UWB flexible assets in radio, access, and network design

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Outline

- UWB Impulse Radio features and framework of application
- Flexible radio
- Flexible MAC
- Flexible routing

UWB Impulse Radio features

The common adoption of the term UWB comes to us from the radar community, and refers to electromagnetic waveforms with an instantaneous fractional bandwidth greater than about **0.20–0.25**

Traditionally, UWB signals have been obtained by transmitting **very short pulses** with typically no Radio Frequencies modulation

(In communication systems, "very short" refers to a duration of the pulse that is typically about a few hundred picoseconds)

This technique goes under the name of

→ **Impulse Radio (IR)**

UWB Impulse Radio features

Since time duration of each pulse is smaller than the original symbol duration, signal energy is spread over a bandwidth which can be much greater than the bandwidth of the user waveform.

In contrast to conventional Spread Spectrum systems, the increase in occupied bandwidth is not due to the presence of spreading sequences: it is the extremely short duration of the basic pulse which makes the system ultra-wide in bandwidth

Very short pulse → **Ultra-Wide Bandwidth**

UWB Impulse Radio features

Most of the IR UWB systems reported in the reference literature differ in terms of modulation techniques and coding strategies.

User data can modulate pulses amplitude with binary antipodal variations (**Pulse Amplitude Modulation PAM**)

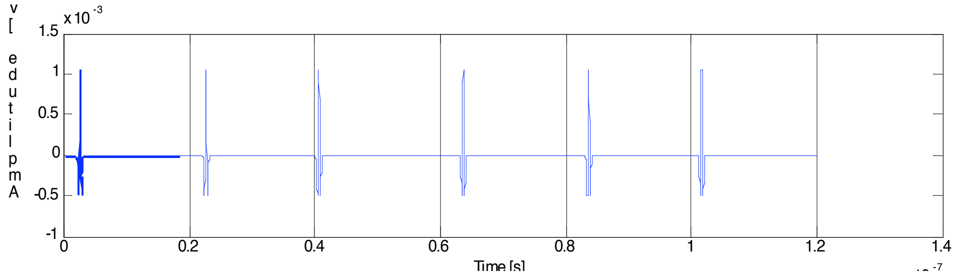
User data can turn the pulses on and off (**On Off Keying** - **OOK**)

User data can dither the pulses position (**Pulse Position Modulation** - **PPM**)

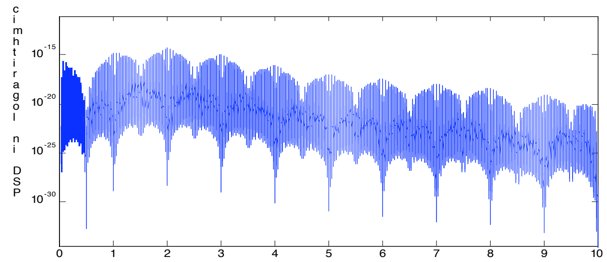
UWB Impulse Radio features

In addition to modulation, and in order to shape the spectrum of the generated signal (and differentiate users), modulated data symbols are generally encoded using time hopping codes.

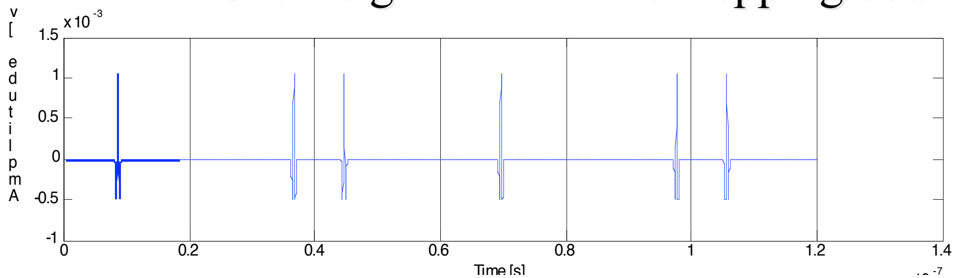
PPM IR UWB signal without coding



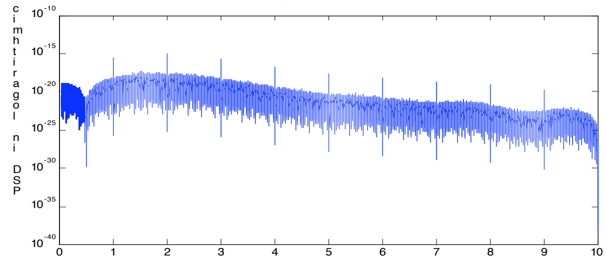
Power Spectral Density



PPM IR UWB signal with Time Hopping coding

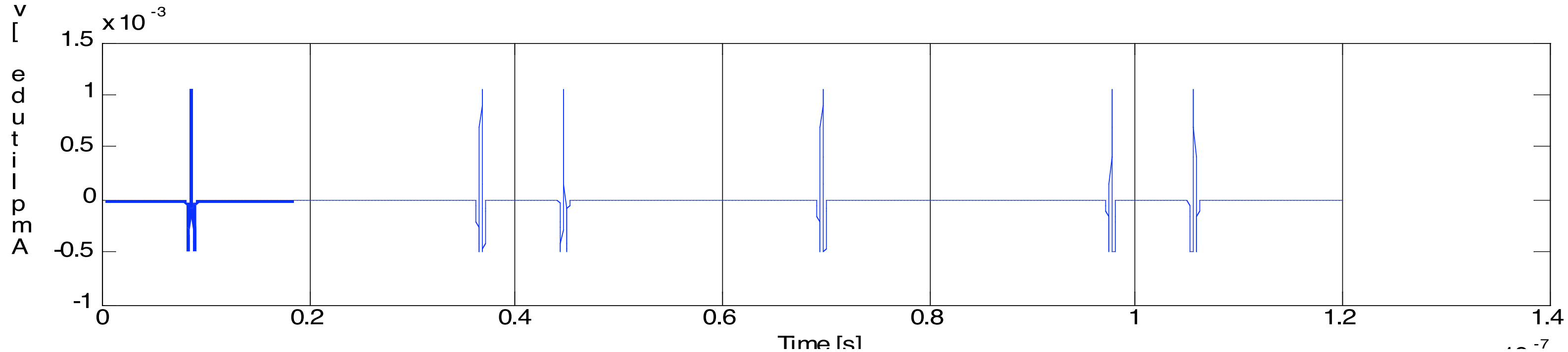


Power Spectral Density



UWB Impulse Radio features

- We focus on a UWB signal format is the one typical of Impulse Radio, with Time-Hopping coding (TH) and binary Pulse Position Modulation (PPM)



Transmitted Signal

$$s(t) = \sqrt{P_{TX} T_S} \sum_j p_w(t - jT_S - c_j - a_j \varepsilon)$$

P_{TX} is the average transmitted power
T_S is the pulse repetition period
$p_w(t)$ is the energy-normalized pulse shape
$c_j < T_S$ is the TH code value for pulse j
a_j is the data symbol carried by pulse j
ε is the PPM shift

UWB Impulse Radio framework of application

Standard for **low-rate** WPANs with multi-month to multi-year battery life.

- IEEE 802.15.4 features include data rates of 20-250 kbps, power management to ensure low power consumption, and low complexity.

- Regarding the introduction of UWB in low-rate, location-enabled applications, standardization is taking place within the **IEEE 802.15.4a** Task Group

UWB Impulse Radio framework of application

- Within the 802.15.4, the Low Rate Alternative PHY Task Group (**TG4a**) is working to provide high precision ranging / location capability (1 meter accuracy and better) and ultra low power.
- In March 2005, TG4a selected two optional PHYs consisting of:
  - a **UWB Impulse Radio** (operating in unlicensed UWB spectrum)
  - a Chirp Spread Spectrum (operating in unlicensed 2.4GHz spectrum).

A Flexible Radio

Flexible radio design: example of application

$$s(t) = \sqrt{P_{TX} T_S} \sum_j p_w(t - jT_S - c_j - a_j \varepsilon)$$

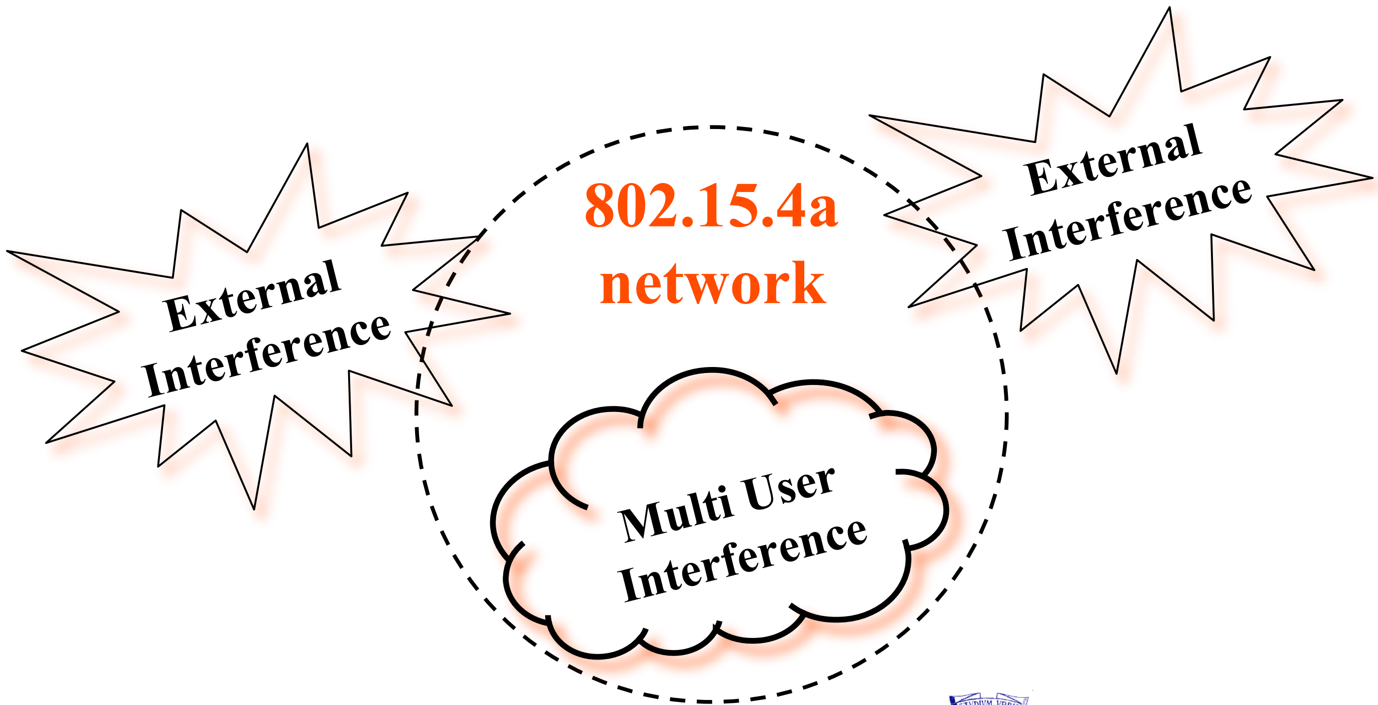
- Different pulse waveforms can be selected for transmission.
- These waveforms lead to different spectral shapes for the transmitted signals, so that the UWB signal can be adapted to different interference scenarios.
- We assume that up to **6 different waveforms** can be selected for transmission

$$w = 1, \ldots, 6$$

M.-G. Di Benedetto, G. Giancola and M.D. Di Benedetto, " Introducing Consciousness in UWB networks by Hybrid Modelling of Admission Control," Mobile Networks and Applications, vol.11 no.4, pp. 521-534 ISSN: 1383-469X. ACM/Springer Journal on Mobile Networks and Applications, Special Issue on "Ultra Wide Band for Sensor Networks" , 2006.

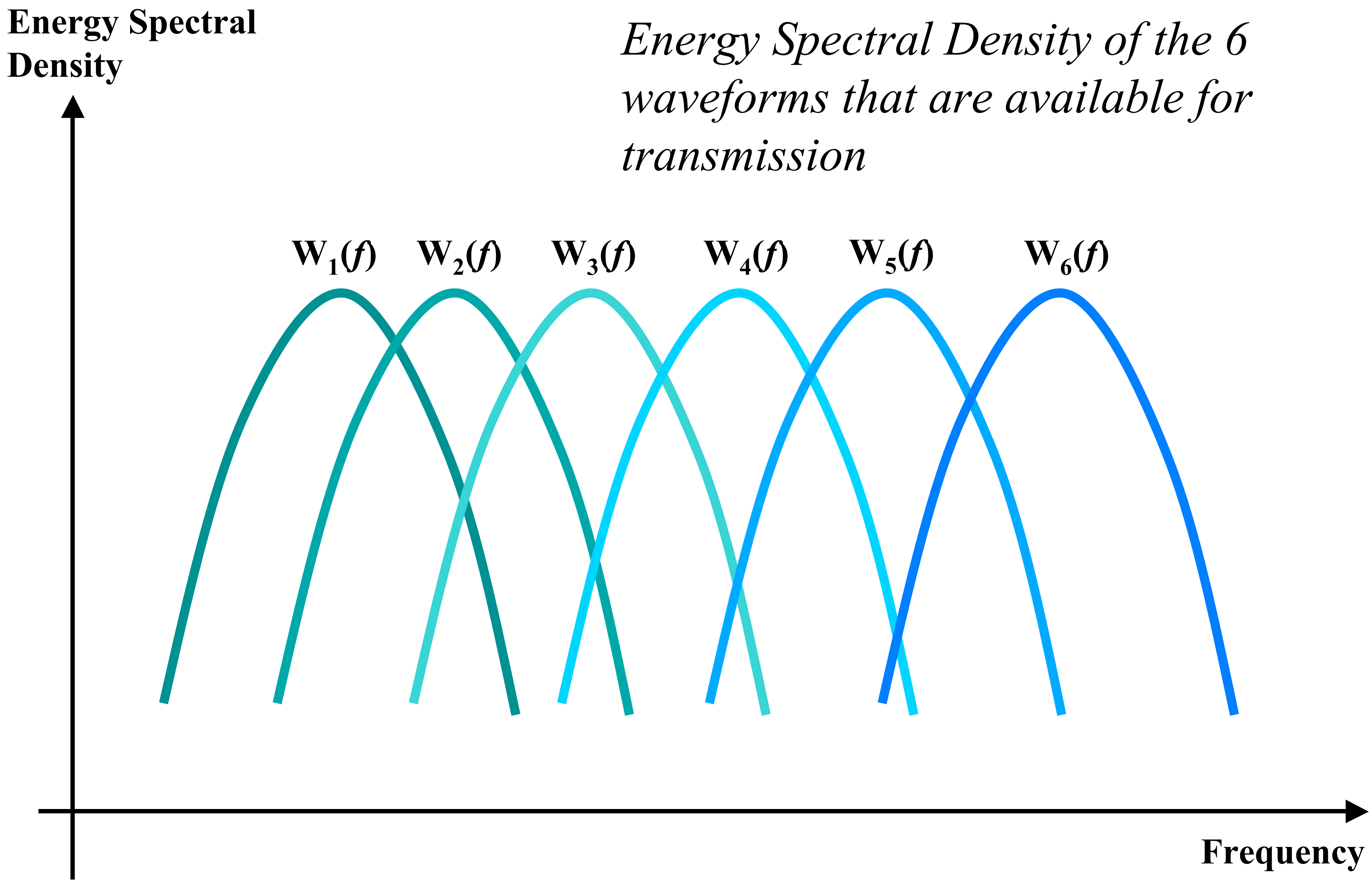
Flexible radio design: example of application

- **Scenario**: a self-organizing network of low-power, low-cost and low-rate IR-UWB devices (as those considered within the IEEE 802.15.4a standard)

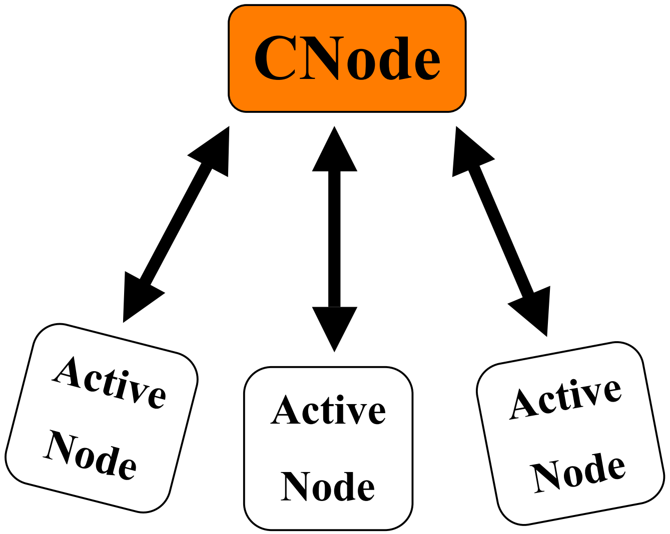


Flexible radio design: example of application

Energy Spectral Density of the 6 waveforms that are available for transmission



Flexible radio design: example of application



- All network nodes communicate through one elected node, denoted as the Conscious Node of the network (**CNode**)
- The **CNode** plays the role of network coordinator

- Time Hopping (TH) coding is used for discriminating among users
- Power control at the CNode is assumed for all uplink connections

Flexible radio design: example of application

- In such system, the performance of a given link between one active node and the CNode is expressed by:

$$\mathrm{BER} = (1/2)\, erfc\left(\sqrt{SNR/2}\right)$$

$$SNR = \frac{1}{R_b} \frac{P_{RX}}{\text{ç}_p(w) + \text{ó}_m^2(w)(N-1)P_{RX}}$$

$\boldsymbol{P_{TX}}$ is the average received power
$\boldsymbol{R_b}$ is the bit rate
→ $\boldsymbol{\eta_p(w)}$ is the variance of noise (thermal noise + external interference) collected for one single pulse [w = 1,2,…,6]
→ $\boldsymbol{\sigma_m^2(w)}$ is a Multi User Interference weight [w = 1,2,…,6]
N is the number of active users

Evaluation of transmission parameters

$$SNR = \frac{1}{R_b} \frac{P_{RX}}{\eta_p(w) + \sigma_m^2(w)(N-1)P_{RX}}$$

- Based on **environment sensing**, the CNode estimates the values of $\boldsymbol{\eta_p(w)}$ and $\boldsymbol{\sigma_m^2(w)}$
- Then, it computes the value of the minimum power $\boldsymbol{P_{min}}$ that must be received from each node in order to guarantee $SNR \geq SNR_0$ (minimum value required for synchronization)

$$P_{min}(w) = \frac{\eta_p(w)}{T_S} \left(\frac{1}{SNR_0} - \frac{\sigma_m^2(w)(N-1)}{T_S} \right)$$

Evaluation of transmission parameters

$$P_{min}(w) = \frac{\varsigma_p(w)}{T_S}\left(\frac{1}{SNR_0} - \frac{\acute{o}_m^2(w)(N-1)}{T_S}\right)$$

- Since P_{min} depends on the adopted waveform, the waveform $p_{w*}(t)$ that better adapts to the environment is the the one leading to the smallest $P_{min}(w)$ value.
- The CNode can thus determine two factors:
  - the waveform $p_{w*}(t)$ to be currently used by the active nodes of the network
  - the corresponding $P_{\min}(w^*)$

The three levels of flexibility

- We considered three different types of CNode for the simulation

Full Flexibility	The CNode is always capable to select the optimum pulse shape among the 6 available waveforms
Intermediate Flexibility	The CNode has **reduced capabilities**, since it is capable to select the pulse shape within a sub-set of the 6 available waveforms.
No Flexibility	The CNode **randomly** selects a waveform at the beginning of network operation and does not perform any further selection during network lifetime

Simulation Analysis

- Performance analysis

Case A
(slow variations)

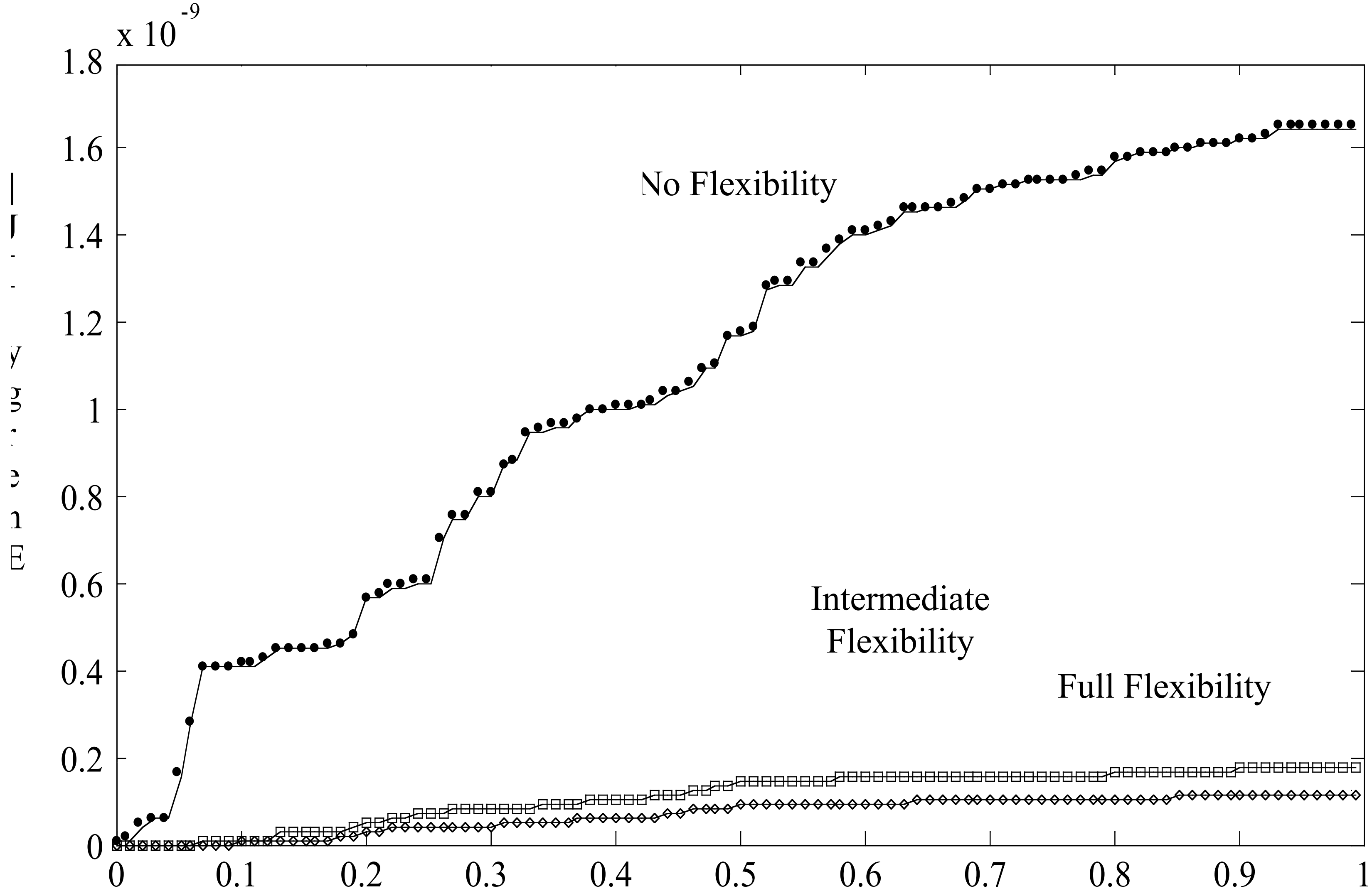
- 20 external devices generate narrowband interfering signals located around 2, 4, 6 and 8 GHz
- Interfering devices switch on and off with an average active time and an average silent time of **100 µs**

Case B
(rapid variations)

- 20 external devices generate narrowband interfering signals located around 2, 4, 6 and 8 GHz
- Interfering devices switch on and off with an average active time and an average silent time of **10 µs**

Results (Case A)

Consumed Energy vs. Time in a reference scenario characterized by slow changes of the external interference pattern



A Flexible MAC

IR UWB flexible MAC design

- IR Ultra Wide Band based on time hopping and impulse radio is characterized by:
  - Low probability of pulse collision
  - Accurate ranging (theoretical limit far below 1 cm)

- Impulse Radio features with respect to MUI and synchronization form the basis for the definition of an UWB-tailored MAC algorithm.

↓

Uncoordinated, Wireless, Baseborn medium access for UWB communication networks $(UWB)^2$

M.-G. Di Benedetto, L. De Nardis, M. Junk,G. Giancola, " (UWB)^2: Uncoordinated, Wireless, Baseborn, medium access control for UWB communication networks," Mobile Networks and Applications, vol. 10 no.5, pp. 663-674. Mobile Networks and Applications special issue on WLAN Optimization at the MAC and Network Levels, 2005.

The $(UWB)^2$ Protocol

- For TH-IR, the probability of successful packet transmission is fairly high, for uncoordinated transmission of several users and in the presence of MUI.
- Based on this result, $(UWB)^2$ adopts a pure Aloha approach
- In addition, $(UWB)^2$ makes use of a synchronization scheme that foresees the presence of a synchronization trailer in each transmitted packet.

$(UWB)^2$ MAC: Design choices

Key assumptions

Simple Synchronization Hardware

Low Data Rate and rare packets
(peak rate ≤ 1 Mb/s,
average rate ≤ 20 Kb/s)

Need for broadcast packets

Time Hopping Impulse Radio with GHz bandwidth

Design Choices

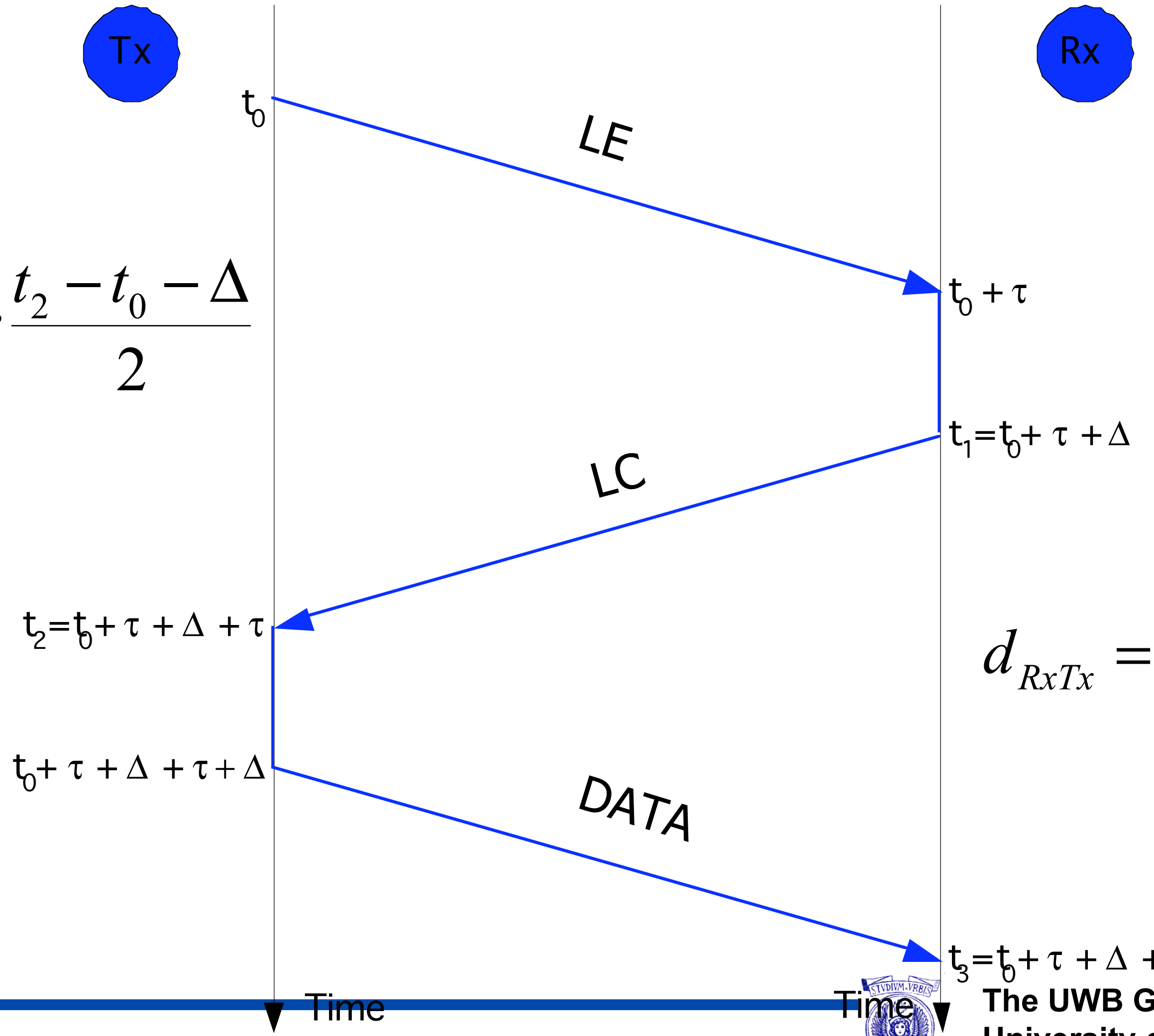
Synchronization is achieved on a packet-by-packet basis

No Carrier Sensing: pure Aloha
(with TH coding)

TH-CDMA:
Common signaling code available to all devices
+
Dedicated data code unique for each transmitter

(UWB)[2] MAC: Transmission and Ranging procedure

- The LE -> LC -> DATA exchange allows both Tx and Rx terminals to determine their distance:



$$d_{TxRx} = c\tau = c\frac{t_2 - t_0 - \Delta}{2}$$

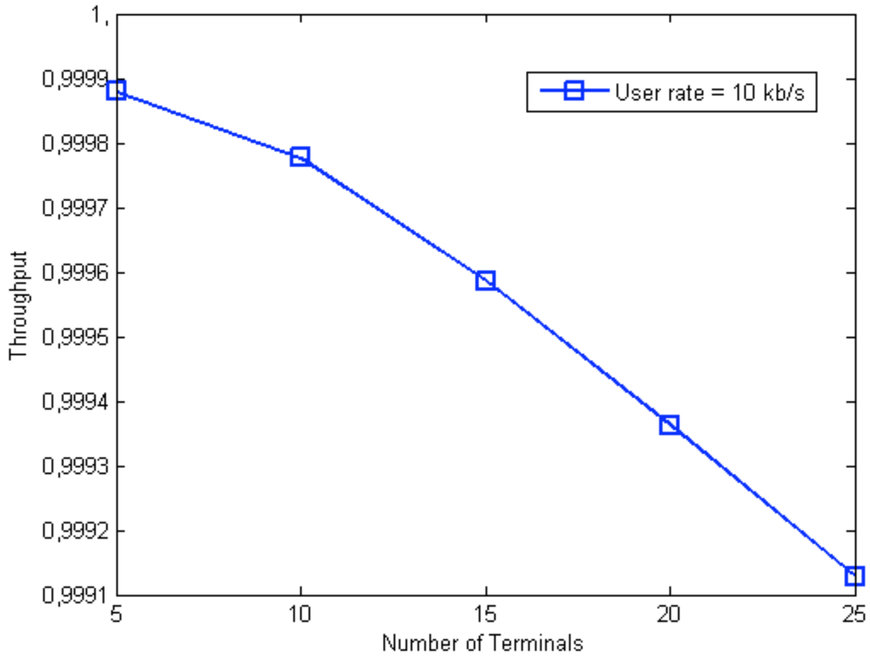
$$d_{RxTx} = c\tau = c\frac{t_3 - t_1 - \Delta}{2}$$

(UWB)^2: Performance analysis

- (UWB)^2 was tested in typical Low Data Rate scenarios:
  - user rates in the range 10-100 kb/s
  - 1 Mb/s on the wireless channel
- Effect of Channel and Multi User Interference was taken into account in the analysis
- Two performance indicators were considered:
  - **Throughput -** % of transmitted packets, that are correctly received
  - **Delay** - Time interval between the first transmission of a packet and its correct reception, including eventually time wasted for retransmissions after packet collisions

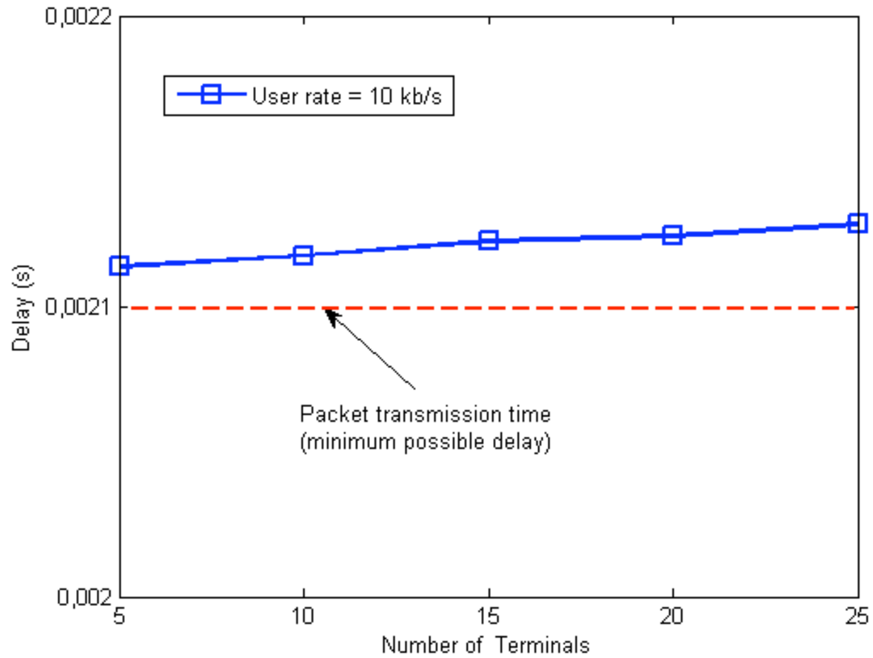
(UWB)^2: Performance analysis

- Impact of number of terminals



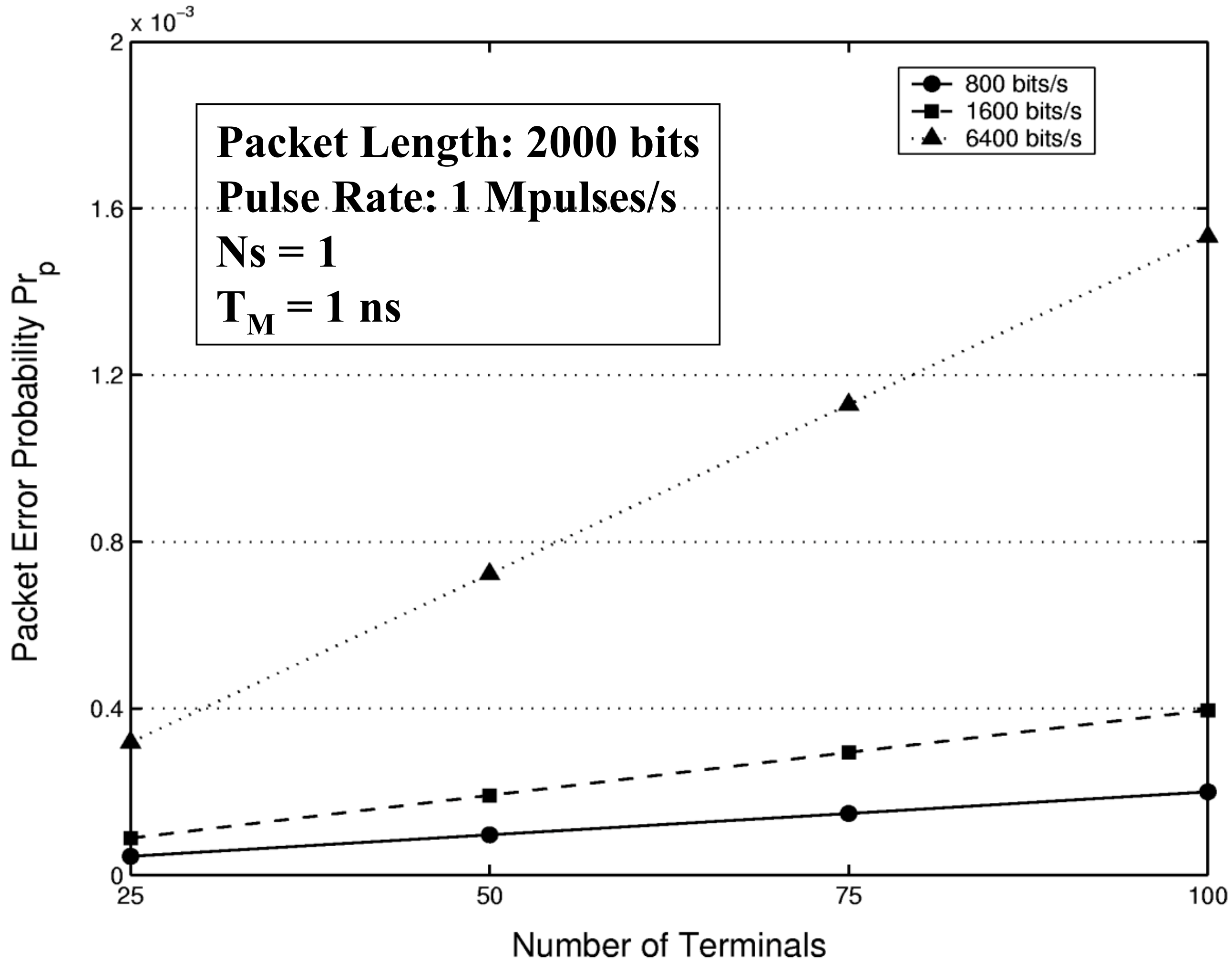
Throughput

Delay



The $(UWB)^2$ Protocol

Performance of $(UWB)^2$ in terms of Packet Error Probability vs. Number of Terminals



A Flexible network

Flexible network

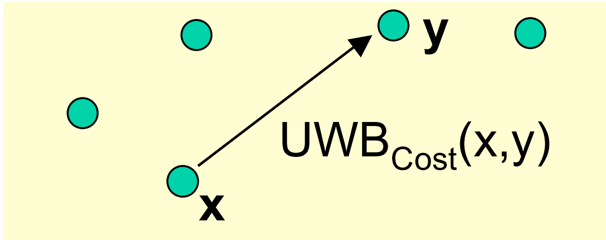
- Based on UWB peculiarities regarding ranging accuracy and power management is a routing strategy that adapts its behavior (i.e. the path selection criterion) to internal and external network conditions feasible?
- What is the impact of such a routing strategy in a power-constrained, interference-prone UWB network, in terms of:
    - Network performance
    - Network lifetime

?

M.-G. Di Benedetto and L. De Nardis, " Cognitive routing in UWB networks," invited paper, IEEE International Conference on UWB 2006 ICUWB 2006, Boston, Massachusetts, USA, September 24-27 2006.

Flexible routing

1. Define a routing metric which determines the cost of a link based on internal and external conditions
2. Select the minimum cost route



We defined the following metric:

$$UWB_{Cost}(x,y) = c_{Sync}(t) \cdot Sync(x,y) + c_{Power}(t) \cdot Power(x,y) +$$
$$+ c_{MUI}(t) \cdot MUI(x,y) + c_{Reliability}(t) \cdot Reliability(x,y) +$$
$$+ c_{Traffic}(t) \cdot Traffic(y) + c_{Delay}(t) \cdot Delay(x,y) +$$
$$+ c_{Autonomy}(t) \cdot Autonomy(y) + c_{Coexistence}(t) \cdot Coexistence(y)$$

Flexible routing

Delay term: $$Delay(x,y)=1$$

Autonomy term: $$Autonomy(y)=1-\frac{ResidualEnergy(y)}{FullEnergy(y)}$$

Coexistence term: $$Coexistence(y)=\frac{MeasuredExternalInterference(y)}{MaximumInterference(y)}$$

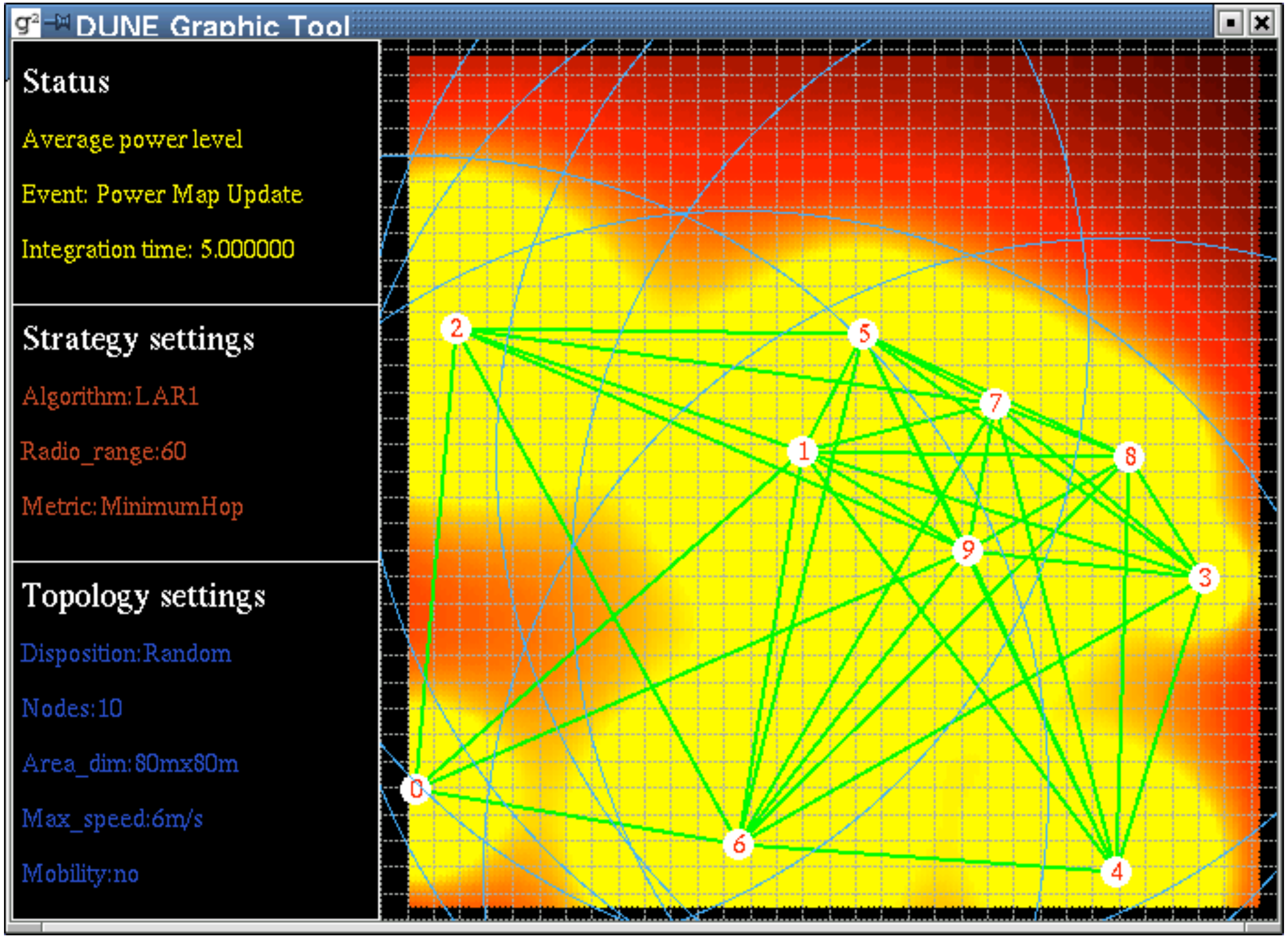
Analysis by simulation

- Three different coefficient sets:

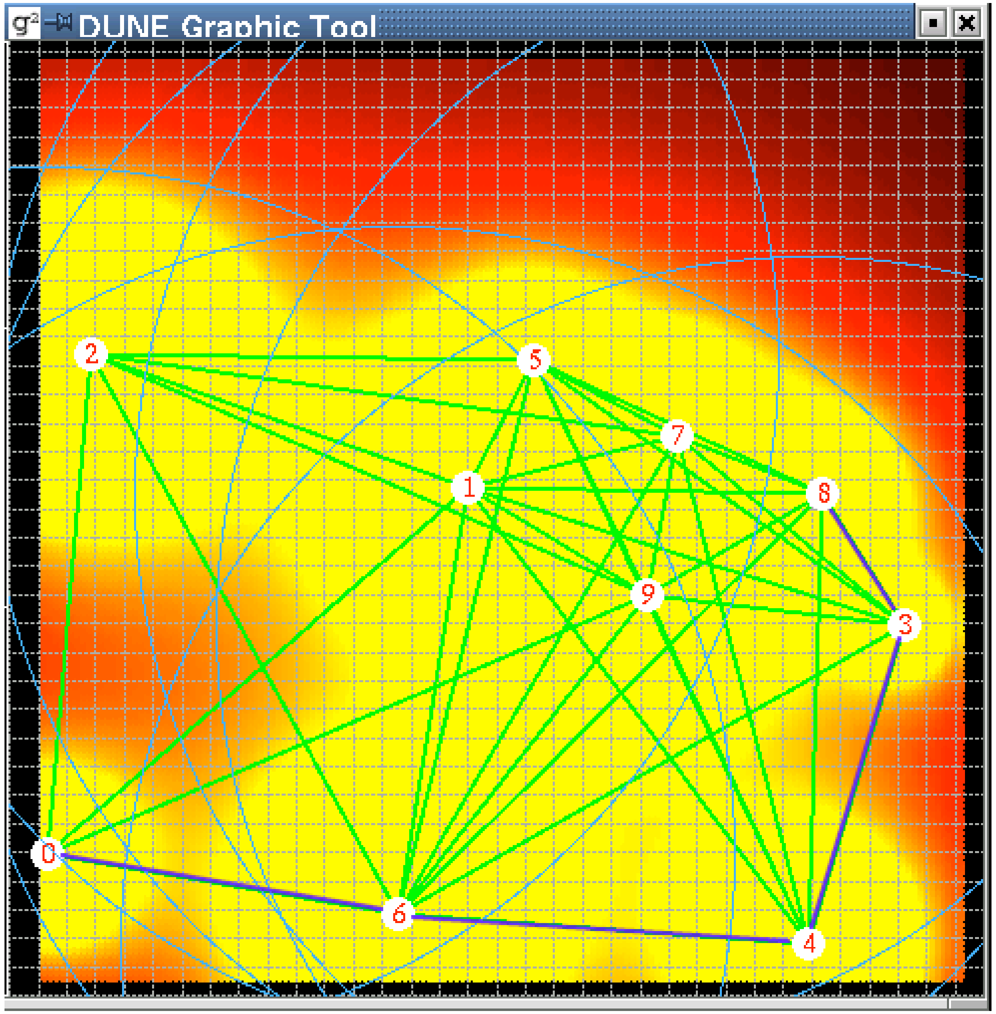
Coefficient	Set 1	Set 2	Set 3
C_{Delay}	1	0.0001	0.0001
$C_{Autonomy}$	0	1	0
$C_{coexistence}$	0	0	1

- Generation of external interferers:
  - f_c=3.5 GHz, B=20 MHz, P_t=10 mW
  - Activity factor *a* random in the interval (0,1]
  - Random position
  - Death/birth of interferers every 100 sec

Example: Power



Example: MUI



Acknowledgement

PULSERS (**P**ervasive **U**ltra-wideband **L**ow **S**pectral **E**nergy **R**adio **S**ystems) and **PULSERS II**

Integrated EU Project launched in January 2004 and January 2006 within the European Union IST 6th Framework

http://www.pulsers.eu