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Outline

- Spectrum usage considerations
- *Cognitive Radio* to increase spectrum efficiency
- *UWB* towards *Cognitive Radio*
- *Coexistence* problem
- *Narrowband* ↔ *UWB* systems
- Example of results
- Conclusions
Traditional spectrum usage policies

Fixed spectrum allocation:
- broadcasting
- cellular..

Spectrum sharing:
- Unlicensed bands (ISM):
  - WiFi
  - ZigBee
  - Bluetooth

Drawbacks:
- Inefficient spectrum usage
- Capacity limited by the allocated frequency bandwidth (data rate)
- Several years needed to start new wireless systems and services

Cognitive Radio is a new radio design philosophy:
1) First sense the spectrum, interference, environment...
2) Then adapt transmission, protocol... to the spectrum available

Cognitive Radio

Allows secondary users to use the spectrum already licenced to primary users, without damaging the primary users’ performance.

- “interwave” approach
  - exploits the spectrum holes (unoccupied frequency bands) opportunistically to communicate, therefore avoiding the overlapping with primary transmissions, which otherwise it would damage.

- “underlay” approach
  - Allows the cognitive users to operate on a certain frequency band, either unoccupied or not, provided that the interference caused to primary users remains below a fixed threshold (interference temperature). This is the case for UWB systems.

- “overlay” approach
  - The cognitive user employs part of its power to maintain or improve the primary users’ performances, so as to compensate for deterioration due to its own transmissions (e.g. by relaying the primary user’s signal).
“Interwave” approach

How much of the spectrum is actually used in space/time?

Example of usage in time in a given location

Spectrum occupancy measurements show that licensed bands are, in many cases, significantly underutilized:

- in some geographical areas (space)
- In time

Examples: TV bands (underutilized in space), bands allocated to emergency services (underutilized in time)
**“Interwave” approach**

Cognitive Radio:

- finds free portions of the spectrum: sensing
- begins to transmit inside those bands: agile spectrum usage
- eventually being get out if needed when the primary users show up

**“underlay” approach**

Allows the cognitive users to operate on a certain frequency band, either unoccupied or not, provided that the interference caused to primary users remains below a fixed threshold.

**UWB systems**

**USA**: regulated by FCC (14/02/2002)
- frequency band 3.1–10.6 GHz
- power spectral density limited to -41.3 dBm/MHz

**EC definition of UWB:**
- a signal with at least 500 MHz bandwidth or fractional bandwidth greater than 20%

**Europe**: regulated by EC (21 Feb. 2007)
- frequency band 6–8.5 GHz
- power spectral density limited to -41.3 dBm/MHz

**EC definition of UWB:**
- a signal with at least 50 MHz bandwidth

**UWB:**

- Time Hopping
- Direct Sequence
- OFDM/Multiband (WiMedia)

*With the possibility of using UWB communication systems, FCC has allowed, for the first time, the use of licensed spectrum to license-exempt users (underlay licensed bands).*
“overlay” approach

The cognitive user employs part of its power to maintain or improve the primary users’ performances, so as to compensate for deterioration due to its own transmissions.

For the ST-SR transmission we could use “writing on dirty paper” techniques.
Cognitive Radio - a definition

“Cognitive radio is an intelligent wireless communication system that is aware of its Radio Frequency (RF) environment, and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the environment by making changes to adjustable parameters, namely transmit power, carrier frequency and modulation strategy, all in real Time” [Mitola, 1999].

Aims:

Reliable communication

Efficient use of the frequency spectrum

Cognitive Cycle

I – Radio scene analysis: interference estimation, spectrum holes detection.
II – Channel identification: estimation of the channel state and of the available capacity.
III – Transmit power control and dynamic spectrum management.
Cognitive Radio: the FCC vision


- A licensee can employ cognitive radio technologies internally within its own network to increase the efficiency of use.

- Cognitive radio technologies can facilitate secondary markets in spectrum use, implemented by voluntary agreements between licensees and third parties. Ultimately cognitive radio devices could be developed that “negotiate” with a licensee’s system and use spectrum only if agreement is reached between a device and the system.

- Cognitive radio technologies can facilitate automated frequency coordination among licensees of co-primary services.

- Cognitive radio technologies can be used to enable non-voluntary third party access to spectrum, for instance as an unlicensed device operating at times or in locations where licensed spectrum is not in use.

Some activities on CR within IEEE

- Proposal IEEE 802.22 for Wireless Regional Area Networks: CR on terrestrial TV broadcasting bands (47-910 MHz)
  - Centralized scenario

  ![Diagram of a centralized scenario with CPEs and a DVT station]

  CPE= Customer Premise Equipment

- IEEE 1900 Standards Coordinating Committee 41 (SCC41), Dynamic Spectrum Access Networks (DySPAN).
UWB & CR

UWB represents a viable solution for CR:

- sensing over a large bandwidth
- spectrum sculpting for interference avoidance
- underlay transmission with low PSD

Coexistence between UWB and NB systems

NB => UWB
UWB => NB
First scenario: NB => UWB-IR

**Propagation scenario**

**Narrowband interference:**
- $\alpha_i$ Rayleigh distributed r.v.

**Ultrawide band system:**
- $L$ paths
- $\alpha_k$ fading amplitude
- $\theta_k \sim U[0, \pi]$  
- $t_k$ path delays

\[
h_{\text{DX}}(t) = \sum_{k=1}^{L} h_k \delta(t - t_k) \quad \text{with} \quad h_k = \alpha_k \cdot e^{j\theta_k}
\]
**The Desired (UWB) Signal**

Binary **TH-PPM**

The Desired (UWB) Signal

\[ s(t) = \sqrt{E_b} \sum_i b(t - iT_b; d_i) \]

with

\[ \rho \triangleq \frac{1}{T_b} \int_{-\infty}^{\infty} b(t; 0)b(t; 1) dt \]

the correlation coeff.

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**First case: NB => UWB-IR**

The primary user model

The **primary user** has a bandwidth of few MHz => it can be approximated as a **TONES** (*).

**The Rake Receiver**

Conditioned on $h_0(t)$ the optimum receiver in the presence of AWGN is a MF matched to the received signal $h_0(t) * s(t)$

\[ \text{this MF is realized adaptively as a Rake receiver} \]

\[ \sqrt{2I_{\alpha} t} \cos(2\pi f_I (t - r) + \phi) \]

\[ h_0(t) * s(t) \]

\[ H(f) \]

\[ u(t) \]

\[ u(t_0) \]

\[ t_0 = t_0 + kT \]

\[ v(t) \]

Assuming perfect synchronization, the output of the MF is:

\[ u(t_0) = s_0 + \sqrt{2I_{\alpha} t} |H(f)| \cos \phi + n_0 \]

where:

\[ s_0 = \sqrt{E_s} \int_{t_0 - T_s}^{t_0} r_b(t; d_0) v(t) dt \]

\[ v(t) = \sum_{k=1}^{L} h_k [b(t - t_k; 0) - b(t - t_k; 1)] \]

\[ |H(f)| = |\mathcal{F} \{ b(t; 0) - b(t; 1) \} | \cdot \left| \sum_{k=1}^{L} h_k e^{-j2\pi f t_k} \right| \]

\[ |H_0(t)| \quad \zeta(h, t) \]

\[ \text{signaling waveform} \quad \text{multipath channel} \]
Secondary user receiver

DS-BPAM system

Assuming a 6-th derivative Gaussian pulse with Fourier T.

\[ W(f) = \frac{8 \pi^3}{3 \sqrt{1155} N_b} T_b^{13/2} e^{-\frac{f^2}{2}} \]

\[ |H_0(f)| = 2 |W(f)| \sum_{k=0}^{N_b-1} c_k e^{j2\pi f k T_b} \]

Example: performance of the SU

System parameters

- DS-BPAM
- pulse duration \( T_w = 0.192 \) ns
- frame duration \( T_f = 100 \) ns
- pulses per bit \( N_b = 6 \)
- DS sequences
  - \( c_1 = \{+1,+1,-1,-1,+1,+1\} \)
  - \( c_2 = \{+1,+1,-1,-1,-1,+1\} \)
  
- \( f_I = 5.003 \) GHz
The spectrum of the SU

The transmitted power spectral density of the secondary user (in this case a DS-BPAM system) is

\[ S(f) = \frac{E_b}{T_b} |W(f)|^2 \left| \sum_{k=0}^{N-1} c_k e^{j2\pi f k T_t} \right|^2 \]

Note that this is proportional to the transfer function of the matched filter at the secondary user receiver

\[ |H_0(f)| = 2 |W(f)| \left| \sum_{k=0}^{N-1} c_k e^{j2\pi f k T_t} \right| \]

Therefore, we can reduce the mutual interference!!!

![The spectrum of the SU](image-url)
Fig. 11. BER for the DS-8PAM system considered with a single tone interferer and AWGN.

Fig. 12. BER for the DS-8PAM system considered with Rake reception and $L = 8$ paths with a tone interferer.
Other case: NB => UWB-OFDM

Frequency-Selective channel for the secondary user link
- block fading channel in the frequency domain
- Channel coding across the subcarriers

Frequency-flat fading channel for the primary-to-secondary user link

Other case: NB => UWB-OFDM

a) $N_0 + E_t$

b) $\gamma_i \cdots \gamma_i \cdot \xi$

$N_{\	ext{sub-carriers}}$
NB => UWB-OFDM: Example of results

Fig. 8. Error probability per codeword, OFDM over a BFC in the frequency-domain with $N_a$ sub-carriers per block, QPSK over all useful 126 sub-carriers, BCH code with $n=126$, $R_b=1/2$ and $t=10$. Narrowband interference over $N_l$ sub-carriers, signal-to-interference ratio $SIR = 0$ dB.

UWB-IR => NB

NB receiver with matched filter receiver
UWB-IR => NB
Signal at the output of the NB MF

Interfering signal
$p(t)$

NB symbol pulse
$g(t)$

Interfering term after the MF
$t_{k-1}$ $t_k$ $t_{k+1}$
Sampling instants

Gaussian approximation for the interference? Shot noise?

UWB workshop, Ferrara, 2008
Marco Chiani

UWB-IR => NB: Example of results

Fig. 16: BEP for the NB victim link affected by a UWB interference on AWGN.
Conclusions

➢ We addressed the coexistence problem by reviewing some recent results on the impact of NB interference on UWB systems.

➢ The analysis has shown the great potential of UWB in adapting the transmitted spectrum to counteract the NB interference and at the same time to guarantee a low spectral emission over the NB communications.

➢ By keeping low the mutual interference, UWB can be a potential technology for an efficient spectrum usage which represent the main goal for Cognitive Radio.

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