Chapter 6

Agile Transmission Techniques
Outline

- Introduction
- Wireless Transmission for DSA
- Non Contiguous OFDM (NC-OFDM)
- NC-OFDM based CR: Challenges and Solutions
- Chapter 6 Summary
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- Introduction
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Introduction

- The utilization efficiency of “prime” wireless spectrum has been shown to be poor.

Figure 6.1: A snapshot of PSD from 88 MHz to 2686 MHz measured on July 11th 2008 in Worcester, MA (N42°16.36602, W71°48.46548)
In order to better utilize wireless spectrum, detection of white spaces in licensed bands and hardware reconfigurability are crucial.

A variant of OFDM named NC-OFDM meets the above requirements and supports high data-rates while maintaining acceptable levels of error robustness.
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Wireless Transmission for DSA

A solution to the artificial spectrum scarcity is shown below.

Figure 6.2: An illustration showing utilization of non-contiguous regions of spectrum for wireless transmission

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Wireless Transmission for DSA

(continued...)

- A recap of the existing approaches to DSA.
  - Spectrum Pooling: Create a common inventory of spectral resources from licensed users
  - Cooperative (exchange of information between users, centralized or non-centralized control etc.,) vs non-cooperative transmission (minimum or no exchange of information, poor spectrum utilization efficiency, nodes act in a greedy fashion)
  - Underlay vs Overlay transmission
Wireless Transmission for DSA (continued...)

- Underlay transmission

Figure 6.3 (a): Underlay spectrum sharing.
Wireless Transmission for DSA (continued...)

- Overlay transmission

Figure 6.3 (b): Overlay spectrum sharing.
Wireless Transmission for DSA

(continued...)

- Challenge: What are the design issues that arise during secondary utilization of a licensed band?
  - Minimum interference to licensed transmissions
  - Maximum exploitation of the gaps in the time-frequency domain.
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Non-contiguous OFDM (NC-OFDM)

NC-OFDM transmitter

Figure 6.4 (a): NC-OFDM transmitter
Non-contiguous OFDM (NC-OFDM)

NC-OFDM receiver

Figure 6.4 (b): NC-OFDM receiver
Outline

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NC-OFDM based CR: Challenges and Solutions

- Challenge #1: Interference mitigation

Figure 6.5: An illustration of the interference due to one OFDM-modulated carrier

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NC-OFDM based CR: Challenges and Solutions (continued…)

□ Challenge #1: Interference mitigation

- Mathematically, the power spectral density of the transmit signal over one subcarrier is,

  \[ \Phi_{ss}(f) = A^2 T \left( \frac{\sin \pi f T}{\pi f T} \right)^2 \]

- Mean relative interference to a neighboring legacy system subband is,

  \[ P_{Interference}(n) = \frac{1}{P_{Total}} \int_n^{n+1} \Phi_{ss}(f) df \]
NC-OFDM based CR: Challenges and Solutions (continued...)

- Challenge #1: Interference mitigation
  - Extended to a system with $N$ subcarriers, the signal over one subcarrier is,

  $$s_n(x) = a_n \frac{\sin(\pi(x - x_n))}{\pi(x - x_n)}, \quad n = 0, 1, 2, \ldots, N - 1$$

  where

  $$a = \begin{bmatrix} a_0 & a_2 & \ldots & a_{N-1} \end{bmatrix}^T$$

  $$x = (f - f_0)^T$$
NC-OFDM based CR: Challenges and Solutions (continued...)

- Challenge #1: Interference mitigation
  - The composite OFDM symbol over the $N$ subcarriers is,

$$S(x) = \sum_{n=1}^{N} s_n(x)$$

and its power spectral density is,

$$\Phi_{ss}(f) = |S(x)|^2 = \left| \sum_{n=1}^{N} a_n \frac{\sin(\pi(x - x_n))}{\pi(x - x_n)} \right|^2$$
NC-OFDM based CR: Challenges and Solutions (continued…)

- Challenge #1: Interference mitigation

Figure 6.6: An illustration of the interference in a BPSK-OFDM system with 16 subcarriers.

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NC-OFDM based CR: Challenges and Solutions (continued…)

Solution #1.1: Windowing

Applied to the time-domain OFDM transmit signal. Raised cosine window defined as shown below is commonly used.

\[
w(t) = \begin{cases} 
\frac{1}{2} + \frac{1}{2} \cos \left( \pi + \frac{\pi t}{\beta T} \right), & \text{for } 0 \leq t < \beta T \\
1, & \text{for } \beta T \leq t < T \\
\frac{1}{2} + \frac{1}{2} \cos \left( \frac{\pi(t-T)}{\beta T} \right), & \text{for } T \leq t < (1 + \beta)T 
\end{cases}
\]
NC-OFDM based CR: Challenges and Solutions (continued...)

Solution #1.1: Windowing

- Expands the temporal symbol duration by $(1+\beta)$ resulting in lowered system throughput.

![Figure 6.7: Structure of the temporal OFDM signal using a raised cosine window](image-url)
NC-OFDM based CR: Challenges and Solutions (continued...)

- Solution #1.1: Windowing
  - Achievable suppression is insignificant for low values of $\beta$.

Figure 6.8: Impact of roll-off factor on the PSD of the rental system signal.

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NC-OFDM based CR: Challenges and Solutions (continued…)

Solution #1.2: Insertion of guard bands

- A waste of spectral resources

Figure 6.9: Interference suppression in a BPSK-OFDM system with 64 subcarriers by inserting guard subcarriers (GCs)
NC-OFDM based CR: Challenges and Solutions (continued...)

- Solution #1.3: Insertion of cancellation subcarriers (CCs)

Figure 6.10: Illustration of sidelobe power reduction with cancellation carriers (CCs).

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NC-OFDM based CR: Challenges and Solutions (continued…)

Solution #1.3: Insertion of cancellation subcarriers (CCs)

The individual subcarriers and the cumulative OFDM signal can be described as:

\[ s_{l_a}(y) = d_{l_a} \frac{\sin\left(\pi \left( y - y_{l_a} \right) \right)}{\pi \left( y - y_{l_a} \right)}, \quad l_a = -L_A/2, \ldots, L_A/2, \]

\[ S(y) = \sum_{l_a=-L_A/2}^{L_A/2} s_{l_a}(y) \]
NC-OFDM based CR: Challenges and Solutions (continued…)

Solution #1.3: Insertion of cancellation subcarriers (CCs)

- The sidelobe level at the $k^{th}$ frequency index can be described as:

$$I_k = \sum_{l_a=-L_A/2}^{L_A/2} s_{l_a}(k)$$

- Insert a subcarrier, $C_j$ at $j = L_A/2+1$ such that $C_k = -I_k$. 

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NC-OFDM based CR: Challenges and Solutions (continued…)

Solution #1.4: Constellation expansion

Figure 6.11: A mapping of symbols from QPSK constellation to an expanded constellation space

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NC-OFDM based CR: Challenges and Solutions (continued...)

- Solution #1.4: Constellation expansion
  - Map symbols from the original constellation space to an expanded one. That is, multiple symbols from the expanded constellation are associated with each symbol from the original constellation.
  - Exploit the randomness in choosing the symbols and consequently, their combination which leads to a lower sidelobe level compared to the original case.
NC-OFDM based CR: Challenges and Solutions

- Challenge #2: FFT Pruning

- In an NC-OFDM scenario, several OFDM subcarriers are turned OFF in order to avoid interfering with an incumbent user.

- If the available spectrum is sparse, the number of zero-valued inputs to the FFT lead to an inefficient use of hardware.

![Subcarrier distribution over wideband spectrum](image)

Figure 6.12: Subcarrier distribution over wideband spectrum
NC-OFDM based CR: Challenges and Solutions

- Challenge #2: FFT Pruning

Figure 6.13: An 8-point DIF FFT butterfly structure for a sparse input
NC-OFDM based CR: Challenges and Solutions

- Existing Solutions: FFT Pruning
  - Alves et al proposed a solution that operates on any input distribution based on the Cooley-Tukey algorithm.
  - Rajbanshi et al proposed a solution based on the above algorithm that achieves greater savings in the execution time for a sparse input.
NC-OFDM based CR: Challenges and Solutions

- Challenge #3: PAPR
  - Both OFDM as well as NC-OFDM suffer from the PAPR problem

\[ s(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} A_k e^{j2\pi k t/T} \]

\[ \text{PAPR}(s(t)) = \frac{\max_{0\leq t \leq T} |s(t)|^2}{E\{|s(t)|^2\}} \]

- However, the characteristics are slightly different due to the non-contiguous spectrum utilization of the latter.
NC-OFDM based CR: Challenges and Solutions

Challenge #3: PAPR

- PAPR distribution of an NC-OFDM signal
  - Peak power of an NC-OFDM signal is given by:

\[
\max_{0 \leq t \leq T} |s(t)|^2 = \max_{0 \leq t \leq T} \left| \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} A_k e^{j2\pi kt/T} \right|^2 \\
\leq \left( \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \max |A_k| \right)^2 \\
\leq \frac{p^2}{N}.
\]

“Cognitive Radio Communications and Networks: Principles and Practice”
NC-OFDM based CR: Challenges and Solutions

- Challenge #3: PAPR
  - PAPR distribution of an NC-OFDM signal
  - Average power of an NC-OFDM signal is given by:

  \[ E \{ |s(t)|^2 \} = E \left\{ \left| \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} A_k e^{j2\pi kt/T} \right|^2 \right\} \]

  \[ = \frac{1}{N} \sum_{k=0}^{N-1} \{ E |A_k|^2 \} \]

  \[ = \frac{p}{N} . \]
NC-OFDM based CR: Challenges and Solutions

- Challenge #3: PAPR
  - PAPR distribution of an NC-OFDM signal
  - Therefore, PAPR of an NC-OFDM signal is given by:

\[
PAPR(s(t)) = \frac{\max_{0 \leq t \leq T} |s(t)|^2}{E\{|s(t)|^2\}} \leq \frac{p^2}{p/N} \leq p.
\]

“Cognitive Radio Communications and Networks: Principles and Practice”
NC-OFDM based CR: Challenges and Solutions

Existing Solutions: PAPR

- Power adjustment based approaches
  - Reduce the total power of all subcarriers
    \[ \sum_{k=0}^{N-1} \pi_k = \pi_{\text{total}} \]
  - Reduce the power of the subcarriers in a window
    \[ \sum_{k=l}^{l+M-1} \pi_k \leq \pi_{\text{max}}, \quad \forall l \quad \text{and} \quad \sum_{k=0}^{N-1} \pi_k = \pi_{\text{total}} \]
NC-OFDM based CR: Challenges and Solutions

□ Existing Solutions: PAPR
  ■ Time-domain based techniques
    □ Clipping
    □ Filtering
  ■ Frequency-domain based techniques
    □ Coding
  ■ Other techniques
    □ Interleaving, Partial Transmit Sequences, Selected Mapping etc.
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- A spectrally agile wireless transceiver is necessary for improving spectrum efficiency.
- This results in several design challenges such as:
  - Avoiding interference to incumbent users
  - Reduce the number of computations involved when using a portion of spectrum that is heavily used by the incumbent user
  - Avoid spectral spillage due to nonlinear distortion of a high PAPR signal
Chapter 6 Summary

Although, several solutions are available in the technical literature, these solutions need to be tweaked for the non-contiguous spectrum usage case.