE solution to the increasing scarcity of available radio spectrum is to achieve improved spectral efficiency by the use of Cognitive Radio (CR). In the context of CR, obtaining knowledge about spectral occupancy and coordinating the nodes of a CR network are two major problems. The classical approach for network coordination is to use a fixed common control channel. For CR this method may not be feasible due to unknown availability of spectrum required to establish the control channel. Instead each receiver of the CR network can perform spectrum sensing and thereby recognize its own network. Furthermore, in CR scenarios the absence of fixed channel pattern may often occur, e.g., as in 802.11 Wi-Fi networks. Then the sensing and detection task becomes considerably more challenging.

The most common and feasible method for spectrum sensing, measuring the spectrum usage, is simple energy detection, that has shown to provide relatively inaccurate result in low SNR scenarios. Some other methods, e.g. detection based on cyclostationary features of the transmitted waveform [1] can achieve better performance in the same conditions if a basic set of signal parameters is known at the receiver.

Software Defined Radio (SDR) has been shown to be an effective architecture, that allows for easy adaption of the physical layer transmission schemes and parameters. Therefore SDR is well suited to implement the nodes of a CR network. When OFDM is used as underlying PHY layer technology, cyclostationary signatures present an efficient method for synchronization and network coordination [2] without the need for a dedicated common control channel.

In this paper the basic idea of cyclostationary signatures is extended such that arbitrary information about the transmitted signal, e.g. currently used modulation scheme, number of occupied subcarriers, etc., can be conveyed within the certain signature patterns. An algorithm for the signature detection with low requirements in terms of processing power is given and the system implementation on a GNU Radio based SDR platform is presented.

The rest of the paper is organized as follows: Section II gives a very short introduction to the theoretical concepts of cyclostationary signal analysis. Based on this, Section III recalls how cyclostationary signatures can be created and detected and explains how we extend them. Section IV describes the simulation setup as well as the GNU Radio implementation. The corresponding results are discussed in Section V. Finally, a summary and conclusion are given in Section VI.

II. CYCLOSTATIONARITY

All kinds of modulated signals exhibit certain periodicities in second or higher order statistics. This is due to periodic components contained in the signal, e.g. modulation schemes, carrier frequency, frame structures, etc. Cyclostationarity can be evaluated using cyclic statistics, e.g. the cyclic autocorrelation

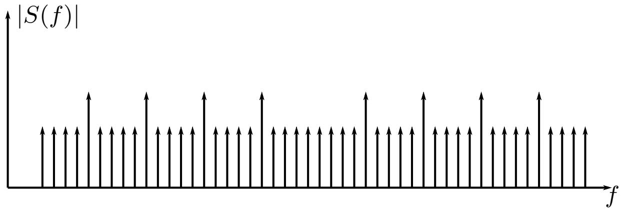

Fig. 1. OFDM subcarrier structure with pilot subcarriers

function (CAF) in time domain and the spectral correlation function (SCF) in frequency domain [1]. Based on the cyclostationary signal analysis, signal recognition can be performed. In [3] for example, authors presented a method for used modulation recognition without prior knowledge.

Wide sense cyclostationarity can be defined based on the autocorrelation function. If R_x fulfills

$$R_x(t+T_0,\tau) = R_x(t,\tau) \quad \forall t,\tau \in \mathbb{R} \tag{1}$$

than $x(t)$ is called a cyclostationary process in the wide sense and $\frac{n}{T_0}, n \in \mathbb{N}$ is called the set of cyclic frequencies α. Since the autocorrelation is periodic for the cyclostationary case, we can then apply a Fourier series expansion:

$$R_x(t,\tau) = \sum_{\alpha} R_x^{\alpha}(\tau) e^{j2\pi\alpha t} , \tag{2}$$

where the coefficients of the Fourier series are given as

$$R_x^{\alpha}(\tau) = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} R_x(t,\tau) e^{-j2\pi\alpha t} dt . \tag{3}$$

For several cyclic frequencies R_x^{α} becomes

$$R_x^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} R_x(t,\tau) e^{-j2\pi\alpha t} dt , \tag{4}$$

which is known as CAF. The CAF can also be formulated as

$$\begin{aligned} R_x^{\alpha}(\tau) &= E\{R_x(t,\tau)e^{-j2\pi\alpha t}\} \\ &= E\{x(t+\tau/2)x^*(t-\tau/2)e^{-j2\pi\alpha t}\} . \end{aligned} \tag{5}$$

Observing the exponential term in (5) reveals that it is basically an correlation of the signal with a frequency shifted version of the signal itself. Furthermore, the Fourier transform

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) e^{j2\pi f t} d\tau \tag{6}$$

of the CAF is called SCF. Sometimes it is also called cyclic spectral density function or spectral correlation density (SCD). Alternatively, it can be derived via [1]:

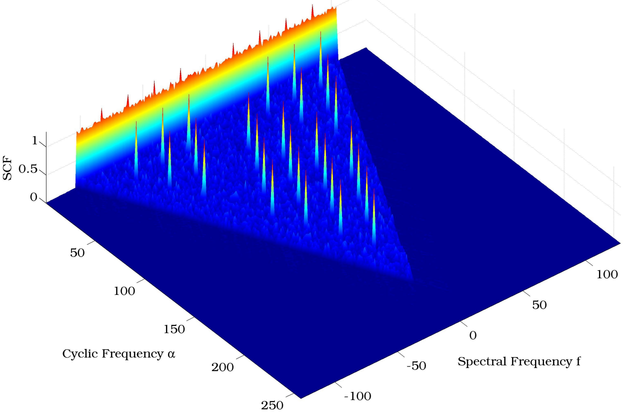

Fig. 2. SCF of OFDM signal with pilot subcarriers

$$S_x^{\alpha}(f) = \lim_{T\to\infty} \lim_{\Delta t\to\infty} \frac{1}{T\Delta t} \int_{-\Delta t/2}^{\Delta t/2} X_T(t, f+\frac{\alpha}{2}) X_T^*(t, f-\frac{\alpha}{2}) dt, \tag{7}$$

where

$$X_T(t,f) = \int_{t-T/2}^{t+T/2} x(u) e^{j2\pi f u} du , \tag{8}$$

is the windowed Fourier transform of $x(t)$. The CAF and SCF of a cyclostationary signal show particular peaks, called cyclostationary features. Moreover, the SCF is particularly useful for the analysis of an OFDM signal in frequency domain, as it can quantify the correlation between the subcarriers. A SCF graph from a Matlab simulation of the OFDM system is plotted in Figure 2. The simulated signal contains 8 pilot subcarriers, as shown schematically in Figure 1, which produce the distinctive peaks in the graph, while cyclic frequency α and spectral frequency f are normalized to the subcarrier spacing.

For the implementation in SDR a discrete estimator of the SCF is necessary. One possibility is to use the time-smoothed cyclic cross periodogram [4] given as

$$S_x^{\alpha}[k] = \frac{1}{L} \sum_{l=0}^{L-1} X_l[k] X_l^*[k-\alpha] W[k] , \tag{9}$$

where L is the length of the estimation window in terms of Fourier transform windows, $W[k]$ is a windowing function and $X_l[k]$ is the discrete Fourier transform of the input

$$X_l[k] = \sum_{n=0}^{N-1} x[n] e^{\frac{-j2\pi nk}{N}} . \tag{10}$$

Another efficient way that has been used in our implementation is to perform SCF estimation by using single coefficient IIR filter:

$$\hat{S}^{\alpha}_{x,l}[k] = \alpha_{avg} \cdot X_l[k] X^*_l[k-\alpha] + (1-\alpha_{avg}) \hat{S}^{\alpha}_{x,l-1}[k] \, . \tag{11}$$

For detecting a signal at a very low SNR it is necessary to use rather long sliding windows, e.g. 100 or 200 OFDM symbols. If the iterative IIR approach is used, the computational effort required by such long windows can be significantly reduced.

III. CYCLOSTATIONARY SIGNATURES

A. Generation

The previous section has explained cyclostationary features contained in arbitrary signals. Those features are inherently defined by the physical layer description of each wireless radio standard. That means that a receiver using a cyclostationary detection algorithm could be able to distinguish signals of several different standards operating within the same band.

However, signals that are based on the same standard and operating in the same band while using the same parameters can not be distinguished. For example, it would be possible to detect the presence of two or more Wi-Fi networks being used in the same neighborhood. Therefore, identification of the different networks on the PHY layer would be impossible as the cyclic statistics of the signals would be the same.

A relatively new approach called cyclostationary signatures can enable this identification of a specific network. By intentionally altering the cyclostationary properties of a signal it becomes unique. In [2], a way of embedding signatures into an (OFDM) based signal has been proposed. One way to generate Signatures as described in the paper is to copy a subcarrier or a group of subcarriers to another spectral position within the signal. This results in a spectral correlation and consequently in a cyclostationary feature. By changing the position of the copied subcarriers, the position of the corresponding feature, i.e. the cyclic and spectral frequency in the SCF, is altered.

A disadvantage of transmitting a signature is its inherent efficiency loss regarding the data rate. If three subcarriers are used to form the signature, the other three subcarriers where they will be copied can not be used for any payload data. This overhead can be reduced if the number of subcarriers is high. However, a certain redundancy is also introduced into the signal which may be exploited at the receiver to reduce the BER for the subcarriers involved in signatures. For example, a Maximum Ratio Combining (MRC) scheme could be used for that purpose.

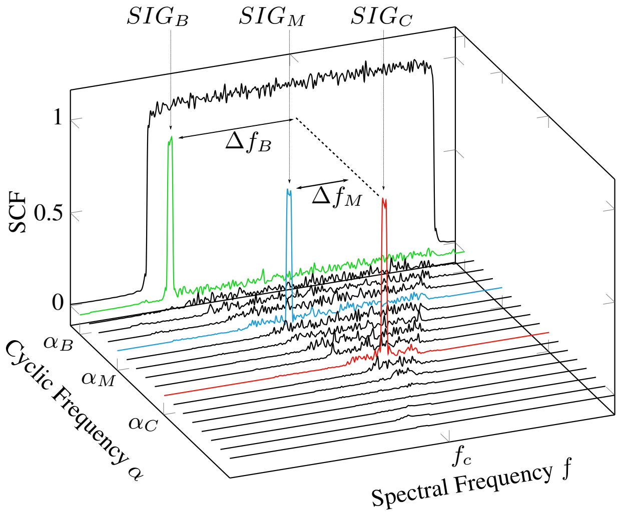

Fig. 3. SCF of OFDM Signal with Signatures

B. Detection

After obtaining the cyclic statistics of a specific signal, it can be tested for the presence of characteristic cyclostationary features or signatures. In this work, the detection problem is only considered in the frequency domain. It has been shown in [1] that the optimum detector is a correlation of the signal SCF with the ideal SCF, i.e.,

$$y_{\alpha}(t) = \int_{-\infty}^{\infty} S^{\alpha}_{ref}(f) S^{\alpha}_{x}(f) \, \mathrm{d}f \, \mathrm{e}^{j2\pi\alpha t} \, , \tag{12}$$

where the ideal SCF $S^{\alpha}_{ref}(f)$ can be found by performing the calculation at the transmitter before any noise or interference is added.

A discrete version of the estimator can be formulated as:

$$y_{\alpha,max} = \max_{m} \sum_{k=0}^{K-1} S^{\alpha}_{x}[k] S^{\alpha}_{ref}[m-k] \, . \tag{13}$$

The simplest example for S^{α}_{ref} would be a rectangular window of the width of the feature in the SCF. By maximizing over m, the spectral position of the feature can be found as well. Using this information, the carrier frequency of the signal can be determined.

To make a decision about the presence of a feature based on the value of y_{α}, an appropriately chosen threshold is required. Using receiver operating characteristics (ROC) analysis, the threshold can be determined experimentally while finding a good compromise between probability of detection and probability

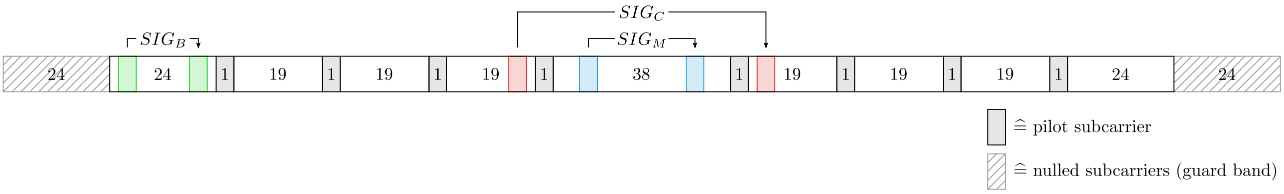

Fig. 4. OFDM subcarrier structure with multiple signatures

of false alarm. Furthermore, to avoid the necessity of an adaptive threshold the SCF must be normalized. The amount of received energy should not have any influence since the detection criteria is the presence or absence of cyclostationary features. In our implementation we normalize the estimated metric, given in (13), after finding the maximum. The normalized detector metric M can be expressed as

$$M = \frac{y_\alpha^2}{\sum_i |X_i|^2 \cdot \sum_j |X_j|^2} \; . \tag{14}$$

where i and j are the indices of the two subcarriers sets that generate the signature.

It is important to mention that the bandwidth of the detector has to be bigger than the signal bandwidth. Additionally, to detect a signal over a very large bandwidth range it may be necessary to swipe or scan the bandwidth in smaller, overlapping steps.

C. Extended Signatures

When embedding a simple cyclostationary signature into the OFDM signal its presence as well as its carrier frequency can be detected at the receiver. In this work we propose an extended method. By embedding other signatures additional information can be encoded, i.e., the occupied bandwidth and the modulation scheme that is used.

For encoding purposes the signature needs to be altered in some way. One constraint is that the overall number of signatures should be kept low as additional signatures will require a lot of subcarriers to be used for that purpose and might result in a decreased efficiency. Different possibilities for encoding can be envisioned:

- Changing the cyclic frequency of a signature, given the fixed spectral frequency
- Changing the spectral frequency of a signature, given the fixed cyclic frequency
- Switching signatures on and off or switching groups of signatures
- Formation of more complex signatures out of multiple sets of subcarriers and manipulating them using one or more of the former methods

From the implementation point of view, it is more simple to recognize a change of the spectral frequency than a change of the cyclic frequency. This is because the spectral position of a signature will be recognized during the detection process anyway. Furthermore, the cyclic frequency of each signature has to be monitored by the receiver. If they are not constant over time, the whole range of cyclic frequencies has to be monitored which is expensive in terms of processing power. The same problem accounts for more complex signatures that might occupy several cyclic frequencies at the same time. For the given reasons, an information encoding based on the spectral position of the signature has been chosen for demonstration. The idea will be explained in the following.

The cyclic frequencies for all signatures are fixed and known at the transmitter and receiver. A primary signature SIG_C, used for carrier frequency estimation, is embedded in such a way that it that has a fixed spectral frequency in the baseband or relative to the carrier frequency of the signal. Different wireless links can use different cyclic frequencies for the primary signature in order to provide unique identification. Moreover, the spectral position of the SIG_C is needed as a reference for the other signatures. As the information is encoded into the spectral frequency of the signatures, the offset towards SIG_C can be used for decoding. Figure 3 shows the SCF of a signal with three embedded Signatures SIG_C, SIG_B, SIG_M.

In our implementation we use SIG_B to encode the occupied bandwidth of the signal which is altered by the activation and deactivation of subcarriers. We chose to place the signature always on the outmost active subcarriers, i.e., if more subcarriers are activated, the signature position will change accordingly. Finally, SIG_M contains the information about the currently used modulation scheme which is in this case constant over all subcarriers. For this signature a set of eight spectral frequencies is mapped to the set of eight modulation schemes from BPSK to 256-QAM. The resulting OFDM subcarrier structure with embedded signatures can be seen in Figure 4.

An additional requirement for this approach is that

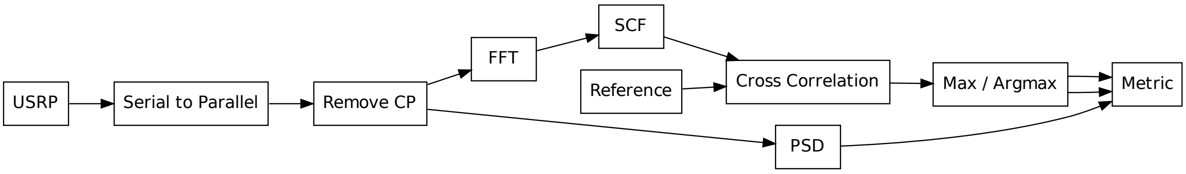

Fig. 5. Signature Detector Flow Graph

the OFDM demodulator must be aware of the dynamic changes in the subcarrier structure. Therefore, his information must be forwarded by the signature detector.

IV. EXPERIMENTAL SETUP

An experimental evaluation of the signature detector has been carried using a Matlab model and a GNU Radio [5] based testbed, a free and open source software toolkit based on hybrid C++/Python programming model that provides library of signal processing blocks for developing communications systems and conducting experiments in different radio scenarios. GNU Radio runs in real time and can be interfaced with RF hardware, thus allowing for transition from experimentation to deployment within the same framework.

The signature detector implementation has been built on top of a previously developed transceiver framework [6]. Figure 6, shows how GNU Radio switches between the signature detector and the OFDM core receiver. Additional features like a graphical user interface for parameter visualization, testing and demonstration purposes [7] have been accompanied within the framework. The GNU Radio flowgraph of the signature detector is shown in Figure 5. The implemented detector is able to synchronize the carrier frequency of the transmitted signal and to jointly identify the number of occupied subcarriers and the modulation scheme by decoding the information from the signatures.

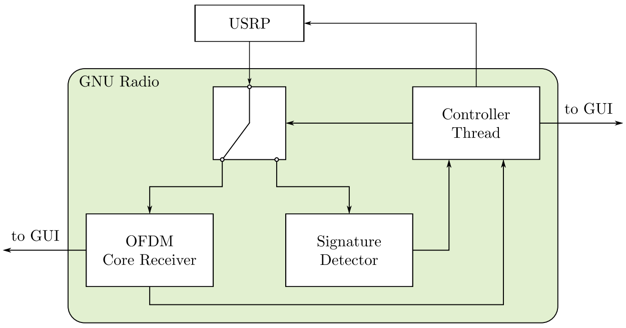

Fig. 6. Receiver Architecture

To incorporate the detector together with the given OFDM receiver, additional control logic has been implemented as a independently running control thread. The control logic is based on GNU Radios functionality for dynamic reconfiguration of the signal processing flowgraph by switching between detector and core receiver. Since our detector design can only observe one cyclic frequency at a time, the control logic also has to take care of reconfiguring the detector to consecutively detect all signatures. The observation time for the detection of a single signature depends on the value of α_{avg} and corresponds to the duration until the step response of the IIR filter, used for the estimation of the SCF, converges. Table I shows some observation times for different coefficients α_{avg}.

V. RESULTS

A number of measurements have been carried out to evaluate the performance of the implemented signature detector.

It is well known that a detector can be characterized by the detection probability P_d that it achieves while satisfying given probability of false alarms P_{fa}. The probabilities depend on the threshold that is chosen for the decision stage. To show how the probabilities behave for different thresholds we first measure the distributions of the detector metric for the case that a signature is present and without signature. Two histograms of the detector metric for SNRs of -6 dB and -3 dB can be seen in Figure 7. As expected the distributions begin to merge into each other for lower SNR values, the same behaviour can be noticed for shorter observation times with less averaging. Next

TABLE I

OBSERVATION TIMES FOR DIFFERENT PARAMETERS

α_{avg}	bandwidth	subcarriers	observation time t_o
0.005	1 MHz	256	0.35 s
0.005	2 MHz	256	0.16 s
0.05	1 MHz	256	0.03 s
0.10	1 MHz	256	0.015 s
0.15	1 MHz	256	0.009 s

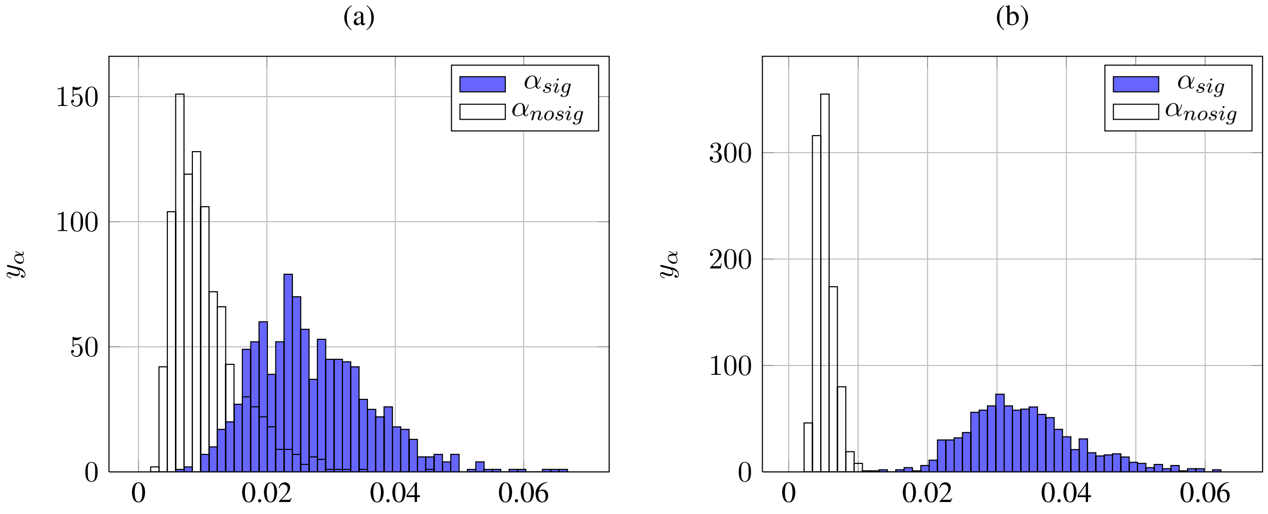

Fig. 7. Histograms of detector metric y_α for (a) SNR=-6dB and (b) SNR=-3db

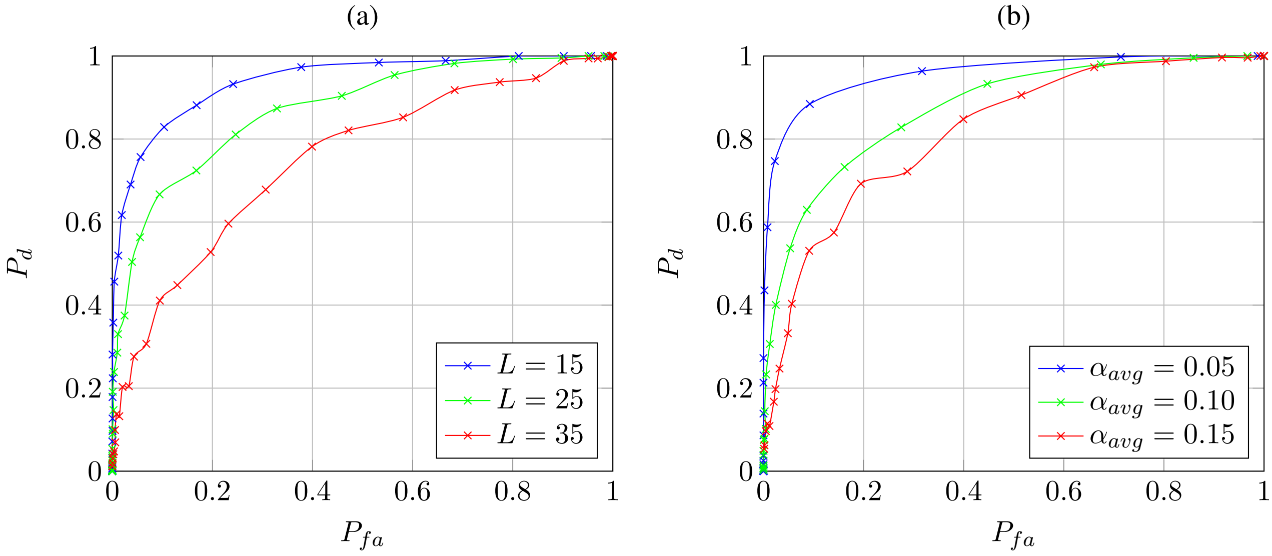

Fig. 8. Receiver Operating Characteristic (ROC), (a) Matlab and (b) GNU Radio

we measure and plot the receiver operating characteristics (ROC) as shown in Figure 8. In the Matlab simulation a moving average filter was used while in GNU Radio the SCF was implemented with an IIR averaging filter. For each point the average of 1000 measurements has been taken at an SNR of -3dB. Groups of 4 subcarriers are used to form the signatures in all considered scenarios.

Another measurement shows the behavior of the detector for low SNR regions. The threshold has been fixed to zero and the probability that the signal is detected at the correct spectral position is measured as showed in Figure 9. As results indicate, it is possible to detect the signal under quite bad SNR conditions using low values for α_{avg} and longer observation times. This was also confirmed during experiments when it was found that the signature detector could perform for SNRs below 0 dB, while the implemented core OFDM receiver was not able to synchronize for a SNR less than about 3 dB to 5 dB.

Here the main problem during measurement was to properly determine the received SNR . As the OFDM receiver only works down to 5 dB, all lower SNR values had to be extrapolated based on the transmit power.

A major issue that we noticed in the experimental stage is that the cyclostationary feature detection is susceptible to clocking offsets, i.e., sampling rate offset between the USRPs. Figure 10 shows the changes of the detector metric over time due to this effects. Another USRP specific problem was that shortly after a reconfiguration of the hardware, e.g., changing the

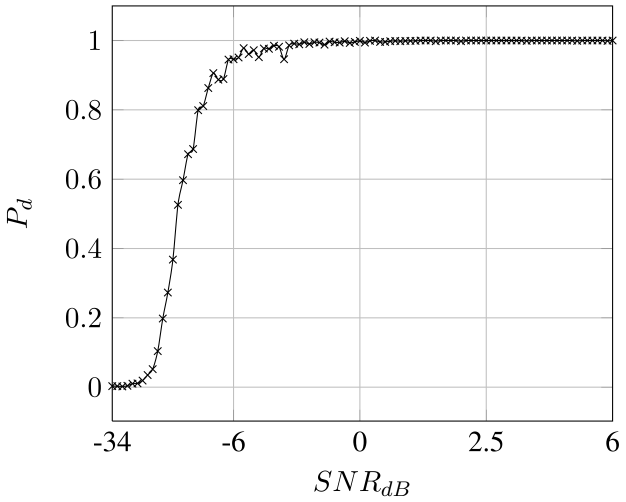

Fig. 9. Probability of detection for different SNR and $\alpha_{avg} = 0.005$ in GNU Radio

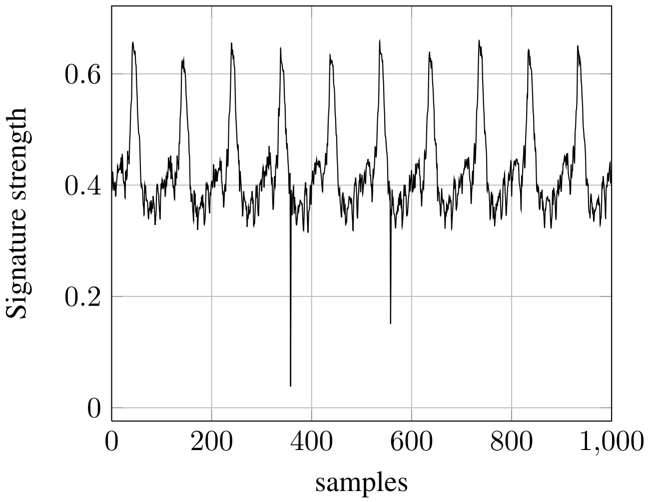

Fig. 10. Signature strength fluctuation due to clocking offsets between USRP's

carrier frequency or decimation rate, some transient peaks occur in the signal. Therefore, an additional time period is needed to avoid these transient before performing the signature detection.

VI. CONCLUSION

In this paper we investigated the performance of a detection and coordination method for OFDM based on cyclostationary signatures. The extension of the signature concept enables the detector on the receiver side to identify important parameters of the transmitted signal. An implementation on a GNU Radio based prototyping platform has been presented. Measurement results indicate that the cyclostationary detection is well suited for low SNR scenarios. Furthermore, future steps will consider analytical optimization of the detection threshold.

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