# Cyclostationary Signatures in OFDM-Based Cognitive Radios With Cyclic Delay Diversity

Shanghai Research Center for Wireless Communications (WiCO), China

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# Outline

1. Introduction
2. System Model
3. Intrinsic Cyclostationary Signatures in CDD-OFDM
4. Application to Spectrum Sensing
   - Asymptotical CFAR Testing Based on Multiple Lags
   - Numerical Results
5. Conclusions

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# Introduction

## Cyclostationary signature for cognitive radios

- As defined in [4], a cyclostationary signature is a feature, intentionally embedded in the physical properties of digital communications signal, which may be easily generated, manipulated, detected and analyzed using low-complexity transceiver architecture.
- The 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.

# Cyclostationarity of OFDM Signals

## CP-induced cyclostationarity

1. Related to the CP length, (cannot be altered).
2. Unsuitable for use in network coordination of cognitive radios.

## Transmitter-induced cyclostationarity

1. subcarrier mapping [4]; specific preamble insertion [7]
2. The cost of bandwidth
3. Only in specific elements of transmitted signal

## CDD-induced cyclostationarity

1. Flexible to manipulate with respect to cyclic delay
2. No bandwidth overhead, while achieving the delay diversity gain
3. Continuous presence in a transmitted signal

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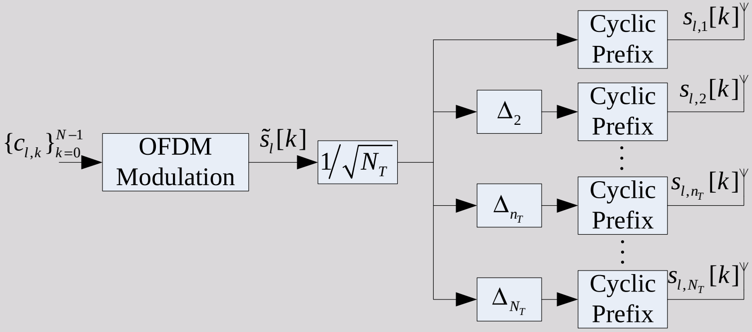
# System Model: CDD-OFDM

## Transmit architecture of OFDM system utilizing CDD



# CDD-OFDM: Appealing Features

1. **Standard conformability**

### Standard conformability

- Implement only in **relay nodes** being transparent to destination receiver side
- It can be incorporated within the **OFDM-based standards** such as WiMAX, 3GPP-LTE, and IEEE 802.11a etc., considering the size and cost of multiple antennas is prohibitive for wireless devices.

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# CDD-OFDM: Appealing Features

1. Standard conformability
2. **Delay diversity gain**

## Delay diversity gain

- Convert virtual **MISO** channel into an equivalent **SISO** channel with increased frequency diversity.
- Transform delay diversity into **frequency diversity**
- Collect increased diversity by an outer **error control coding** such as convolutional coding

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# CDD-OFDM: Appealing Features

1. Standard conformability
2. Delay diversity gain
3. **Saturation effect**

## Saturation effect [1]

- $\Delta_{n_T} \geq \frac{1}{BT_s}$ $(n_T = 1, 2, \cdots, N_T)$ is a saturation region in terms of cyclic delays, where $B$ is bandwidth of OFDM signal and $T_s$ is sample period.
- In the saturation region, the system can achieve almost **the same** delay diversity gain approaching to the maximum.
- *Saturation effect allows for* ***tuning cyclic delays for other metrics****, while keeping the desirable performance of antenna system.*

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# System Model: Signal Formulation

- $$s_{l,n_T}(k) = \frac{1}{\sqrt{N_T}} \tilde{s}_l[(k - \Delta_{n_T}) \bmod N], \quad n_T = 1, 2, \cdots, N_T \qquad (1)$$

  where $\Delta_{n_T}$ is the antenna-dependent cyclic delay $(0 = \Delta_1 < \Delta_2 < \cdots < \Delta_{N_T})$.

- $$s_{n_T}(n) = \frac{1}{\sqrt{N_T N}} \sum_{l=-\infty}^{+\infty} g(n - lM) \sum_{k=0}^{N-1} c_{l,k} W_N^{k\Delta_{n_T}} W_N^{k(lM-n)} \qquad (2)$$

  where $M = N + N_G$ and $g(n) = R_{[0,M-1]}^{(n)}$ with

  $$R_{[T_1,T_2]}^{(n)} = \begin{cases} 1 & n = T_1, T_1 + 1, \cdots, T_2 \\ 0 & \text{else} \end{cases} . \qquad (3)$$

- The CDD-OFDM signal received by one antenna can be written as

  $$r(n) = \sum_{l=0}^{L_h} \mathbf{h}_l \mathbf{s}(n - l) + w(n) \qquad (4)$$

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# Cyclostationary Characteristics of CDD-OFDM Signal

- Defining the correlation matrix of the vector random process $\mathbf{s}(n)$ as

$$\mathbf{C_s}(n,\tau) = E\{\mathbf{s}(n)\mathbf{s}^H(n+\tau)\} \tag{5}$$

- Cyclic Autocorrelation Function (CAF)

$$\begin{aligned} \tilde{c}_r(k,\tau) &= \sum_{n=0}^{M-1} c_r(n,\tau) W_M^{kn} \\ &= \sum_{l=0}^{L_h} \mathbf{h}_l W_M^{kl} \sum_{r=\tau+l-L_h}^{\tau+l} \tilde{\mathbf{C}}_s(k,r)\mathbf{h}^H_{\tau+l-r} + c_w(\tau)\delta(k) \end{aligned} \tag{6}$$

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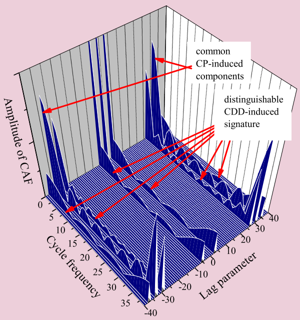
# Cyclostationary Characteristics of CDD-OFDM Signal

- $$[\mathbf{C_s}(n,\tau)]_{i,j} = \frac{1}{N_T}\sum_{l=-\infty}^{+\infty} g(n-lM)g(n+\tau-lM)\delta_N[\tau-(\Delta_j-\Delta_i)]$$

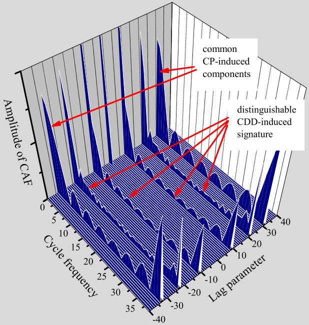
$$= \begin{cases} \frac{1}{N_T}\sum_{l=-\infty}^{+\infty} R_{[0,M-1-(\Delta_j-\Delta_i)]}^{(n-lM)} & 0\leq\tau=(\Delta_j-\Delta_i) \\ \frac{1}{N_T}\sum_{l=-\infty}^{+\infty} R_{[-(\Delta_j-\Delta_i),M-1]}^{(n-lM)} & \tau=(\Delta_j-\Delta_i)<0 \\ \frac{1}{N_T}\sum_{l=-\infty}^{+\infty} R_{[0,M-1-N-(\Delta_j-\Delta_i)]}^{(n-lM)} & 0\leq\tau=N+(\Delta_j-\Delta_i)\leq M-1 \\ \frac{1}{N_T}\sum_{l=-\infty}^{+\infty} R_{[N-(\Delta_j-\Delta_i),M-1]}^{(n-lM)} & 1-M\leq\tau=-N+(\Delta_j-\Delta_i)\leq 0 \\ 0 & \text{else} \end{cases} \quad (7)$$

# Intrinsic Cyclostationary Signatures in CDD-OFDM ($N_T = 2, N = 32, N_G = 8$)

## $\Delta_2 = 4$




## $\Delta_2 = 10$




- A sequence of lag-indexed spectrum lines indexed by the following indices set

$$\Omega = \{\tau | \tau = \pm(\Delta_j - \Delta_i), N \pm (\Delta_j - \Delta_i), -N \pm (\Delta_j - \Delta_i); i, j = 1, 2, \cdots, N_T\}. \quad (8)$$

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# Application to Spectrum Sensing

## Asymptotical CFAR testing based on multiple lags

- The hypothesis testing for the presence of primary user can transform to the problem for testing if $\alpha$ is a cyclic frequency, formulated as

$$\begin{aligned} &H_0 : \forall \boldsymbol{\tau} \Rightarrow \hat{\mathbf{c}}_r(\alpha, \boldsymbol{\tau}) = \boldsymbol{\varepsilon}(\alpha, \boldsymbol{\tau}); \\ &H_1 : \text{For some } \boldsymbol{\tau} \subseteq \Omega \Rightarrow \hat{\mathbf{c}}_r(\alpha, \boldsymbol{\tau}) = \mathbf{c}_r(\alpha, \boldsymbol{\tau}) + \boldsymbol{\varepsilon}(\alpha, \boldsymbol{\tau}) \end{aligned} \tag{9}$$

- $\boldsymbol{\varepsilon}(\alpha, \boldsymbol{\tau})$: $\lim_{L\to\infty} \sqrt{L}\boldsymbol{\varepsilon}(\alpha, \boldsymbol{\tau}) \sim \mathcal{N}(\mathbf{0}, \Sigma_r(\alpha, \boldsymbol{\tau}))$.
- Generalized Likelihood Ratio (GLR):

$$T_r(\alpha, \boldsymbol{\tau}) = -2 \ln \Lambda = L\hat{\mathbf{c}}_r(\alpha, \boldsymbol{\tau})\hat{\Sigma}_r^{-1}(\alpha, \boldsymbol{\tau})\hat{\mathbf{c}}_r^T(\alpha, \boldsymbol{\tau}). \tag{10}$$

- Under the null hypothesis, $T_r(\alpha, \boldsymbol{\tau})$ is asymptotically $\chi^2_{2N_\tau}$ distributed. As a result, we can present the test which is based on a CFAR approach for selecting a threshold.

# Common Simulation Parameters

| PARAMETER | DESCRIPTION | VALUE |
|---|---|---|
| $N$ | DFT size | 128 |
| $\Delta_f$ | Subcarrier frequency spacing | 10.9325 kHz |
| $f_s$ | Sampling frequency | 2.798720 MHz |
| $N_G/N$ | CP ratio | 1/8 |
| $f_c$ | Carrier frequency | 2.5 GHz |
| $T_o = 1/\Delta_f$ | OFDM symbol duration without CP | 91.43 $\mu$s |
| $T$ | OFDM symbol duration with CP | 102.86 $\mu$s |
| | Modulation | 16QAM |
| $N_T$ | Number of transmit antennas | 2 |
| $v$ | Velocity | 0 m/s |
| $SNR$ | Signal-to-noise ratio | $-10 \log \sigma_w^2$ dB |
| $L$ | Length of observations | $10 \times T$ |
| $L_w$ | Length of Kaiser window | 1029 |
| $\beta$ | $\beta$ parameter of Kaiser window | 10 |
| $\alpha$ | Given cyclic frequency for detection | $1/T$ |

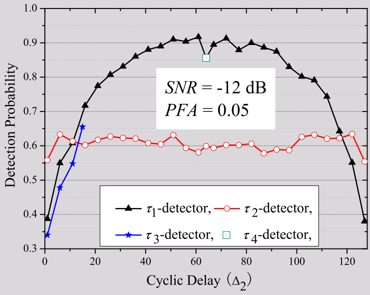
# Simulation results

## Typical set of multiple lags

From the set of $\Omega$, we adopt the following typical sets as observation spots

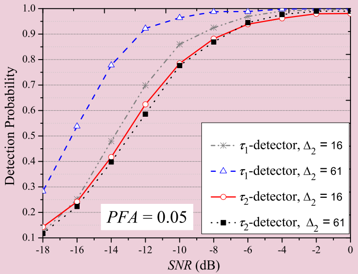
$$
\begin{aligned}
\boldsymbol{\tau}_1 &= [-128, -128+\Delta_2, -\Delta_2, \Delta_2, 128-\Delta_2, 128], \\
&\quad (\Delta_2 \neq 64) \\
\boldsymbol{\tau}_2 &= [-128, 128] \\
\boldsymbol{\tau}_3 &= [-128-\Delta_2, -128, -128+\Delta_2, -\Delta_2, \Delta_2, \\
&\quad 128-\Delta_2, 128, 128+\Delta_2], \quad (\Delta_2 \leq 15) \\
\boldsymbol{\tau}_4 &= [-128, -64, 64, 128].
\end{aligned} \tag{11}
$$

## Detection probability versus cyclic delay with different methods

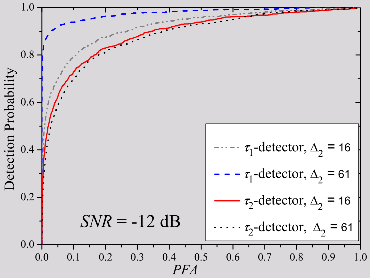


# Simulation results

## Detection probability versus SNR with different methods




## Receiver operating characteristics with different methods



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# Conclusions

**The procedure of Cyclic Delay Diversity (CDD) simultaneously possess the dual advantages in terms of antenna diversity and cognitive radios.**

- For the OFDM-based cognitive radios, the CDD procedure can be characterized as a cost-efficient approach to generating flexible cyclostationary signatures.
- the CDD-induced cyclostationary signatures may be easily implemented, manipulated, detected and analyzed using the standard compatible CDD-OFDM architectures without suffering signaling overhead.
- The novel approach still achieves the initial goal toward the delay diversity gain which originally drives the CDD procedure into real applications.