Transmission Techniques for Wireless Channels
“Stato dell’Arte e Futuro delle Tecniche di Trasmissione Wireless”

Dr. Andrea Tonello
e-mail: tonello@uniud.it - http://www.diegm.uniud.it/tlc/tonello

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.

Wireless Communications

Some reasons for success
- Wireless connection
- Simple and cheap deployment
- Coverage
- Mobility

Terrestrial Radio Systems

Satellite Systems

Free space Optical Comm.

enjoy ubiquitous communications!
Research and Technology Drivers

Marketing
Increasing Demand for Ubiquitous High Rate, Real Time Services

Develop Spectral Efficient Air-interfaces
  - Source Codes
  - Channel Codes
  - Modulation and Multiple Access Techniques
  - Media Access Control and Resource Allocation Algorithms

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

Existing and Emerging Wireless Technologies

<table>
<thead>
<tr>
<th>Existing Technologies</th>
<th>Standard</th>
<th>Data Rate</th>
<th>Band</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPAN (Bluetooth)</td>
<td>IEEE 802.15.1</td>
<td>1 Mb/s</td>
<td>ISM 2.4 GHz</td>
<td>Low</td>
</tr>
<tr>
<td>WLAN</td>
<td>IEEE 802.11b</td>
<td>11 Mb/s</td>
<td>ISM 2.4 GHz</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>IEEE 802.11a</td>
<td>54 Mb/s</td>
<td>ISM/UNI 5 GHz</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>IEEE 802.11g</td>
<td>54 Mb/s</td>
<td>ISM 2.4 GHz</td>
<td>Low</td>
</tr>
<tr>
<td>MAN</td>
<td>IEEE 802.16</td>
<td>134 Mb/s</td>
<td>10-48 GHz</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>IEEE 802.15a</td>
<td>70 Mb/s</td>
<td>2-11 GHz</td>
<td>None</td>
</tr>
<tr>
<td>Cellular 1G</td>
<td>AMPS, ETACS</td>
<td>Analog FM</td>
<td>0.8 GHz</td>
<td>High</td>
</tr>
<tr>
<td>Cellular 2G</td>
<td>IS-136 TDMA, GSM, GPRS, EDGE</td>
<td>5.5-10 kbps</td>
<td>0.8 - 0.9 - 1.8 GHz</td>
<td>High</td>
</tr>
<tr>
<td>Cellular 3G</td>
<td>UMTS/WCDMA</td>
<td>2 Mb/s</td>
<td>1.9 - 2.025 GHz</td>
<td>High</td>
</tr>
</tbody>
</table>

Emerging Technologies

<table>
<thead>
<tr>
<th>System</th>
<th>Standard</th>
<th>Data Rate</th>
<th>Band</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPAN (UWB)</td>
<td>IEEE 802.15.3</td>
<td>Up to 460 Mb/s</td>
<td>3.1-10.6 GHz</td>
<td>Low</td>
</tr>
<tr>
<td>WLAN</td>
<td>?</td>
<td>Up to 1 Gbps</td>
<td>?</td>
<td>Low - High</td>
</tr>
<tr>
<td>Sensor Networks Ubiquitous Computing</td>
<td>IEEE 802.15.4</td>
<td>5-200 Kbps</td>
<td>0.433, 0.806, 0.916, 2.4 GHz</td>
<td>None</td>
</tr>
<tr>
<td>Cellular 4G</td>
<td>?</td>
<td>Up to 100 Mb/s</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

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

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

Time-Variant Flat Fading
\[ h(t; \tau) = a(t) \delta(\tau) \]

Frequency Selective Fading
\[ h(t; \tau) = \sum_{j=1}^{M} a_j(t) \delta(t - \tau_j) \]

\[ x_i(t) = x_i(kT) = a(kT) + \eta_i \]

Modelled as zero mean complex Gaussian (Rayleigh Fading)
PART I

Multiple Antenna Systems

Multiple In – Multiple Out (MIMO) System Capacity

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

The channel capacity conditioned on a channel realization reads

$$C_H = \log_2 \det \left( I + \frac{E_r}{N_t} H H^H \right) \text{ bit/s/Hz}$$

We assume $H$ to have independent complex Gaussian entries (Rayleigh fading)

The **Outage Capacity** is the distribution of $C_H$

$$C = P[C_H < K]$$

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

$$\overline{C} = E[C_H]$$
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 $N_R \geq N_T$.

$$C < 9.16 \text{ bit/s/Hz}$$ with $N_T = N_R = 1$

**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.

$$P_e \sim \left( \frac{1}{SNR} \right)^L \left( \frac{1}{2} \right)^L \quad L \leq N_T N_S$$

**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.
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.

The receiver has to separate the overlapping signals and recover the information bits.

Turbo (iterative) processing is the state-of-the-art detection/decoding approach.

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.

Example of Application to GSM/EDGE Air Interface


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.

Efficient Digital Implementation

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

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.

Cyclically Prefixed DMT / OFDM

Transmitter
- $M$ points IDFT
- Add a cyclic prefix of duration $\mu T$
- Sub-channel symbol period $T_p = NT = (M+\mu)T$
- $x(nT) = \sum_{k=0}^{M-1} \sum_{\mu=0}^{\mu-1} a_k^\mu DT_k^n e^{-j2\pi k n M^{-1}}$ $n = 0,\ldots,N-1$

Receiver
- Disregard cyclic prefix
- $M$ points DFT
- One tap equalizer
One Tap Equalization for CP-DMT

- **Hypothesis**
  - Channel with duration shorter than $\mu T$: $R_{c,i}(nT) = \sum_{p=1}^{L_p} a_p \delta(nT - pT)$
  - 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.

\[ z'(I_T) = DFT[y(I_T)]^{(i)} = DFT[A(I_T)]^{(i)} DFT[a]^{(i)} = a'(I_T) \left( \sum_{m=0}^{M-1} g_m e^{-j2\pi \alpha m} \right) \]

- Transmitted block is cyclically convolved with the channel.

Equalization for FMT

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

- **Thesis**
  - The receiver simplifies into a bank of independent equalizer.

\[ z'(I_T) = a'(I_T) y_m(0) + \sum_{m=0}^{M-1} a'(I_T - mT) g_m(z_m) + \eta(I_T) \]

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

FMT: Digital Implementation

- **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.

Ref: Cherubini, Eleftheriou, Ofor, Cioffi, 2000
Example of Sub-Channel Frequency Response

- **NCS-FMT**: square root raised cosine pulses
- **CS-FMT**: rectangular windowed pulses + 4 virtual carriers
- **CP-DMT**: CP length = 30 chips + 16 virtual carriers

**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 \( u \)
  \[
  s_u(t) = \sum_{k} b_{uk} C_m^{TH}(t - k LT_f) \Rightarrow s_u(t) = \sum_{k} b_{uk} C_m^{TH}(t - k LT_f)
  \]
  - \( b_{uk} \) = \( \pm 1 \) bit sequence
  - \( C_m^{TH} \) = monocycle
  - \( \sum_{k} b_{uk} \) = hopping codeword of user \( u \) and length \( L \)
- Aggregate data rate:
  \[
  R = \frac{1}{T_s + 1/N_s} \quad \frac{1}{T} \to \frac{1}{T}
  \]

**DS-CDMA Solution**

- TX signal of user \( u \)
  \[
  s_u(t) = \sum_{k} b_{uk} \sum_{m} C_m^{DS}(t - mT_f - kLT_f) \Rightarrow s_u(t) = \sum_{k} b_{uk} C_m^{DS}(t - mT_f - kLT_f)
  \]
  - \( b_{uk} \) = \( \pm 1 \) bit sequence
  - \( C_m^{DS} \) = signature waveform
  - 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 \( g(t) - e^{-\frac{t^2}{2T^2}} \)
- The antennas act as a filter: they differentiate the wide band impulse signal.

FCC Requirements

- 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 !!

Multiuser Scenario

- Composite RX signal

\[
y(t) = \sum_{u=1}^{U} s_u \ast g^{\text{eq}}(t - \Delta u_t) + \eta(t) = \sum_{u=1}^{U} \sum_{k=1}^{N} h_u s_u g^{\text{eq}}(t - kLT_f - \Delta u_t) + \eta(t)
\]

Convolution of the \( u \)-th user's signature waveform with the \( u \)-th user channel

Single User Receiver

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

\[
Z_u(k) = \int_{-\infty}^{\infty} y(t) g_u^{\text{eq}}(kLT_f + \Delta t - t) dt
\]

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

\[
g_u^{\text{eq}}(t) = v_u^{\text{eq}}(t) \ast g_u^{\text{eq}}(-t)
\]

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

\[
Z_u(k) = h_u \int_{-\infty}^{\infty} v_u^{\text{eq}}(t) \ast w(k) dt + \sum_{n=1}^{N-1} \sum_{k} h_u \int_{-\infty}^{\infty} v_u^{\text{eq}}(t + nLT_f + \Delta u_t) g_u^{\text{eq}}(t) dt + u(k)
\]

useful term

MAI

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).

\[ h_n(t) = \sum_{\tau} \alpha_{\tau} \delta(t - \tau) \]

- The received signature waveform can be synthesized as follows

\[ v^{\text{TH,DS}}_n(t) = \sum_{k} \sum_{m} \sum_{\tau} \alpha_{\tau} \delta(t - \tau) \]

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

- 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

Simulation Results

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

References

- Space-Time Coding
  - Foschini, Bell Labs Tech. Journal 1996
- OFDM – FMT Systems
- UWB Systems