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

Impulse radio UWB signals are 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

Time duration of a pulse is smaller than original symbol duration

→ energy is spread over a large bandwidth

Contrarily to conventional Spread Spectrum, increased bandwidth is not provoked by spreading sequences, but rather by the

<u>extremely short pulse duration that induces ultra-wide bandwidth</u>

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

UWB Impulse Radio features

Impulse Radio systems differ in terms of modulation and coding

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

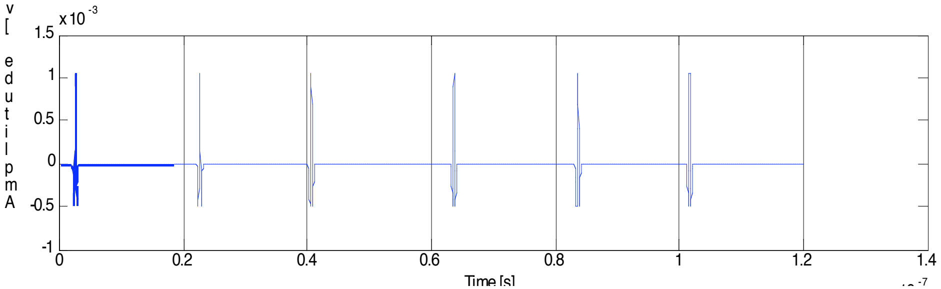
User data can turn pulses on and off
(**On Off Keying OOK**)

User data can dither pulse position
(**Pulse Position Modulation PPM**)

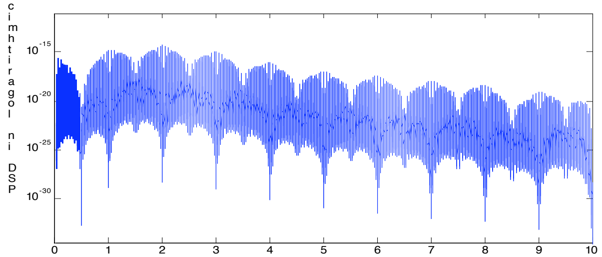
UWB Impulse Radio features

On top of modulation, symbols are encoded using Time Hopping TH codes for pulse shaping and user differentiation

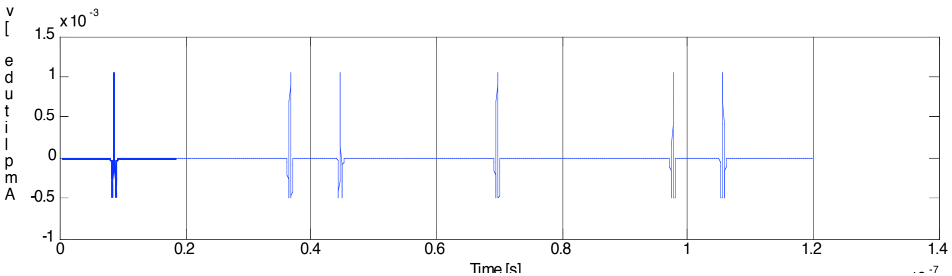
PPM IR UWB signal without coding



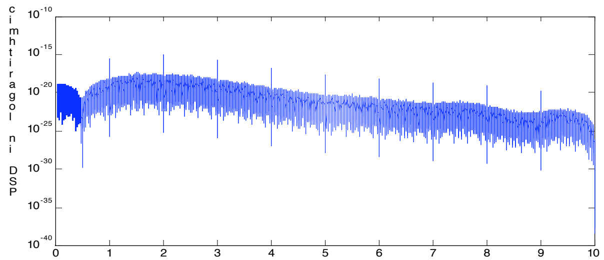
Power Spectral Density



PPM IR UWB signal with TH coding

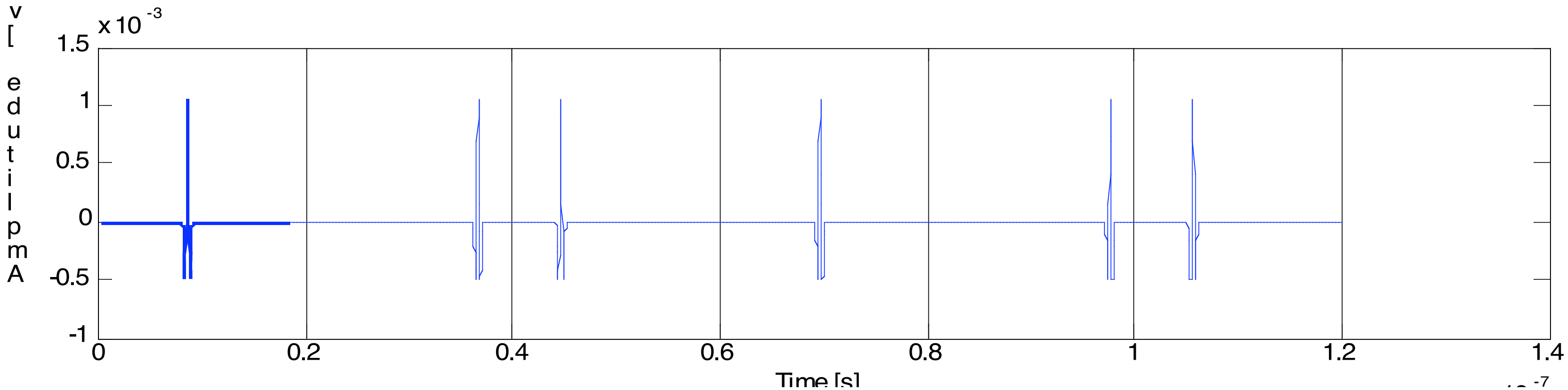


Power Spectral Density



UWB Impulse Radio features

We focus on a typical signal format: Time Hopping coding TH and binary Pulse Position Modulation PPM



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

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:

- ✓multi-month to multi-year battery life
- ✓data rates of 20-250 kbps
- ✓power management for low power consumption
- ✓low complexity

Same as above, plus:

- ✓**location enabled: high precision ranging/location (at least 1 meter accuracy)**
- ✓**ultra low power**

UWB Impulse Radio in the IEEE 802.15.4a standard

In March 2005, **TG4a** selected two optional PHYs:

- **UWB Impulse Radio** (unlicensed UWB spectrum)
- Chirp Spread Spectrum (unlicensed 2.4 GHz spectrum)

A Flexible Radio

Flexible radio design: example of application

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

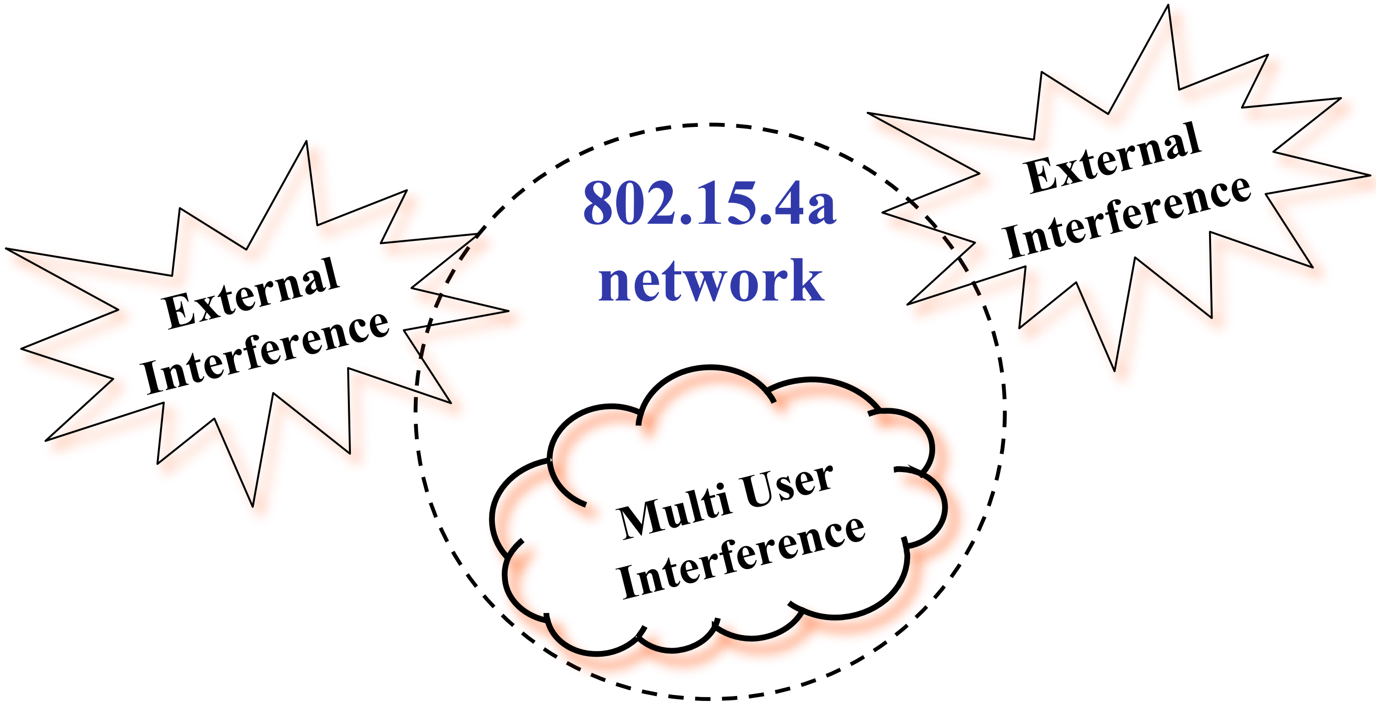
- Different waveforms can be selected for transmission.
- Waveforms lead to different spectral shapes for the transmitted signals, so that the UWB signal can be adapted to different interference scenarios.
- We suppose up to **6 possible different pulses**

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

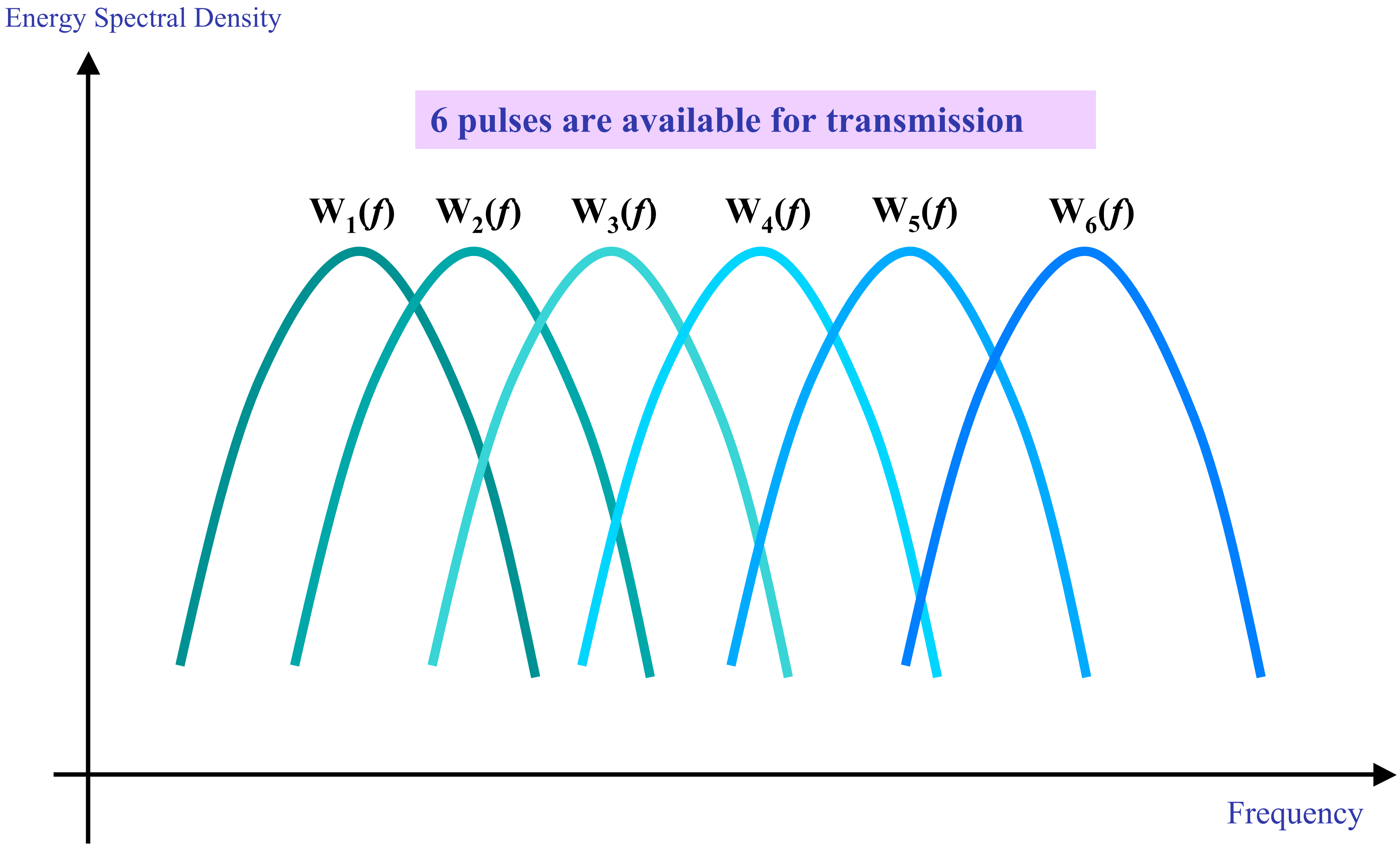
M.-G. Di Benedetto, G. Giancola and M.D. Di Benedetto, " Introducing Consciousness in UWB networks by Hybrid Modelling of Admission Control," Mobile Networks and Applications, vol.11 no.4, pp. 521-534 ISSN: 1383-469X, ACM/Springer Journal on Mobile Networks and Applications, Special Issue on "Ultra Wide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

Flexible radio design: example of application

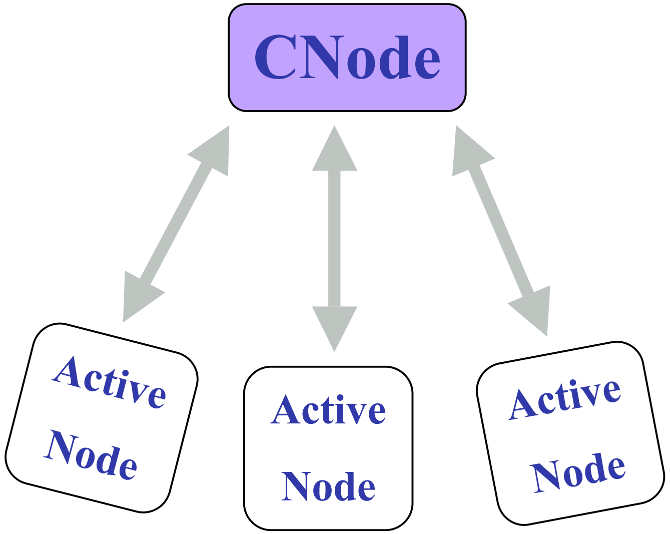
Scenario: a self-organizing network of low-power, low cost and low rate IR-UWB devices (IEEE 802.15.4a like devices)



Flexible radio design: example of application



Flexible radio design: example of application



- All 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 identifying users
- Power control at the CNode is assumed for all uplink connections

Flexible radio design: example of application

Performance of a link between one active node and the CNode is expressed by

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

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

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

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

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

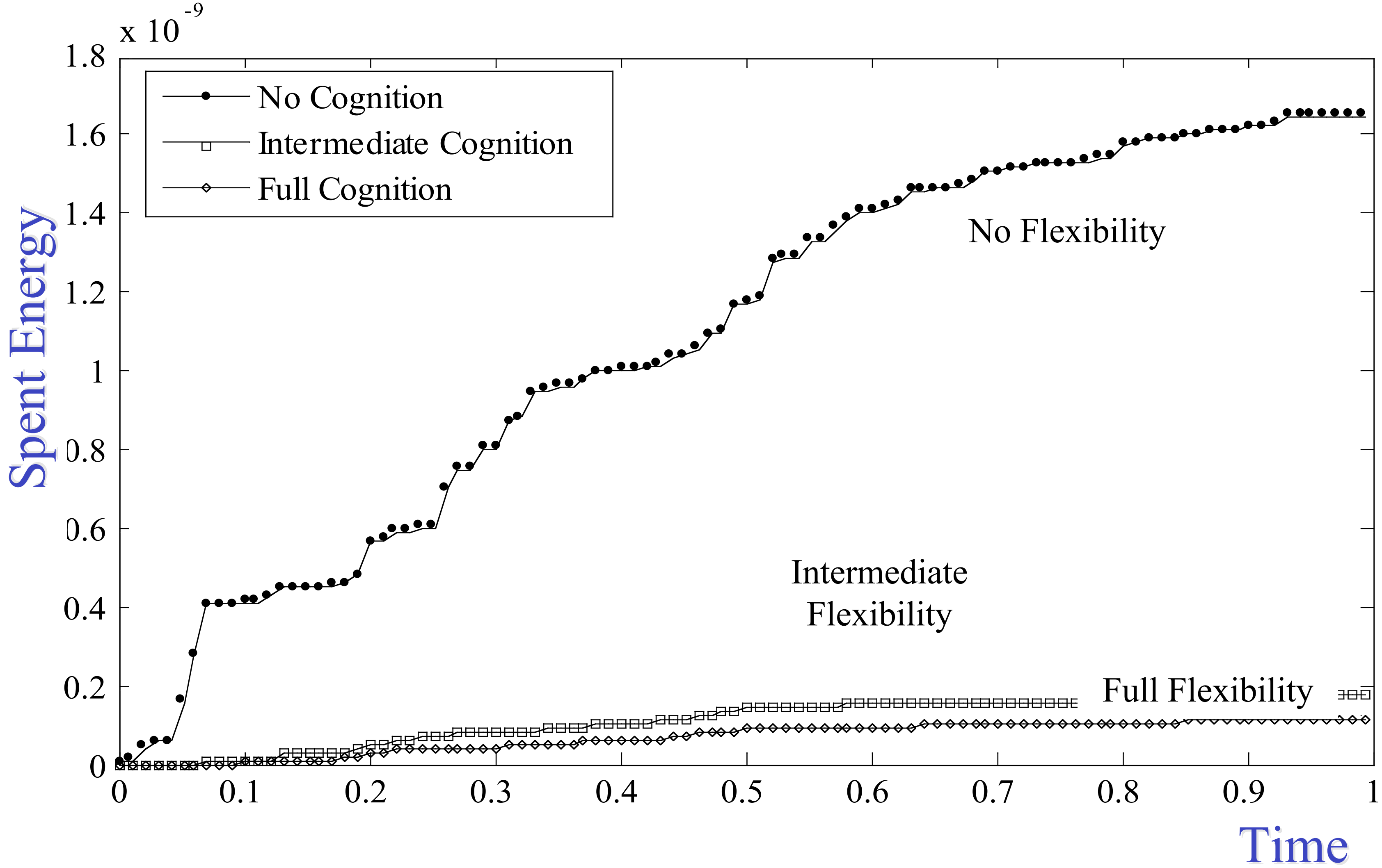
The three levels of flexibility

We simulated three different types of Cnode

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

Results

Interference pattern: 20 external interferers generating narrowband signals located @ 2, 4, 6 and 8 GHz switching on and off, with average active and silent time of **100 µs**



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.

(UWB)^2 Mac

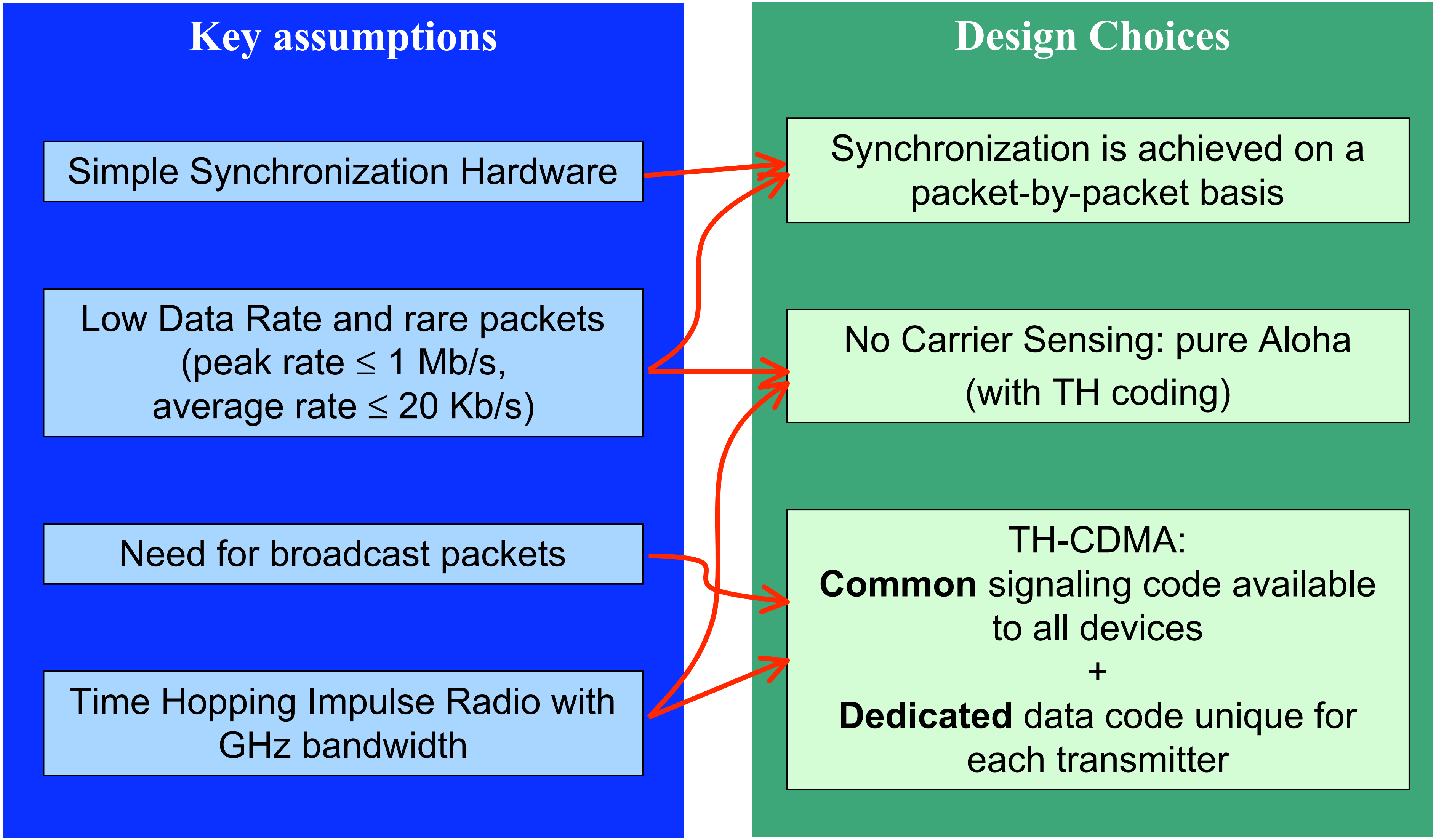
- For TH-IR, the probability of successful packet transmission for uncoordinated transmission of several users and in the presence of MUI is fairly high.

- Based on this result, (UWB)^2 was the first MAC protocol to propose a **pure Aloha approach**

- For synchronization purposes (UWB)^2 foresees the presence of a synchronization trailer in each transmitted packet

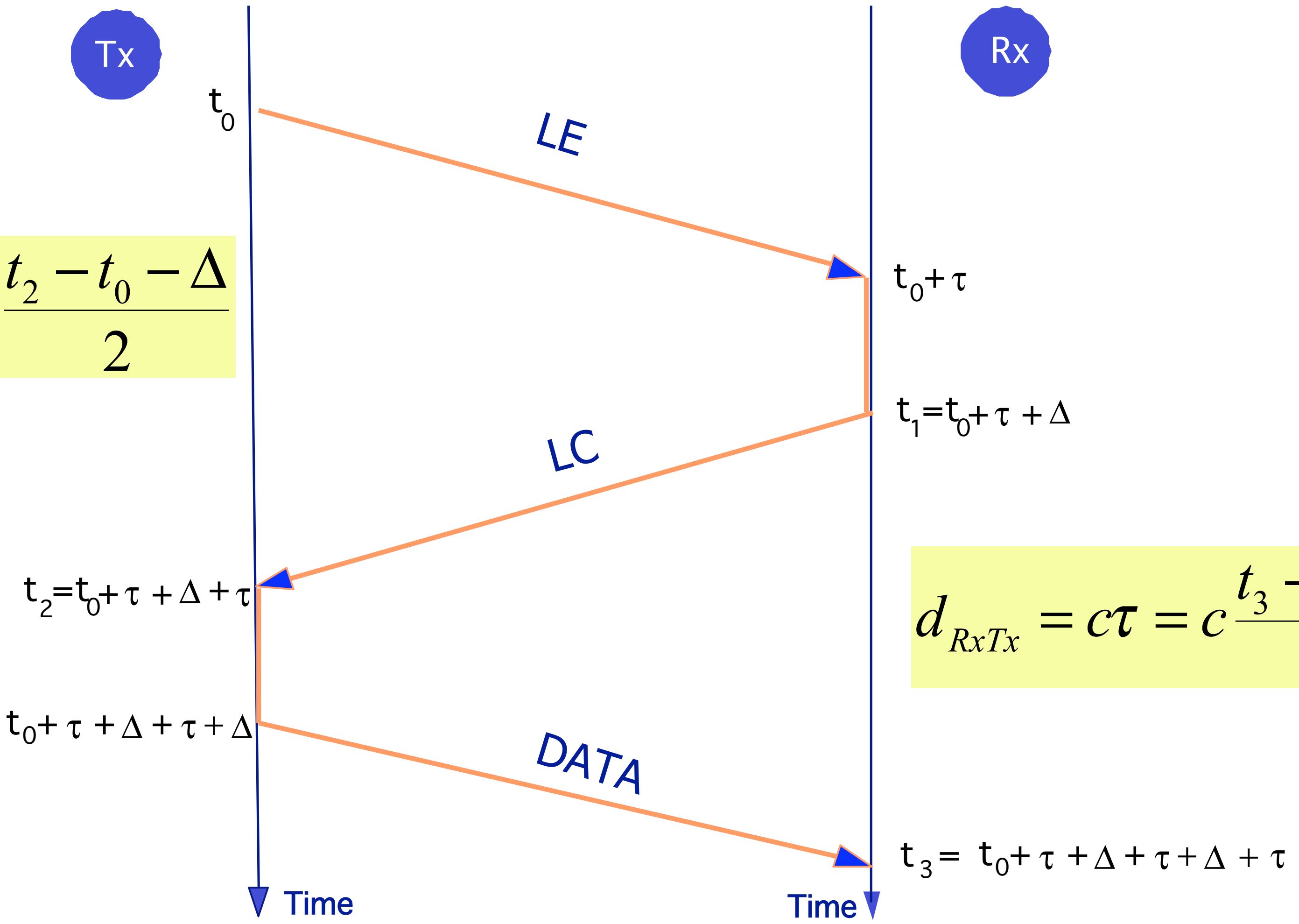
The (UWB)^2 approach was proposed and adopted with large majority of votes within the IEEE 802.15.4a group

(UWB)^2 MAC: design choices



$(UWB)^2$ MAC: Transmission and Ranging procedure

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



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

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

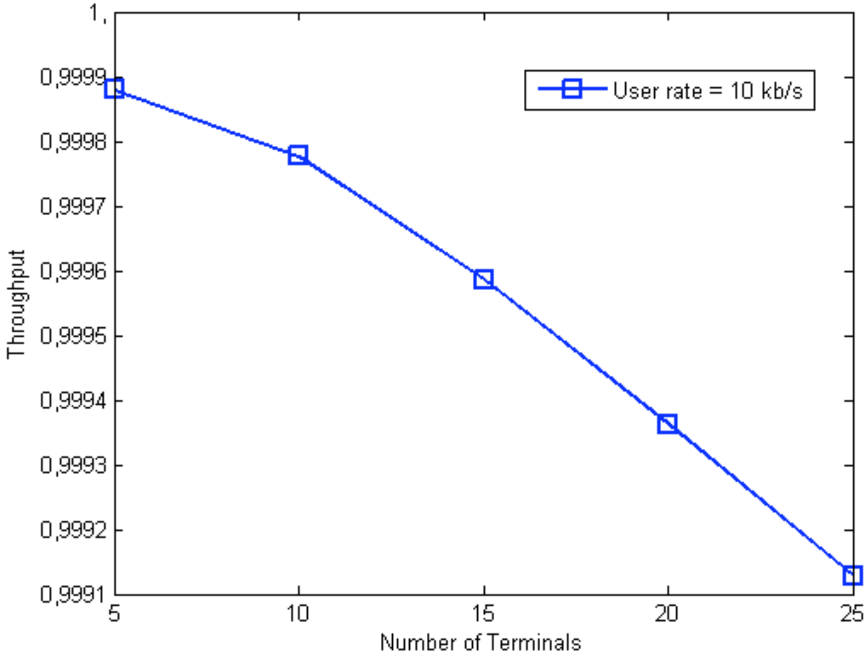
$(UWB)^2$: Performance analysis

- $(UWB)^2$ was tested by simulation in a typical Low Data Rate scenario:
  - user rates in the range 10-100 kb/s
  - 1 Mb/s on the wireless channel
- Channel effect and Multi User Interference were taken into account
- Two performance indicators were considered:
  - **Throughput** - % of transmitted packets, that are correctly received
  - **Delay** - Time gap between first transmission of a packet and its correct reception, including retransmissions of collided packets
  - **Packet Error Probability**

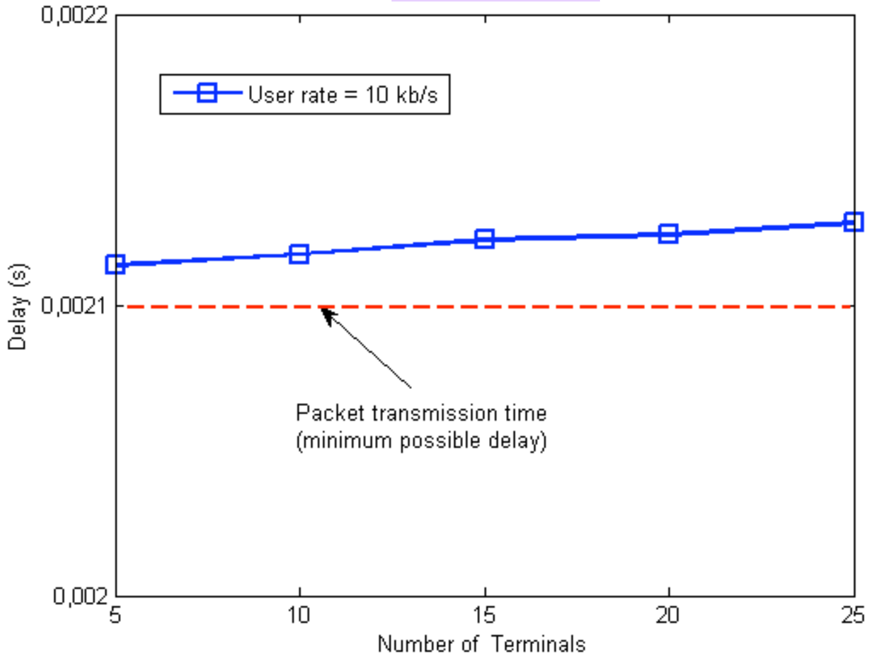
(UWB)^2: Performance analysis

Throughput and delay as a function of number of terminals

Throughput

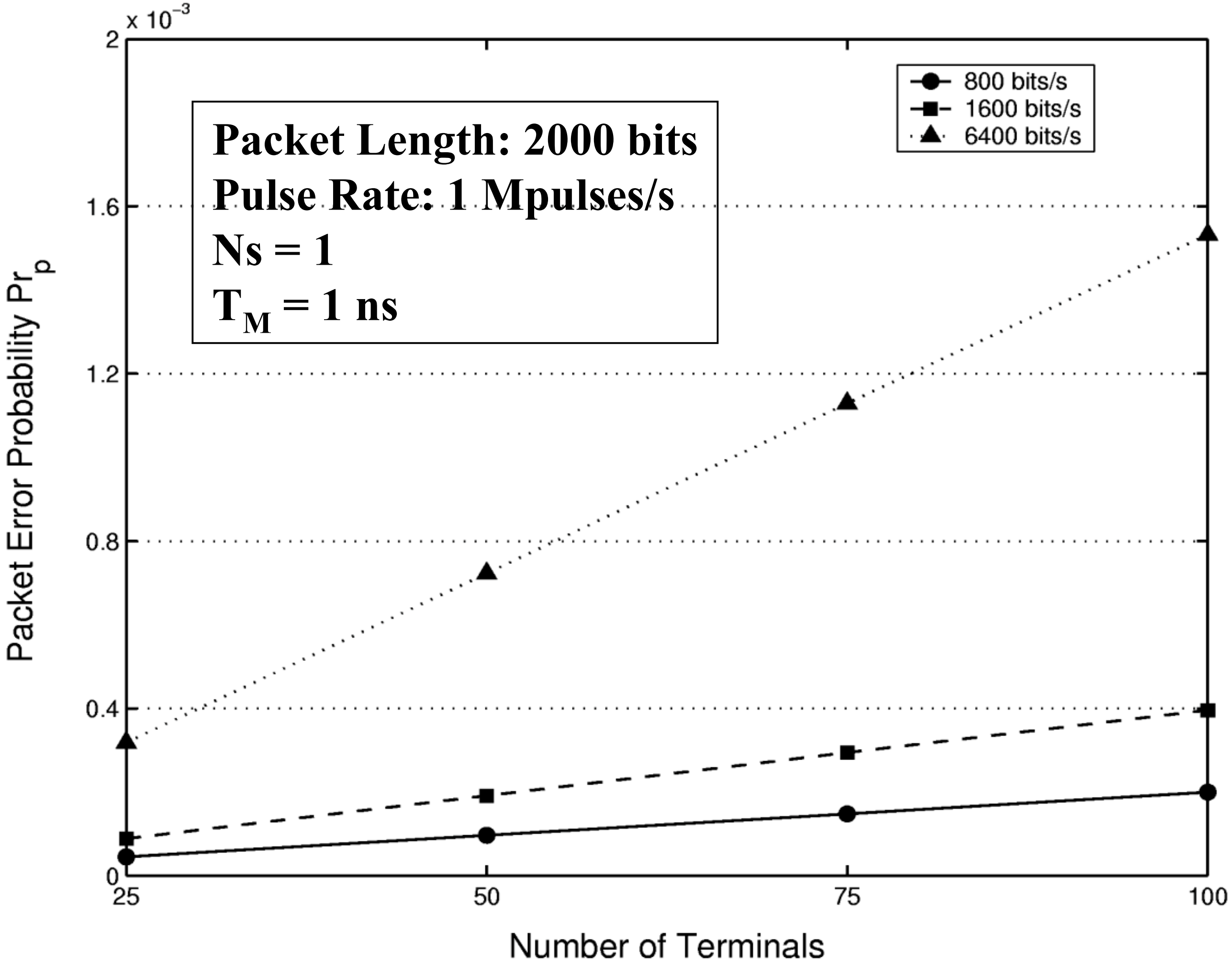


Delay



$(UWB)^2$: Performance analysis

Packet Error Probability as a function of number of terminals



A Flexible network

Flexible routing

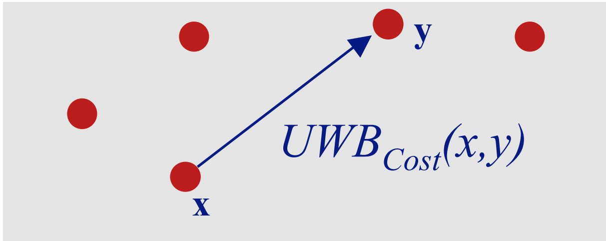
UWB allows accurate ranging accuracy and power management

- Is it feasible to design a routing strategy that adapts its path selection criterion to internal and external network conditions?
- 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 that determines the cost of a link based on internal and external conditions
2. Select the minimum cost route



The following metric was defined

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

Flexible routing

Delay term

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

Autonomy term

$$Autonomy(y) = 1 - \frac{Residual\ Energy(y)}{Full\ Energy(y)}$$

Coexistence term

$$Coexistence(y) = \frac{Measured\ External\ Interference(y)}{Maximum\ Interference(y)}$$

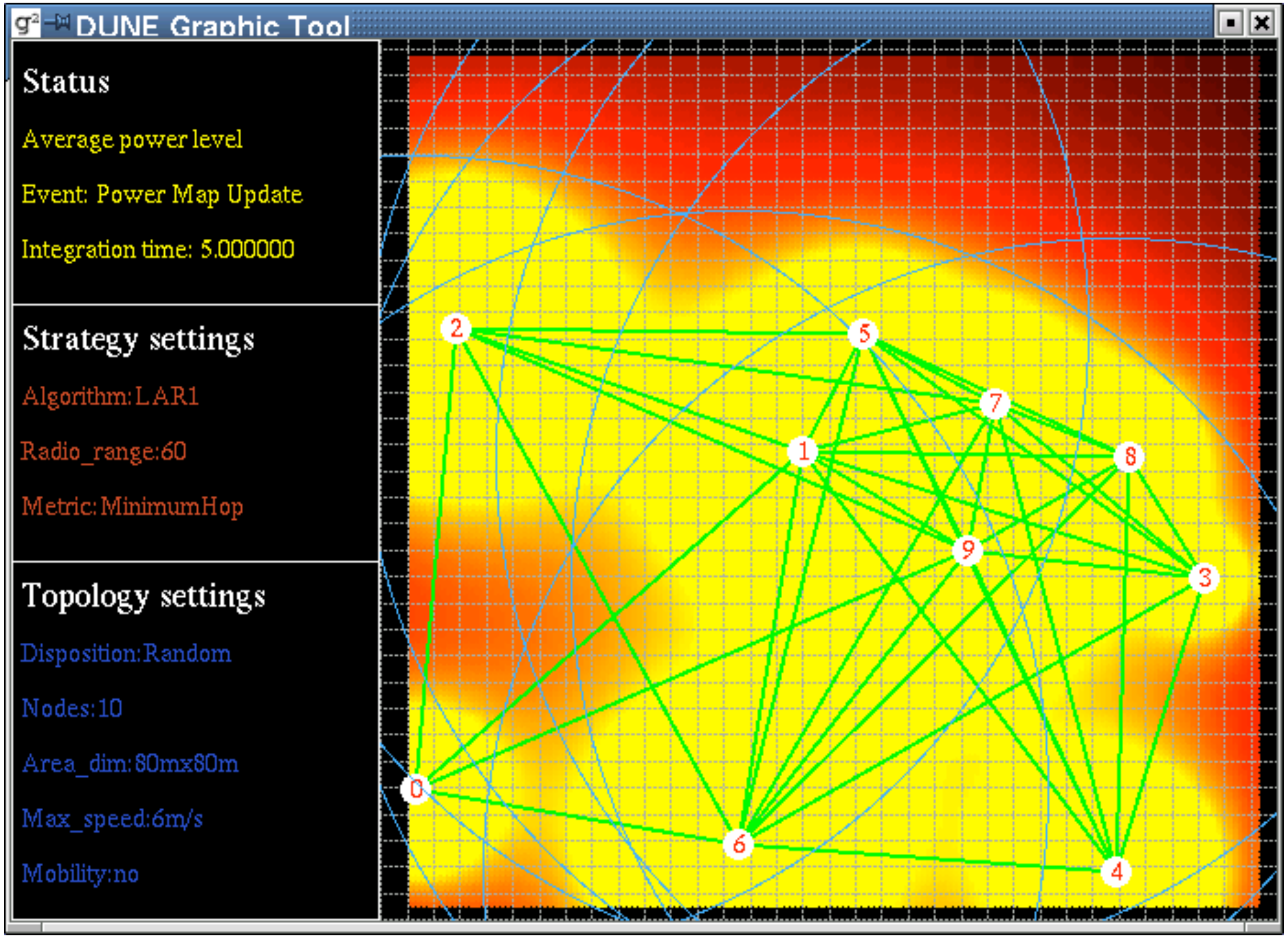
Analysis by simulation

- Three different coefficient sets

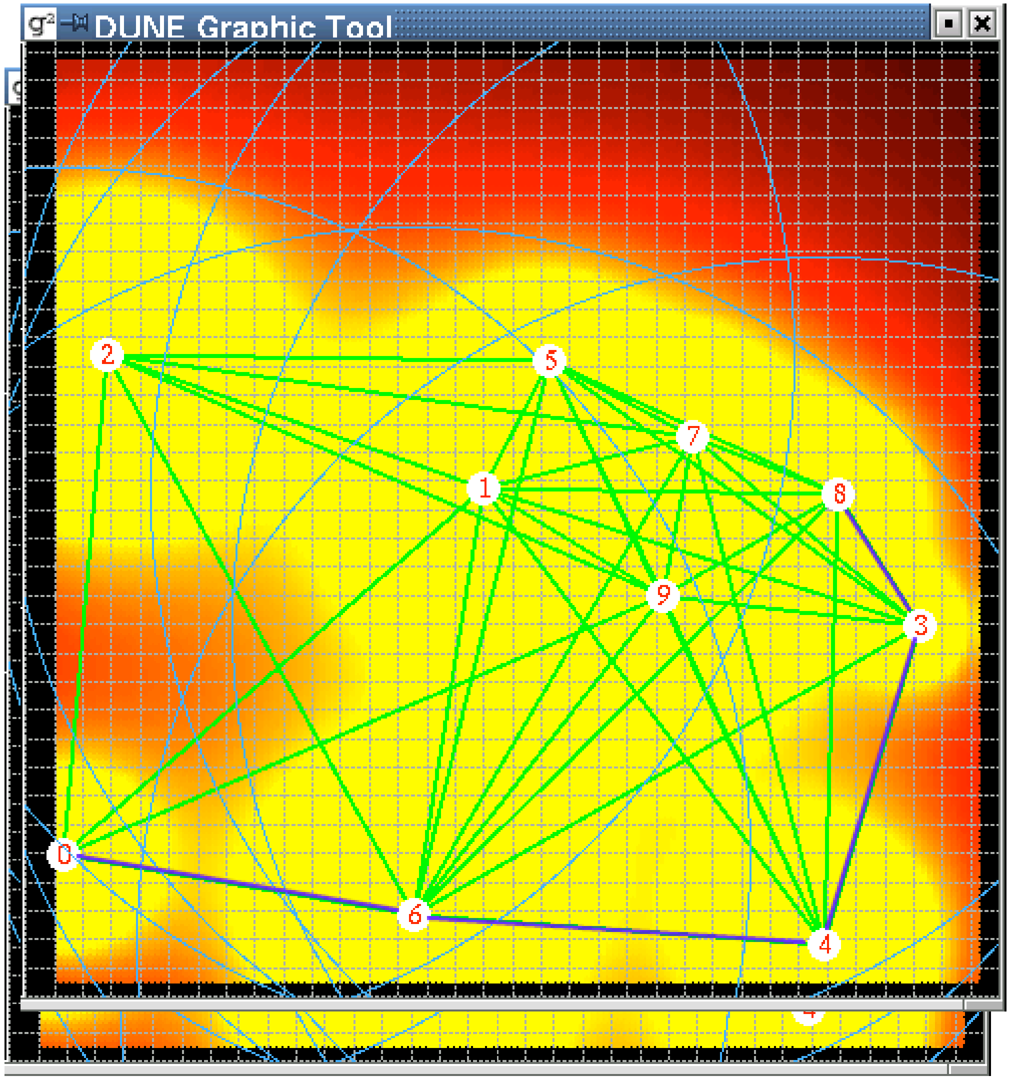
Coefficient	Set 1	Set 2	Set 3
C_{Delay}	1	0.0001	0.0001
$C_{Autonomy}$	0	1	0
$C_{coexistence}$	0	0	1

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

Effect on Power



Effect on Multi User Interference



Acknowledgment

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http://www.pulsers.eu/