

Cyclostationary Signatures in Practical Cognitive Radio Applications

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Abstract—We define a *cyclostationary signature* as a feature which may be intentionally embedded in a digital communications signal, detected through cyclostationary analysis and used as a unique identifier. The purpose of this paper is to demonstrate how cyclostationary signatures can be exploited to overcome a number of the challenges associated with network coordination in emerging cognitive radio applications and spectrum sharing regimes. In particular we show their uses for signal detection, network identification and rendezvous and discuss these in the context of dynamic spectrum access. We present a theoretical discussion followed by application-oriented examples of the cyclostationary signatures used in practical cognitive radio and dynamic spectrum usage scenarios. We focus on orthogonal frequency division multiplexing (OFDM) based systems and present an analysis of a transceiver implementation employing these techniques developed on a cognitive radio test platform.

Index Terms—Cyclostationary signatures, cognitive radio, dynamic spectrum access, network coordination, network rendezvous.

I. INTRODUCTION

THE FIELD of *dynamic spectrum access* focuses on new and very dynamic methods for managing spectrum that extend beyond the traditional *command and control* means of regulation. Dynamic spectrum access techniques promise greater spectral-usage efficiency and enhanced access to frequency spectrum and can help enable more technologically and economically innovative uses of this resource. Many approaches to dynamic spectrum access exist, extending from opportunistic usage regimes [3], [4], to commons models [5], [6], to exclusive usage-rights schemes [7], [8]. The communications devices that will facilitate this vision will tend to be reconfigurable devices, with frequency agile front-ends that are capable of adapting their behavior and modifying their parameters of operation to make best use of the available spectrum and the wider radio and network resources. Cognitive radio technology can offer these capabilities.

We consider a network of cognitive radio nodes operating within a spectrum band which is shared with other networks including high priority primary users and other secondary use cognitive networks. Nodes of the network coordinate to establish network connectivity using spectrum *white space* - bands

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which are unused at a given time and place. As the availability of such white space spectrum depends upon the operation of other networks in the band, it may fluctuate unexpectedly over time. Nodes must therefore adapt to robustly maintain network connectivity and optimize use of the available resources.

The challenge of cognitive network coordination thus involves the establishment of communication links within a network and the robust maintenance of these links under conditions of changing spectrum availability.

Coordination may be achieved through use of a static common control channel [9]–[11]. Such an approach however, requires allocation of dedicated spectrum to support the control channel. In the case of opportunistic spectrum use, spectrum availability depends upon the occupancy of high priority primary users as well as other co-existing secondary users and a static control channel may not be supported. An alternative approach [12], [13] involves the use of local control channels which are dynamically assigned within cognitive node clusters. Within a node cluster, spectrum availability may be considered uniform and a control channel may be allocated. However, the successful creation and maintenance of node clusters involves considerable additional network complexity and overhead.

We therefore examine an alternative approach to the use of control channels in the process of cognitive network coordination using *cyclostationary signatures*. A cyclostationary signature is a feature, *intentionally* embedded in the physical properties of a digital communications signal, which may be easily generated, manipulated, detected and analyzed using low complexity transceiver architectures. This feature is present in all transmitted signals, requires little signaling overhead and may be detected using short signal observation times. The signature may be used to uniquely identify a cognitive network and upon detection, facilitates signal acquisition and the establishment of a communications link. In this way, cyclostationary signatures may be used to facilitate cognitive radio rendezvous and perform a key role in the process of network coordination without the need for a control channel.

Many of the communications signals in use today contain inherent cyclostationary features arising from underlying periodicities within those signals. These features, however, may not be manipulated unless key properties of the underlying waveforms can be altered.

This paper builds upon previous work by the authors [1], [2] and makes four distinct and novel contributions. Firstly, a flexible, low-complexity technique for embedding cyclostationary signatures in OFDM-based waveforms is introduced. Secondly, a robust approach for the detection and analysis of

signatures is presented. The use of cyclostationary signatures for signal detection, cognitive network identification and frequency rendezvous is discussed and performance is examined using simulation results. Finally, the implementation and analysis of an OFDM-based transceiver that uses cyclostationary signatures on a real cognitive radio test platform is presented.

We therefore contend that:

- Cyclostationary signatures may be effectively used to overcome a number of the key limitations associated with the use of inherent cyclostationary features for signal detection and analysis.
- Cyclostationary signatures provide a robust mechanism for signal detection, network identification and signal acquisition as part of the process of network coordination without the requirement of a dedicated control channel.
- Existing transmitter architectures may be easily adapted to use cyclostationary signatures with minimal additional complexity.
- Detection and analysis of cyclostationary signatures may be achieved using low-complexity receiver architectures and short signal observation durations.

The remainder of this paper is structured as follows. Cyclostationarity in wireless telecommunications signals is discussed in Section II. Section III presents a low complexity technique for artificially embedding unique cyclostationary signatures in OFDM-based signals. A low-complexity, robust approach for cyclostationary signature detection is presented in Section IV and use of signatures for signal detection, network identification and signal acquisition is examined using simulation results. The implementation of a full OFDM-based transceiver system using cyclostationary signatures upon a cognitive radio test platform is presented and performance is examined using experimental results in Section V. Finally, Section VI concludes.

II. CYCLOSTATIONARY SIGNAL ANALYSIS

Many of the communications signals in use today may be modeled as cyclostationary signals due to the presence of one or more underlying periodicities which arise due to the coupling of stationary message signals with periodic sinusoidal carriers, pulse trains or repeating codes. These underlying periodicities may also occur as a result of other processes used in the generation of the signal including sampling and multiplexing.

A signal $x(t)$ is defined to be second order cyclostationary (in the wide sense) if its autocorrelation function,

$$R_x(t, \tau) = E\{x(t + \tau/2)x(t - \tau/2)\} \quad (1)$$

is periodic in time t for each time lag τ . These periodicities are examined using the cyclic autocorrelation function (CAF) [14],

$$R_x^\alpha(\tau) = \lim_{\Delta t \rightarrow \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} x(t + \tau/2) \cdot x(t - \tau/2) e^{-i2\pi\alpha t} dt \quad (2)$$

for cyclic frequency α and measurement interval Δt .

Second order cyclostationarity gives rise to specific correlation patterns which occur in the spectrum of the signal.

These patterns may be used equivalently to examine the cyclostationarity of the signal and may be analyzed using the spectral correlation function (SCF) [14],

$$S_x^\alpha(f) = \lim_{\Delta f \rightarrow \infty} \lim_{\Delta t \rightarrow \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} \Delta f X_{1/\Delta f}(t, f + \frac{\alpha}{2}) \cdot X_{1/\Delta f}^*(t, f - \frac{\alpha}{2}) dt \quad (3)$$

where

$$X_{1/\Delta f}(t, v) = \int_{t-1/2\Delta f}^{t+1/2\Delta f} x(u) e^{-i2\pi v u} du \quad (4)$$

represents the complex envelope of the narrow-band-pass component of $x(t)$ with center frequency v and bandwidth Δf . Together the CAF and SCF provide a comprehensive means of examining the second-order cyclostationarity of a signal.

Much of the initial work demonstrating the power of cyclostationary signal analysis when applied to wireless communications was carried out by Gardner and his colleagues [15]–[18]. Additionally, cyclostationary analysis has been extensively examined as a technique for achieving a wide range of tasks including signal detection [14], classification [19], synchronization [20], [21] and equalization [22]. In [23], Gardner identifies a number of advantages provided by cyclostationary signal analysis over alternative radiometric approaches. Among these are a reduced sensitivity to noise and interfering signals as well as the ability to extract key signal parameters including carrier frequencies and symbol rates.

Cyclostationary signal analysis provides a number of additional advantages in the context of coordination for dynamic spectrum access. Coherent approaches such as matched filtering typically require close synchronization with the signal of interest. However, cyclostationary analysis does not require frequency or phase synchronization, making it an attractive approach for detection of signals whose carrier frequencies and symbol timing are unknown.

Well recognized limitations of cyclostationary signal analysis are the computationally complex receiver designs required for SCF estimation over a wide range of cyclic frequencies and the typically long observation times required for reliable signal analysis. In [24], Gardner shows that the reliability of an SCF estimate is dependent upon the spectral resolution Δf and the temporal resolution Δt . Particularly, in order to obtain a substantial reduction in random effects in estimates calculated using a spectrally or temporally smoothed approach, the temporal-spectral resolution product must greatly exceed unity

$$\Delta t \Delta f \gg 1 \quad (5)$$

Thus a greater observation time is needed to obtain a reliable SCF estimate where a smaller spectral resolution Δf is required to resolve the individual features of that SCF.

Cyclostationary signatures provide an effective mechanism for overcoming these drawbacks while allowing the key advantages of cyclostationary signal analysis to be realized.

III. SIGNATURE GENERATION

The inherent cyclostationarity caused by use of a cyclic prefix in orthogonal frequency division multiplexing (OFDM) signals may be exploited to perform key tasks including synchronization [21] and blind channel identification [22]. In this section we examine the key limitations associated with use of such inherent signal cyclostationarity to achieve cognitive network coordination and present a low-complexity approach for overcoming these limitations using transmitter induced cyclostationary signatures.

Orthogonal frequency division multiplexing (OFDM) signals may be represented as a composite of N statistically independent subchannel quadrature amplitude modulated (QAM) signals [25]:

$$w(t) = \sum_k \sum_{n=0}^{N-1} \gamma_{n,k} e^{j(2\pi/T_s)nt} q(t - kT) \quad (6)$$

where $w(t)$ is the complex envelope of an OFDM signal with a cyclic prefix, $\gamma_{n,k}$ is an independent and identically distributed (IID) message symbol sequence, N is the number of subcarriers and $q(t)$ is a square shaping pulse of duration T . T_s is the source symbol length and T_g is the cyclic prefix length such that $T = T_s + T_g$.

Due to the statistical independence of the subchannel QAM signals, the problem of cyclostationary analysis of OFDM may be reduced to analysis of these QAM signals. In the absence of a cyclic prefix, subcarrier orthogonality causes destruction of the individual QAM signal cyclostationarity. However, the use of a cyclic prefix causes a loss of subcarrier orthogonality and permits inherent QAM signal features to be detected [25]. Features arising due to use of the cyclic prefix are examined in [25] and the spectral correlation of the complex envelope $w(t)$ of an OFDM signal is derived as:

$$S_w^\alpha(f) = \begin{cases} \frac{\delta_\gamma^2}{T} \sum_{n=0}^{N-1} Q(f - \frac{n}{T_s} + \frac{\alpha}{2}) \\ \cdot Q^*(f - \frac{n}{T_s} - \frac{\alpha}{2}), & \alpha = \frac{k}{T} \\ 0, & \alpha \neq \frac{k}{T} \end{cases} \quad (7)$$

where

$$Q(f) = \frac{\sin(\pi f T)}{\pi f} \quad (8)$$

is the Fourier transform of the square shaping pulse $q(t)$.

The SCF for an OFDM signal with cyclic prefix $T_g = \frac{T_s}{4}$ and $N = 16$ is illustrated in Fig. 1. Inherent cyclostationary features are shown for cyclic frequencies $\frac{1}{T}$, $\frac{2}{T}$ and $\frac{3}{T}$.

These inherent features of OFDM signals may be used to perform tasks such as blind channel identification [22] however they are unsuitable for use in the context of cognitive network coordination for dynamic spectrum access. In order to embed unique signatures using cyclostationary features, it must be possible to directly control and manipulate the properties of those features. In the case of these inherent features, this involves altering T_g , the cyclic prefix length. As the cyclic prefix length is a key parameter determining the performance of an OFDM-based system, this may not be possible. Furthermore, low computational complexity and

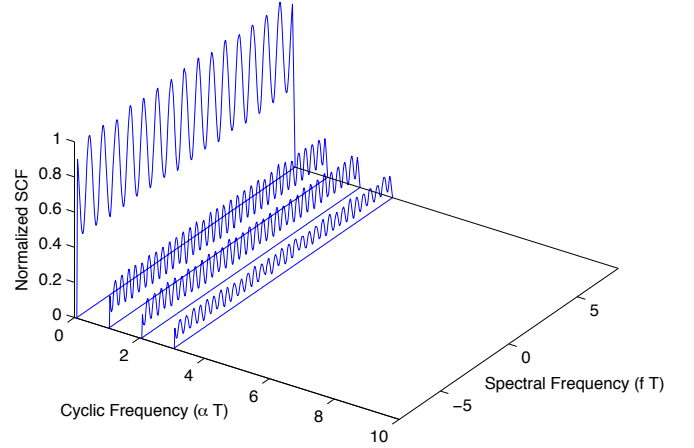


Fig. 1. Normalized SCF for OFDM with cyclic prefix showing inherent cyclostationary features. $T_g = \frac{T_s}{4}$. Features are shown for cyclic frequencies $\frac{1}{T}$, $\frac{2}{T}$ and $\frac{3}{T}$.

rapid signal detection are key requirements for coordination. As the power of inherent OFDM features are low relative to that of the signal, reliable detection of these features requires the use of complex receiver architectures and long signal observation times.

Second order cyclostationarity is manifested as distinct patterns of correlation in the spectrum of a signal. In order to generate a distinctive *cyclostationary signature*, such a correlation pattern may be intentionally created by manipulating the message symbols $\gamma_{n,k}$, assigned to individual subcarriers. By mapping a set of subcarriers onto a second set as:

$$\gamma_{n,k} = \gamma_{n+p,k}, \quad n \in M \quad (9)$$

where M is the set of subcarrier values to be mapped and p is the number of subcarriers between mapped symbols, message symbols are redundantly transmitted on more than one subcarrier, a correlation pattern is created and a cyclostationary feature is embedded in the signal. This introduction of a statistical dependence between certain subcarriers of an OFDM signal results in the spectral correlation:

$$S_w^\alpha(f) = \begin{cases} \frac{\delta_\gamma^2}{T} \sum_{n=0}^{N-1} Q(f - \frac{n}{T_s} + \frac{\alpha}{2}) \\ \cdot Q^*(f - \frac{n}{T_s} - \frac{\alpha}{2}), & \alpha = \frac{k}{T} \\ \frac{\delta_\gamma^2}{T} \sum_{n=0}^{N-1} Q(f - \frac{n}{T_s} + \frac{\alpha}{2}) \\ \cdot Q^*(f - \frac{n+p}{T_s} - \frac{\alpha}{2}), & \alpha = \frac{p}{T_s} \pm \frac{k}{T}, n \in M \\ 0, & \alpha \neq \frac{k}{T}, \frac{p}{T_s} \pm \frac{k}{T} \end{cases} \quad (10)$$

where M is the set of mapped subcarriers. The SCF for an OFDM signal containing an embedded cyclostationary signature is illustrated in Fig. 2 where $p = 6$, $N = 16$ and a single subcarrier is mapped. The strong feature which is

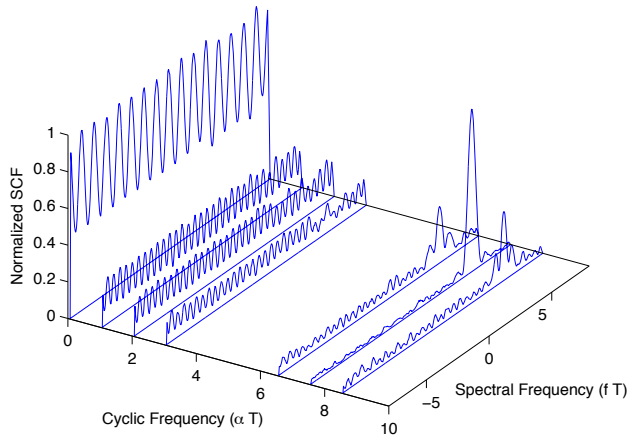


Fig. 2. Normalized SCF for OFDM with cyclic prefix and embedded cyclostationary signature. $T_g = \frac{T_s}{4}$. Features are shown for cyclic frequencies $\frac{1}{T}$, $\frac{2}{T}$, $\frac{3}{T}$, $\frac{p}{T_s} - \frac{1}{T}$, $\frac{p}{T_s}$ and $\frac{p}{T_s} + \frac{1}{T}$.

associated with the cyclostationary signature can be seen at cyclic frequency $\alpha = \frac{p}{T_s}$.

A number of key advantages may be realized through the use of OFDM subcarrier set mapping to generate cyclostationary signatures for cognitive network coordination.

Firstly, subcarrier set mapping permits cyclostationary signatures to be embedded in data-carrying waveforms without adding significant complexity to existing transmitter designs. OFDM signal generation may be efficiently implemented using an inverse discrete Fourier transform (IDFT). As illustrated in Fig. 3, cyclostationary signatures may be incorporated in existing transceiver architectures simply by mapping one set of subcarriers to another. Here, F_0 is the carrier frequency, F_{sig} is the signal bandwidth and p is the subcarrier set separation. A spectral correlation is created by simultaneously transmitting data symbols on more than one subcarrier. By mapping a set of subcarriers in this way, a larger correlation pattern is created.

A second key advantage of the use of subcarrier set mapping lies in the observation times and receiver complexity required for reliable signature detection. Cyclostationary signatures may be reliably detected using a spectral resolution Δf equal to the OFDM subcarrier spacing. However, successful detection of inherent features such as those arising due to the use of a cyclic prefix requires use of a smaller spectral resolution. As SCF estimate reliability depends upon the spectral-temporal resolution product $\Delta f \Delta t$ (see (5)), longer observation times are required for reliable detection of inherent OFDM features than those needed for cyclostationary signatures.

Reduced receiver complexity may be achieved as the key feature associated with a cyclostationary signature occurs at a single cyclic frequency, $\alpha = \frac{p}{T_s}$. Successful detection and analysis of the signature may be performed using estimation of the SCF at this cyclic frequency alone using a low complexity single-cycle estimator.

A significant advantage in the context of cognitive network identification is the ability to generate unique signatures. Cyclostationary features generated using OFDM subcarrier set mapping may be directly manipulated in both the cyclic and

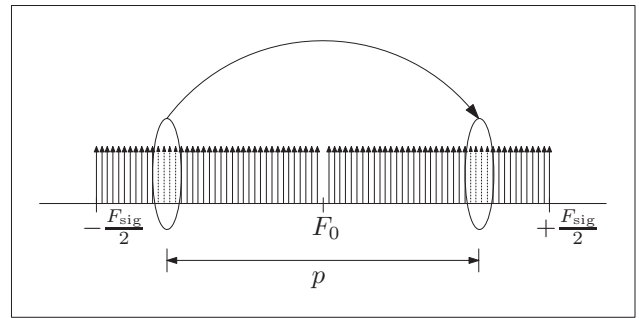


Fig. 3. Generation of a Cyclostationary Signature using OFDM Subcarrier Set Mapping. A spectral correlation is created in each OFDM symbol by simultaneously transmitting data symbols on more than one subcarrier.

spectral frequency domains through careful choice of mapped subcarrier sets. The cyclic frequency of a cyclostationary signature is determined by the OFDM source symbol duration T_s and the number of subcarriers between mapped sets p as

$$\alpha_{sig} = \frac{p}{T_s} \quad (11)$$

Thus by altering the spacing between mapped sets, p may be chosen and the cyclic frequency of the resulting cyclostationary signature determined. In this way a network may be uniquely identified by the cyclic frequency of the signature embedded in signals transmitted by nodes of that network. This approach is discussed further in Section IV-C.

As well as facilitating cognitive network identification, cyclostationary signatures may be leveraged to achieve another key task associated with cognitive network coordination - that of frequency rendezvous and signal acquisition. The spectral frequency of an embedded cyclostationary signature is determined by the carrier frequency of the signal and the properties of the subcarrier sets used in its generation. For example, mapping of one subcarrier set onto a second set, equidistant from the carrier frequency (as in Fig. 3) results in a cyclostationary feature which is centered upon that carrier frequency. This may be seen in Fig. 4 which illustrates the spectral frequency at cyclic frequency α_{sig} for $N = 256$ and a signature generated using a mapped set of 3 subcarriers. The significance of signature spectral frequency for rendezvous is discussed in more detail in Subsection IV-D.

A final key advantage of the use of OFDM subcarrier set mapping is the continuous presence of the cyclostationary signature in the transmitted OFDM signal due to the consistent mapping of carriers for every generated OFDM symbol. This permits cyclostationary signal detection to be performed using any received portion of the signal. This is in contrast to approaches involving cyclostationarity induced only in specific elements of an OFDM signal, such as the preamble-based technique outlined in [26].

A major consideration in the design of an embedded-signature OFDM transmitter is the overhead incurred as a result of the carrier mapping used. The number of carriers available for data transmission is reduced by the number used to carry mapped data symbols, causing a reduction in the overall data rate which may be supported. However, there exists an important trade off between the number of carriers used in a mapped set and the detection performance which

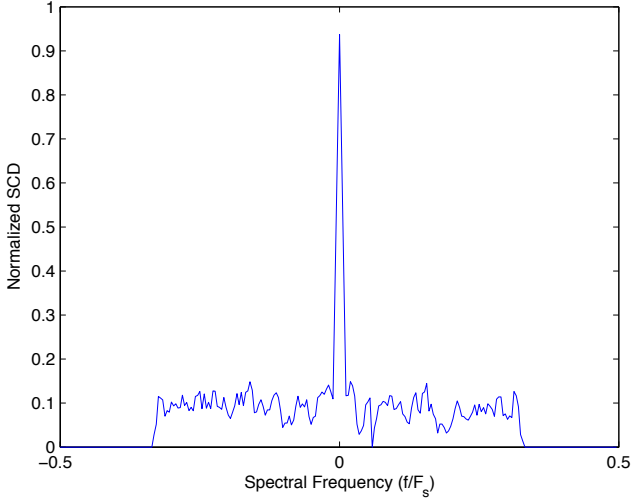


Fig. 4. Spectral frequency at α_{sig} , the signature cyclic frequency. The signature is centered at the signal carrier frequency, f_0 and may be used to perform coarse carrier frequency estimation.

may be achieved. This trade off is examined using simulation results in Subsection IV-A.

IV. SIGNATURE DETECTION AND ANALYSIS

In order to examine the use of cyclostationary signatures in the process of cognitive network coordination, a low-complexity spectral correlation estimator may be designed for practical implementation. Existing OFDM receiver designs typically involve the use of a Fourier transform in order to demodulate a received signal. In designing an estimator based on the use of a Fourier transform it may be possible to incorporate the use of cyclostationary signatures using minor modifications to an existing OFDM receiver design.

The design adopted uses a time-smoothed cyclic cross periodogram [27]:

$$\hat{S}_x^\alpha[k] = \frac{1}{L} \sum_{l=0}^{L-1} X_l[k] X_l^*[k - \alpha] W[k] \quad (12)$$

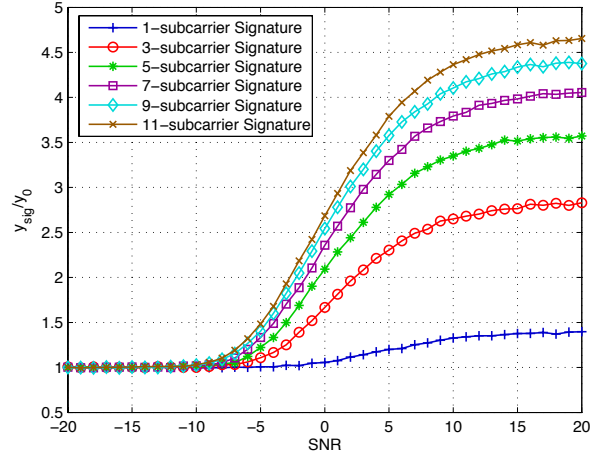
where $W[k]$ denotes a smoothing spectral window and $X_l[k]$ is the Fourier transform of the received signal $x[n]$,

$$X_l[k] = \sum_{n=0}^{N-1} x[n] \exp\left(\frac{-j2\pi nk}{N}\right) \quad (13)$$

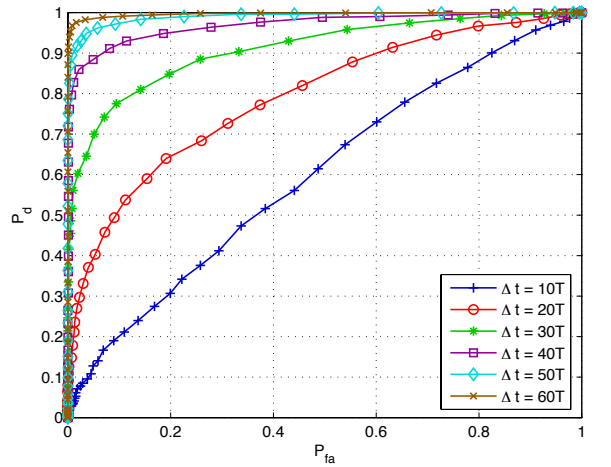
Estimates are calculated using L windows of length N where N is the duration of a single OFDM symbol. This has been shown to be a consistent, asymptotically unbiased and complex normally distributed estimator for the cyclic cross spectrum [27]. By estimating the cyclic cross spectrum at a range of cyclic frequencies, the SCF may be obtained.

A. Detection

Optimum feature detection is performed through correlation of the cyclic periodogram with the ideal spectral correlation function [14]:



(a) Signature detection performance using increasing mapped set sizes.



(b) Receiver operating characteristic (ROC) performance with increasing observation time, Δt .

Fig. 5. Simulation results for cyclostationary signature detection.

$$y_\alpha(t) = \int_{-\infty}^{\infty} S_s^\alpha(f) * \tilde{S}_x^\alpha(f) df e^{i2\alpha\pi t} \quad (14)$$

where $\tilde{S}_x^\alpha(f)$ is the cyclic periodogram following notch filtering to remove strong narrow-band interference.

Cyclostationary features generated through OFDM subcarrier set mapping may be successfully detected using spectral resolution Δf , equal to the OFDM subcarrier spacing. Using this approach, the ideal spectral correlation function may be approximated using a simple rectangular window of width $M \cdot \Delta f$, where M is the number of subcarriers in the mapped set. In this way, a low-complexity single-cycle signature detector may be implemented as:

$$y_\alpha = \max_m \sum_{k=0}^{K-1} \hat{S}_x^\alpha[k] W[m - k] \quad (15)$$

where $W[k]$ is a rectangular window.

The overhead associated with use of cyclostationary signatures depends upon the number of subcarriers used to create the signature. The performance of signatures created

TABLE I
SIGNATURE OVERHEAD

Set Size	% Overhead
1	0.52
3	1.56
5	2.60
7	3.65
9	4.69
11	5.73

using different mapped subcarrier set sizes is examined using simulation. We consider 256-subcarrier OFDM signals with carriers designated as follows: 192 data, 8 pilot, 55 guard, 1 DC carrier. Subcarriers are modulated using QPSK message symbols. Signatures with cyclic frequency, $\alpha = \frac{34}{256}F_s$ are generated using subcarrier set mapping. Gaussian white noise is added to each signal to result in signal-to-noise ratio (SNR) values of between -20 dB and 20 dB. Results are illustrated in Fig. 5(a) for observation time, $\Delta t = 100T$. Results are averaged over 1000 simulations and normalized across signature types using the mean detector output for OFDM signals without embedded cyclostationary signatures, y_0 . The detection metric y_{sig}/y_0 may be interpreted as a measure of confidence in the presence of a signature.

Fig. 5(a) shows the improvement in detection performance with increasing set size. The associated overheads for a signal with 192 data carriers are outlined in Table I. A large performance improvement may be realized by increasing the subcarrier set size from 1 to 3; however, it can be seen that the relative performance improvement diminishes as set sizes are increased. Performance deteriorates rapidly with SNR below 0 dB. However, at these low levels OFDM-based systems typically experience very high bit-error rates and so rendezvous may not be achieved.

A key performance metric for cyclostationary signatures used in the context of cognitive network coordination is the time taken to reliably detect and analyze an embedded signature. Although reliable analysis of inherent signal features typically requires high spectral resolution and long signal observation times, the use of cyclostationary signatures facilitates the use of spectral resolution on the order of OFDM subcarrier spacings and thus relatively short observation times. The effect of observation times upon signature detection performance is examined using further simulations. 256-subcarrier OFDM signals are considered as before. Signatures are embedded with $M = 3$, $\alpha = \frac{34}{256}F_s$ and SNR = 5 dB. Results are illustrated for 2000 simulations using receiver operating characteristic (ROC) performance in Fig. 5(b) for $10T \leq \Delta t \leq 60T$. P_d and P_{fa} are the probabilities of detection and false alarm respectively.

It can be seen that detection performance improves considerably with increased observation times. A detection rate of 100% may be achieved for an associated false alarm rate of 0% as determined over 2000 simulations using an observation time of $60T$, equivalent to the duration of 60 OFDM symbols. An IEEE 802.16 WiMax system using a 3.5 MHz bandwidth and 1/8 cyclic prefix requires a minimum frame size of 34 symbols [28]. Thus a 3-carrier cyclostationary signature may be successfully detected using an observation time equivalent

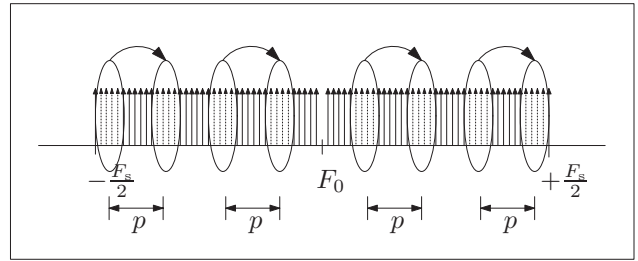


Fig. 6. Generation of a Cyclostationary Signature using Multiple OFDM Subcarrier Set Mappings.

to just two IEEE 802.16 frames. This performance may be further improved through use of larger mapped subcarrier set sizes.

B. Frequency-Selective Fading Channels

A limitation of cyclostationary signatures generated using single OFDM subcarrier set mapping is the sensitivity exhibited to frequency-selective fading. A deep fade occurring at the frequency of a mapped set may severely distort the signature and deteriorate detection performance. Robustness is provided in typical OFDM-based systems through the use of a cyclic prefix, however this approach requires close frequency and time synchronization with the signal of interest. In the context of signal detection, this is not possible and so an alternative approach is required.

The effects of frequency selective fading may be overcome by increasing the frequency diversity of the cyclostationary signature. This may be achieved through use of multiple mapped subcarrier sets in order to generate features at a number of discrete spectral frequencies as illustrated in Fig. 6. Through use of a constant mapping separation, p , each feature occurs at a single cyclic frequency, α and the optimum single-cycle feature detector may be approximated by:

$$y_\alpha = \max_m \sum_{k=0}^{K-1} \hat{S}_x^\alpha[k] H[m-k] \quad (16)$$

As features due to each mapped set may be approximated using a rectangular window, the ideal spectral correlation function for multiple-feature signatures may be approximated by $H[k]$, a periodic pulse train. It should be noted that unique multiple-feature signatures may still be generated through choice of set spacing p to generate a signature at discrete cyclic frequency α_{sig} . Thus multiple-feature signatures may be used for cognitive network identification.

The performance improvements associated with the use of multiple-feature cyclostationary signatures under frequency-selective fading conditions are illustrated using simulation results in Fig. 7. Once again, 256-subcarrier OFDM signals are considered. Two signature types are compared - a single-feature signature generated using a single mapped set of 3 subcarriers and a multiple-feature signature generated using four mapped sets of 3 subcarriers. The time-variant multipath channel model adopted is the COST 207 Bad Urban model [29] with six Rayleigh-fading paths. Signal path powers and delays are given in Table II. Additionally, maximum

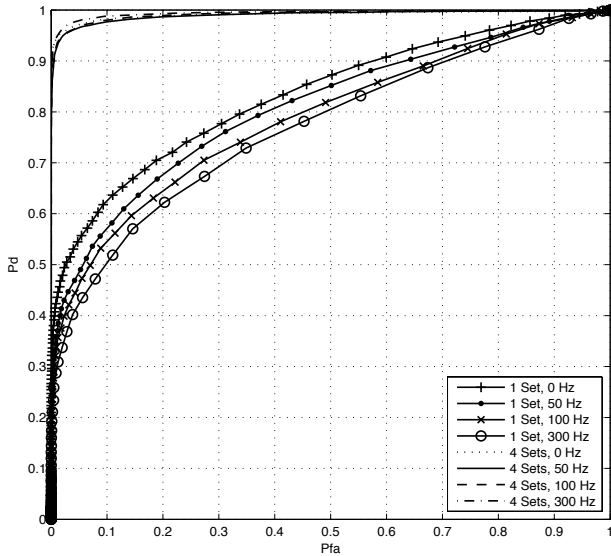


Fig. 7. Detection Performance under Time-Variant Multipath Conditions. Single-feature signatures are compared with multi-feature signatures for $SNR = 5$ dB, $\Delta t = 60T$. The COST 207 Bad Urban channel model is used.

TABLE II
COST 207 BAD URBAN CHANNEL MODEL

Path Number	Delay (μs)	Power (dB)
1	0.0	-2.5
2	0.3	0
3	1.0	-3.0
4	1.6	-5.0
5	5.0	-2.0
6	6.6	-4.0

Doppler frequencies of between 0 and 300 Hz are specified for each path, representing movement speeds of up to 100 m/s for a carrier frequency of 900 MHz.

Results show that detection of single-feature signatures is greatly deteriorated under multipath conditions. Additionally, as the Doppler frequency increases, detection performance deteriorates further. However, performance may be improved considerably through use of a multiple-feature signature. By generating a signature with four independent features, all at the same cyclic frequency, the spectral frequency diversity of the signature is increased and sensitivity to frequency selective fading reduced. The effect of increased Doppler frequencies may also be reduced through use of multiple-feature signatures.

A drawback associated with the use of multiple-feature signatures is the increased overhead incurred through the use of multiple subcarrier set mappings. In the case where four sets are mapped in order to generate independent features, the associated overhead increases by a factor of 4. However in the context of cognitive radio operation, the decision to use single or multiple-feature signatures may be made dynamically, depending upon the channel conditions observed. In this way, the overhead incurred may be minimized.

TABLE III
SIGNATURE CYCLIC FREQUENCIES

Signature	Cyclic Frequency
α_1	$\frac{17}{256} F_s$
α_2	$\frac{34}{256} F_s$
α_3	$\frac{51}{256} F_s$
α_4	$\frac{68}{256} F_s$

Cyclostationary features generated using multiple subcarrier set mappings only occur at a single cyclic frequency due to the use of a constant set separation, p . For this reason, the number of cyclic frequencies which may be used as unique identifiers are not reduced and the use of signatures to identify multiple independent networks is unaffected.

C. Network Identification and Rendezvous

Using OFDM subcarrier-mapping, cyclostationary features may be generated at one of a number of discrete cyclic frequencies. Thus, by embedding a signature with a particular cyclic frequency in a waveform, a transmitting device allows that waveform to be uniquely identified by receiving devices. In the context of cognitive network coordination, all nodes within a single network may embed the same unique signature within any transmitted signals. Nodes wishing to join the network may then detect peer nodes and establish a communications link by detecting this unique signature.

Monte-Carlo simulations are used to examine the performance of signatures used for waveform identification under multipath channel conditions. Four unique signatures are considered with cyclic frequencies outlined in Table III.

A time-variant multipath channel is simulated using the COST 207 Bad Urban channel model (see Table II) and multiple-feature signatures containing 4 independent features are generated as before. Gaussian white noise is added for -16 dB $\leq SNR \leq 16$ dB. For each iteration, a signal is generated with embedded signature α_i randomly chosen for $i \in [1, 2, 3, 4]$. Detection is performed for each cyclic frequency using the single-cycle detector (16) and identification is performed using decision statistic:

$$z = \arg \max_i y_{\alpha_i} \quad (17)$$

A probability of identification, P_i is defined as:

$$P_i = p(z = i | x_i) \quad (18)$$

where x_i is an OFDM signal containing a cyclostationary signature with cyclic frequency α_i . Results are presented in Fig. 8 for observation times between $10T$ and $60T$.

Results indicate that cyclostationary signatures may be used for reliable identification of signals received with SNR of 0 dB and greater. Once again, performance improvements may be realized through use of increased observation times. Using an observation time equivalent to 60 OFDM symbol durations, signals containing one of 4 possible signatures may be identified at 0 dB SNR with a probability of 98%.

Within a shared spectrum band occupied by more than one cognitive network, each network requires a unique cyclostationary signature to identify nodes operating as part of that

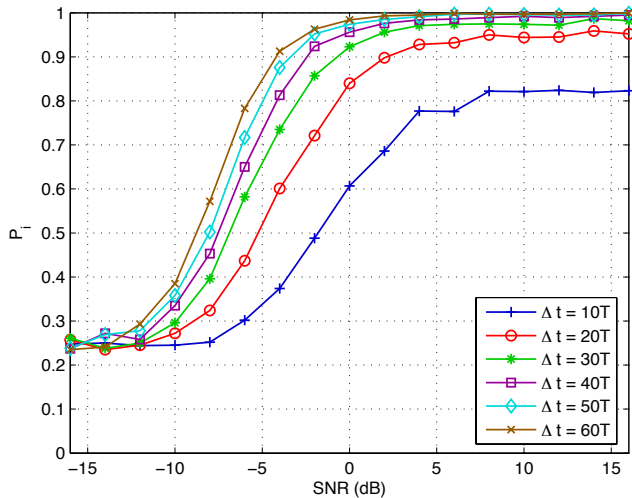


Fig. 8. Signal Identification using Cyclostationary Signatures. Identification is performed for 4 unique signatures under conditions of time-variant multipath fading.

network. Thus a signature assignment mechanism is required. In the case where networks require approval or certification in order to operate within a given band, signatures could be assigned in a centralized manner by the approving authority. In the absence of such an authority, a distributed assignment mechanism may be possible based upon observations made of other networks active within the same spectrum band.

D. Frequency Acquisition

Following signature detection and network identification, the third key task in cognitive radio rendezvous is that of frequency acquisition. Once the signal of interest has been acquired, timing and close frequency synchronization may take place and a communication link can be established.

Signature detection through use of cyclic periodogram estimation permits signature features to be accurately located in the frequency domain. In the case where the operating bandwidth of the receiver is greater than that of the signal of interest, this approach facilitates detection and carrier frequency estimation of signals containing embedded signatures operating at any frequency within that receiver bandwidth.

Due to the sensitivity exhibited to adjacent carrier interference (ACI), OFDM systems typically employ a two-stage approach to carrier frequency synchronization - a coarse carrier frequency estimation stage and a fine-frequency tracking stage. In [30], Schmidl and Cox propose the use of a two-symbol training sequence to facilitate frequency and timing synchronization. The first symbol, $c_{1,k}$, contains a half-symbol repetition and is used for timing synchronization and estimation of the fractional frequency offset. This approach extends that first proposed by Moose [31] and provides an acquisition range of ± 1 subcarrier spacings. The second symbol, $c_{2,k}$, contains a pseudonoise (PN) sequence and is used in conjunction with the first to correct the remaining frequency offset - an integer multiple of the subcarrier spacing.

For OFDM signals containing embedded cyclostationary signatures, the signature location alone may be used to per-

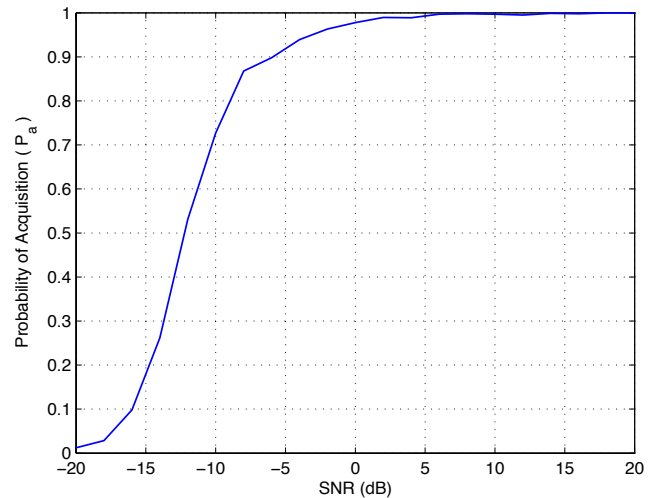


Fig. 9. Carrier Frequency Acquisition Using Cyclostationary Signatures. Probability of acquisition, P_a , is the probability of the carrier frequency estimate lying within ± 1 subcarrier spacing of the true value.

form frequency acquisition to within ± 1 subcarrier spacing. Thus, the second training symbol proposed in [30] is not required for integer frequency offset correction.

Monte-Carlo simulations are used to examine frequency offset estimation performance using embedded cyclostationary signatures. A 5MHz spectrum band is simulated using a 1280-bin inverse fast Fourier transform (IFFT). Of these, 256 contiguous bins are chosen to simulate a signal transmitted using 20% of the available bandwidth. As before, subcarriers are allocated as follows: 192 data, 8 pilot, 55 guard, 1 DC carrier. The index of the DC carrier bin, n_0 is randomly chosen as $128 \leq n_0 \leq 1152$ and a further fractional frequency offset f_{frac} is added as

$$y[k] = x[k]e^{2\pi f_{frac}ki} \quad (19)$$

A multiple-feature cyclostationary signature is generated with cyclic frequency $\alpha = 34/256F_s$, using four sets of 3 mapped subcarriers. A time-variant multipath channel is simulated using the COST 207 Bad Urban channel model with path delays and powers outlined in Table II. Gaussian white noise is added for $-20 \text{ dB} \leq \text{SNR} \leq 20 \text{ dB}$. Signature detection is performed over the full simulated bandwidth as before using the single-cycle detector (16). An observation time of $\Delta t = 60T$ is considered, and carrier frequency estimation is performed using the detected signature. Carrier frequency estimates are used to establish a probability of acquisition defined as

$$P_a = p(f_0 - \Delta f \leq f_{est} \leq f_0 + \Delta f) \quad (20)$$

where Δf is the subcarrier spacing and f_0 is the true carrier frequency. Results are presented in Fig. 9.

Simulation results indicate that cyclostationary signatures may be very reliably used for carrier frequency acquisition to within one subcarrier spacing of the true carrier frequency. This is shown to be true for signals received with SNR of greater than 0dB under multipath channel conditions. Thus, cyclostationary signatures may be effectively used for coarse

carrier frequency acquisition prior to fine frequency tracking using a single symbol preamble as described in [30], [31]. These results are examined further using experimental results in Section V.

V. EXPERIMENTATION

Simulations provide a valuable tool for assessing the performance of detection, classification and frequency acquisition techniques provided through the use of cyclostationary signatures. However, in order to gain a deeper insight into the requirements and advantages of a full transceiver implementation, experimentation using a flexible cognitive network experimentation platform is invaluable. This section presents experimental results obtained using a full OFDM transceiver implementation utilizing cyclostationary signatures upon such a platform.

A. The Plastic Project

The *Plastic Project* [32] is a cognitive network experimentation platform developed within the Emerging Networks strand of the Centre for Telecommunications Value-Chain Research (CTVR) based at University of Dublin, Trinity College, Ireland. The platform is general-purpose processor (GPP) based and facilitates the component-based construction of highly flexible network nodes for cognitive network experimentation. At the physical layer of the platform is a reconfigurable software radio architecture known as IRIS (Implementing Radio in Software) [33]. IRIS allows a physical layer signal path to be created using chains of software signal processing units and facilitates reconfiguration of these units during the course of radio operation. A highly flexible radio frequency (RF) front-end known as the Universal Software Radio Peripheral (USRP) [34] is used together with IRIS and the plastic project to transmit and receive signals in frequency bands between DC and 2.9 GHz. An OFDM transceiver making use of cyclostationary signatures for signal detection, identification and frequency acquisition was implemented upon the plastic project platform.

B. Transmitter

An OFDM transmitter supporting the generation of embedded cyclostationary signatures was created through the adaptation of an existing IRIS signal processing unit. The reconfigurable OFDM modulator was adapted to permit the mapping of subcarrier subsets and a number of parameters were included to allow the dynamic alteration of the signature types which can be generated. In addition to the adapted OFDM modulator, a number of pre-existing signal processing units were included in the transmitter design. Further information on the implementation of a reconfigurable OFDM modulator using IRIS may be found at [35].

C. Receiver

In designing an OFDM receiver to utilize cyclostationary signatures for signal detection, network identification and frequency acquisition, the signature detector outlined in Section IV was implemented as an IRIS signal processing unit. A

similar approach to that used in the transmitter could have been taken by adapting the design of an existing OFDM demodulator. However, by separating the signature analysis functionality into a standalone unit and using it in tandem with the OFDM demodulator, it was possible to maintain the reusability of both units.

Fig. 10 outlines the detailed structure of the signature detector unit as well as the structure of the OFDM receiver implementation.

Within the receiver structure, two mutually exclusive signal paths are supported. The upper path contains the signature detector unit and the lower path contains the typical OFDM receive chain including the reconfigurable OFDM demodulator. A switch is used to direct signal flow to one of the two paths. In this way, initial signature detection and carrier frequency offset estimation may be performed by guiding signal flow to the signature detector unit. Upon detection of a signature, an event is triggered by the unit and the carrier frequency offset estimate is used to adjust the receive frequency of the USRP. At this time, the flow of received signal samples is switched to the lower signal path and initial frame detection is performed by the OFDM demodulation unit.

The receiver element located between both signal paths in Fig. 10 is termed *control logic* and is a radio structure-specific agent with responsibility for handling triggered events and executing reconfigurations within the radio during the course of its operation.

D. Results

In order to examine the performance of the transceiver implementation outlined in the previous section, experiments were carried out in the 2.35 GHz CTVR licensed band using the Plastic Project platform.

QPSK modulated random data was used to create 256-subcarrier OFDM symbols and signatures were embedded in each through the mapping of a single set of 3 subcarriers. Signatures were centered at the signal carrier frequency, f_0 , and a signature cyclic frequency of $\alpha = \frac{21}{256}F_s$ was used. These signals were transmitted at 2.3405 GHz and with a bandwidth of 1 MHz. In order to achieve precise control over the transmission frequency, power and bandwidth, generated signals were transmitted using an Anritsu MG3700A Vector Signal Generator.

Signals were received using the USRP front-end and analyzed using the reconfigurable cyclostationary detector. The USRP was software configured to sample a 4 MHz bandwidth, centered at 2.34 GHz. The detector was configured to perform signature detection and carrier frequency estimation at the signature cyclic frequency, $\alpha = \frac{21}{256}F_s$, using a 1024-bin Fourier transform. Experiments were conducted in an indoor environment over a range of approximately five meters.

Initial tests were carried out to examine the performance of the signature detector with increasing signal observation times. Signals were transmitted at a range of power levels using the signal generator. SNR was estimated at the receiver and detection was performed over a range of observation times. One hundred tests were carried out for each transmit power level and detector observation time and results were

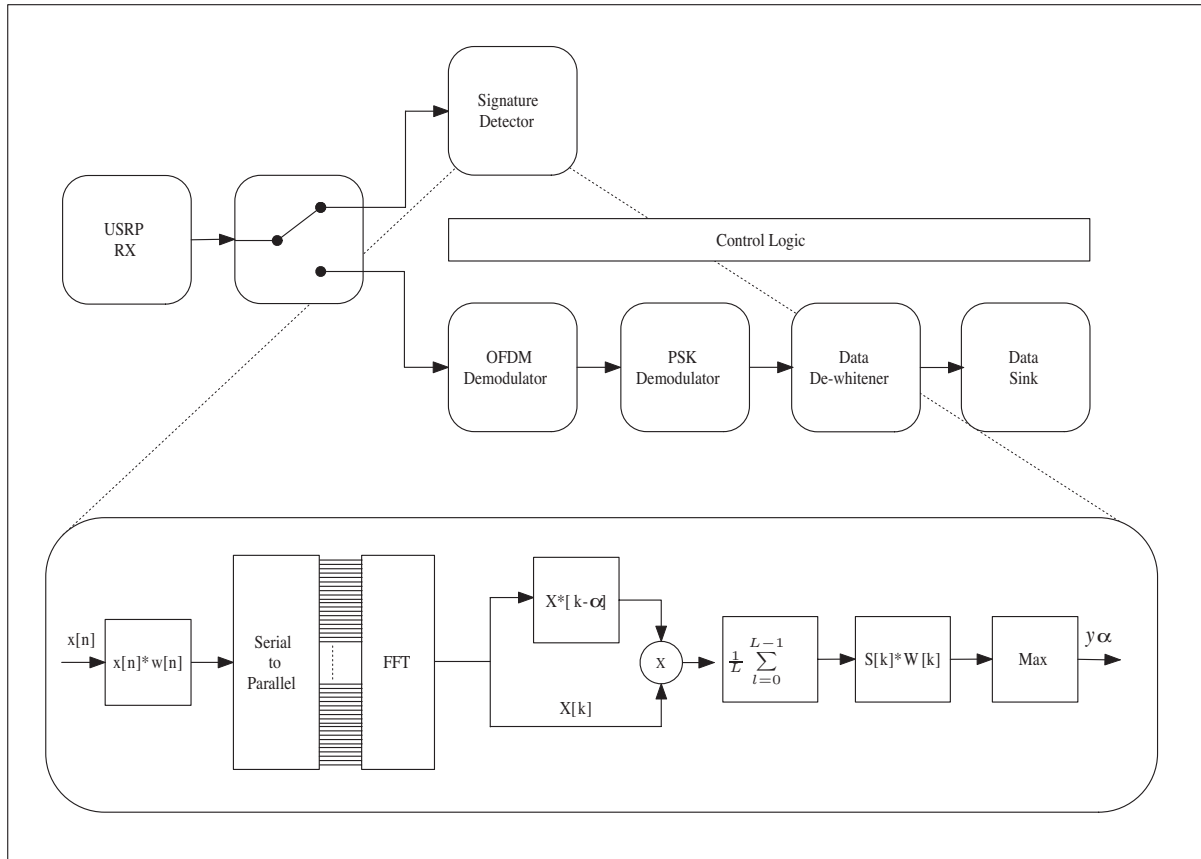


Fig. 10. Receiver Structure. A dual signal path structure is adopted with a switch for directing received signal samples to the signature detector or OFDM demodulator as required.

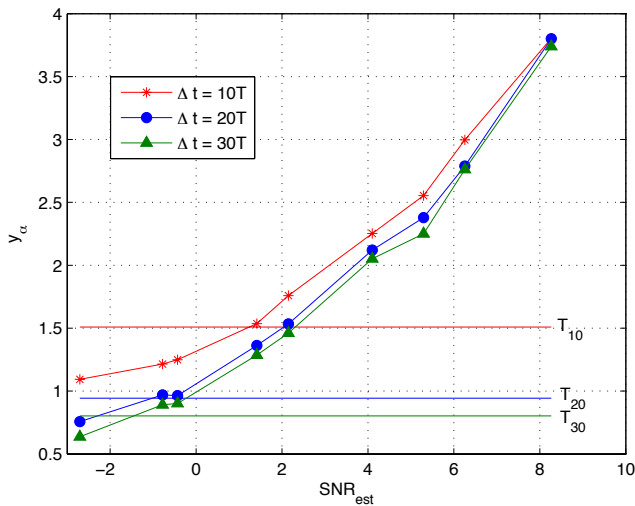


Fig. 11. Detector Performance. T_{10} , T_{20} and T_{30} represent the minimum threshold levels required for a false alarm rate of 0% as determined over 100 tests for observation times of 10, 20 and 30 transmitted symbol durations respectively.

recorded. Detector performance in the absence of transmitted signals was also examined in order to determine suitable detection thresholds. One hundred tests were carried out for each observation time, and thresholds were chosen to give an estimated probability of false alarm, P_{fa} , of 0.

Results are illustrated in Fig. 11. The detector output, y_α , is shown for observation times of 10, 20 and 30 transmitted OFDM symbol durations. In addition, threshold values, T_{10} , T_{20} and T_{30} , are shown for each. These thresholds represent the minimum level required for a P_{fa} of 0 as determined over 100 tests.

Results show that with an observation time of just 10 transmitted symbol durations, signatures may be reliably detected in signals received with SNR of greater than 2 dB. It can be seen that, though y_α varies little with increased signal observation time, the threshold required for a low P_{fa} falls considerably. Thus reliable signal detection may be performed at lower levels of SNR using increased observation times.

Fig. 12 illustrates receiver operating characteristic (ROC) performance for received SNR of 0 dB. Performance is seen to improve considerably with increased observation times, Δt . A detection rate of 100% is achieved for an associated false alarm rate of 0% as determined over 100 tests using observation time, $\Delta t = 60T$. These results closely match predictions made using simulations in Section IV.

Further experimentation was carried out in order to examine the practical use of cyclostationary signatures for rendezvous and carrier frequency acquisition in cognitive radio applications. Signals were generated as before and transmitted at 2.3405 GHz and with a bandwidth of 1 MHz. Cyclostationary signatures were embedded using a single set of three mapped subcarriers and were centered at the signal carrier frequency, f_0 .

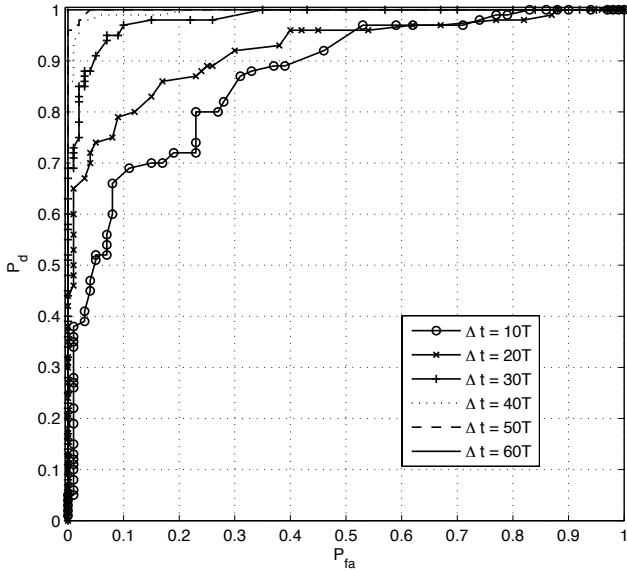


Fig. 12. Receiver operating characteristic (ROC) performance for $SNR_{est} = 0$ dB. Performance improves considerably with increased observation times.

Signals were received using the USRP which was software configured to receive a 4 MHz bandwidth centered at 2.34 GHz. Carrier frequency estimation was performed using the reconfigurable signature detector.

Signals were transmitted at -25 dBm to give an approximate SNR of 6 dB at the receiver. 500 tests were carried out and carrier frequency estimation was performed using a range of observation times. For each observation time, a probability of acquisition, P_a , was determined for estimation accuracies of between ± 0.5 and 2.5 subcarrier spacings from the true carrier frequency. Results from this test are illustrated in Fig. 13.

It can be seen that the accuracy of carrier frequency estimates improves considerably as detector observation times are increased. Indeed, using an observation time of 40 transmitted OFDM symbol durations, it was found that signal carrier frequency could be very reliably estimated to within ± 1 subcarrier spacing of the true value. Therefore, cyclostationary signatures may be effectively used to perform initial carrier frequency acquisition prior to a fine frequency tracking stage such as that described in [31] and [30]. In order to achieve fine frequency tracking with an acquisition range of ± 1 subcarrier spacing, a single OFDM symbol containing a half-symbol repetition may be utilized in the frame preamble [30], [31]. This approach is adopted for uplink frames in the IEEE 802.16 WiMax specifications [28].

VI. CONCLUSIONS AND FUTURE WORK

This paper has introduced cyclostationary signatures as an effective tool for overcoming a number of the principal challenges associated with network coordination in cognitive radio and dynamic spectrum access applications. It has been shown that cyclostationary signatures may be used to overcome a number of the key limitations associated with the use of inherent cyclostationary features for signal detection

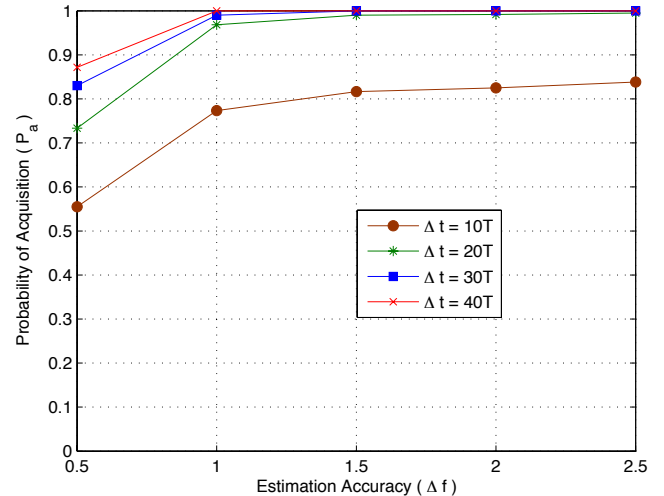


Fig. 13. Frequency Acquisition Performance. Estimation accuracy rises with increasing observation times.

and analysis. Robust, low-complexity approaches for signature generation, detection and analysis were presented and the use of embedded cyclostationary signatures to achieve signal detection, network identification and frequency rendezvous were examined. Using a highly flexible cognitive radio platform, the implementation of a full OFDM-based transceiver using cyclostationary signatures was presented and system performance was examined using experimental results.

Continuing from the initial research outlined in this paper, future work will be undertaken to examine the uses of cyclostationary signatures in the development of MAC protocols for networks of cognitive radios. In addition, further applications of cyclostationary signatures will be examined and experimentation will be carried out using the Plastic Project platform.

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