TECHNIQUES FOR COGNITIVE RADIO

H. NIKOOKAR

International Research Centre for Telecommunications and Radar (IRCTR)
Delft University of Technology
The Netherlands

Instituto Superior Tecnico, Lisbon, Portugal, 27 September 2007.

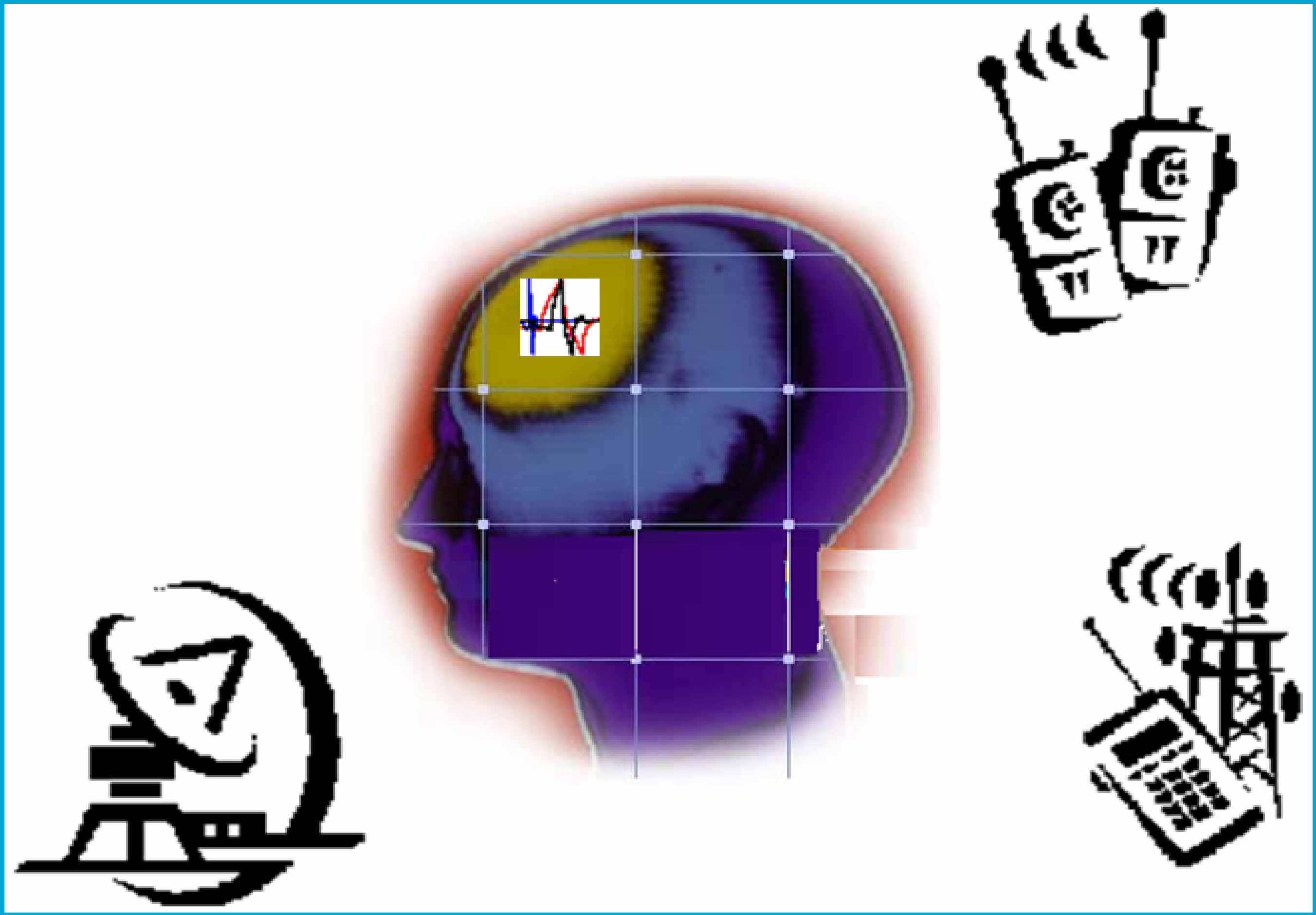
Delft University of Technology

Cognitive Radio

Cognitive Radio=an intelligent wireless communication system aware of its surrounding environment.

CR uses the methodology of understanding by building to learn from the environment and adapt to statistical variations in the radio channel.

Changing operating parameters in real time and efficient utilization of the radio spectrum.

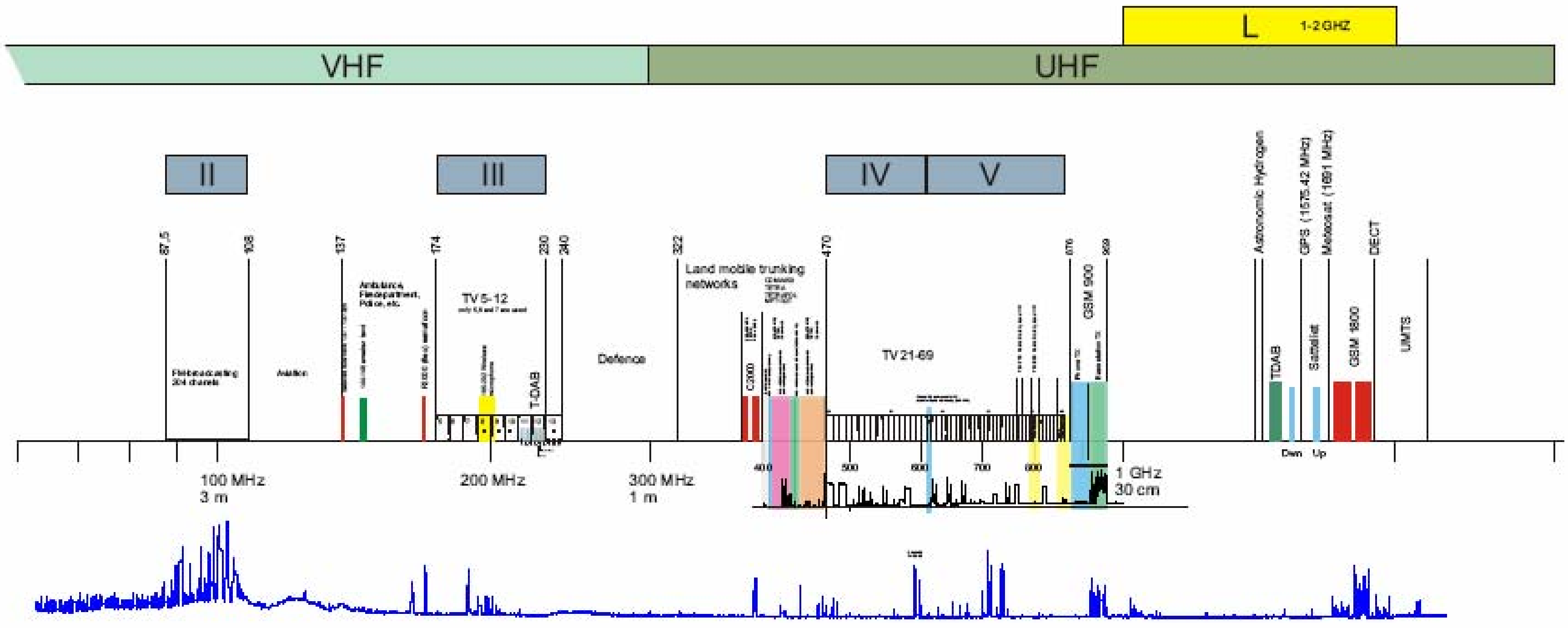


Cognitive Radio: A radio (to generate, transmit, receive and process of wireless signals) and a cognitive brain which learns from the environment and performs rational processes and predicts probable consequences and remembers past successes and failures.

Talk Outline

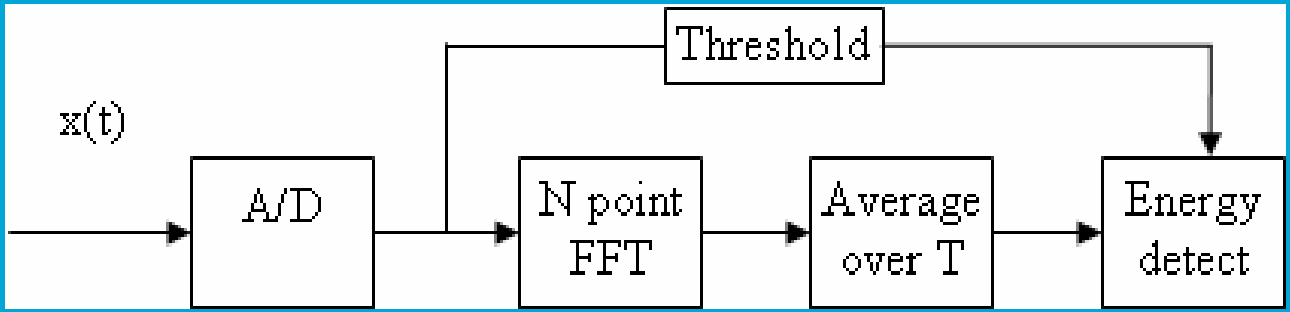
- Spectrum Overview
- Spectrum Sensing
- Adaptive OFDM and Spectrum Pooling
- Waveshaping
    - ❖ Transfer Domain Communication System (TDCS)
    - ❖ Wavelet Domain Communication System (WDCS)
    - ❖ Multi Carrier Wavelet Packet Modulation with Interference Mitigation
- Beamforming
- Summary

Spectrum Overview

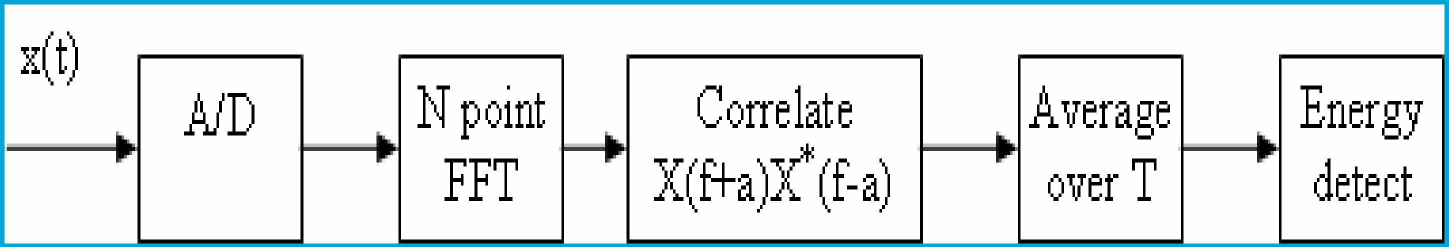


Spectrum Sensing

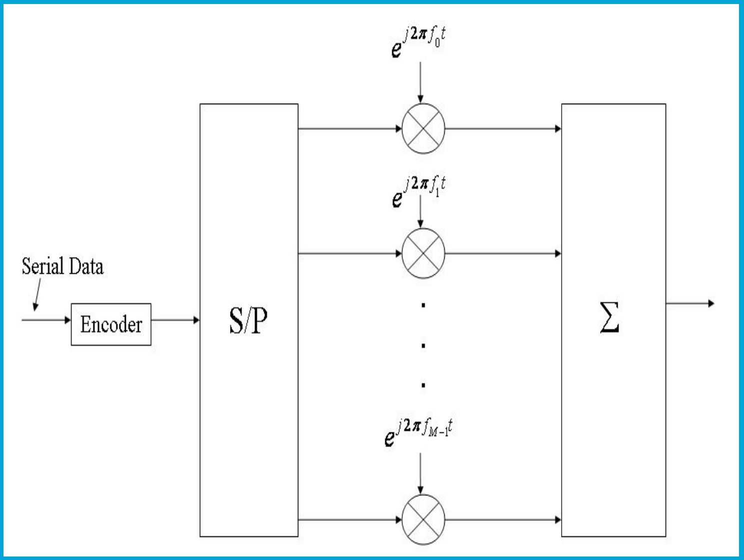
- Energy Detector

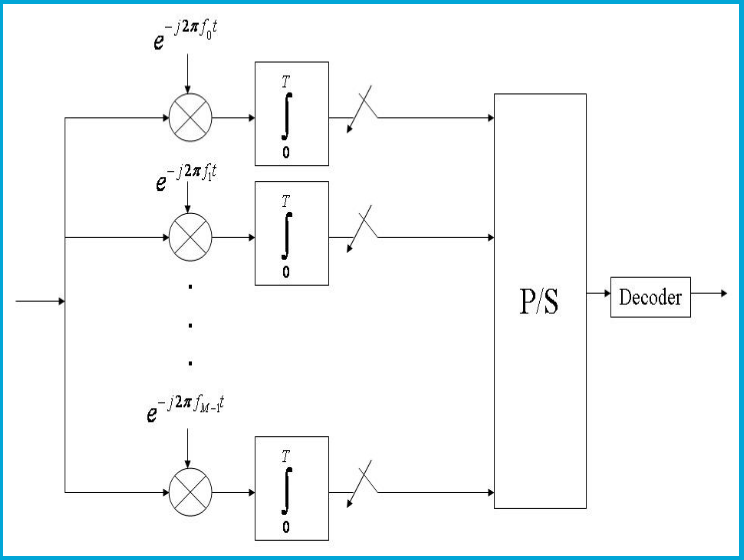


- Cyclostationary feature detector

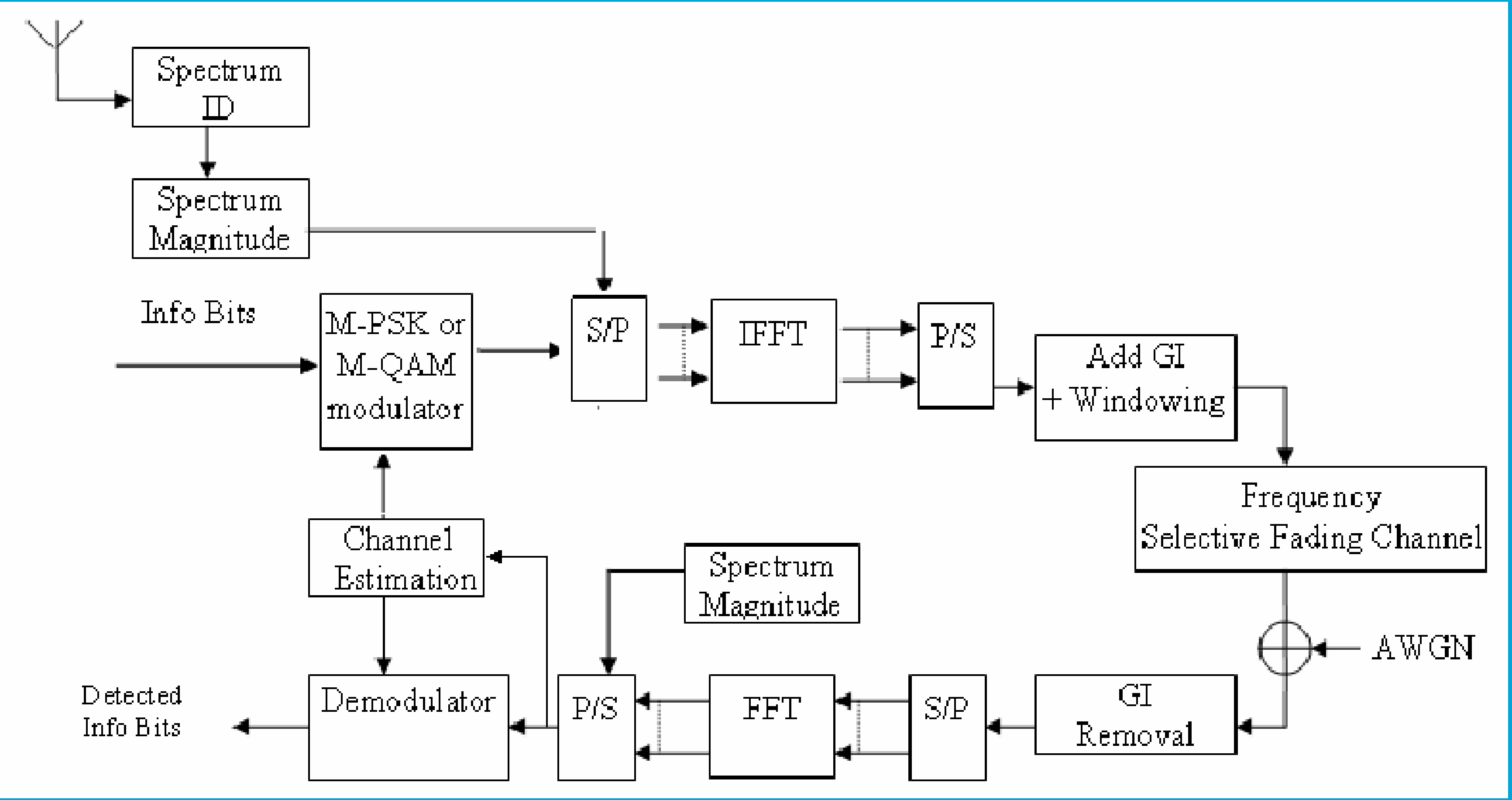


OFDM


$e^{j2\pi f_0 t}$
$e^{j2\pi f_1 t}$
Serial Data
Encoder
S/P
Σ
$e^{j2\pi f_{M-1} t}$


$e^{-j2\pi f_0 t}$
$\int_0^T$
$e^{-j2\pi f_1 t}$
$\int_0^T$
P/S
Decoder
$e^{-j2\pi f_{M-1} t}$
$\int_0^T$

Adaptive OFDM and Spectrum Pooling (1)



Adaptive OFDM and Spectrum Pooling (2)

Reasons for using of OFDM as modulation scheme in Cognitive Radio :

- Many Parameters to be altered based on channel and spectrum information
- FFT for OFDM and its use for spectrum sensing

Adaptive OFDM :

- Adaptive bit loading
    - Chow
    - Fischer
    - Simple Blockwise Loading Algorithm (SBLA)
    - Fischer Groupwise
- Adaptive power loading
- Combination of adaptive bit and power loading

Adaptive OFDM and Spectrum Pooling (3)

Adaptive Bit Loading :

- **Fischer-Huber Algorithm :** ***Minimizing the probability of error*** **with the constraints of** ***limited total power and total number of bits allocation*****.**

- **Chow Algorithm :** ***Maximizing allowable additional amount of noise that the system can tolerate*****, with the constraints of** ***limited total power and total number of bits allocation*****.**

- **Simple Blockwise Algorithm : Grouping of subcarriers and modulation modes based on the** ***mean SNR per group*****.**

- **Blockwise bit loading with Fischer - Huber algorithm : Bit loading (per group) using the information of** ***mean channel gain per group of subcarriers*****.**

Adaptive OFDM and Spectrum Pooling (4)

- Adaptive Bit loading :

1. Fischer-Huber algorithm , Minimizing $p_n = K_n . Q\left(\sqrt{\frac{d_n}{2N_n}}\right)$ subject to $\sum_n P_n = P_T$ and $\sum_n R_{Qn} = R_T$ where $P_n = C.\frac{N_n}{|H_n|^2} 2^{R_{Qn}}$

Bit allocation :

$$R_n = \frac{1}{N_c}\left[R_T + log_2\left(\prod_{n=0}^{K-1} \frac{N_n}{|H_n|^2}\right) - N_c log_2\left(\frac{N_n}{|H_n|^2}\right)\right]$$

K_n: Number of nearest neighbour
d_n: Minimum distance between constellation points
p_n: Error rate in subcarrier n
R_n : Number of allocated bits to subcarrier n
R_{Qn} : Quantized number of allocated bits (0,1,2,4,6) based on constellation size to subcarrier n
R_T: Number of bits per OFDM symbol
K : Number of active carriers
P_n : Allocated power to subcarrier n
P_T: Total available power for an OFDM symbol
H_n: Complex channel gain at subcarrier n
N_n: Noise variance at subcarrier n
C : Constant

Adaptive OFDM and Spectrum Pooling (5)

2. Chow algorithm

$$\max \ \gamma_{margin} \quad Subject \quad to$$
$$\sum_{n=1}^{N_c} R_n = R_{target}, \quad \sum_{n=1}^{N_c} P_n = P_{budget}$$

bit allocation :

$$R_n = \log_2 \left[1 + \frac{S_n}{N_n.(\Gamma + \gamma_{margin})} \right]$$

R_n : Transmission rate of carrier n

R_{target} : Target allocation bits per OFDM s

S_n : Signal power of carrier n

N_n : Equivalent noise power of carrier n

Γ : SNR gap is a constant, where $\Gamma = \frac{1}{3}\left[Q^{-1}\left(\frac{SER}{4}\right)\right]^2$

γ_{margin} : Noise margin

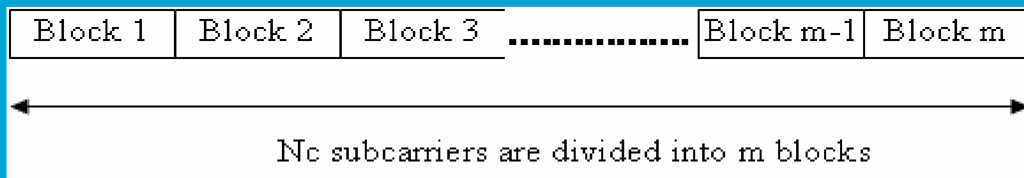
P_n: Power allocation in subcarrier n

P_{budget} : Total available power / OFDM symbol

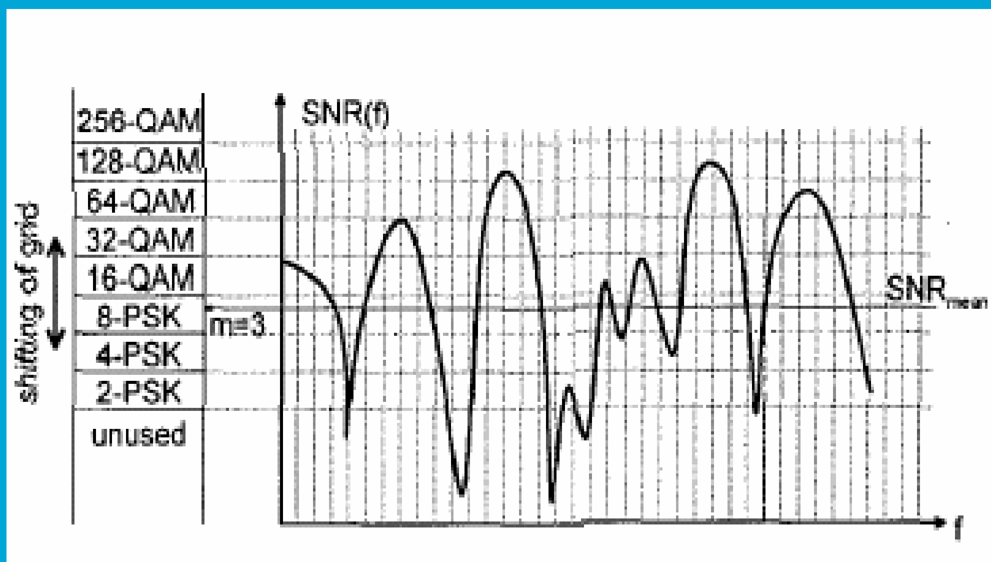
Modulation mode	Number of bits	Modulation mode	Number of bits
BPSK	1	16-QAM	4
QPSK	2	64-QAM	6

Adaptive OFDM and Spectrum Pooling (6)

3. Blockwise loading algorithm



Initial bits / modulation mode allocation



The grid is shifted according on the average SNR and average number of bits per carrier

If the total number of bits is not equal to the desired rate, addition/ subtraction is applied with priority is given to the highest/lowest SNR per group until the total number of bits fulfills the desired rate.

Adaptive OFDM and Spectrum Pooling (7)

4. Groupwise bit loading with Fischer Algorithm, subcarriers are divided into G groups, error probability is minimized, bit allocation :

$$R_i = \frac{R_T}{G'} + \frac{1}{G'} \cdot \log_2 \left(\frac{\left(|H_i|^2\right)^{G'}}{\prod_{k \in \psi} |H_k|^2} \right)$$

subject to

$$\sum_{i=1}^{G} R_i = R_{Target} \qquad \sum_{i=1}^{G} P_i = P_T$$

R_i : Transmission rate of carrier group i

R_{target} : Target allocation bits per OFDM symbol

G ` : Number of active groups

H_i : Average channel power on carrier group i

ψ : subset of active groups

Adaptive OFDM and Spectrum Pooling (8)

Adaptive Power Allocation: Power is allocated to each carrier to minimize error probability

$$P_k = \frac{(M-1)\sigma_k^2}{3\phi_k} W(\phi_k \eta)$$

subject to

$$\sum_{k=1}^{N_c} P_k = P_T$$

P_n : Power allocated on the n'th carrier
P_T : Total power
M : Constellation size
W(.) : Lambert function (inverse function of $f(w)=we^w$)
$\phi_k = |H_k|^2$, where H_k is the estimated channel gain on carrier k
η : constant
σ_k^2 **: noise variance on carrier k**

TU Delft

Adaptive OFDM and Spectrum Pooling (9)

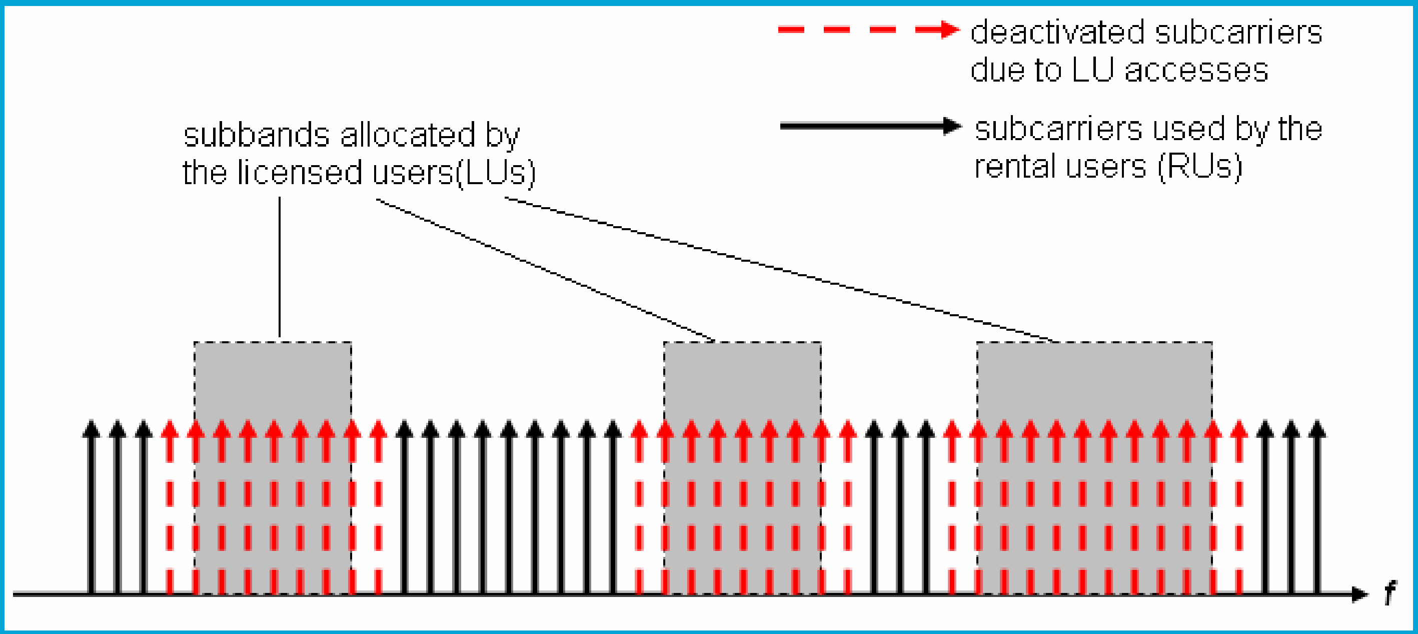
Spectrum Pooling : Public access to the spectrum without sacrificing the transmission quality of license owners.

OFDM use in Spectrum Pooling

- Deactivation of subcarriers. Non Contigiuous OFDM
  (important parameters are b=# deactivated carriers, $LU/\Delta f = a$; pool occupancy = b/N)
- Interference to licensed users can be mitigated by windowing of OFDM signal.
  Different windows : Bartlett
  Raised Cosine
  Better than Raised Cosine
- Combination of windowing and carriers deactivation

Adaptive OFDM and Spectrum Pooling (10)

- Spectrum Pooling with dynamic deactivation of subcarriers adjacent to licensed user's band



Adaptive OFDM and Spectrum Pooling (11)

Raised Cosine window

$$g(t) = \begin{cases} \dfrac{1}{T_u} & 0 \le |t| \le \dfrac{T_u(1-\alpha)}{2} \\ \dfrac{1}{2T_u}\left\{1 + \cos\left[\dfrac{\pi}{\alpha T_u}\left(|t| - \dfrac{T_u(1-\alpha)}{2}\right)\right]\right\} & \dfrac{T_u(1-\alpha)}{2} \le |t| \le \dfrac{T_u(1+\alpha)}{2} \\ 0 & \text{Otherwise} \end{cases}$$

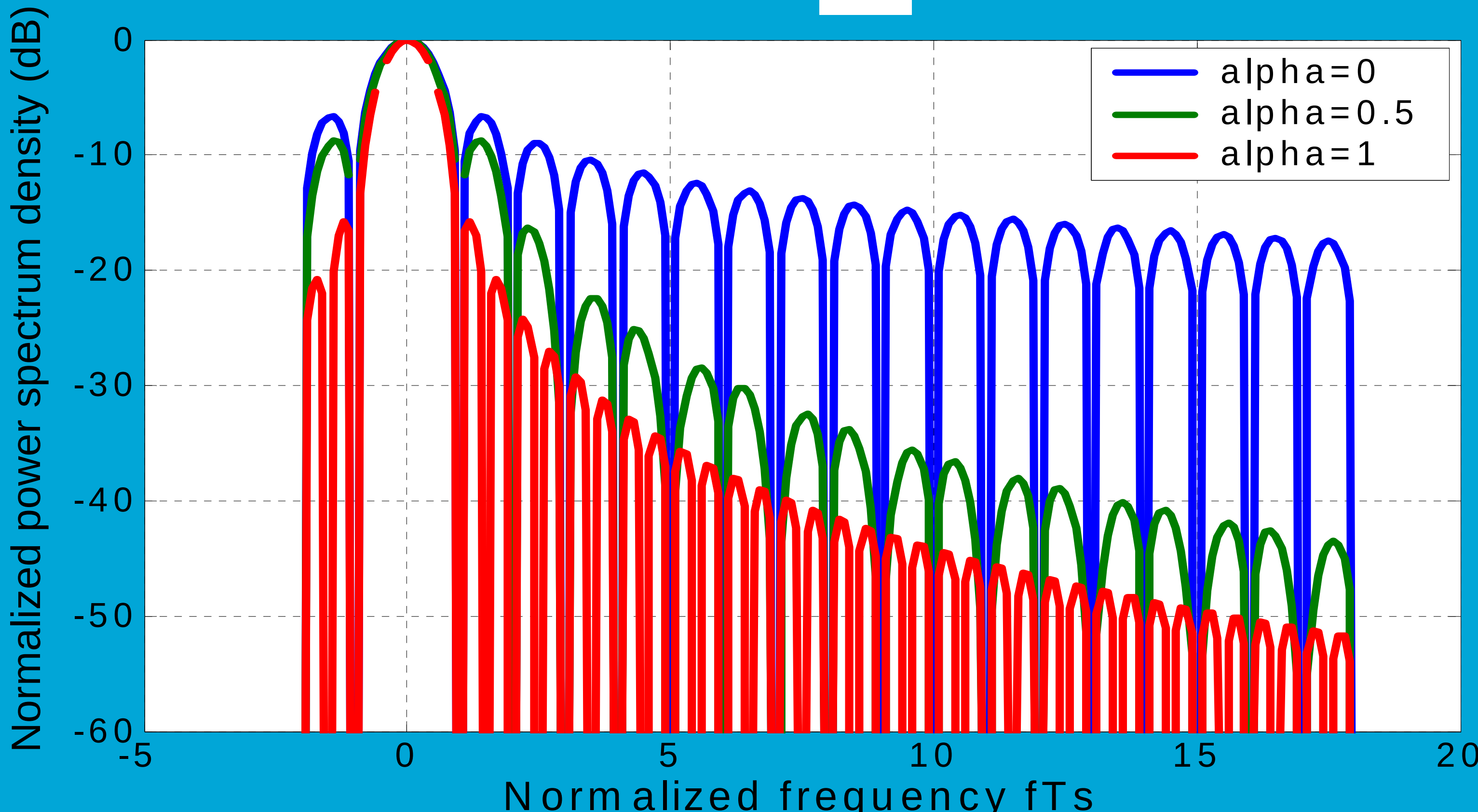
g(t) : window function

T_u : OFDM useful symbol duration

α : roll off factor

Adaptive OFDM and Spectrum Pooling (12)

Spectrum of Raised Cosine window with Variation of roll off factor (α)



Adaptive OFDM and Spectrum Pooling (13)

Bartlett window

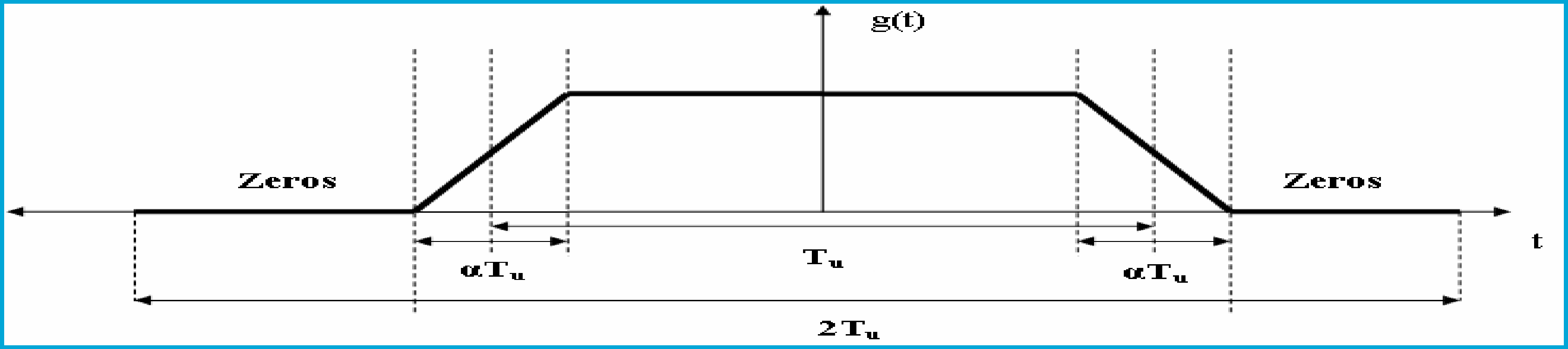
$$g(t) = \begin{cases} \dfrac{1}{T_u} & 0 \le |t| \le \dfrac{T_u(1-\alpha)}{2} \\ \dfrac{1}{2T_u} - \dfrac{1}{T_u}\left[\dfrac{|t|}{\alpha T_u} - \dfrac{1}{2\alpha}\right] & \dfrac{T_u(1-\alpha)}{2} \le |t| \le \dfrac{T_u(1+\alpha)}{2} \\ 0 & \mathit{Otherwise} \end{cases}$$

Better than Raised Cosine Window

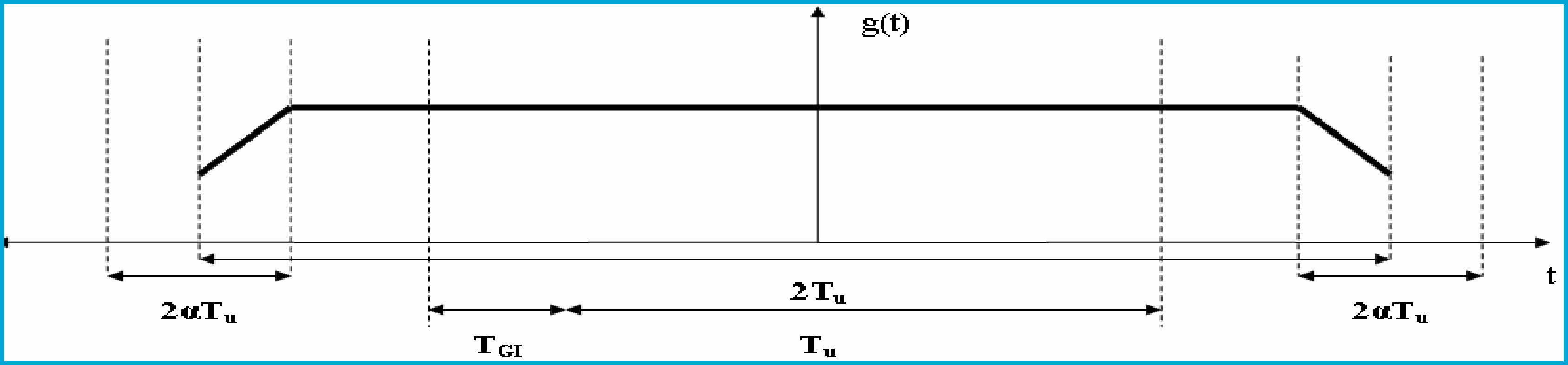
$$g(t) = \begin{cases} 1 & 0 \le |t| \le \dfrac{T_u(1-\alpha)}{2} \\ e^{\left(\frac{-2\ln 2}{\alpha T_u}\right)\left[|t| - \frac{T_u(1-\alpha)}{2}\right]} & \dfrac{T_u(1-\alpha)}{2} \le |t| \le \dfrac{T_u(1+\alpha)}{2} \\ 0 & \mathit{Otherwise} \end{cases}$$

Adaptive OFDM and Spectrum Pooling (14)

Window design with influence on the transmitted signal



Window design without influence on the transmitted signal



Adaptive OFDM and Spectrum Pooling(15)

$$PDS(\omega) = \frac{1}{N_{FFT}} \left| \sum_{m=0}^{N_{FFT}-1} \sqrt{p(\omega_m)}\, A(\omega_m) e^{j\theta(\omega_m)} \int_{-(1+\alpha)\frac{T}{2}}^{(1+\alpha)\frac{T}{2}} g(t) e^{-j(\omega-\omega_m)t} dt \right|^2$$

$\omega_m = 2\pi f_m$, f_m frequency on subcarrier m

$A(\omega_m)$ the symbol from constellation PSK or QAM on subcarrier m

$g(t)$ window function

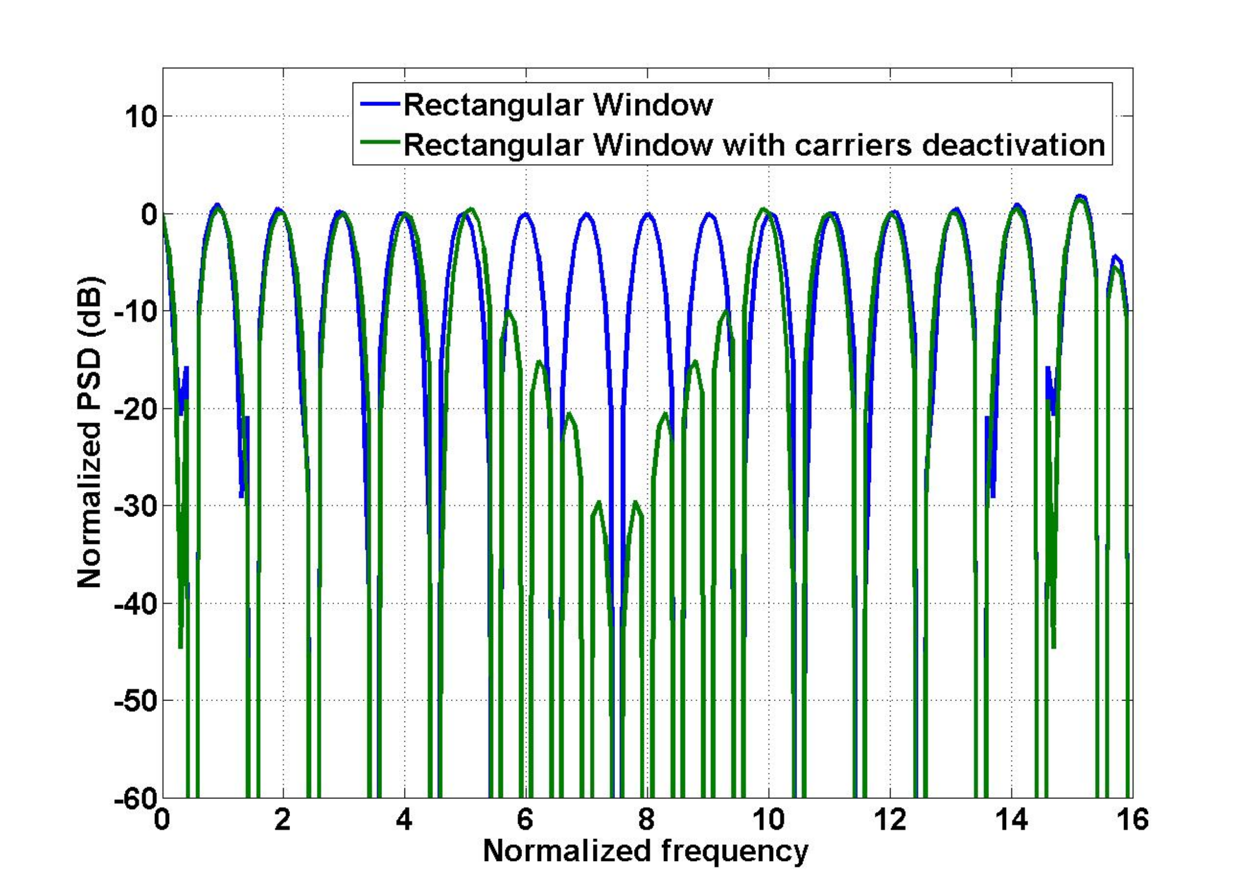
$p(\omega_m)$ power allocation to subcarrier m

$\theta(\omega_m)$ phase of carrier m

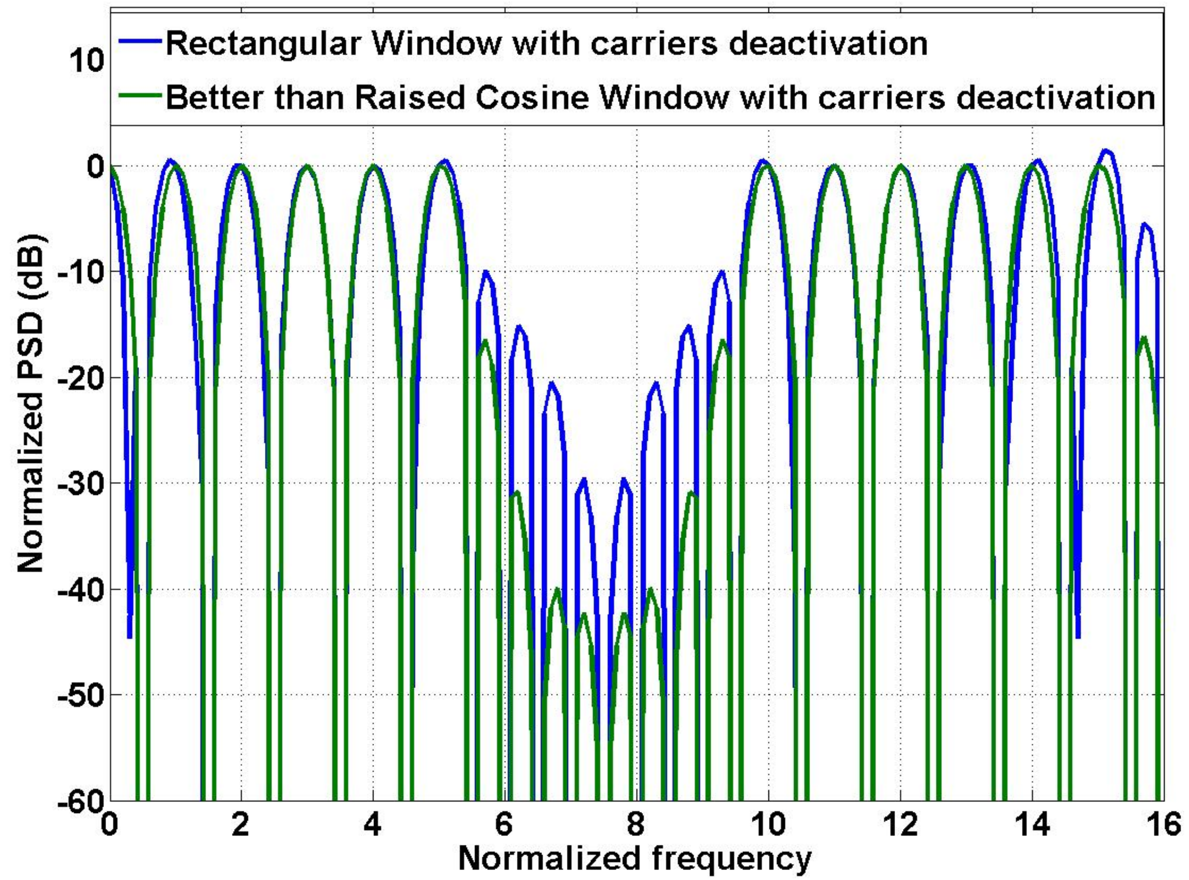
T OFDM useful symbol duration

Adaptive OFDM and Spectrum Pooling (16)

Windowing effect



Adaptive OFDM and Spectrum Pooling (17)



Waveshaping (1)

•Shaping the spectrum of transmitted signal in such a way not to interfere to licensed users

Transform Domain Communication System (TDCS)

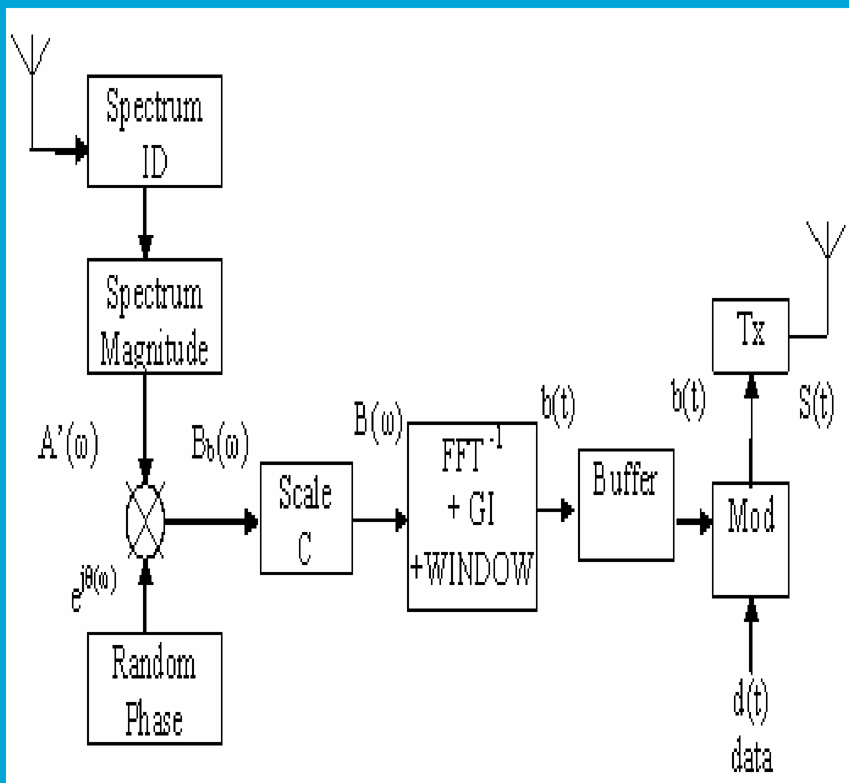
Wavelet Domain Communication System (WDCS)

Wavelet based interferece mitigation

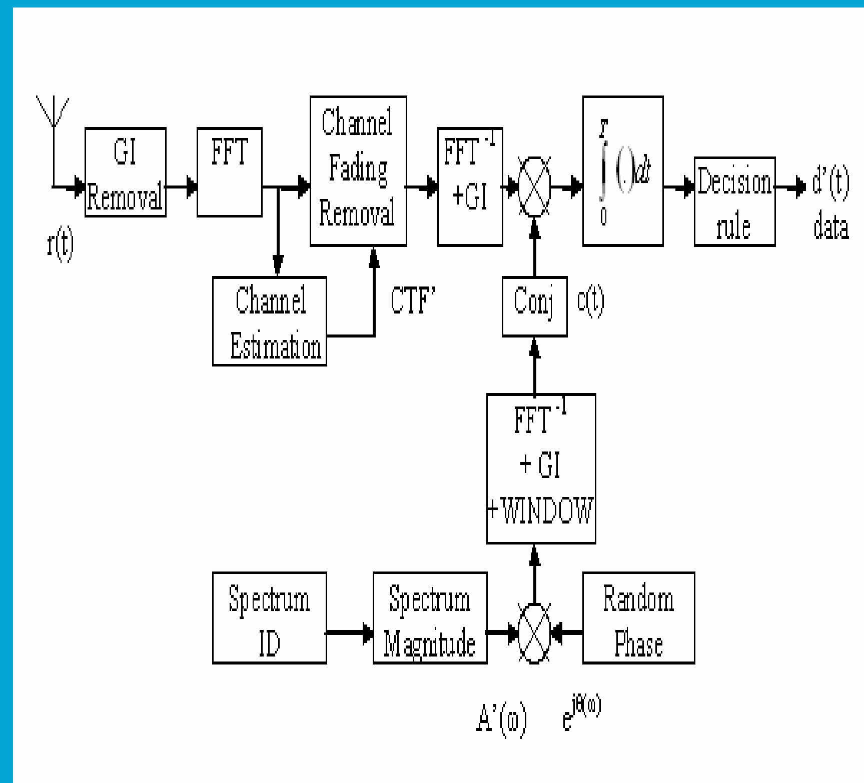
Waveshaping (2)

Transform Domain Communication System (TDCS)

Transmitter

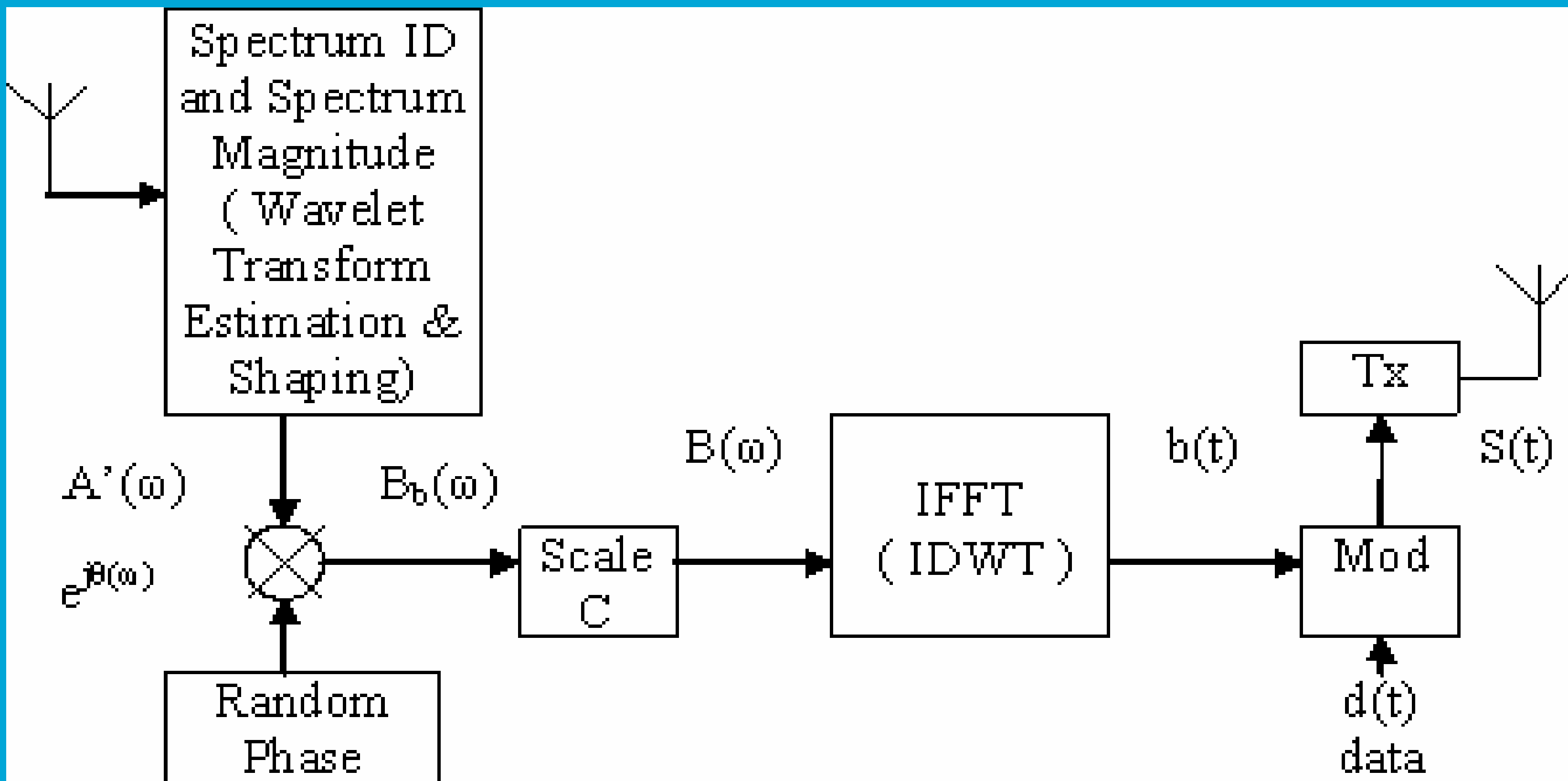


Receiver



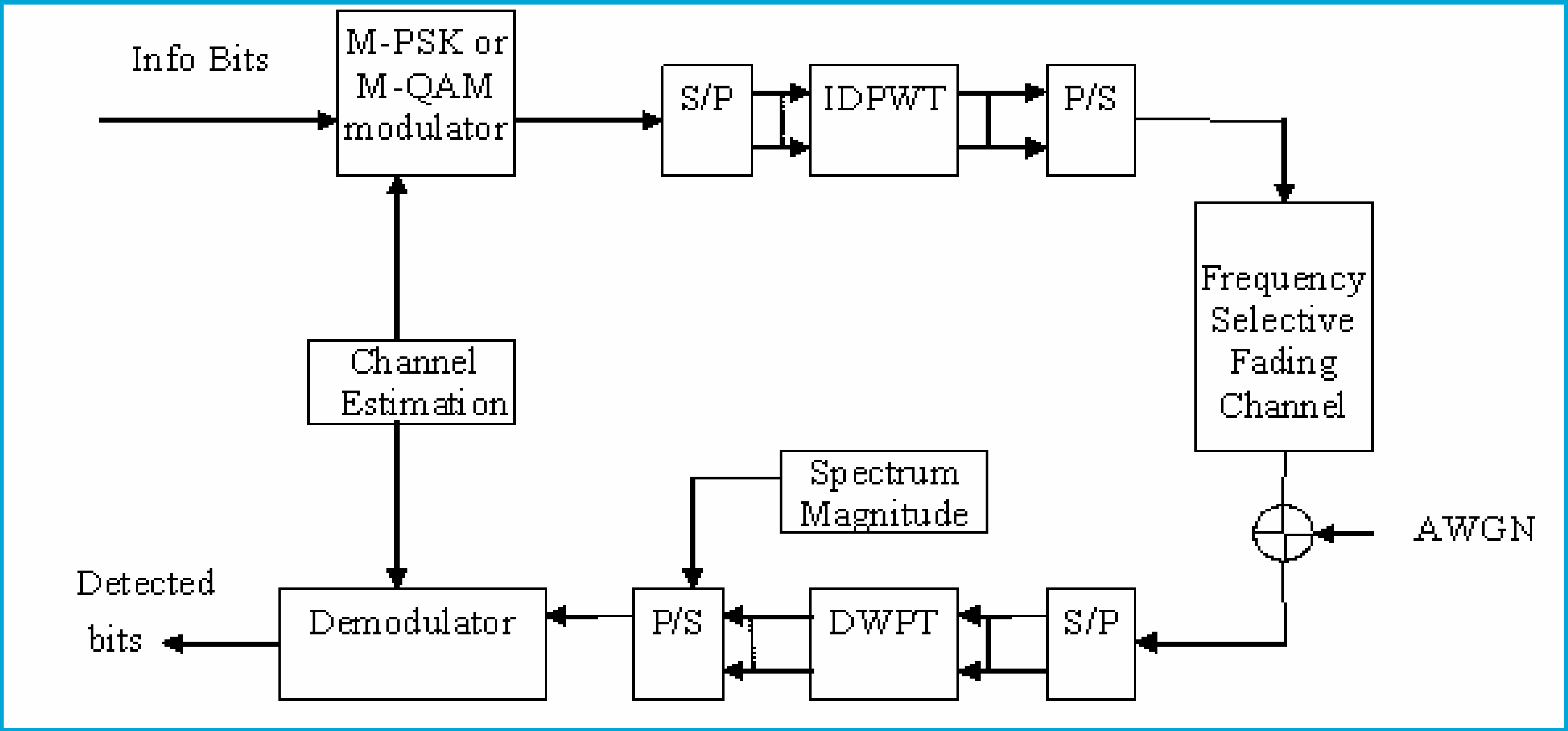
Waveshaping (3)

Wavelet domain communication system (WDCS)

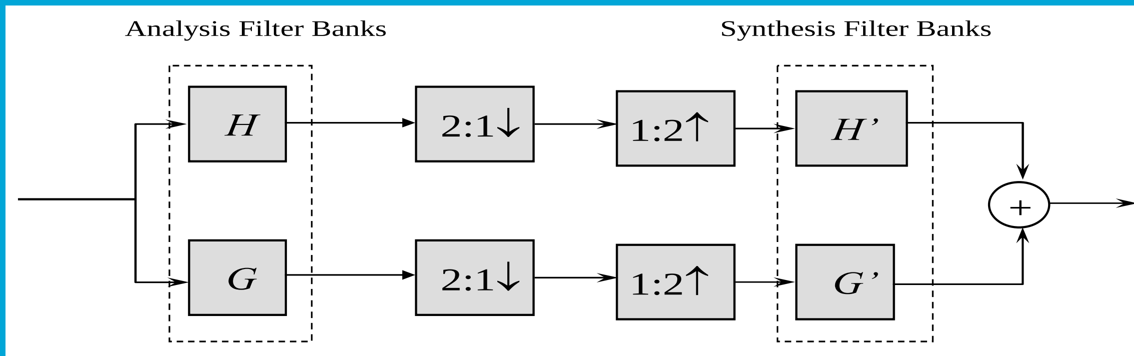


Waveshaping (4)

Multi Carrier Wavelet Packet Modulation

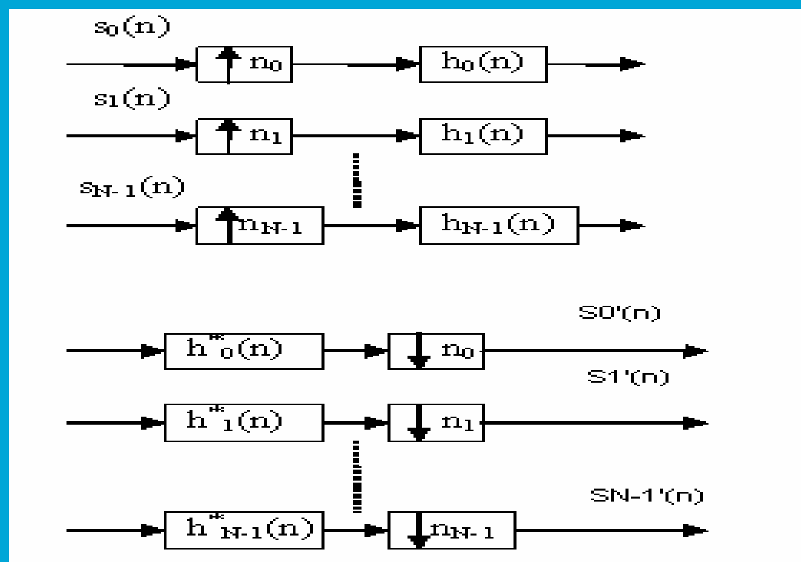


Waveshaping (5)



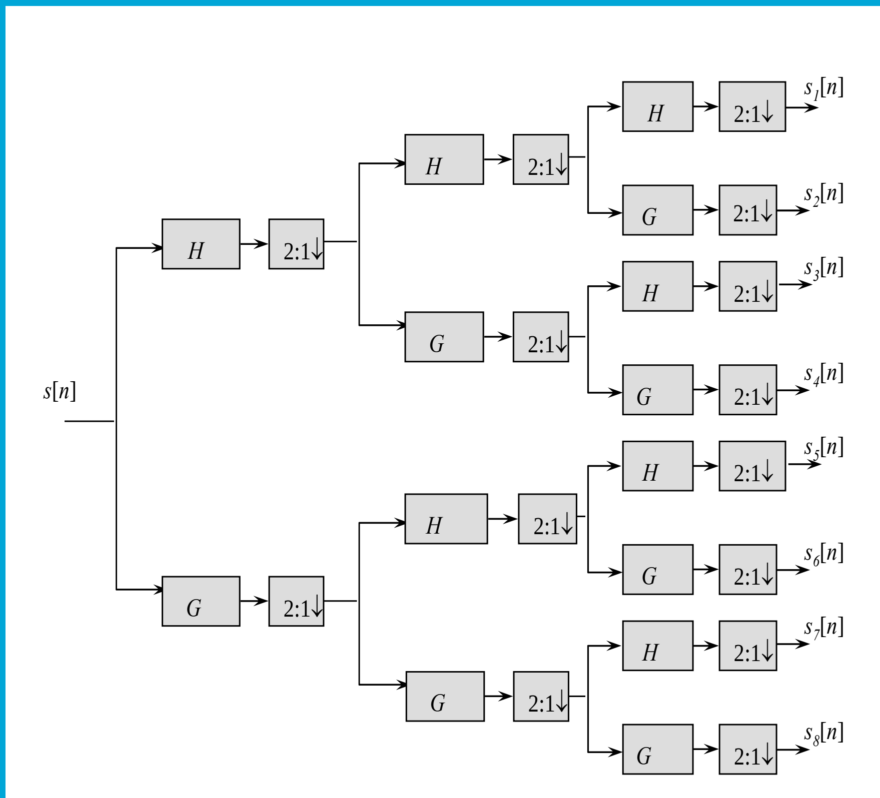
Wavelet design for LU Interference rejection

Analysis

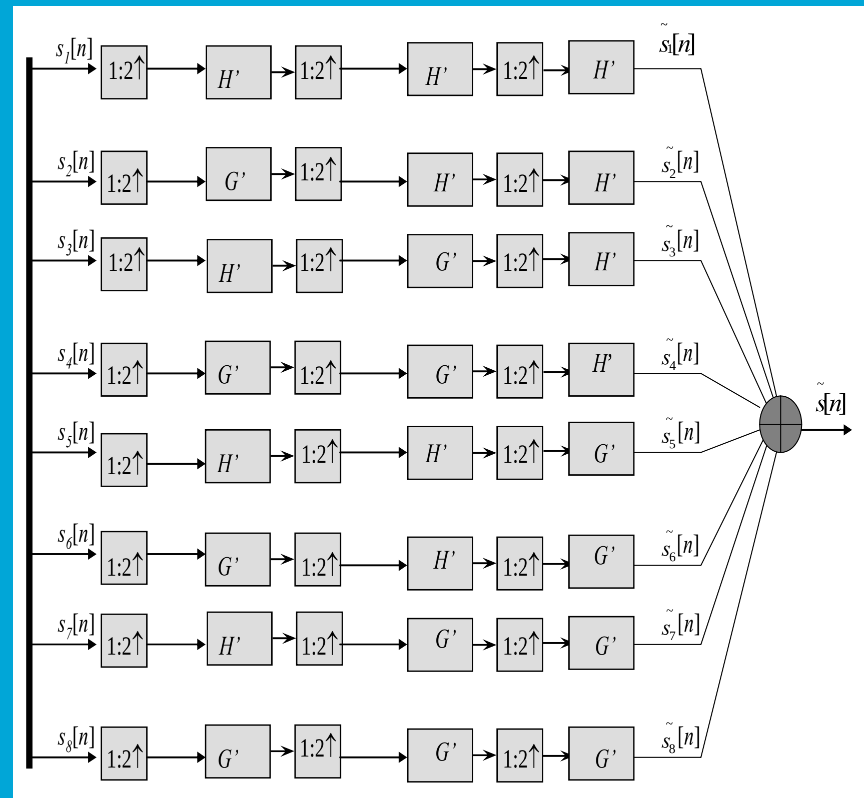


Synthesis

Waveshaping (6)



Wavelet Packet Decomposition of Signal



Wavelet Packet Reconstruction of Signal

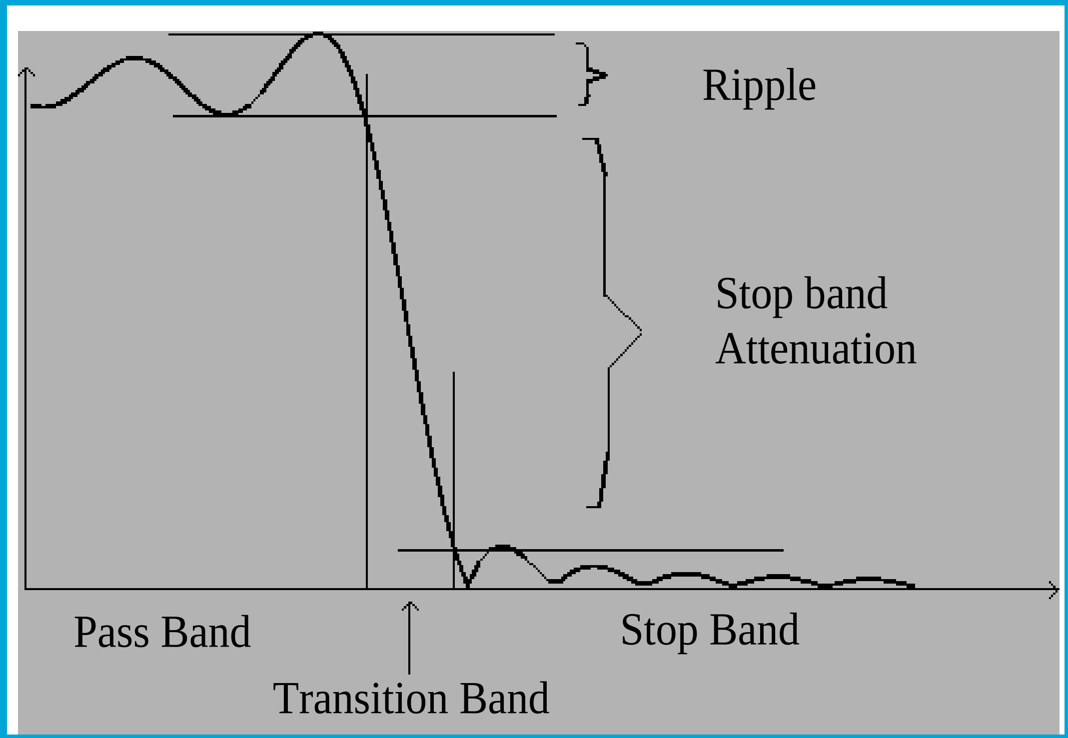
Waveshaping (7)

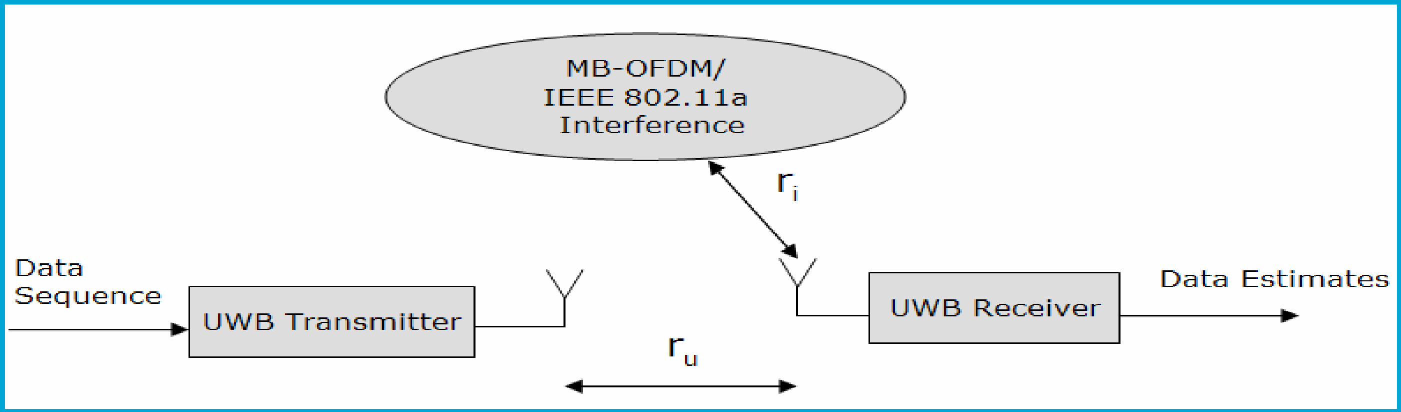
Subband Removal according to Gray code position

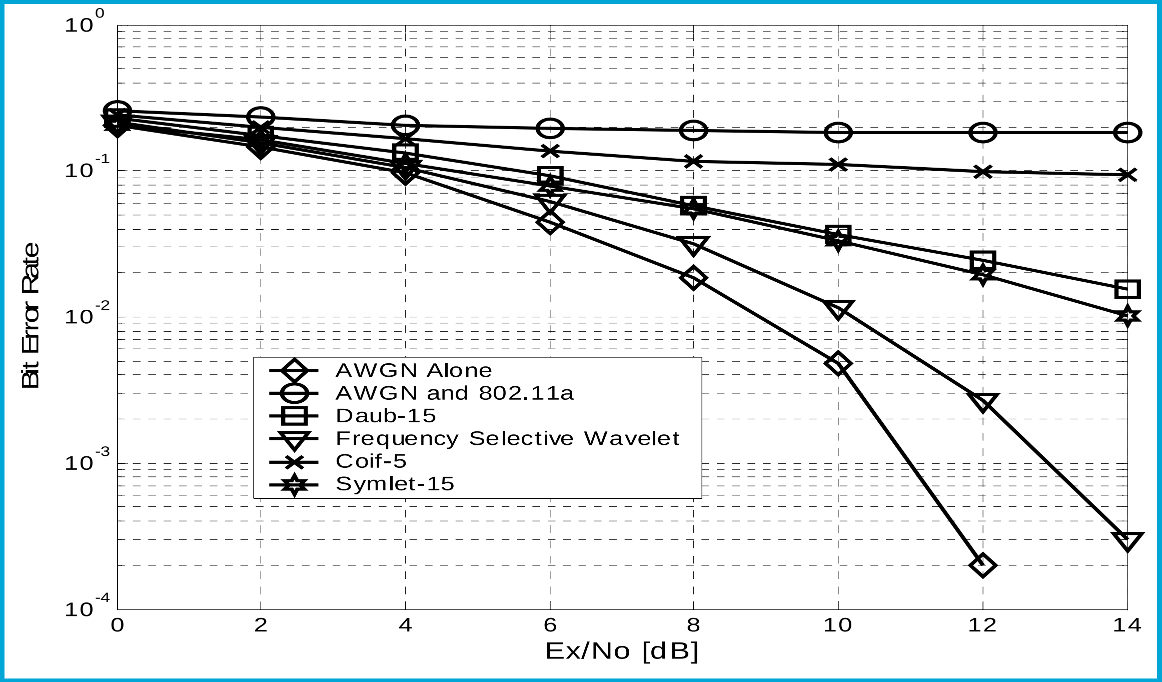
Coeffecient	0	1	3	2	6	7	5	4	12	13	15	14	10	11	9	8
Binary Represenation	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
Frequency Range	0 - 1.56 Ghz		1.56- 3.12 GHz		3.12- 3.9	3.9- 4.68	4.68- 5.45	5.45- 6.25	6.25- 7.81 GHz		7.81 - 9.37 GHz		9.37- 10.03GHz		10.03 - 12.5 GHz	

Waveshaping (8)

Maximally frequency selective wavelet according to Remez Algorithm



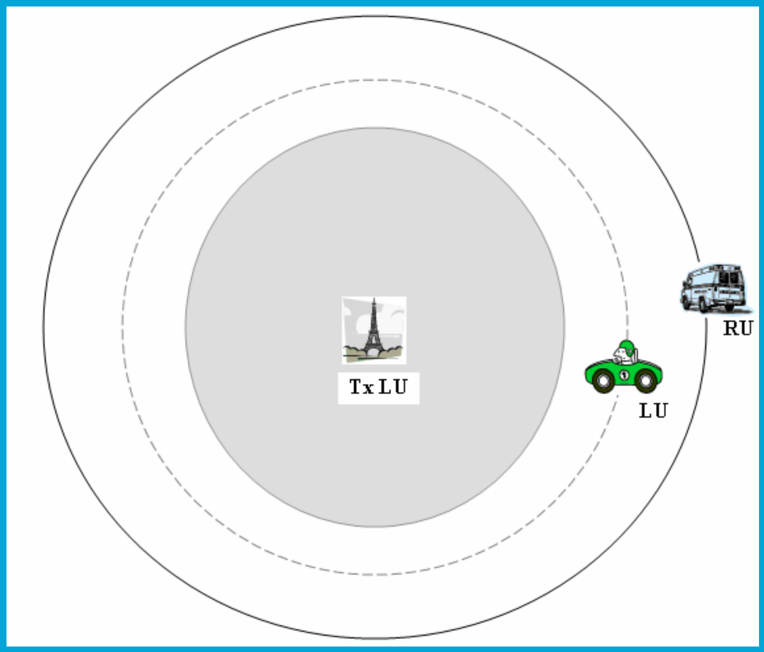

MB-OFDM/
IEEE 802.11a
Interference
r_i
Data
Sequence
UWB Transmitter
r_u
UWB Receiver
Data Estimates


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Bit Error Rate
0
2
4
6
8
10
12
14
Ex/No [dB]
AWGN Alone
AWGN and 802.11a
Daub-15
Frequency Selective Wavelet
Coif-5
Symlet-15

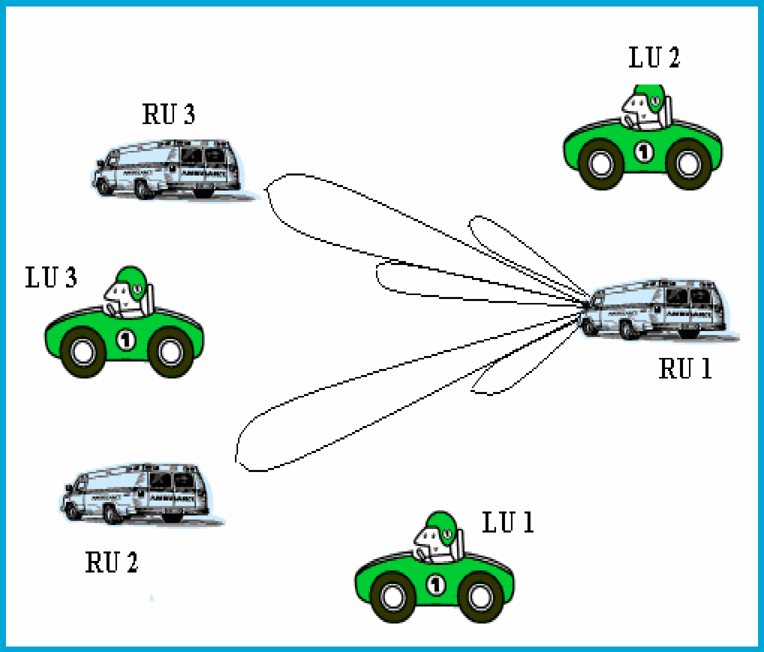
Beamforming (1)

- **Interference avoidance to LU by not directing signal to LU while occupying LU freq**

Communicating CR nodes without interfering each other

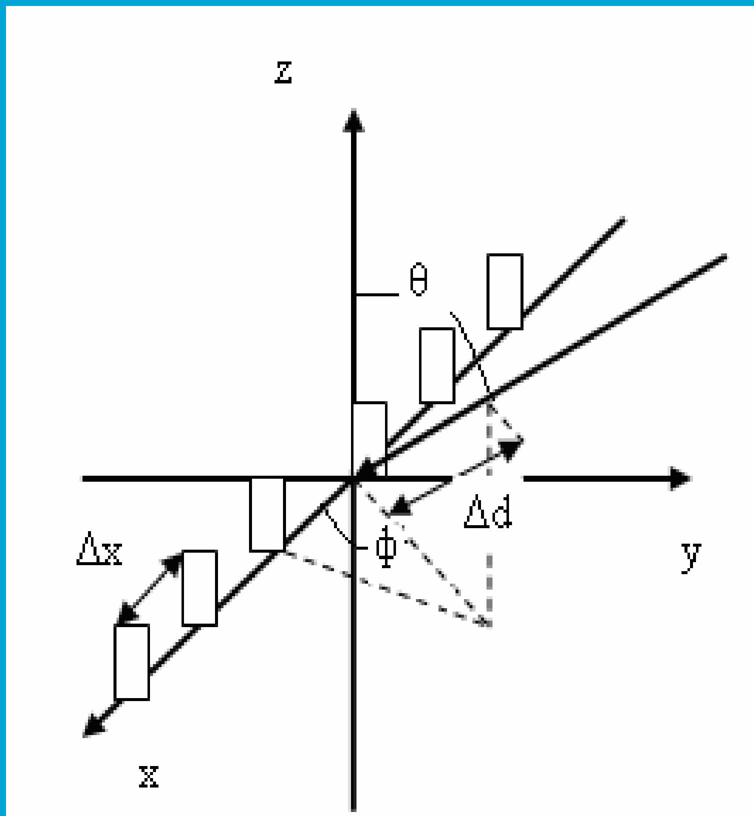


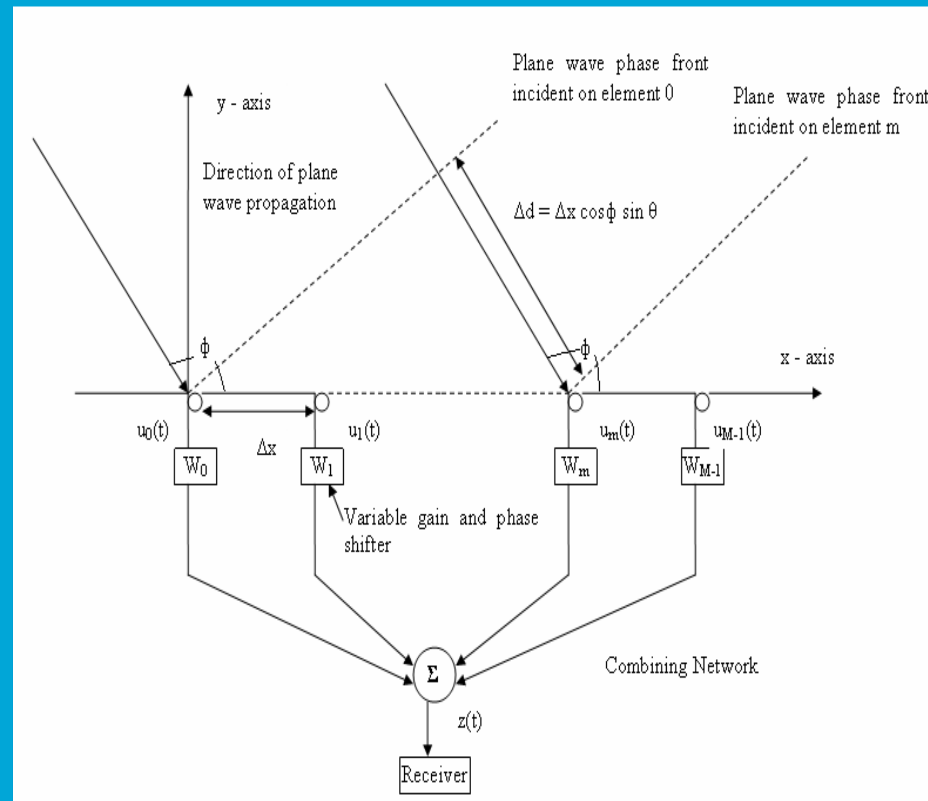
CR Without Beamforming



CR With Beamforming

Beamforming (2)





A linear equally spaced array antenna

Baseband model of a linear equally spaced array

Summary

- Spectrum sensing is the critical ingredient of CR. All the transmission techniques for CR rely on the accurate information from the spectrum sensing module.
- Multicarrier Non contiguous OFDM has been introduced as a CR technique. Proper window will further decrease the level of interference to LUs. Loss of bitrate due to carriers deactivation and long window duration is compensated by applying higher modulation modes to the carriers with good channel condition.
- Single carrier TDCS as an alternative CR technique was reviewed.
- Wavelet basis function as replacement of Fourier transform in OFDM and TDCS for CR system is a research issue for further investigation.
- Beamforming as a spatial interference avoidance technique in CR has been discussed.