

TECHNIQUES FOR COGNITIVE RADIO

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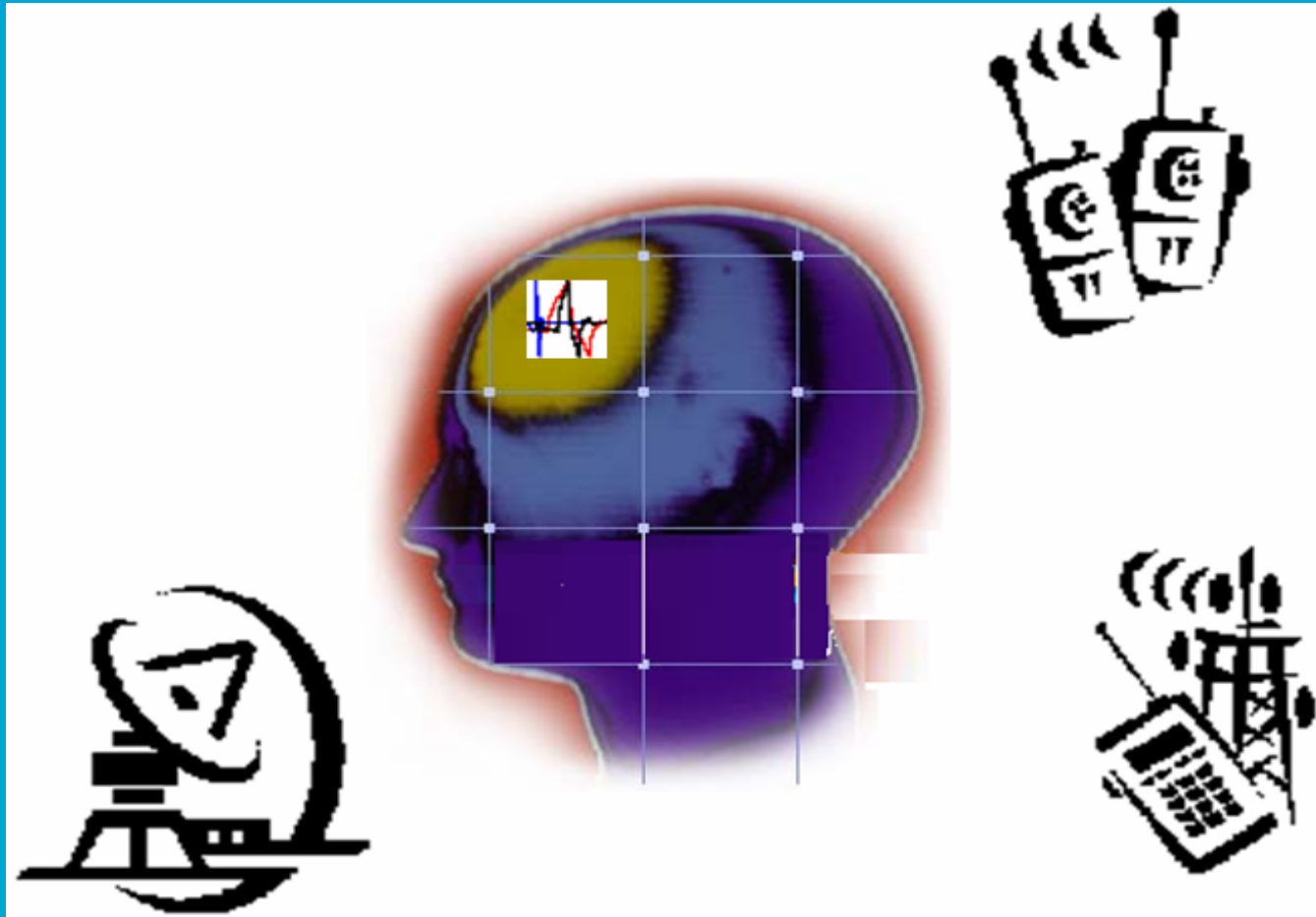


Cognitive Radio

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.

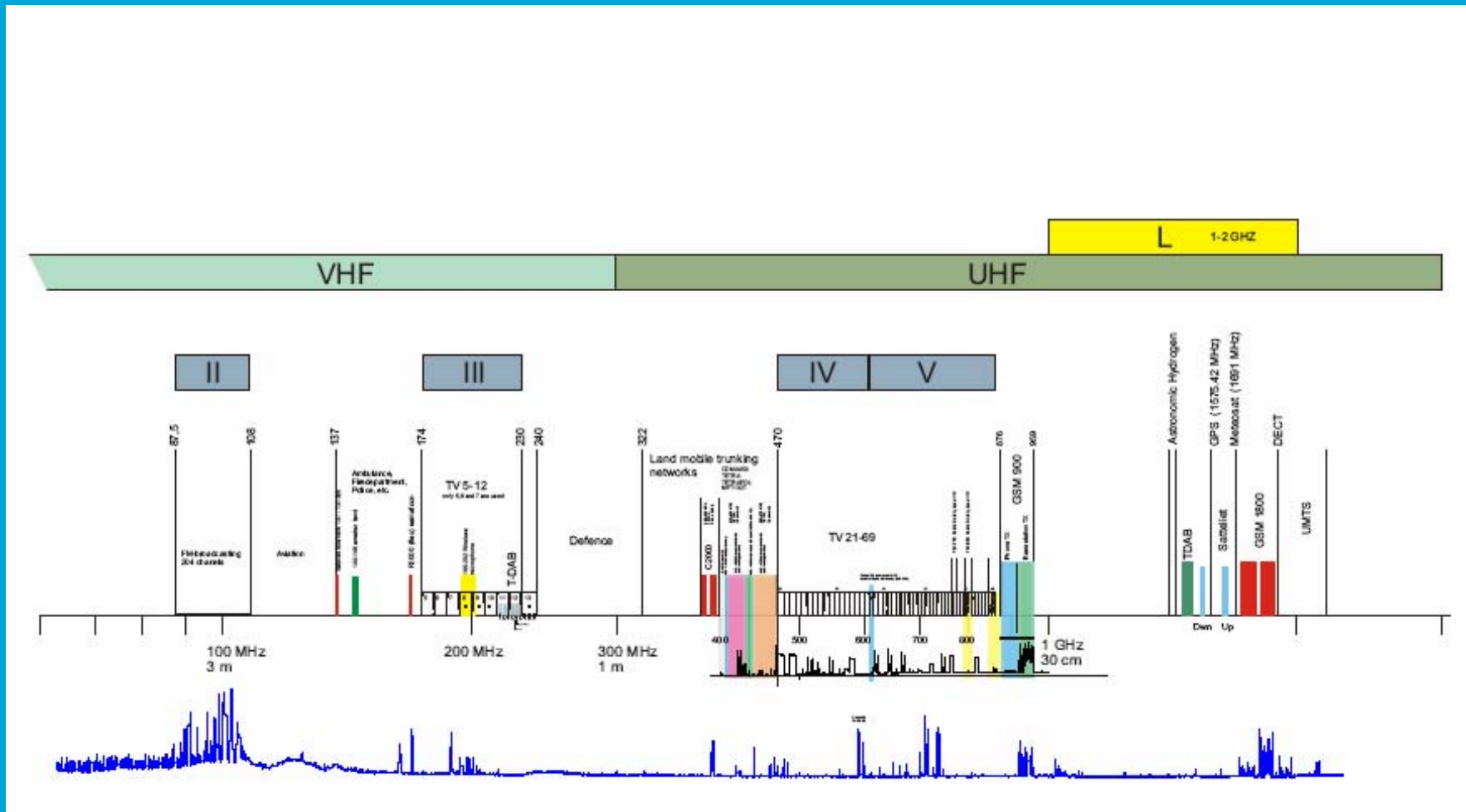


Cognitive Radio: A radio (to generate, transmit, receive and process of wireless signals) and a cognitive brain which learns from the environment and performs rational processes and predicts probable consequences and remembers past successes and failures.

Talk Outline

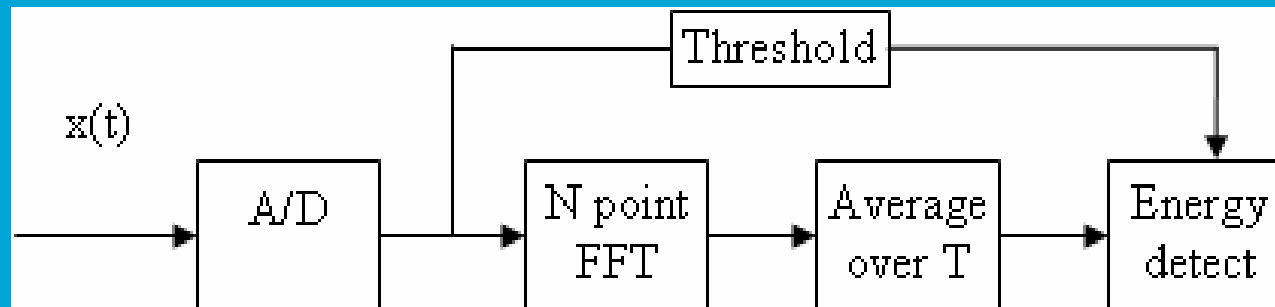
- Spectrum Overview
- Spectrum Sensing
- Adaptive OFDM and Spectrum Pooling
- Waveshaping
 - ❖ Transfer Domain Communication System (TDCS)
 - ❖ Wavelet Domain Communication System (WDCS)
 - ❖ Multi Carrier Wavelet Packet Modulation with Interference Mitigation
- Beamforming
- Summary

Spectrum Overview

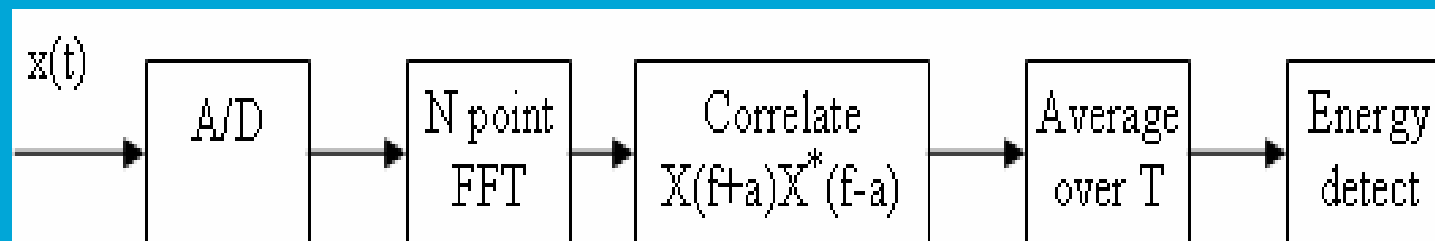


Spectrum Sensing

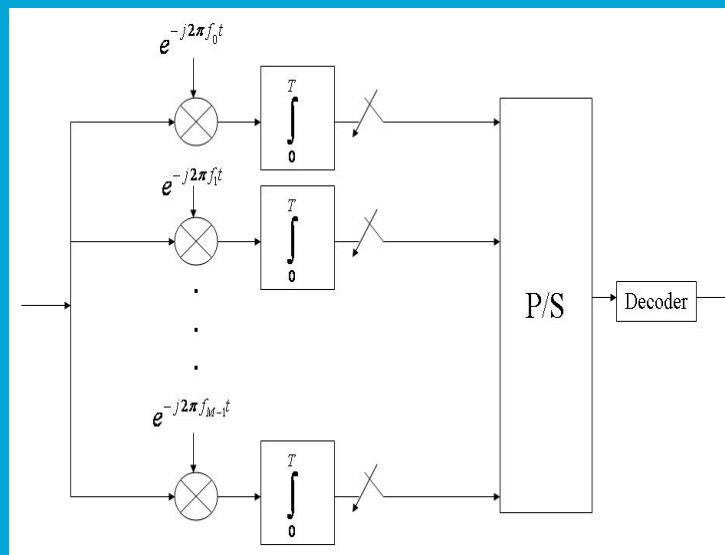
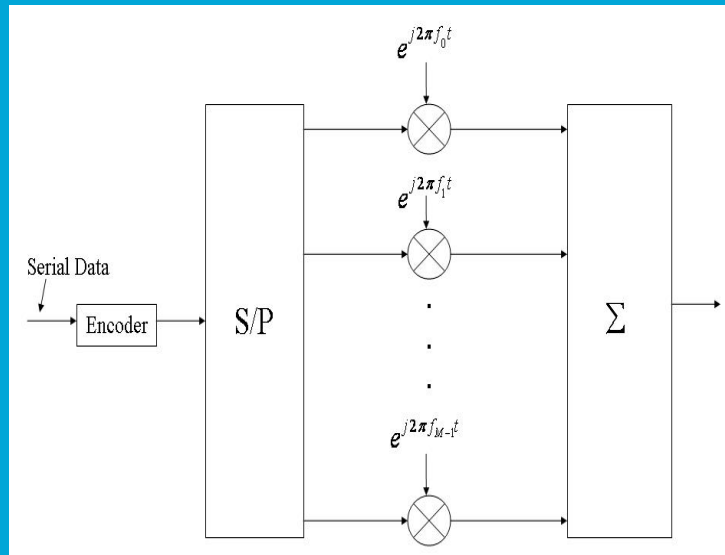
- Energy Detector



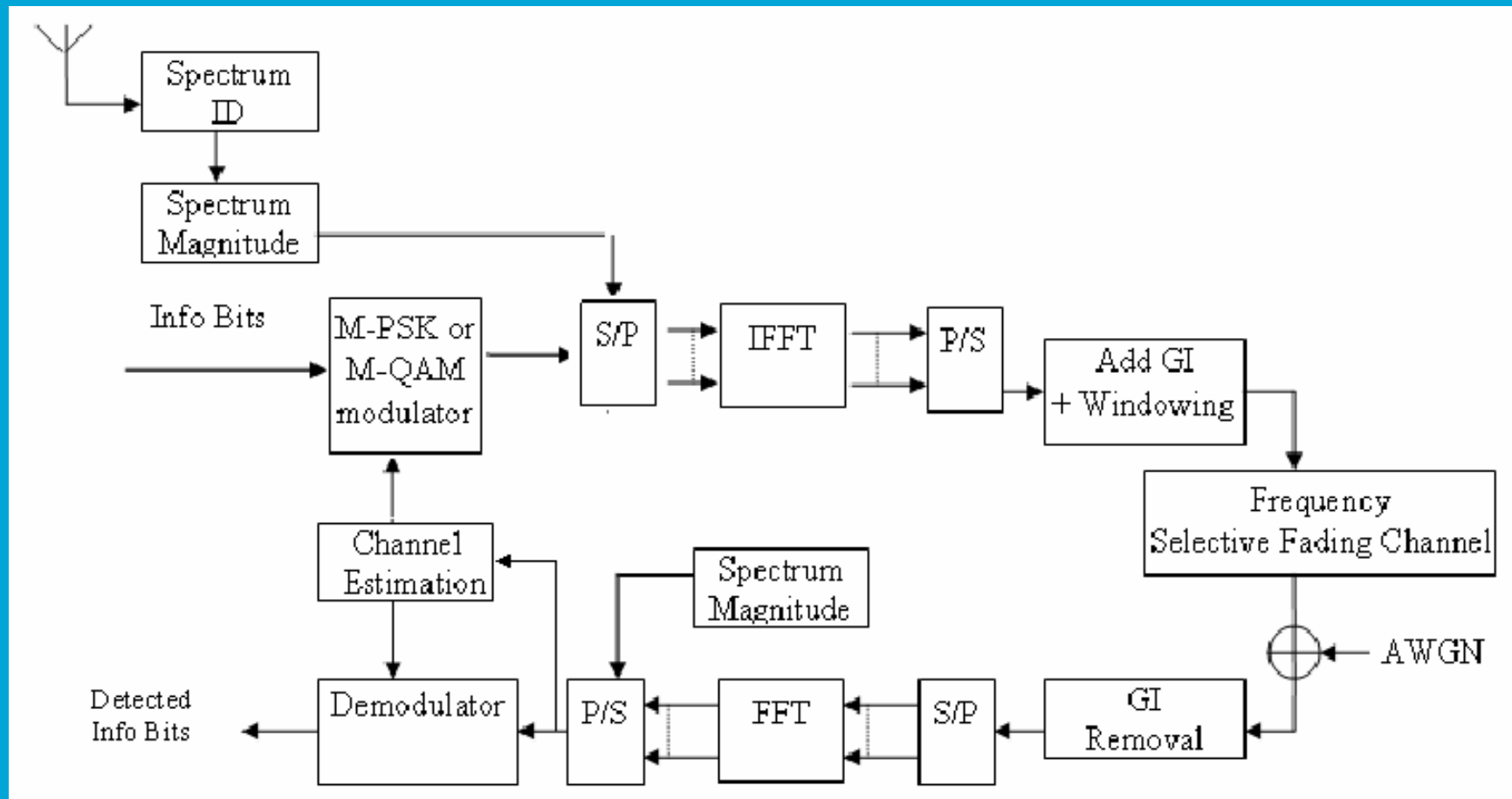
- Cyclostationary feature detector



OFDM



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 :

- Fischer-Huber algorithm ,
and $\sum_n R_{Qn} = R_T$ where

$$\sum_n R_{Qn} = R_T$$

$$P_n = C \cdot \frac{N_n}{|H_n|^2} 2^{R_n}$$

$$p_n = K_n \cdot Q \left(\sqrt{\frac{d_n}{2N_n}} \right)$$

subject to

$$\sum_n P_n = P_T$$

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

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

bit allocation :

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

R_n : Transmission rate of carrier n

P_n : Power allocation in subcarrier n

R_{target} : Target allocation bits per OFDM s

P_{budget} : Total available power / OFDM symbol

S_n : Signal power of carrier n

N_n : Equivalent noise power of carrier n

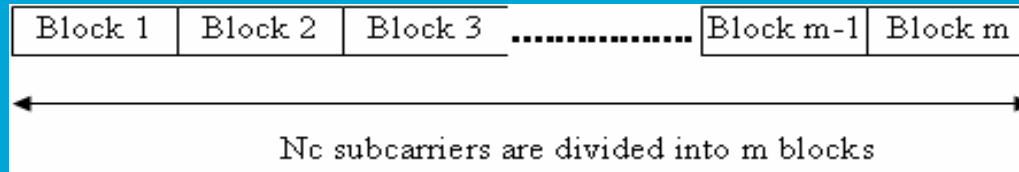
Γ : SNR gap is a constant, where $\Gamma = \frac{1}{3} \left[Q^{-1} \left(\frac{SER}{4} \right) \right]^2$

γ_{margin} : Noise margin

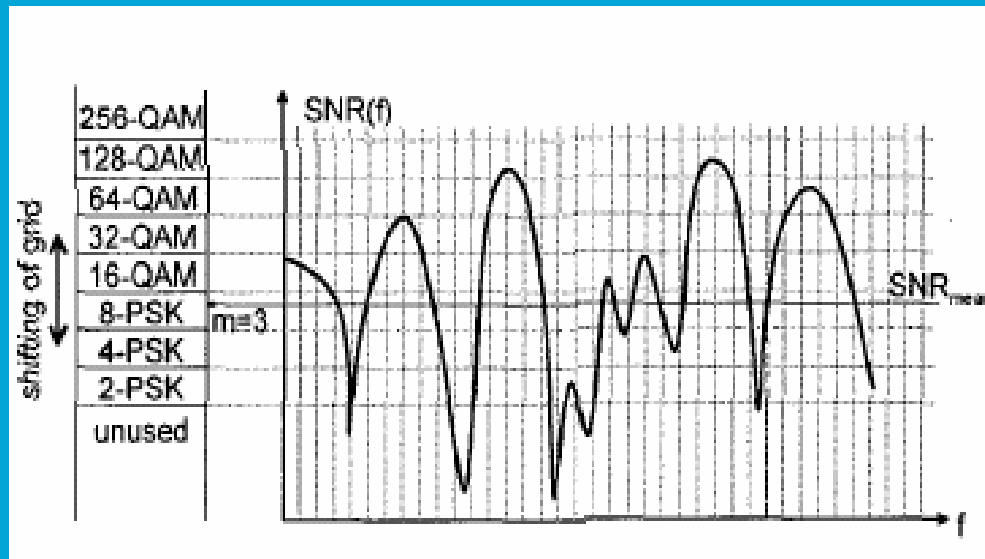
Modulation mode	Number of bits	Modulation mode	Number of bits
BPSK	1	16-QAM	4
QPSK	2	64-QAM	6

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

$$\sum_{i=1}^G R_i = R_{\text{target}} \quad \sum_{i=1}^G P_i = P_T$$

- 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

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

P_n : Power allocated on the n'th carrier

P_T : Total power

M : Constellation size

$W(.)$: Lambert function (inverse function of $f(w) = we^w$)

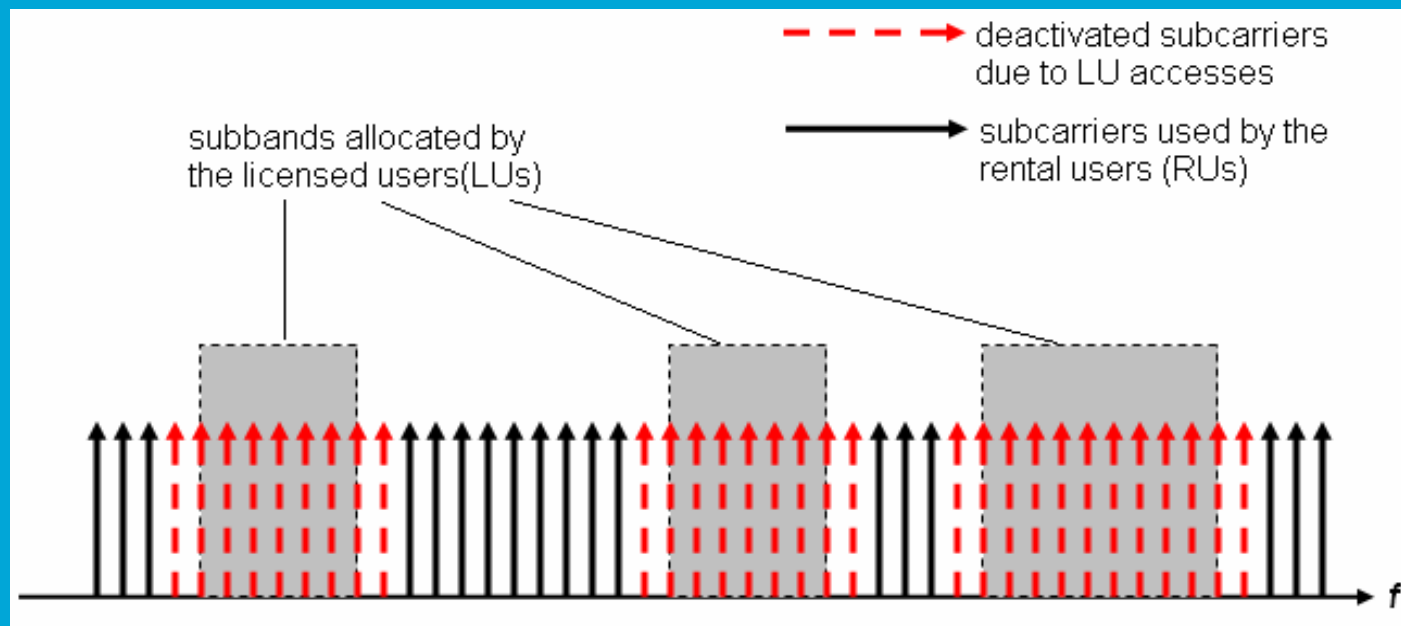
$\phi_k = |H_k|^2$, where H_k is the estimated channel gain on carrier k

η : constant

σ_k^2 : noise variance on carrier k

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

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

$g(t)$: window function

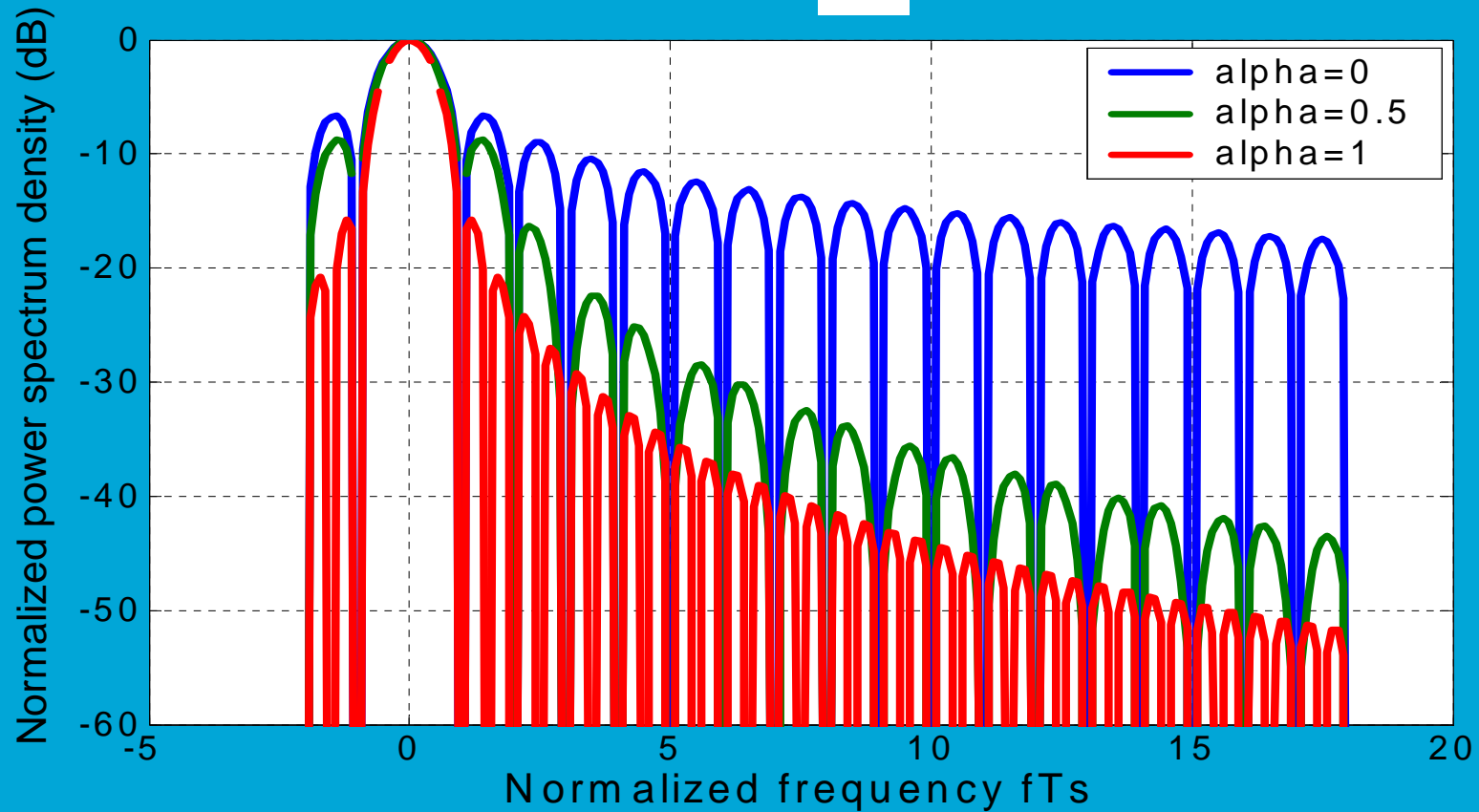
T_u : OFDM useful symbol duration

α : roll off factor

α

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

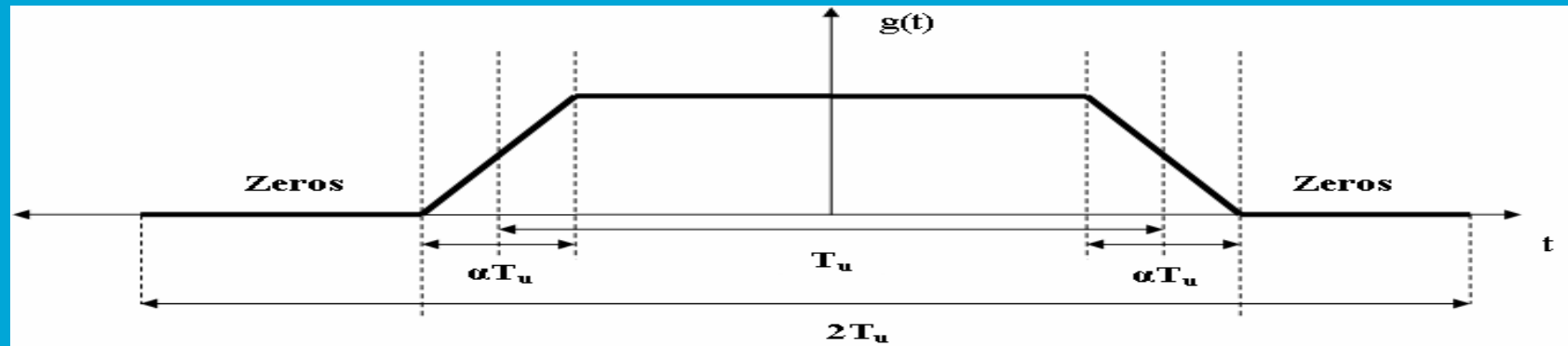
$$g(t) = \begin{cases} \frac{1}{T_u} & 0 \leq |t| \leq \frac{T_u(1-\alpha)}{2} \\ \frac{1}{2T_u} - \frac{1}{T_u} \left[\frac{|t|}{\alpha T_u} - \frac{1}{2\alpha} \right] & \frac{T_u(1-\alpha)}{2} \leq |t| \leq \frac{T_u(1+\alpha)}{2} \\ 0 & \text{Otherwise} \end{cases}$$

Better than Raised Cosine Window

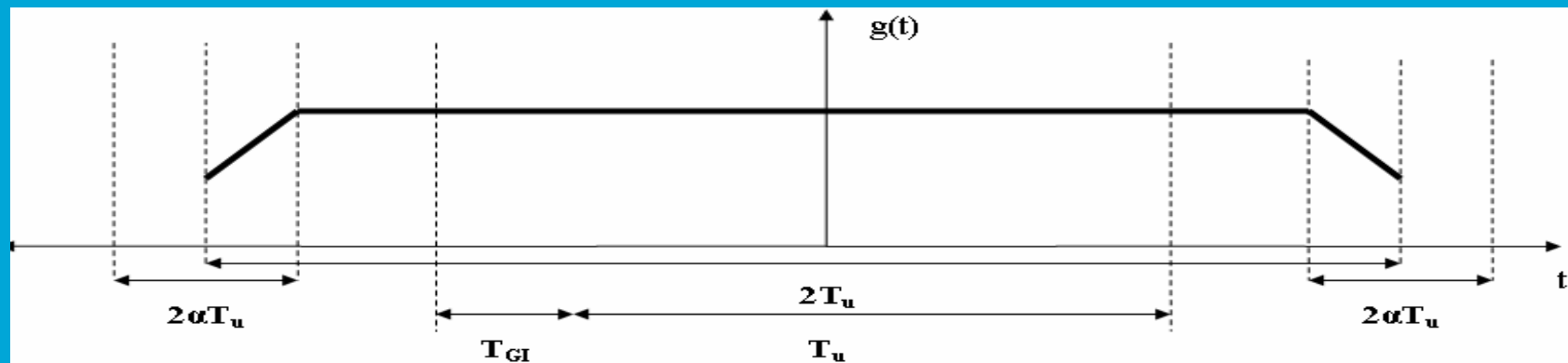
$$g(t) = \begin{cases} \frac{1}{T_u} & 0 \leq |t| \leq \frac{T_u(1-\alpha)}{2} \\ e^{\left(\frac{-2 \ln 2}{\alpha T_u}\right) \left[|t| - \frac{T_u(1-\alpha)}{2} \right]} & \frac{T_u(1-\alpha)}{2} \leq |t| \leq \frac{T_u(1+\alpha)}{2} \\ 0 & \text{Otherwise} \end{cases}$$

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

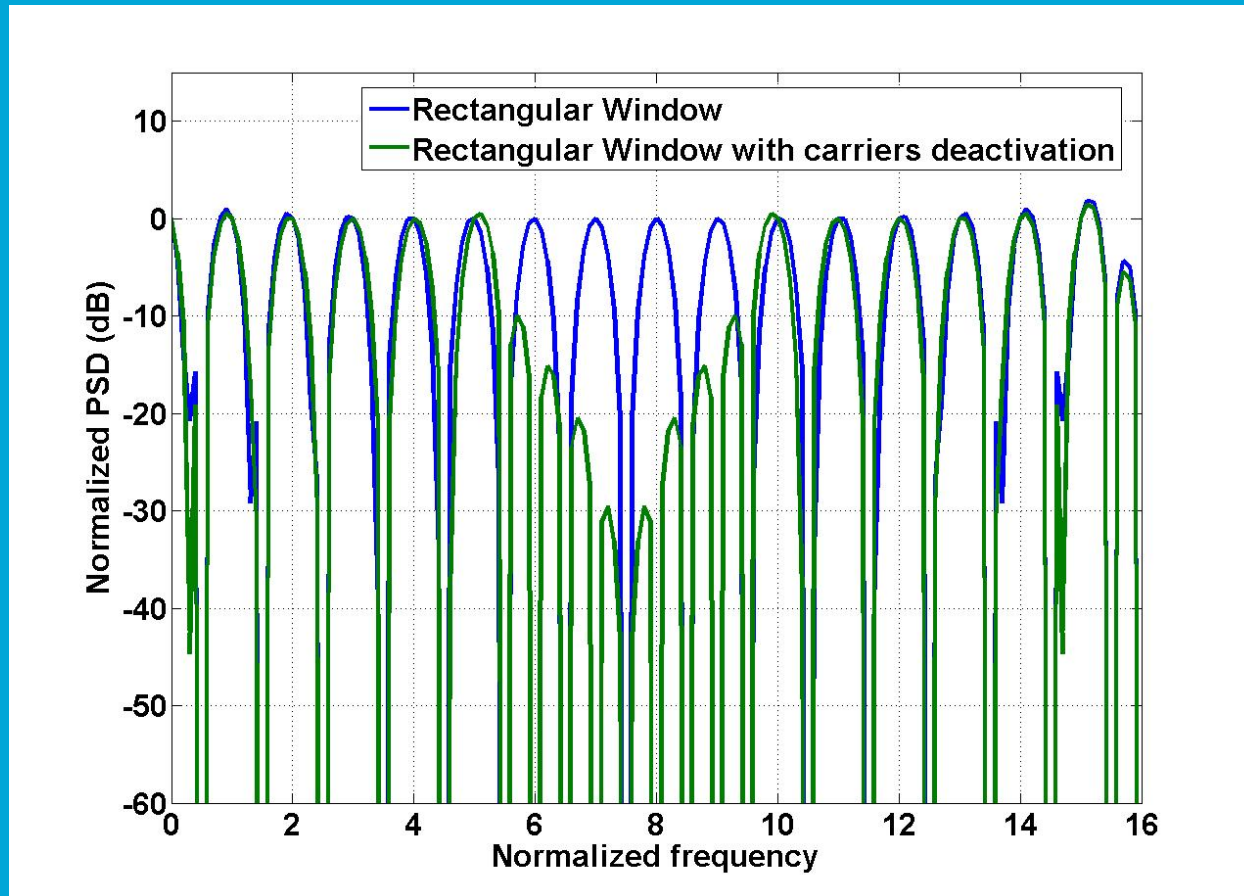
$p(\omega_m)$ power allocation to subcarrier m

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

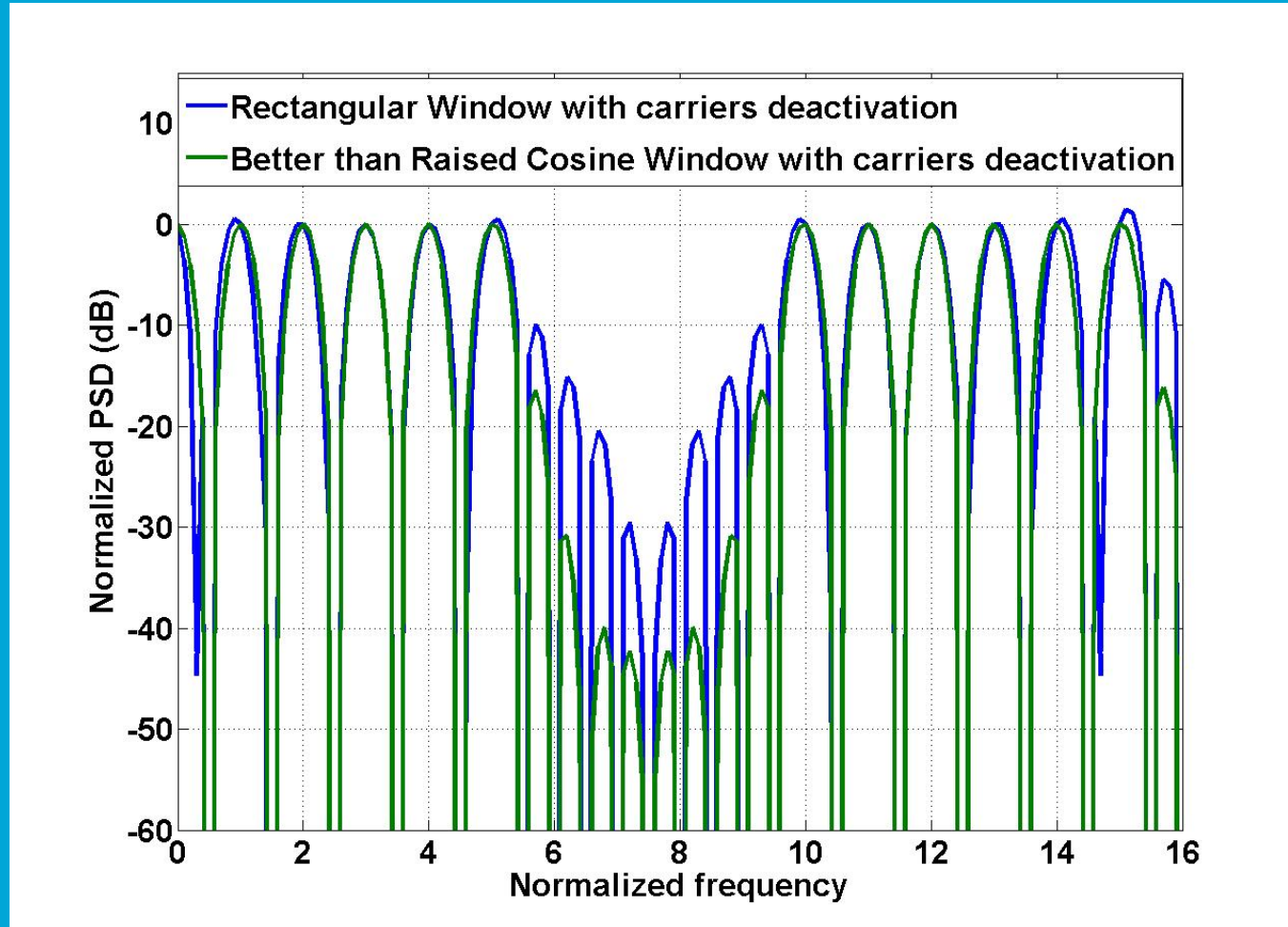
T OFDM useful symbol duration

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)**

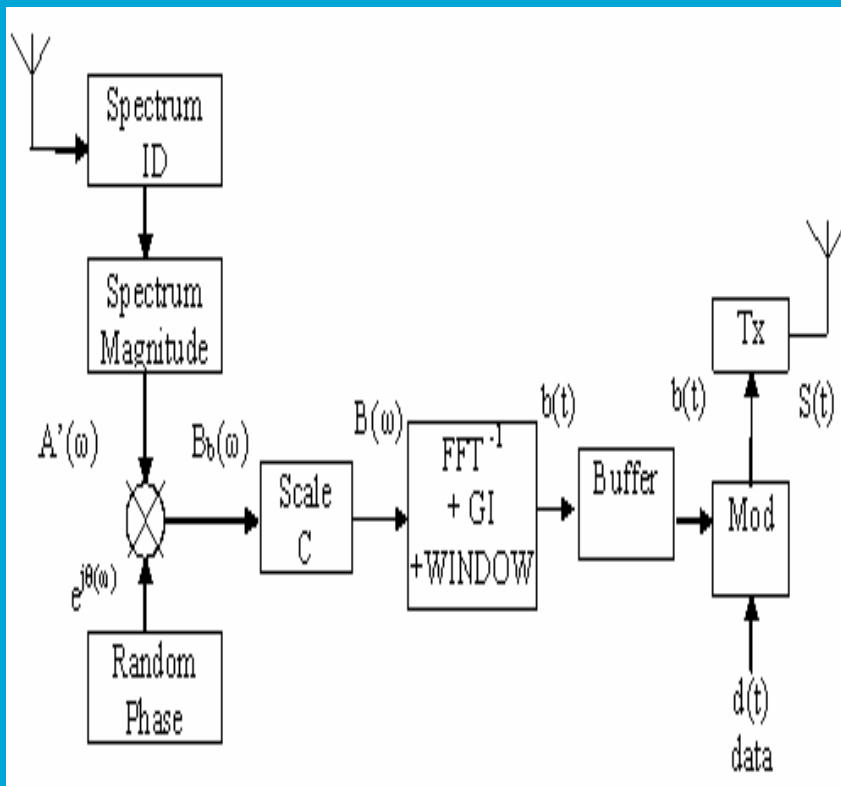
**Wavelet Domain Communication System
(WDCS)**

Wavelet based interference mitigation

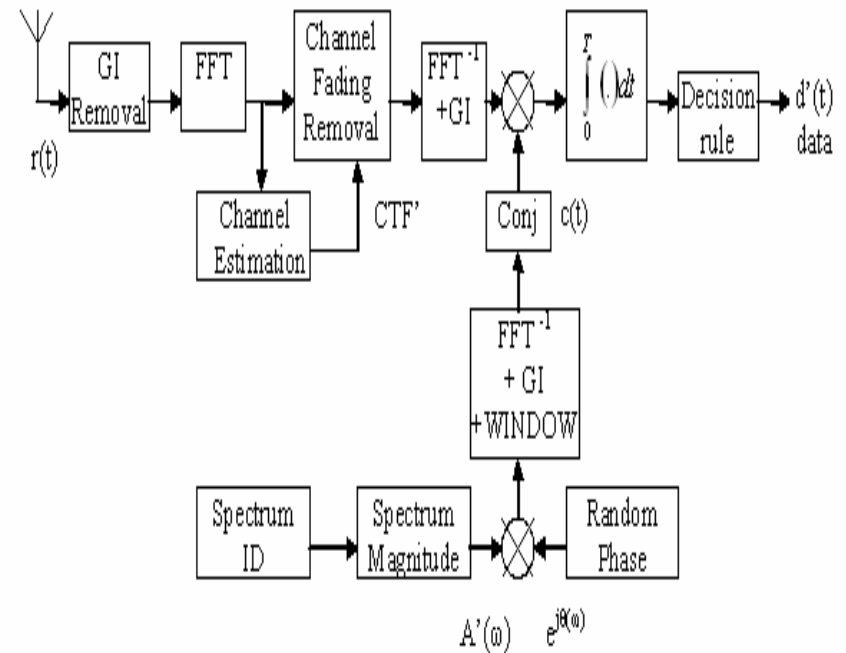
Waveshaping (2)

Transform Domain Communication System (TDCS)

Transmitter

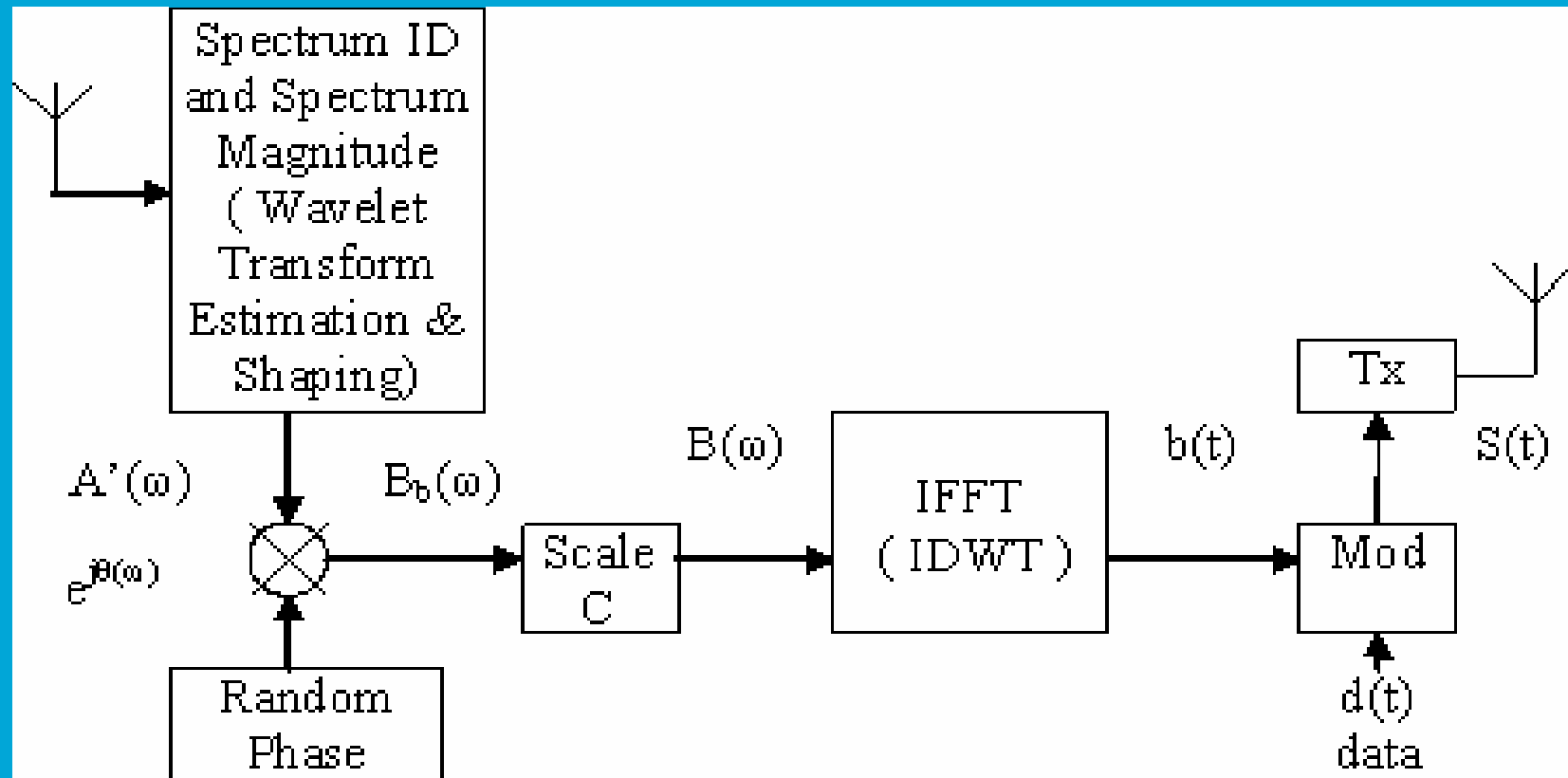


Receiver



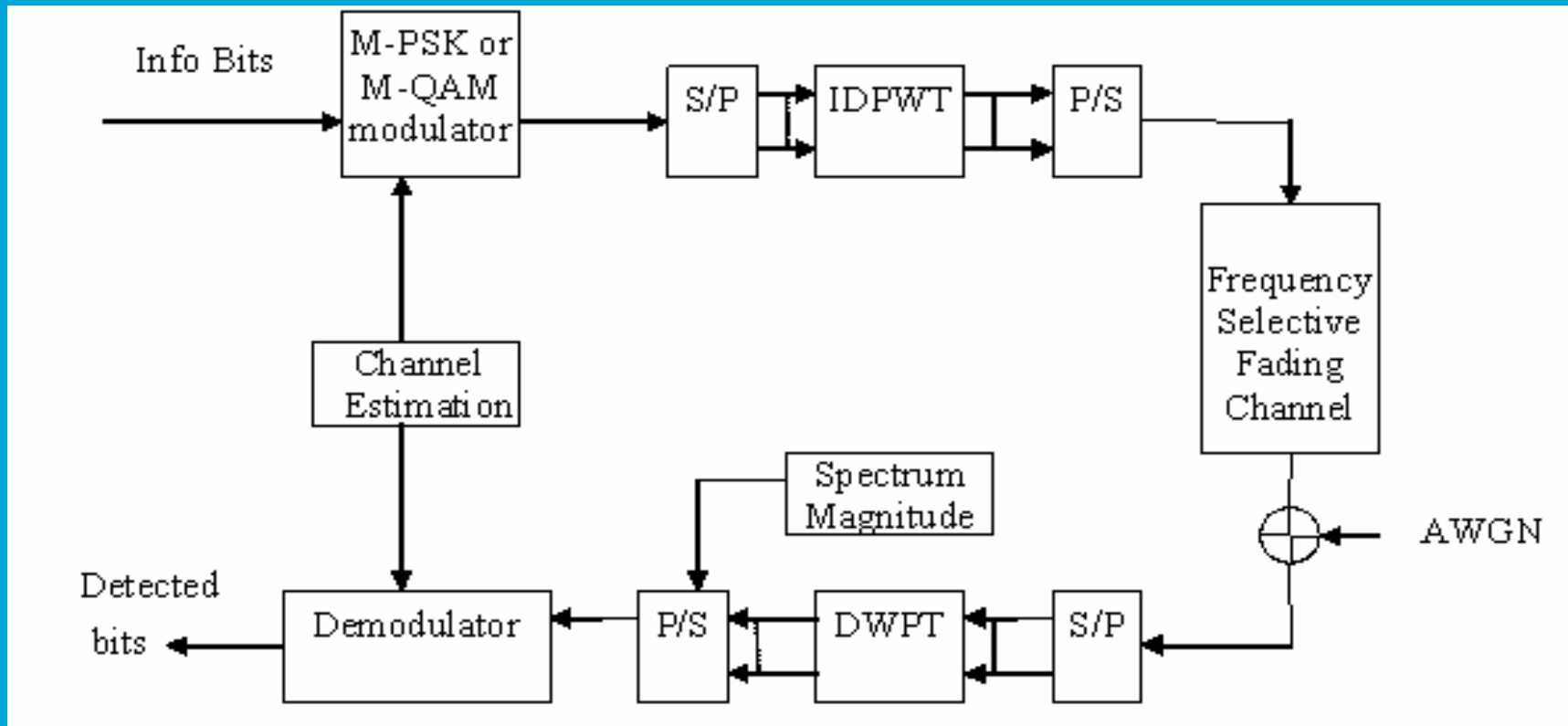
Waveshaping (3)

Wavelet domain communication system (WDCS)

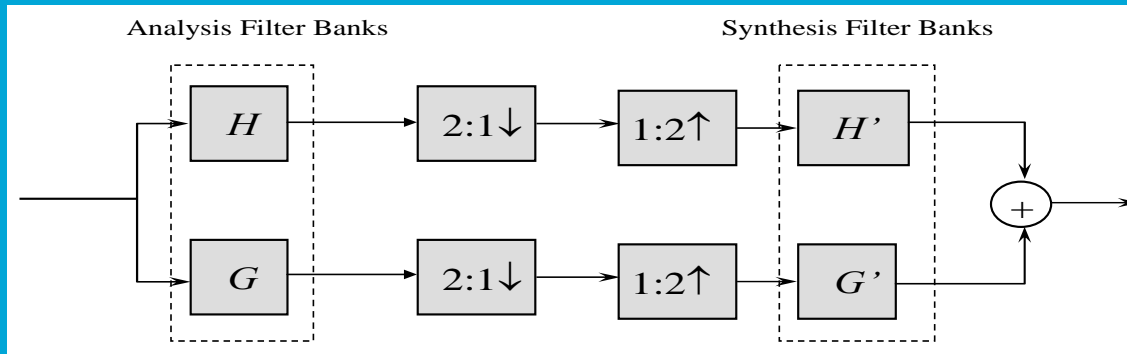


Waveshaping (4)

Multi Carrier Wavelet Packet Modulation



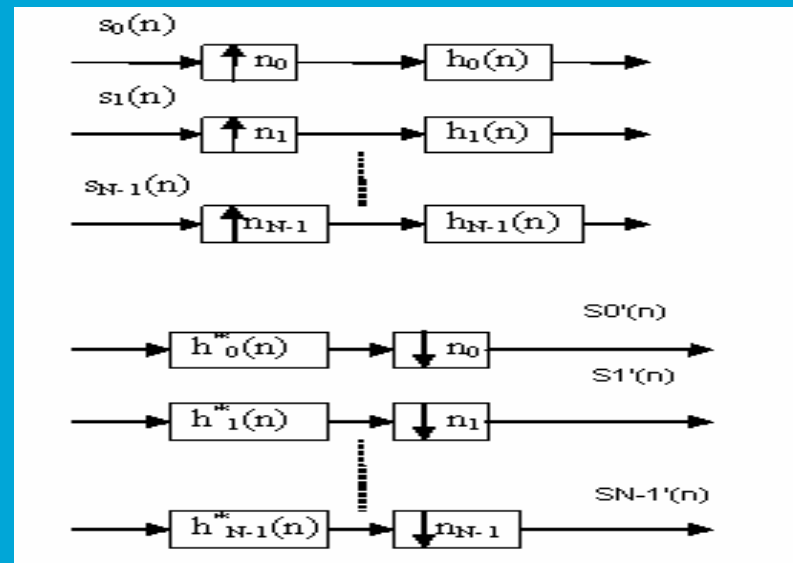
Waveshaping (5)



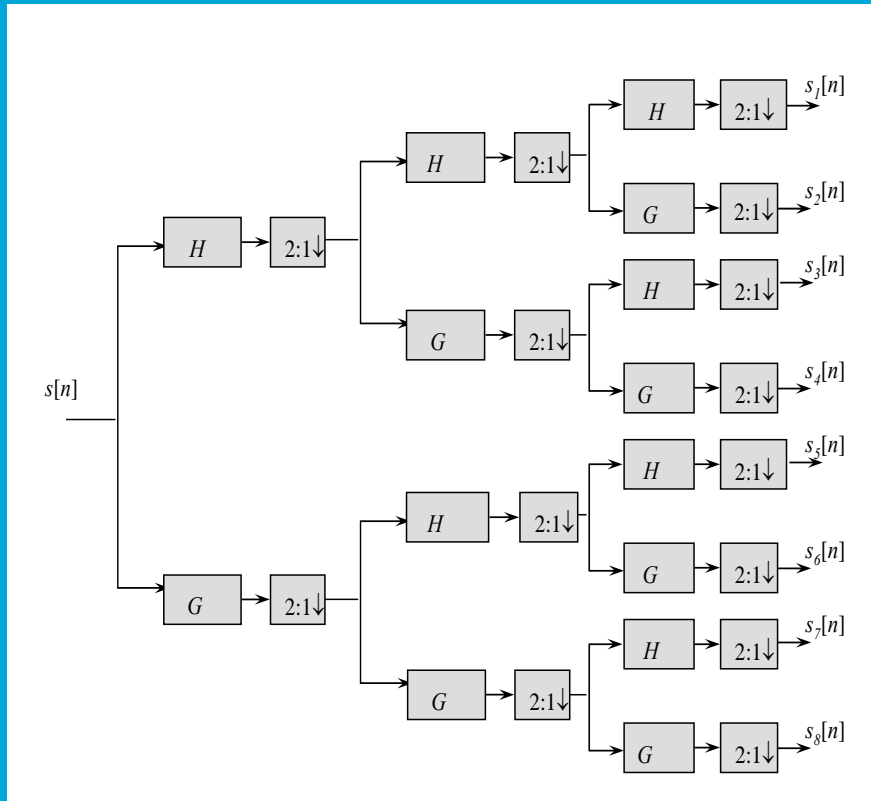
Wavelet design for LU
Interference rejection

Analysis

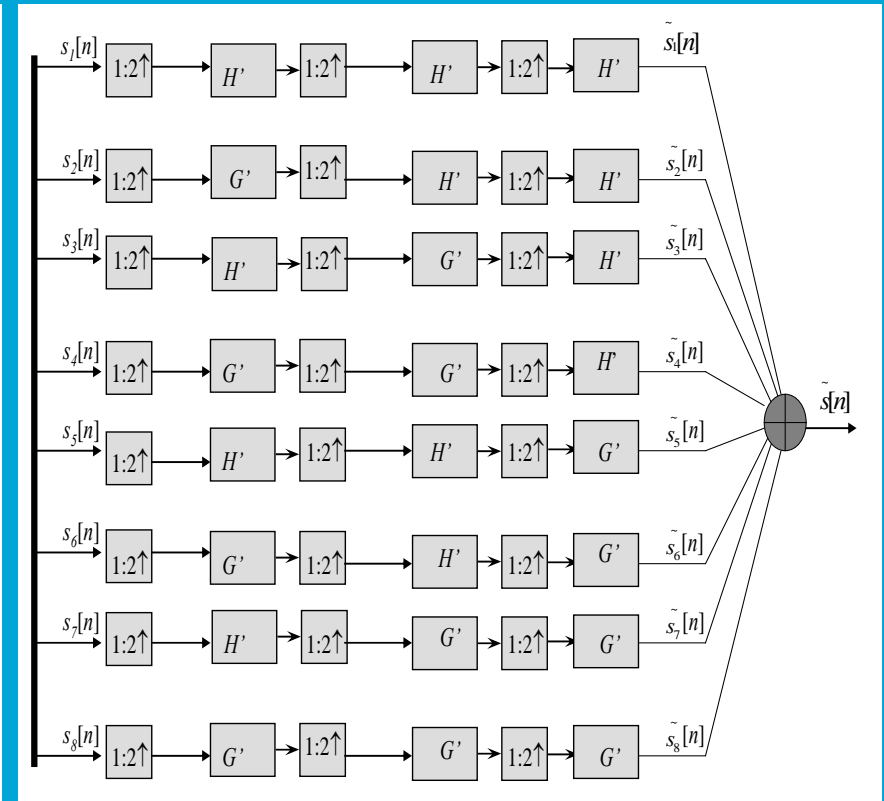
Synthesis



Waveshaping (6)



Wavelet Packet Decomposition of Signal



Wavelet Packet Reconstruction of Signal

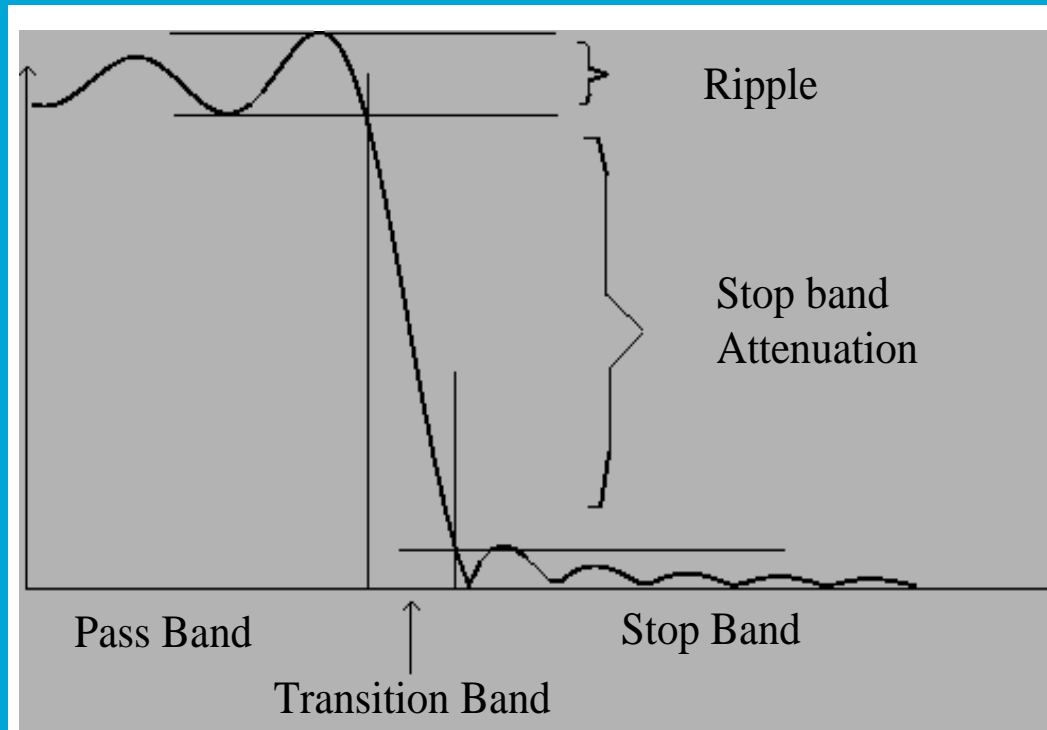
Waveshaping (7)

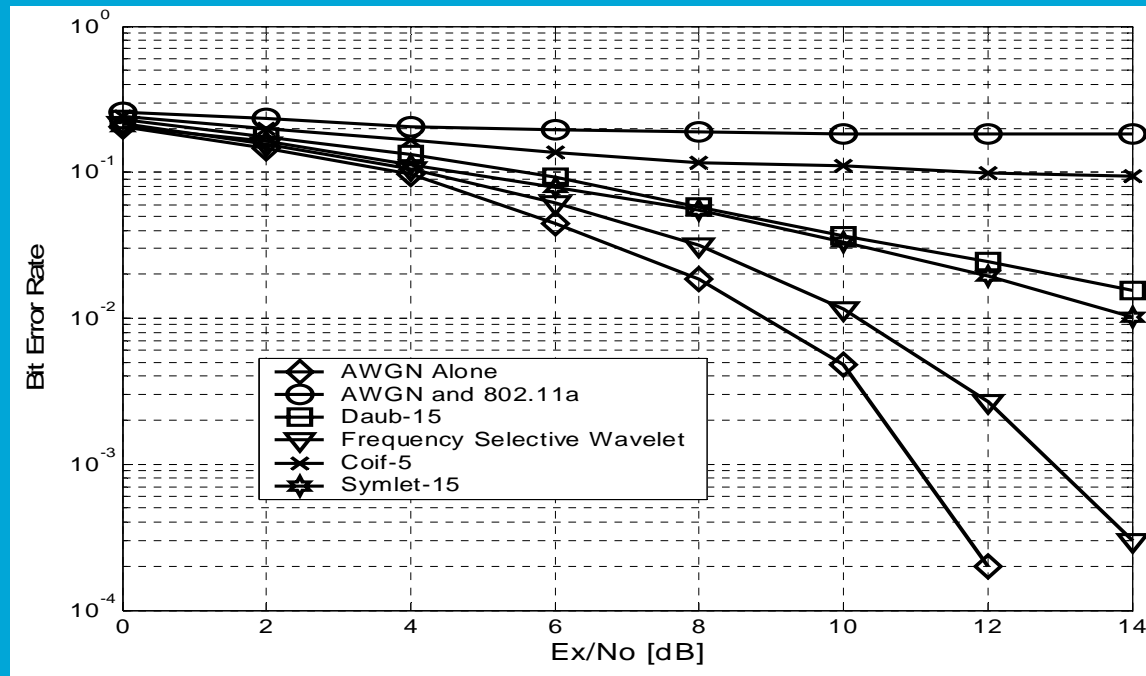
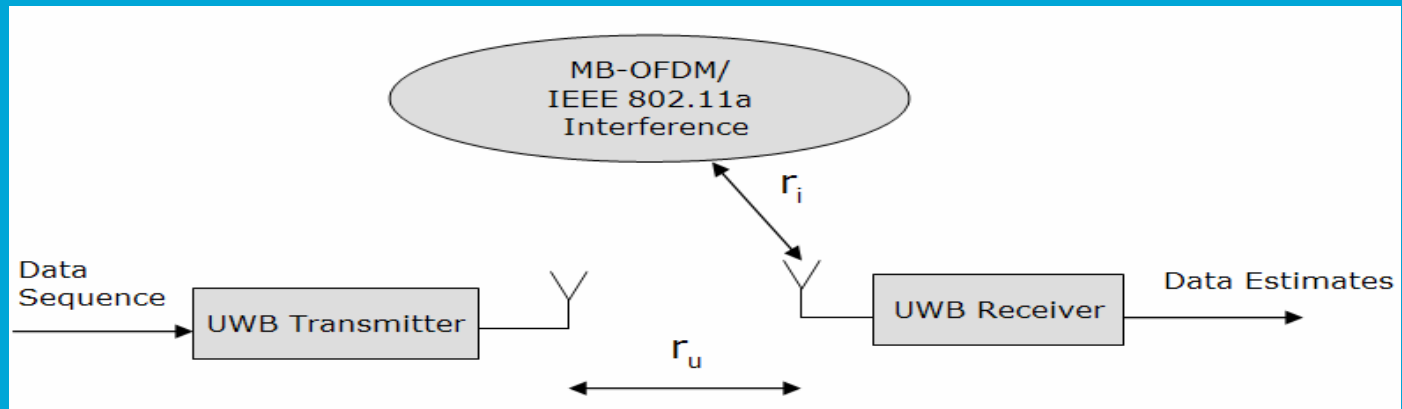
Subband Removal according to Gray code position

Coefficient	0	1	3	2	6	7	5	4	12	13	15	14	10	11	9	8
Binary Representation	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)

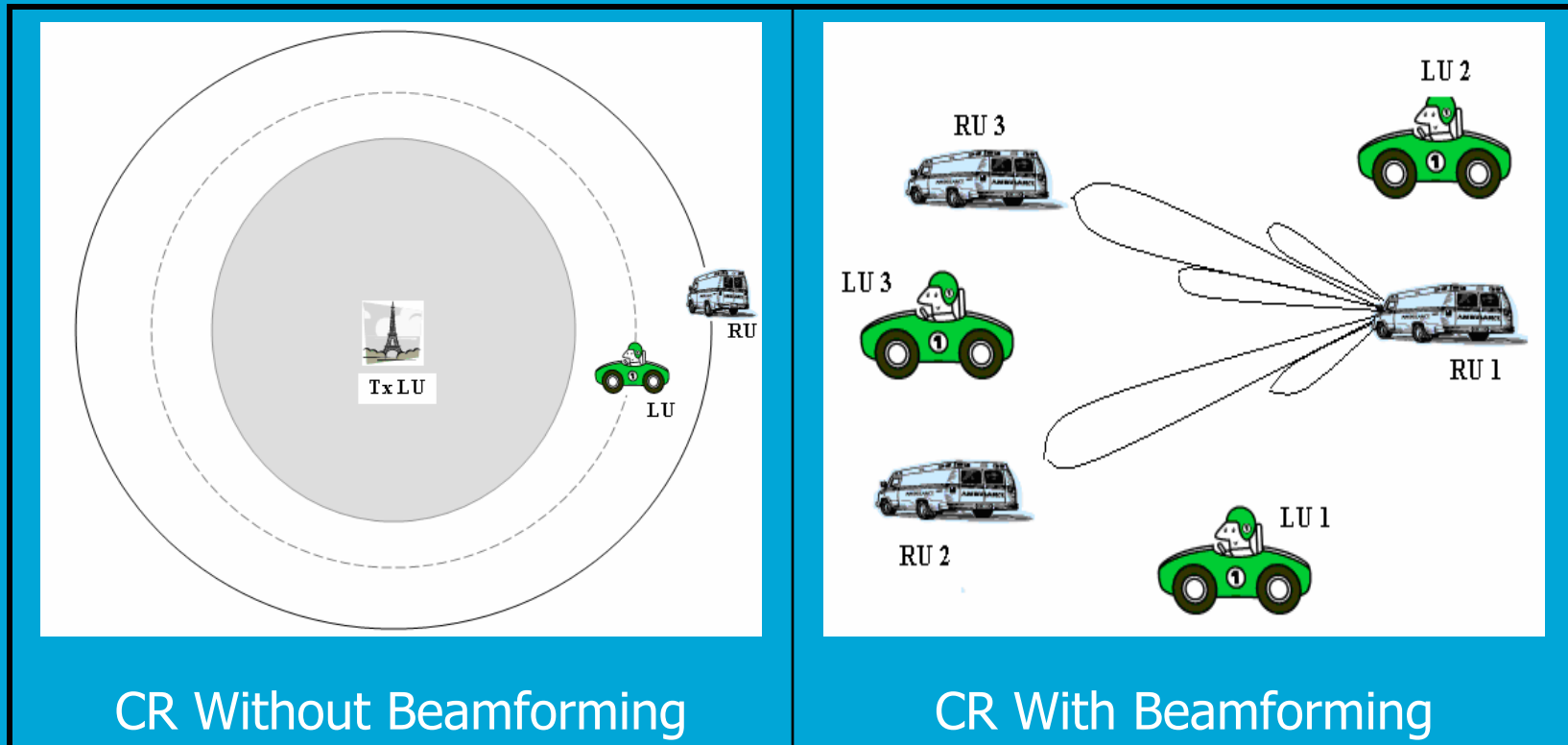
Maximally frequency selective wavelet according to Remez Algorithm





Beamforming (1)

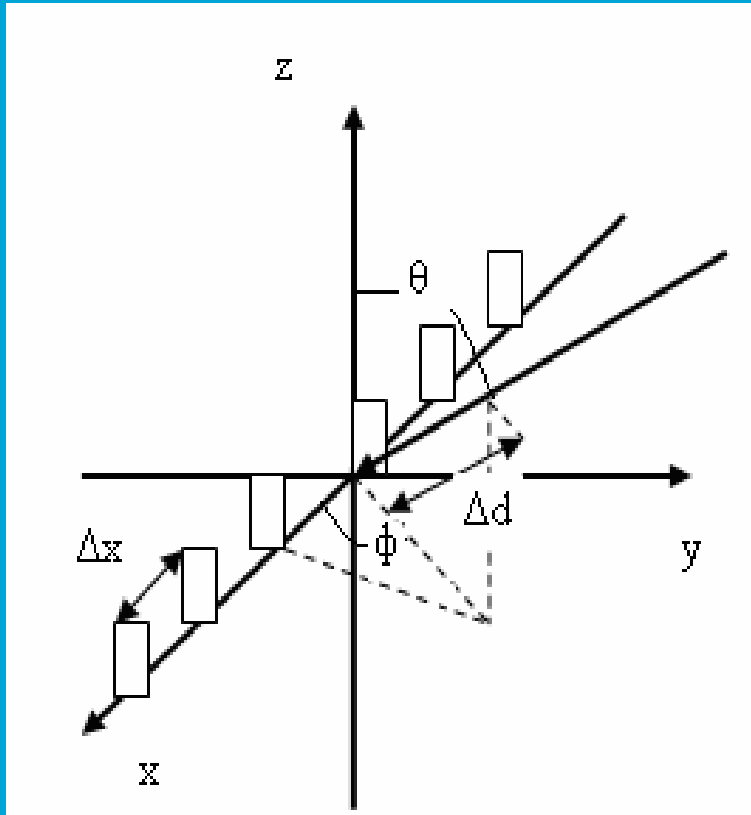
- Interference avoidance to LU by not directing signal to LU while occupying LU freq
Communicating CR nodes without interfering each other



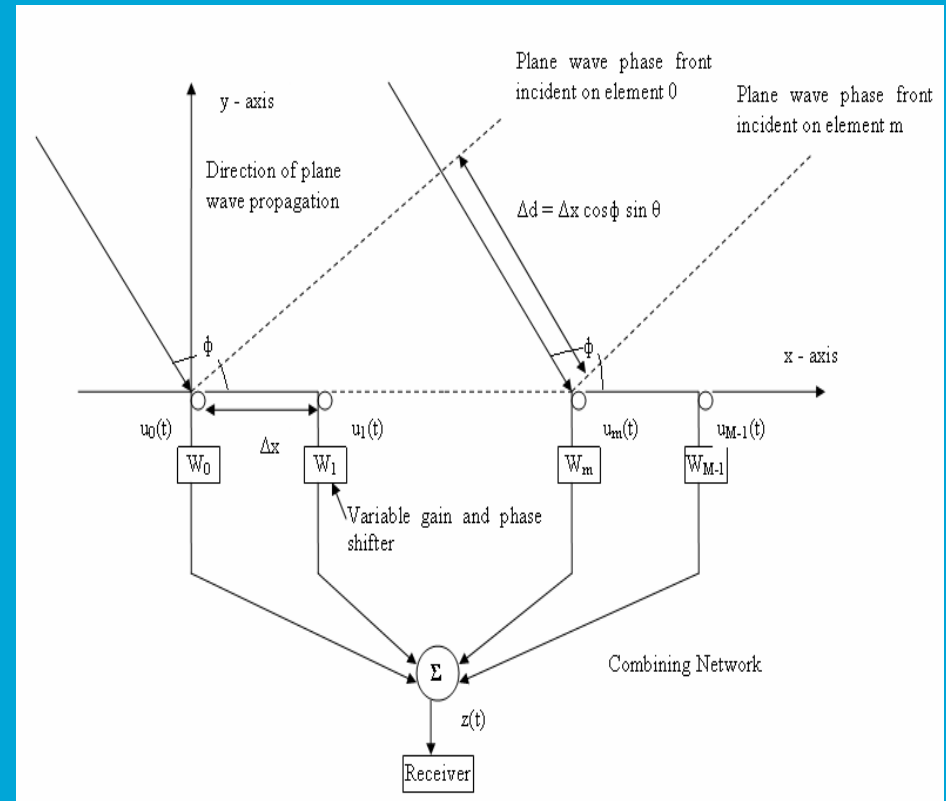
CR Without Beamforming

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.