Lecture on

Comunicazioni Wireless Ubique: Tecnologie Esistenti e Future

CISM - Centro Internazionale di Scienze Meccaniche

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Transmission Techniques for Wireless Channels

"Stato dell'Arte e Futuro delle Tecniche di Trasmissione Wireless"

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UNIVERSITÀ DEGLI STUDI DI UDINE

DIEGM DIPARTIMENTO DI INGEGNERIA ELETTRICA, GESTIONALE E MECCANICA

Outline

- ❑ Introduction to Wireless Communication Systems.
- ❑ Part I
  - Multiple Antenna Systems and Space-Time Coding.
- ❑ Part II
  - Multicarrier Transmission.
- ❑ Part III
  - Ultra Wide Band Communications.

Introduction

Wireless Communications

Satellite Systems

Terrestrial Radio Systems

Free space Optical Comm.

Some reasons for success

- Wireless connection
- Simple and cheap deployment
- Coverage
- Mobility

⇨ *enjoy ubiquitous communications !*

Research and Technology Drivers

Marketing

Increasing Demand for Ubiquitous High Rate, Real Time Services

Technical Challenge

- Spectrum Limitations
- Wireless Channel Unreliability
- Co-channel Interference
- Power Limitations

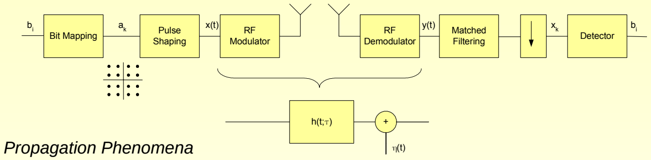
Develop Spectral Efficient Air-Interfaces

- Source Codes
- Channel Codes
- Modulation and Multiple Access Techniques
- Media Access Control and Resource Allocation Algorithms

Existing and Emerging Wireless Technologies

System	*Standard*	*Data Rate*	*Band*	*Mobility*
Existing Technologies				
WPAN (*Bluetooth)*	IEEE 802.15.1	1 Mb/s	ISM 2.4 GHz	Low
WLAN	IEEE 802.11b IEEE 802.11a IEEE 802.11g	11 Mb/s 54 Mb/s 54 Mb/s	ISM 2.4 GHz ISM/UNI 5 GHz ISM 2.4 GHz	Low
WMAN	IEEE 802.16 IEEE 802.16a	134 Mb/s 70 Mb/s	10-66 GHz 2-11 GHz	None
Cellular 1G	AMPS ETACS	Analog FM	0.8 GHz	High
Cellular 2G	IS-136 TDMA GSM GPRS EDGE	9.6 kb/s 9.6 kb/s 115 kb/s 384 kb/s	0.8 - 0.9 - 1.8 - 1.9 GHz	High
Cellular 3G	UMTS / WCDMA	2 Mb/s	1.9 - 2.025 GHz	High
Emerging Technologies				
WPAN (*UWB)*	IEEE 802.15.3	Up to 400 Mb/s	3.1-10.6 GHz	Low
WLAN	?	Up to 1 Gb/s	?	Low - High
Sensor Networks Ubiquitous Computing	IEEE 802.15.4	5-200 Kb/s	0.433, 0.866, 0.916, 2.4 GHz	None
Cellular 4G	?	Up to 100 Mb/s		High

Wireless Channel in Mobile Wireless Networks



Propagation Phenomena

- ❑ **Attenuation** (path-loss)
- ❑ **Slow Fading** (shadow fading)
  - Slow variations of the received power caused by obstructions.
- ❑ **Fast Fading**
  - Fast variations of the received power caused by multipath propagation in correspondence to movement in the order of the wavelength.
  - Performance of digital transmission is severely affected by fading.

Base-Band Channel Impulse Response

❑ **Narrow Band Systems**

- Signal Bandwidth < Channel Coherence Band
- Symbol duration ~ Channel Coherence Time

Time-Variant Flat Fading

$$h(t;\tau)=\alpha(t)\delta(\tau)$$

⇩

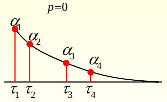
$$x_k=x(kT)=\alpha(kT)a_k+\eta_k$$

❑ **Wide Band Systems**

- Signal Bandwidth > Channel Coherence Band
- Symbol duration < Channel Coherence Time

Frequency Selective Fading

$$h(t;\tau)=\sum_{p=0}^{N_P}\alpha_p(t)\delta(\tau-\tau_p)$$



⇩

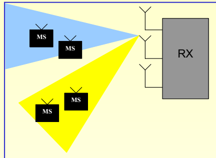
$$x_k=x(kT)=\sum_{p=0}^{N_P}\alpha_p a_{k-p}+\eta_k$$

Modelled as zero mean complex Gaussian (***Rayleigh Fading)***

PART I

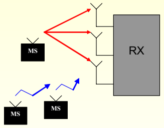
Multiple Antenna Systems

Multiple Antenna Systems



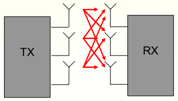
Smart Antennas

Generate beams with phased arrays to sectorize coverage.



Adaptive Antennas

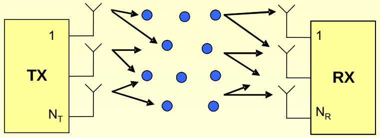
Receive antenna combining to gain spatial diversity and cancel co-channel interference.



Space-Time Coding

Multiple transmit and receive antennas to increase capacity.

Multiple In – Multiple Out (MIMO) System Capacity



$$y^r = \sqrt{\frac{E_S}{N_T}} \sum_{t=1}^{N_T} \alpha^{r,t} x^t + n^r \qquad r = 1,\dots,N_R$$

AWGN, m=0, $\sigma^2=N_0$

transmitted complex signal by antenna t

channel weight link antenna (t-r)

- The received signal is the superposition of the N_T *transmitted signals.*
- All antenna links experience independent fading *“in rich scattering”.*
- We keep the average transmitted energy constant.

MIMO Capacity, *cont.ed*

$$\begin{bmatrix} y^1 \\ \dots \\ y^{N_R} \end{bmatrix} = \sqrt{\frac{E_S}{N_T}} \begin{bmatrix} \alpha^{1,1} & \dots & \alpha^{1,N_T} \\ \dots & \dots & \dots \\ \alpha^{N_R,1} & & \alpha^{N_R,N_T} \end{bmatrix} \begin{bmatrix} x^1 \\ \dots \\ x^{N_T} \end{bmatrix} + \begin{bmatrix} n^1 \\ \dots \\ n^{N_R} \end{bmatrix} \Rightarrow \boldsymbol{y} = \sqrt{\frac{E_S}{N_T}} \boldsymbol{Hx} + \boldsymbol{n}$$

- The channel capacity conditioned on a channel realization reads

$$C_H = \log_2 \det\left(\boldsymbol{I} + \frac{E_S / N_0}{N_T} \boldsymbol{HH}^\dagger \right) \quad bit/s/Hz$$

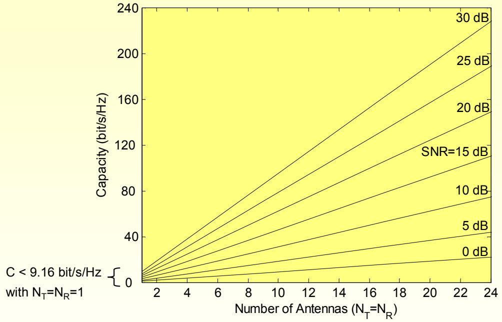
- We assume ***H*** to have independent complex Gaussian entries (Rayleigh fading)
- The **Outage Capacity** is the distribution of C_H

$$C = P\left[C_H < K\right]$$

- The **Ergodic Capacity** is the average of C_H

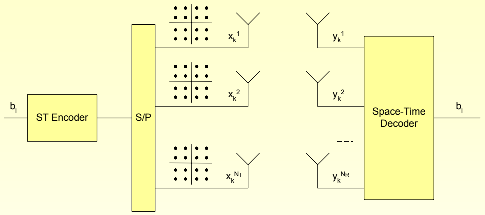
$$\overline{C} = E\left[C_H\right]$$

Mean Capacity



- ❑ Ergodic Capacity is used to characterize fast fading channels.
- ❑ Outage Capacity is used to characterize quasi-static fading channels.
- ❑ Fundamental contribution by *Foschini* (1996 Bell Labs):
  - ▪ Capacity increases linearly with the number of TX antennas if $N_R \geq N_T$.

Space-Time Coding



- ❑ To approach the Shannon Capacity we need to design powerful space-time codes:
  - ▪ joint channel coding, modulation, with transmission over multiple antennas.
- ❑ Fundamental contribution by *Tarokh*, *Seshadri*, and *Calderbank* (1998 AT&T Labs)

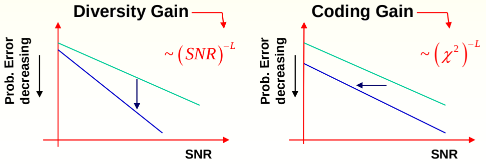
Space-Time Coding Classes

❑ Three Main ST Coding Approaches

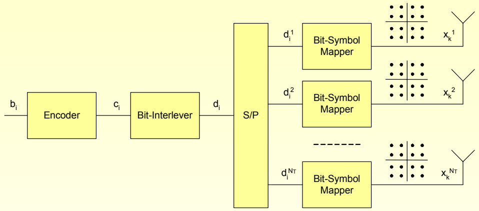
- ▪ ST Trellis Codes: extension of the *TCM (trellis coded modulation)* concept.
- ▪ ST Block Codes: M-QAM block codes with orthogonal structure.
- ▪ ST Bit-interleaved Codes

❑ **Diversity Gains** and **Coding Gains** are determined by the rank and determinant of certain matrices constructed from complex codewords. Recall that the transmitted signals overlap, therefore, the ST code must have a structure that allows to separate the signals at the receiver.

$$Pe \sim \left(\frac{1}{SNR}\right)^{L}\left(\frac{1}{\chi^{2}}\right)^{L} \qquad L \leq N_T N_R$$



ST-BICM: ST Bit-Interleaved Coded Modulation



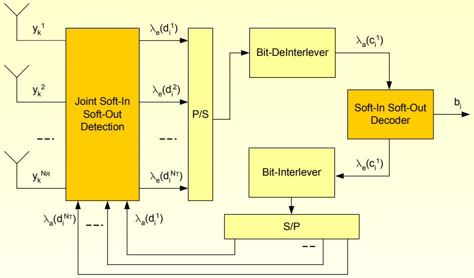
❑ ST-BICM comprises

- ▪ coder (block, convolutional, turbo)
- ▪ bit interleaver
- ▪ space-time mapper (M-PSK / M-QAM).

❑ Flexible approach.

❑ Full diversity codes can be designed for both quasi-static and time-variant fading channels.

Turbo MIMO Decoding



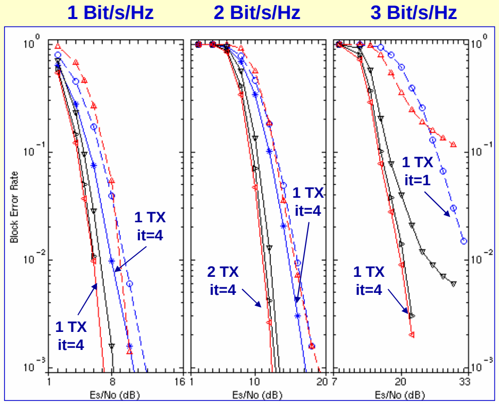
$$y_k^r = y^r(kT) = \sum_{t=1}^{N_T} \sum_n x^t(nT) g_{CH}^{t,r}(kT - nT) + \eta(kT)$$

- ❑ The receiver has to separate the overlapping signals and recover the information bits.
- ❑ Iterative (turbo) decoding procedure:

MIMO Demapping at the Detector: ***A Posteriori Probability Calculator for Each Coded Bit.***

Maximum a Posteriori Channel Decoder: ***Improved Extrinsic Information for the Coded Bits.***

Example of Application to GSM/EDGE Air Interface



Single receive antenna – TU channel model – 4/8 PSK with STBI convolutional coding.

Remarks

- ❑ Spectral efficiency of wireless channels is significantly increased with MIMO technology
- ❑ It is fundamental to
  - Study and model the MIMO channel
  - Design good Space-time codes
  - Develop simplified decoding algorithms
  - Turbo (iterative) processing is the *state-of the art* detection/decoding approach.

PART II

Multicarrier Transmission

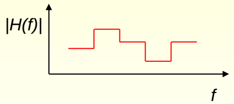
Multicarrier Transmission Principles

Motivation

- Simplify the equalization task in wide band frequency selective channels.

Principle

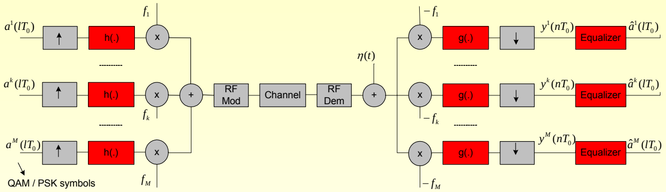
- Divide the spectrum in a number of narrow band sub-channels (flat faded).
- Allocate transmission power over the good channels (water filling principle).



Applications

- ADSL : *advanced digital subscriber line*
- DAB : *digital audio broadcast*
- DVB : *digital video broadcast*
- IEEE 802.11 and Hiperlan II : *wireless LAN*
- proposed although killed for 3rd generation cellular
- likely to be chosen for next generation cellular.

General Multicarrier Architecture



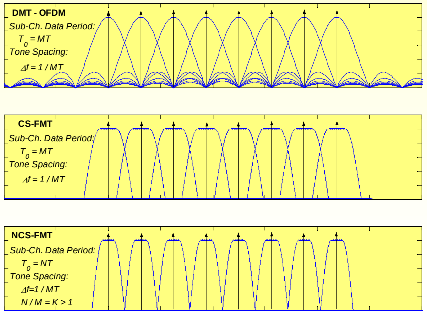
Two efficient digital implementations

DMT (Discrete Multitone): well known OFDM (orthogonal frequency division multiplexing) scheme. Prototype filter with rectangular impulse response.

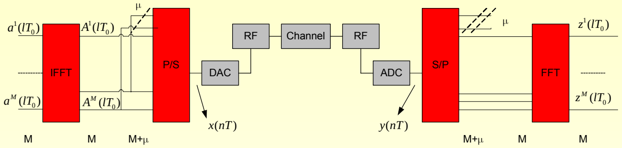
FMT (Filtered Multitone): prototype pulse with time-frequency concentrated response.

Efficient Digital Implementation

- Overall bandwidth W = 1 / T.
- Uniformly spaced sub-carriers $f_k = k / (MT)$, *k=0,…,M-1.*
- *DMT – OFDM :* Rectangular impulse response prototype pulse *h(nT).*
- *FMT :* Frequency concentrated prototype pulse, e.g., square root raised cosine.



Cyclically Prefixed DMT / OFDM



- Transmitter
  - *M* points IDFT
  - Add a cyclic prefix of duration μT
  - Sub-channel symbol period $T_0 = NT = (M + \mu)T$

$$x(nT + lT_0) = \sum_{k=1}^{M} a^k(lT_0)\, e^{j\frac{2\pi}{M}(n-\mu)(k-1)} \qquad n = 0,\dots,N-1$$

- Receiver
  - Disregard cyclic prefix
  - M points DFT
  - One tap equalizer

One Tap Equalization for CP-DMT

❑ *Hypothesis*

- Channel with duration shorter than μT: $g_{CH}(nT) = \sum_{p=0}^{N_P \le \mu} \alpha_p \delta(nT - pT)$
- Static over a DMT symbol

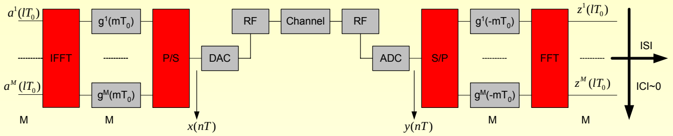
❑ *Thesis*

- The DFT output equals the data symbol weighted by the channel frequency response.
- The receiver simplifies into a simple one-tap equalizer.

$$z^k(lT_0) = DFT\{\mathbf{y}(lT_0)\}^{(k)} = DFT\{\mathbf{A}(lT_0)\}^{(k)} DFT\{\boldsymbol{\alpha}\}^{(k)} = a^k(lT_0)\left(\sum_{p=0}^{N_P} \alpha_p e^{-j\frac{2\pi}{M}p(k-1)}\right)$$

DFT received block *Transmitted block is cyclically convolved with the channel*

FMT: Digital Implementation



CS-FMT

$$f_k = \frac{k-1}{T_0} \qquad T_0 = MT \qquad k = 1,\dots,M$$

$$g^k(mT_0) = h((k-1)T + mT_0)$$

Prototype pulse

Ref: Cherubini, Eleftheriou, Olcer, Cioffi, *2000*

Equalization for FMT

❑ *Hypothesis*

- Frequency separated sub-channels and static wide band channel.

❑ *Thesis*

- The receiver simplifies into a bank of independent equalizer.

l-th output sample of the *k*-th RX filter

$$z^k(lT_0) = a^k(lT_0)g^k_{EQ}(0) + \sum_{m\ne 0} a^k(lT_0 - mT_0)g^k_{EQ}(mT_0) + \eta(lT_0)$$

useful data *ISI* *equivalent sub-channel impulse response*

- In general scenarios we get both inter-symbol (ISI) and inter-carrier interference (ICI).

FMT, *cont.ed*

❑ The presence of some sub-channel ISI can be handled with

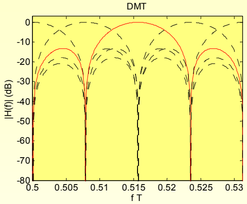
- Linear or DFE equalization.
- Optimal maximum likelihood detection (Viterbi equalization).

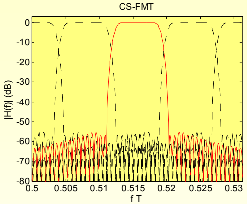
❑ The sub-channel equalizer has low complexity since the sub-channel impulse response is short (sub-channel is narrow band).

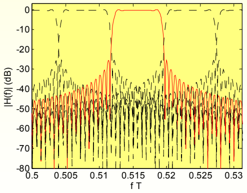
❑ Practical issues (real world !!)

- Extra ICI and ISI because of
  - Overlapping sub-channels (finite duration TX pulses)
  - Timing Errors (Time Offsets) and Carrier Frequency Offsets.

Example of Sub-Channel Frequency Response







M = 128 B = 25 MHz

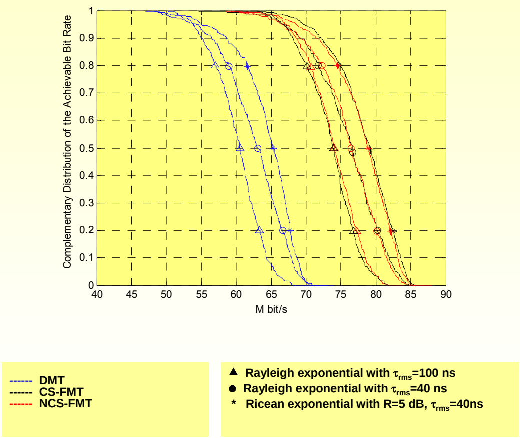
NCS-FMT: square root raised cosine pulses

N/M = 1.125 + 4 virtual carriers

CS-FMT: rectangular windowed pulses + 4 virtual carriers

CP-DMT: CP length = 30 chips + 16 virtual carriers

Probability [Achievable Bit Rate > K]



Remarks

- ❑ DMT-OFDM is an elegant simple solution to overcome channel frequency selectivity.
- ❑ FMT can yield higher spectral efficiency than DMT.
- ❑ FMT is more robust to time and frequency offsets.
- ❑ FMT is more complex than DMT since it requires filtering and equalization.

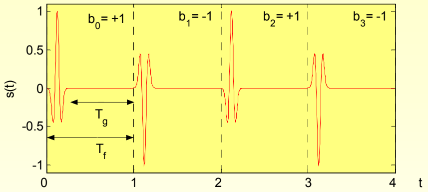
PART III

Ultra Wide Band Communications

UWB Main Characteristics

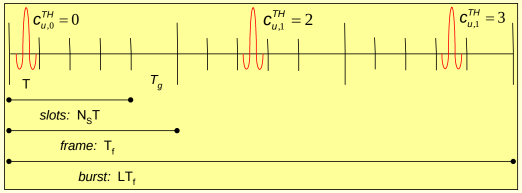
- ❑ FCC definition of UWB:
  - Signal bandwidth > 500 MHz or Bandwidth / Center-frequency ≥ 0.2
- ❑ Most popular schemes are based on impulse modulation with short duration pulses
  - Simple base band (*carrier less*) implementation.
  - Good penetration properties.
  - Good spatial and temporal resolution.
  - Co-existence with other radio systems.
- ❑ Very tight emission masks have been set. Therefore, practical application is limited to short range communications.

Impulse Modulation



- ❑ Convey a bit sequence via a sequence of *monocycles* (short duration pulses)
  - ***Bi-Phase PAM modulation*** or Time-Hopped modulation.
  - Guard time to cope with the channel time dispersion.
- ❑ Multiplex users via *Time Hopping* or *DS-CDMA* with codes of length *L* frames.

Time-Hopped Solution



- ❑ *TX signal of user u*

$$s_u(t)=\sum_k b_{u,k}\sum_{l=0}^{L-1} g(t-c_{u,l}^{TH}T-lT_f-kLT_f) \;\Rightarrow\; =\sum_k b_{u,k}v_u^{TH}(t-kLT_f)$$

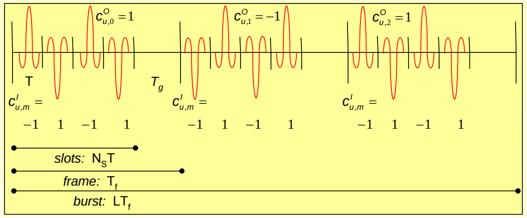
± 1 bit sequence monocycle

signature waveform

hopping codeword of user *u* and length *L*

- ❑ *Aggregate data rate:* $R=\dfrac{1}{T+T_g/N_S}\xrightarrow{N_S\to\infty}\dfrac{1}{T}$

DS-CDMA Solution



- ❑ *TX signal of user u*

$$s_u(t)=\sum_k b_{u,k}\sum_{l=0}^{L-1} c_{u,l}^{O}\sum_{m=0}^{N_S-1} c_{u,m}^{I}\,g(t-mT-lT_f-kLT_f) \;\Rightarrow\; s_u(t)=\sum_k b_{u,k}v_u^{DS}(t-kLT_f)$$

monocycle

signature waveform

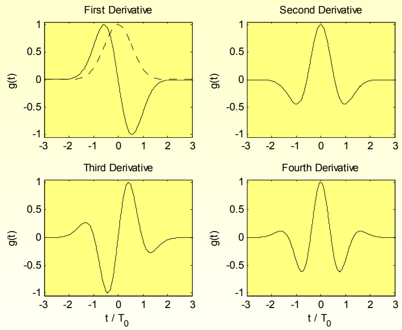
± 1 bit sequence

inner codeword user *u* and length N_s

outer codeword user *u* and length *L*

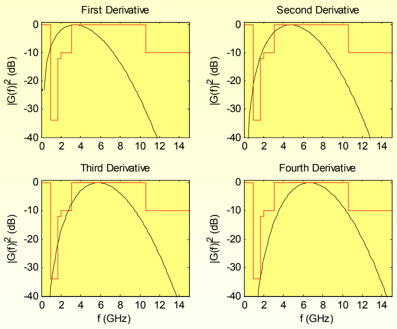
- ❑ *Aggregate data rate identical to the TH solution.*

Monocycle Shape



- ❑ We can use time-frequency concentrated pulses as the family of:
  - Derivatives of Gaussian monocycle $g(t) \sim e^{-\frac{\pi}{2}(t/T_0)^2}$
- ❑ The antennas act as a filter: *they differentiate the wide band impulse signal*.

FCC Requirements

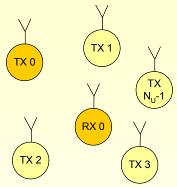


---- FCC spec

T_0 = 0.087 ns

- ❑ The FCC specifications are very tight:
  - Transmission band 3.1 -10.6 GHz with Spectral Density of -41 dBm/MHz
  - We can transmit 0.6 mW !!
- ❑ *The fourth derivative of G-Pulse matches the FCC specs !*

Multiuser Scenario



- ❑ *Composite RX signal*

$$y(t)=\sum_{u=0}^{N_U-1} s_u * g_u^{CH}(t-\Delta t_u)+\eta(t)=\sum_{u=0}^{N_U-1}\sum_k b_{u,k}v_u^{EQ}(t-kLT_f-\Delta t_u)+\eta(t)$$

↓

Convolution of the *u*-th user’s signature waveform with the *u*-th user channel

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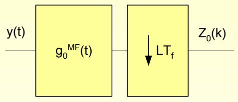
Single User Receiver

- ❑ Matched Filter Receiver is optimal with guard time longer than the channel dispersion and single user.



$$Z_0(k)=\int_{-\infty}^{\infty} y(t)g_0^{MF}(kLT_f+\Delta t-t)dt$$

- ❑ The RX filter has to be matched to the equivalent signature waveform:

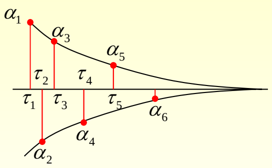
$$g_0^{MF}(t)=v_0^{EQ}(-t)=v_0^{TH-DS} * g^{CH}(-t)$$

- ❑ ISI is assumed to be zero (it can be controlled with the guard time)

$$Z_0(k)=\underbrace{b_{0,k}\int_0^{LT_f}|v_0^{EQ}(t)|^2\,dt}_{\text{useful term}}+\underbrace{\sum_{u=1}^{N_U-1}\sum_{n=0}^{1}b_{u,k-n}\int_0^{LT_f}v_u^{EQ}(t+nLT_f+\Delta t_0-\Delta t_u)v_0^{EQ}(t)dt}_{\text{MAI}}+\underbrace{w(k)}_{\text{noise}}$$

Synthesis of Matched Filter and Rake Reception

- ❑ UWB channel is highly frequency selective.
- ❑ We assume to synthesize the channel with a finite number of taps (FIR filter).



$$g_u^{CH}(t)=\sum_{p=1}^{N_P}\alpha_{p,u}\,\delta(t-\tau_{p,u})$$

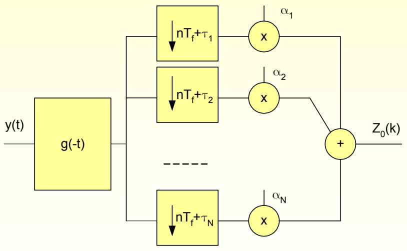
- ❑ The received signature waveform can be synthesized as follows

$$\hat{v}_0^{EQ,TH}(t)=\sum_{l=0}^{L-1}\sum_{p=1}^{N_P}\hat{\alpha}_{0,p}\,g(t-c_{0,l}^{TH}T-lT_f-\hat{\tau}_{0,p})$$

$$\hat{v}_0^{EQ,DS}(t)=\sum_{l=0}^{L-1}c_{0,l}^{O}\sum_{m=0}^{N_S-1}c_{0,m}^{I}\sum_{p=1}^{N_P}\hat{\alpha}_{0,p}\,g(t-mT-lT_f-\hat{\tau}_{0,p})$$

Cont. ed

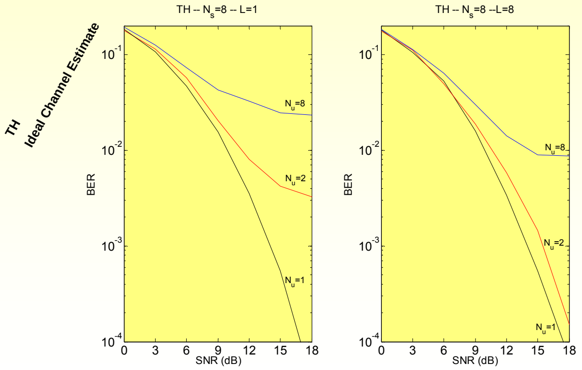
- ❑ We need to estimate the channel tap delays and amplitudes. It can be done with a training approach.
- ❑ We can implement a mixed Analog-Digital Rake Receiver



No Spreading / TH

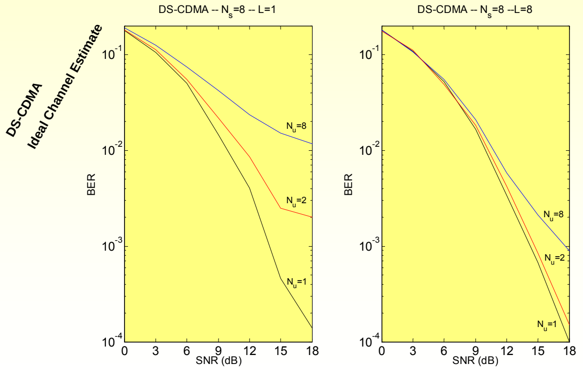
Simulation Results

- Frame structure: 8 slots of duration D, plus 4D guard time. Orthogonal codes.
- Channel: Exponential delay profile, 10 Rayleigh faded rays (with sign) and with uniform delay distribution in [0 4D].
- Search and estimate only 3 taps with 100 training bits.



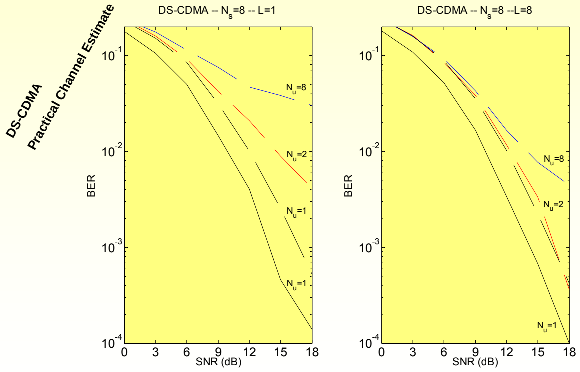
Cont. ed

- DS-CDMA UWB works better than TH UWB especially with a high number of users.



Cont. ed

- **With practical channel estimation we get a tolerable performance loss.**



Remarks

- ❑ UWB systems allow very high transmission speed (say in the order of Gb/s)

- ❑ Potentially, their implementation is simple, however,

  - – Optimal receivers may be too complex.

  - – All-digital receiver is not currently applicable.

Conclusions

- ❑ Reliable spectral efficient transmission over wireless channels is an *Algorithmic Challenge*.

- ❑ The state of the art is represented by
  - Multiple Antenna Technology
  - Multi-carrier Modulation
  - Ultra Wide Band Transmission.

- ❑ A powerful air interface allows for
  - Higher receiver sensitivity (coverage)
  - Robustness to co-channel interference (spectral efficiency)
  - Lower transmission power
  - Simpler processing complexity.

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