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Wake-Up Transceiver Architectures with Symbol Time Estimation Schemes for ElectroMagnetic NanoNetworks

FINAL YEAR PROJECT

ESCOLA TÈCNICA SUPERIOR D'ENGINYERIA DE TELECOMUNICACIÓ DE BARCELONA

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Introduction to Nanonetworks

[1] Ian F. Akyildiz and J.M. Jornet. Electromagnetic wireless nanosensor networks. *Nano Communication Networks, 2010.*

- Nanotechnology is enabling the control of matter at an atomic and molecular scale:
  - At this scale, novel nanomaterials show new properties not observed at the microscopic level which can be exploited to develop new devices and applications.

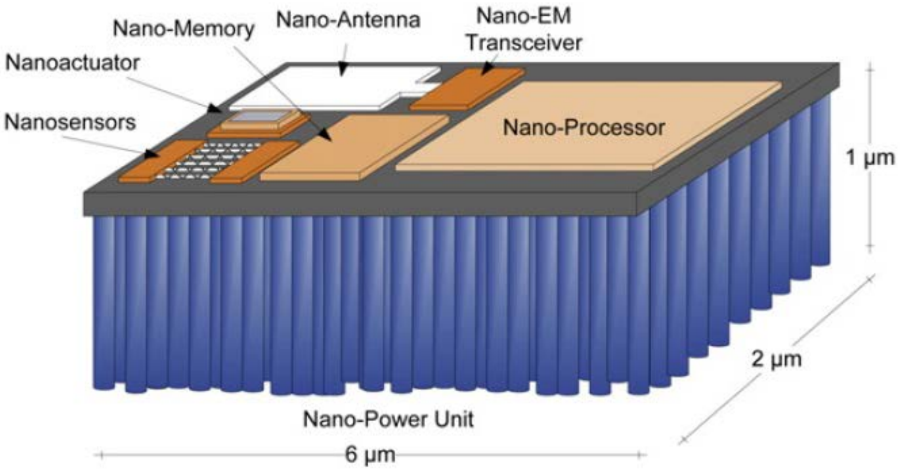

Fig. 1 - Nanosensor device. [1]

Introduction to Nanonetworks

[1] Ian F. Akyildiz and J.M. Jornet. Electromagnetic wireless nanosensor networks. *Nano Communication Networks, 2010.*

- Graphene: a one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice.
  - A prime candidate to become the silicon of the 21st century due to:
    - Very High Electron mobility → Supporting fast operating frequencies
    - Thermoelectric current effect → Self cooling and heat reabsorption

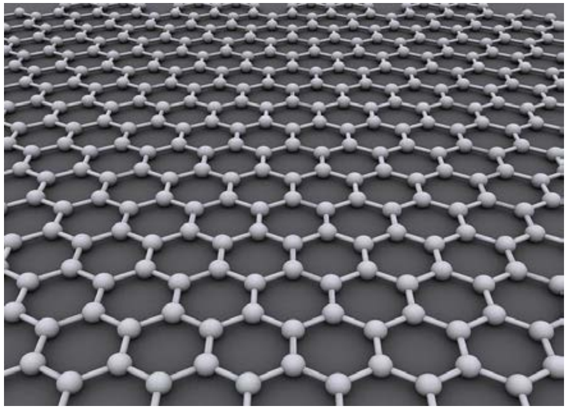

Fig. 2 - Graphene atomic structure.

Introduction to Nanonetworks

[2] J.M. Jornet and Ian F. Akyildiz. Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band. In *Antennas and Propagation (EuCAP), 2010 Proceedings of the Fourth European Conference on, pages 1 –5, 2010..*

- Graphene can be used to manufacture novel nano-antennas with atomic precission.
    - New antenna theory has been required to model the quantum effects that affect the propagation of EM waves in graphene

- Using a 1 um x 10 nm graphene-based nano-antenna we can radiate in the Terahertz Band (0.1 – 10 THz)
    - Which coincides with the expected operating frequency of graphene devices.

Introduction to Nanonetworks

[3] J.M. Jornet and I.F. Akyildiz. Channel capacity of electromagnetic nanonetworks in the terahertz band. pages 1 –6, may. 2010.

- The Terahertz Band (0.1-10 THz) is strongly affected by molecular absorption from different types of molecules (specially water vapor).
  - For communications over a few tens of meters, this limits the potential of the band to a single transmission window at 300 GHz.
  - For the expected distances in nanonetworks (below 1 meter), the Terahertz Band offers huge bandwidths, almost 10 THz.

Introduction to Nanonetworks

[4] J.M. Jornet and I.F. Akyildiz, “Information Capacity of Pulse-based Wireless Nanosensor Networks,” in Proc. of Proc. of the 8th Annual IEEE SECON, Salt Lake City, Utah, USA, June 2011.

- TS-OOK (Time Spread On/Off Keying Mechanism)
  - A new communication scheme based on the asynchronous exchange of femtosecond-long pulses.
  - Allows very simple and energy efficient nano-transceiver architectures.
  - Femtosecond-long pulses are already being used for nanoscale sensing and imaging.
  - It provides almost orthogonal channels for different users.

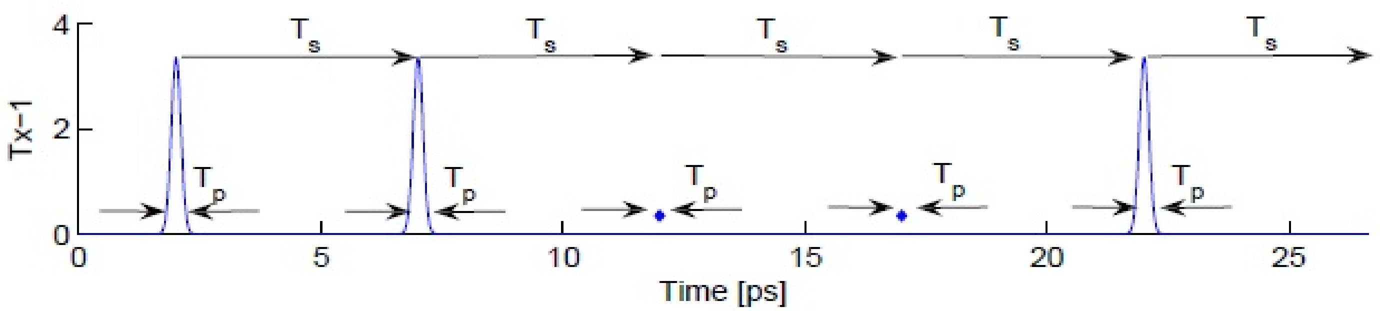

Fig. 3 – TS-OOK modulation scheme. Not in scale

Introduction to Nanonetworks

[5] M. Dragoman and A.A. Dragoman, D.and Muller. High frequency devices based on graphene. In Proc. of *International Semiconductor Conference , September* 2007.
[6] Alma E. Wickenden, et al., Spin torque nano oscillators as potential Terhertz communications devices. Technical report, Army Research Laboratory, 2009.

- Promising Terahertz sources can be classified into:
  - RF NEMS: Oscillation beyond 1 Terahertz will be possible [5]. This technology leads to full graphene circuits.
  - STNO: Future low-voltage, room temperature Terahertz Oscillators [6].

- In any case, the oscillation frequency of these sources depend on the energy supplied.
  - *The Energy constraints will provide bad Terahertz Sources*

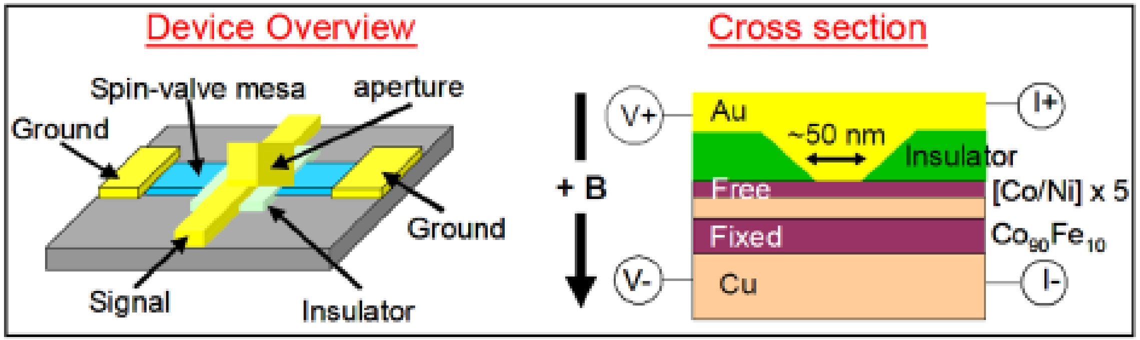

Fig. 4 – STNO device geometry.

Introduction to Nanonetworks

Our Work

- The timing and energy constraints limit the performance of nanonetworks and present a challenge to guarantee the communication among nanodevices.
    - Timing: There are frequency drifts among nanodevices
    - Energy: A nanodevice can send just a few hundred of bits every minute

- We provide the bridge between the antenna and the nanodevice which consists of three main contributions:
    - A transceiver architecture designed to improve the Symbol Error Rate in the Terahertz channel for pulse-based modulations, which simplifies synchronization schemes built on top.
    - A symbol time estimation built on top of the transceiver architecture to guarantee the successful reception of the symbols.
    - An asynchronous synchronization scheme to detect new transmissions based on a Wake-Up receiver module.

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Transceiver Architecture for EM Nanonetworks

- Goal:
  - We present a very simple transceiver architecture that:
    - Supports pulse-based modulations in the Terahertz band.
    - Simplifies future synchronization designed on top.

- Properties:
  - Simple architecture → Suited for nanodevices.
  - Outperforms previous architectures in terms of pulse detection capabilities.
  - Simplifies the symbol time estimation designed on top of this architecture.

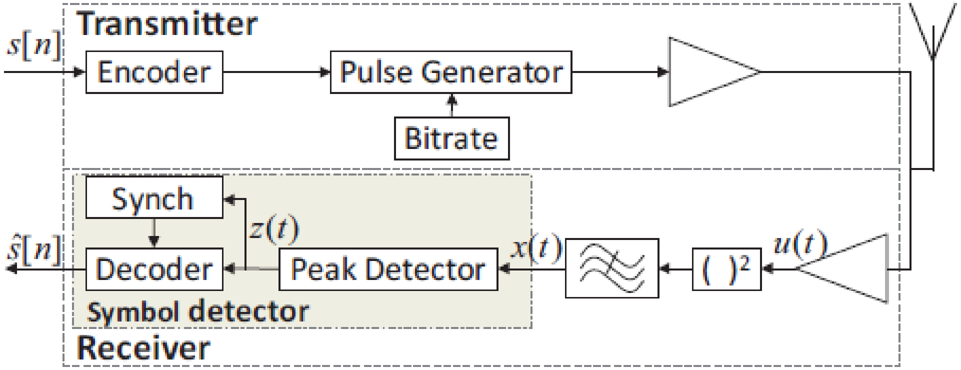

Fig. 5 – Transceiver block diagram architecture

Transceiver Architecture for EM Nanonetworks

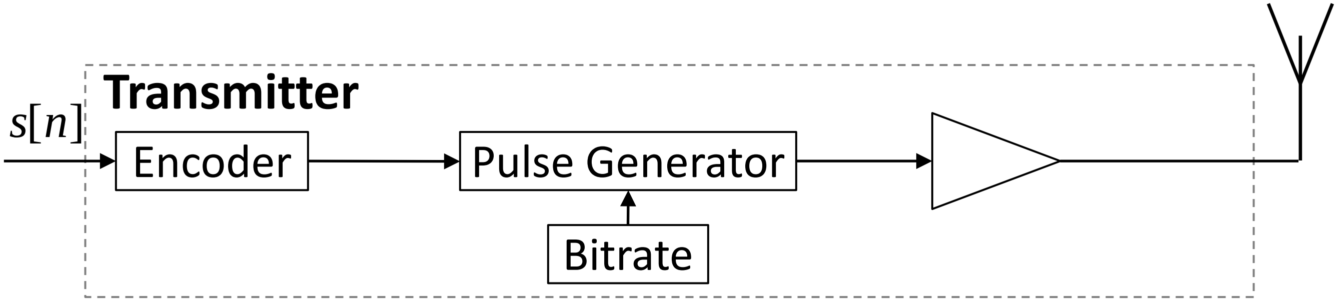

Fig. 6 – Transmitter block diagram architecture

- Transmitter
  - Encoder:
    - Buffer or memory
    - Codification schemes
  - Pulse Generator:
    - Converts the logical values into voltage
  - Bitrate:
    - Decides when the next symbol is sent
  - Output Amplifier
    - Matches antenna
    - Provides enough power

Transceiver Architecture for EM Nanonetworks

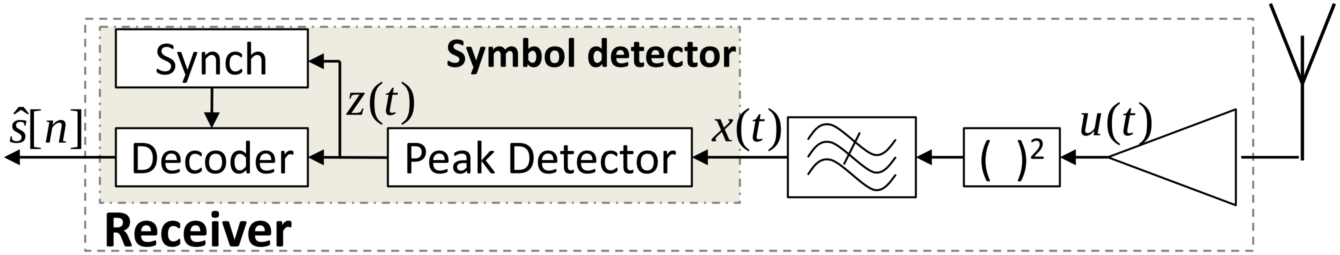

Fig. 7 – Receiver block diagram architecture

- Receiver
  - Terahertz Front-End
    - Dual to Output amplifier
  - Power Detection
    - Calculates the input power
  - Low pass filter
    - It approximates an ideal integrator
  - Peak detector
    - It fixes its output value to "1" when its input is above the threshold. Continuous comparison.
  - Decoder
    - Decodes the received packet
  - Synch
    - Switches On and Off the receiver

Transceiver Architecture for EM Nanonetworks

[9] R. Mills and G. Prescott. A comparison of various radiometer detection models. IEEE Transactions on Aerospace and Electronic Systems, 1996

- Ideal Non-Coherent Receiver

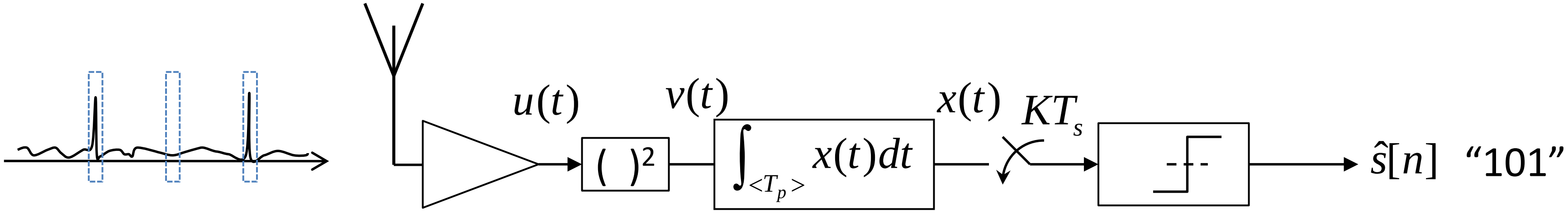

Fig. 9 – Architecture of an ideal non-coherent receiver

- Main Challenges:
  - The receiver should operate at 10 THz
  - Time-spread modulations, the pulse time is 1000 times shorter than.
  - Estimating the time of arrival with an error of some femtoseconds is very challenging
- Solution:
  - The expected time of arrival can be larger than the pulse time

Transceiver Architecture for EM Nanonetworks

[10] A. Gerosa, S. Solda, A. Bevilacqua. An energy-detector for noncoherent impulse-radio UWB receivers. IEEE Transactions on Circuits and Systems I, May 2009

[11] F.S. Lee and A.P. Chandrakasan. A 2.5 nJ/bit 0.65 V pulsed UWB reveiver in 90 nm CMOS. IEEE Journal of Solid-State Circuits, December 2007.

Usual Symbol Detection

- In [10,11], the integration time is increased in 10-100 times
  - Decomposing this integration time into N integrations:

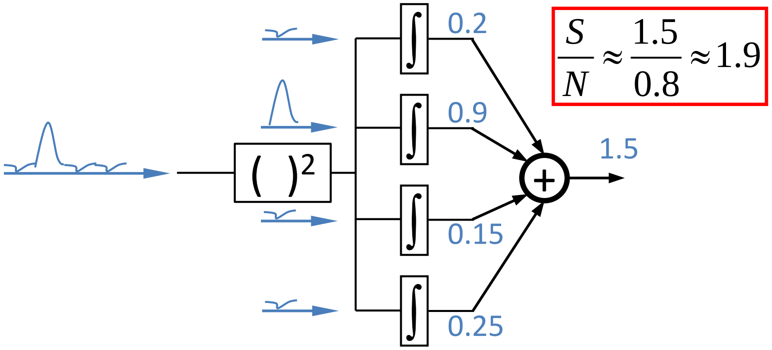

Fig. 10 – Example of the noise effect in typical symbol detectors

  - As soon as the integration time is increased, the noise is averaged with the signal.
  - This effect drops the performance of the receiver.

Our Symbol Detection

- We propose to use a the maximum function instead of the addition:

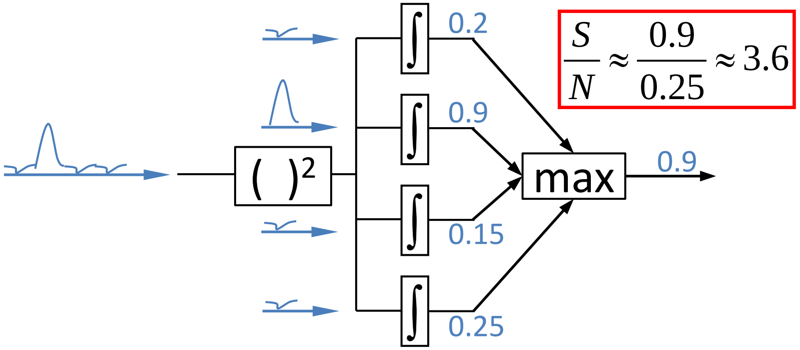

Fig. 11 – Example of the noise effect in the proposed symbol detector

  - Better Signal to Noise ratio
  - But:
    - Do we have to implement N integrators?
    - What if the pulse is received in the middle of two of this intervals?

Transceiver Architecture for EM Nanonetworks

- Receiver Architecture for EM Nanonetworks with Continuous-time integration
  - If we use $N \to \infty$ Integrators, we convert the system into a linear system with input-to-output relationship:

$$x(t) = \int_{t-T_p}^{t} u(\tau)^2 \, d\tau$$

  - We seek for the maximum of this function over a time T

$$\hat{s}[n] = \begin{cases} 1 & \text{if } \max_{t \in (0,T)} x(t) > V_{th} \\ 0 & \text{otherwise} \end{cases}$$

  - However, since there is no ideal continuous-time integrator we propose the use of a second order low-pass filter.

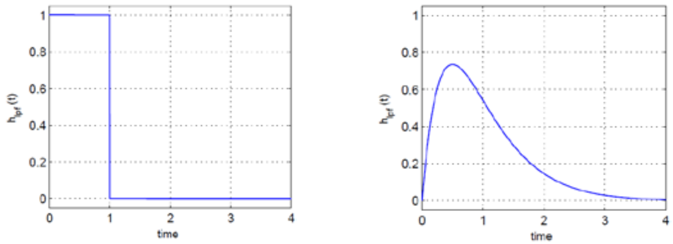

Fig. 12 – Comparison between the integrator (left) and second order low-pass filter (right) impulse responses (arbirtrary units)

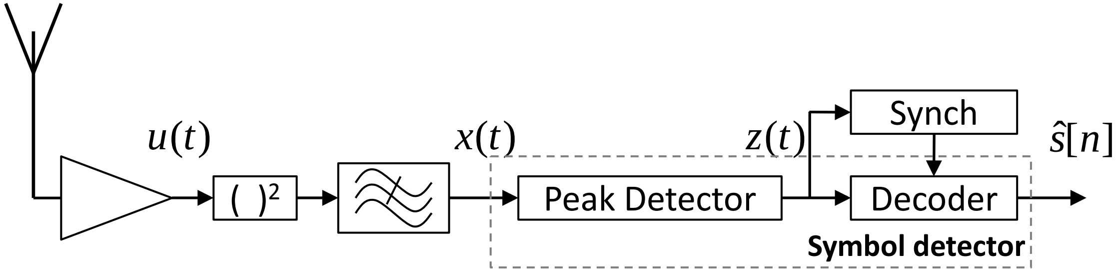

Fig. 13 – Receiver architecture block diagram

Transceiver Architecture for EM Nanonetworks

- Detection of logical "0"
  - We discretize $x(t)$ into *N* independent random variables X_i with probability density function:

$$f_n(y) = \frac{1}{2^{v/2}\Gamma(\frac{v}{2})} y^{(v-2)/2} e^{-y/2}, \quad y \geq 0$$

$$\text{where } Y = 2X / N_0$$

    - Chi-square distribution
  - Thus, the the probability density function of $\max \mathbf{X} = \max\{X_1, \cdots, X_N\}$:

$$f_{max,n}(y, N) = NF_n(y)^{N-1} f_n(y)$$

Transceiver Architecture for EM Nanonetworks

- Detection of logical “1”
  - We discretize $x(t)$ into:
    - N_n random variables of noise with probabilty density function:

$$f_n(y) = \frac{1}{2^{v/2}\Gamma(\frac{v}{2})} y^{(v-2)/2} e^{-y/2}, \quad y \geq 0, \quad f_{max,n}(y,N) = NF_n(y)^{N-1} f_n(y)$$

    - N_s random variables of signal with probability density function:

$$f_s(y) = \frac{1}{2}\left(\frac{y}{\lambda}\right)^{(v-2)/4} e^{-(y+\lambda)/2} I_{(v-2)/2}(\sqrt{y\lambda}), \quad y \geq 0$$

where:

$Y = 2X/N_0$

$\lambda = 2E / N_0$

    - Thus, the the probability density function of $\max \mathbf{X} = \max\{X_1, \cdots, X_N\}$:

$$f_{max,sn}(y, N_s, N_n) = F_{max,s}(y, N_s) f_{max,n}(y, N_n) + f_{max,s}(y, N_s) F_{max,n}(y, N_n)$$

Where:

$$f_{max,s}(y,N) = NF_s(y)^{N-1} f_s(y)$$

Transceiver Architecture for EM Nanonetworks

[12] J. M. Jornet and I. F. Akyildiz. Channel capacity of electromagnetic nanonetworks in the terahertz band. In *Proc. of IEEE International Conference on Communications,* May 2010.

Model Validation

- Assumptions:
  - Path loss and noise from [12]. These values are expressed in terms of the distance
  - TS-OOK modulation scheme. Almost orthogonal channels, so we do not consider collisions
  - The transmitter encodes logical “1” with second derivative 1 pJ femtosecond-long gaussian pulse
  - The receiver is perfectly synchronized
- We validate the expressions for “1”s and “0”s in the Terahertz channel for a distance of 66mm.

T	N	N_s
3 T_p	2	2
30 T_p	15	2
300 T_p	110	2

Table. 1 – Relation between the time interval and number of random variables to model the symbol detection

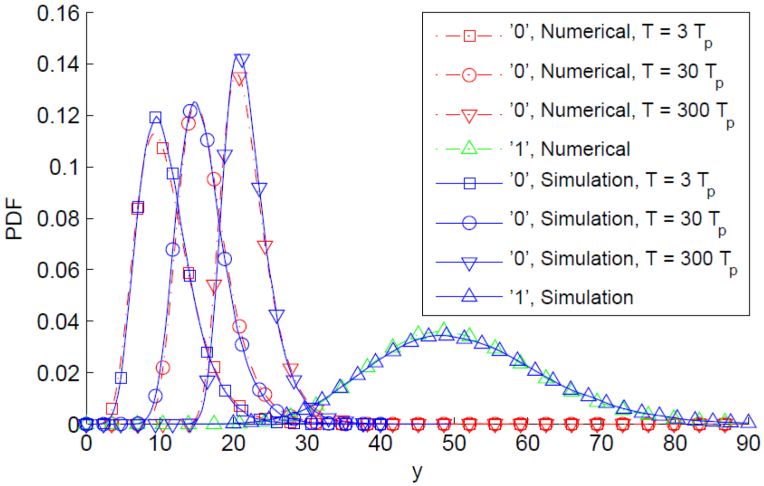

Fig. 15 – Model Validation. Numerical over simulation results

Transceiver Architecture for EM Nanonetworks

- Symbol Error Rate Estimation
  - We compare the SER estimation of our symbol detector to the SER estimated in a usual receiver architecture.

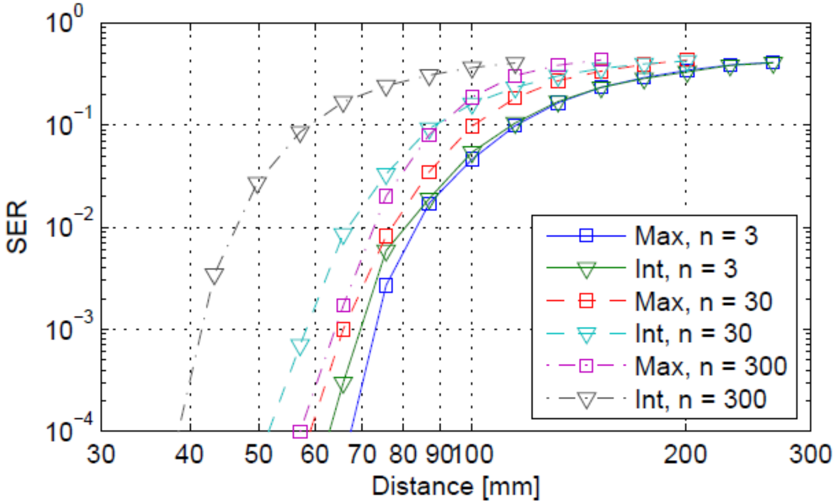

Fig. 16 – Comparison between the SER provided by the proposed receiver and current receiver in terms of the distance for different time intervals

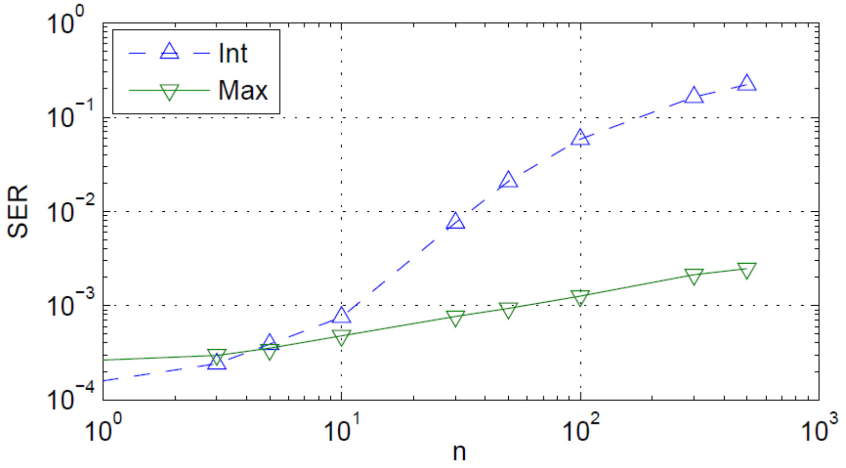

Fig. 17 – Comparison between the SER provided by the proposed receiver and current receiver in terms of the time interval width for a distance of 66 mm

- The SER has a log-log dependence with the width of the time interval
- $n = T / T_p$

Transceiver Architecture for EM Nanonetworks

[9] R. Mills and G. Prescott. A comparison of various radiometer detection models. IEEE Transactions on Aerospace and Electronic Systems, 1996

- Symbol Error Rate Estimation
  - We propose the following model

$$SER_n = n^{0.45} SER_{n=1}, \quad SER(r) = r^{0.45} SER_{n_1}$$

  - Then, we obtain the value in origin (n = 1) using the model of ideal symbol detectors in [9].

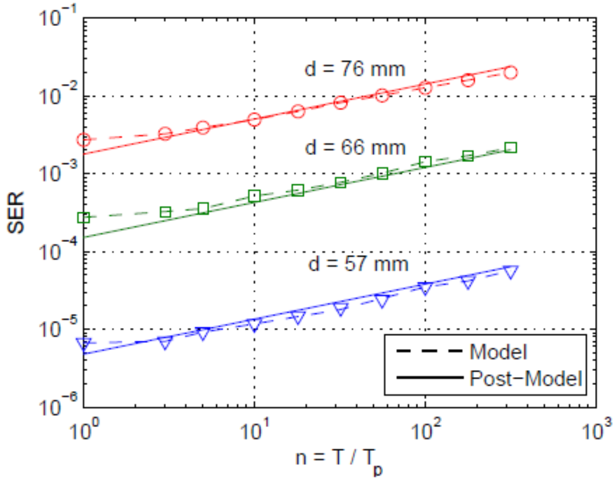

Fig. 18 – Comparison between the SER provided by the proposed receiver and current receiver in terms of the distance for different time intervals

- Maximum Bitrate
  - The use of second-order low-pass filters instead of ideal integrators adds InterSymbol Interference (ISI)
  - This ISI affects the receiver only if pulses are not spread in time

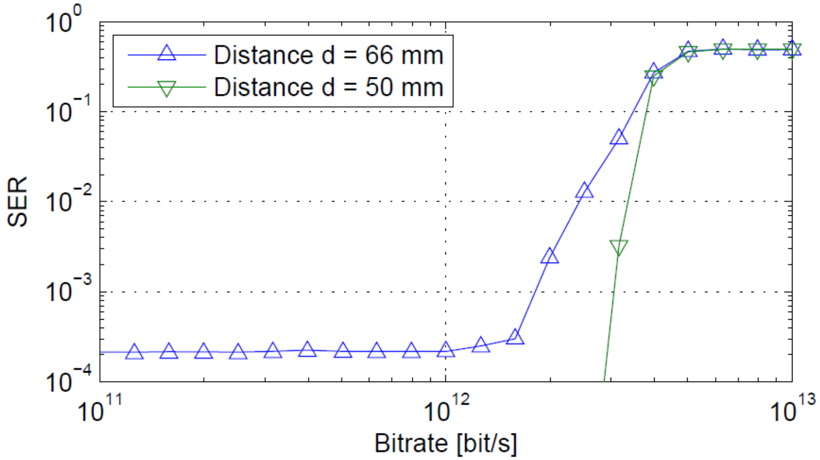

Fig. 19 – SER in terms of bitrate

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Symbol Time Synchronization Scheme

- Goal:
  - We propose a simple frequency estimation scheme that:
    - Is built on top on the transceiver architecture
    - Guarantees the successful reception of the packets
    - Is evaluated in terms of Packet Error Rate estimation

- Properties:
  - It uses special properties from the receiver architecture
  - Low overhead. This symbol time estimation needs less than 10 pulses to synchronize
  - Simple algorithm

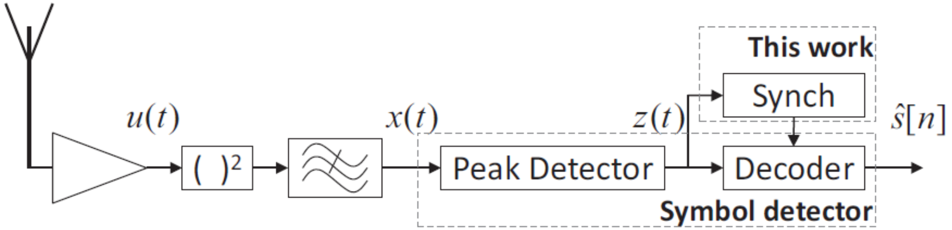


Fig. 20 – Context of the symbol time synchronization block

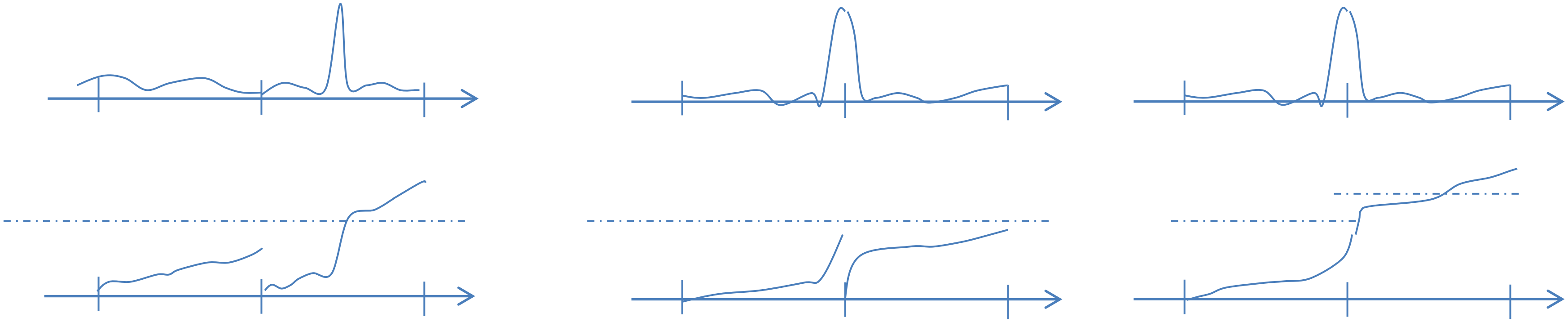
Symbol Time Synchronization Scheme

[5] M. Dragoman and A.A. Dragoman, D.and Muller. High frequency devices based on graphene. In Proc. of *International Semiconductor Conference , September* 2007.
[6] Alma E. Wickenden, et al., Spin torque nano oscillators as potential Terhertz communications devices. Technical report, Army Research Laboratory, 2009.
[13] M. A. Hoefer, et al., Theory of magnetodynamics induced by spin torque in perpendicularly magnetized thin films. *Physical Review* Letters, 2005.
[14] Lin, L. Y.,et al, “A Frequency Synchronization Method for IR-UWB System”, In Proc. of International Conference on Wireless Communications, Networking and Mobile Computing, 2007

- Motivation:
  - RF NEMS and STNO are expected to provide Terahertz oscillation in the nanoscale but they are energy dependent[5],[6],[13].
  - Thus, we expect the operating frequency of different nanodevices to be different.
  - PLL synchronization is discouraged in carrierless pulse based communications[14].
  - The transceiver architecture proposed provides very interesting synchronization options.

Symbol Time Synchronization Scheme

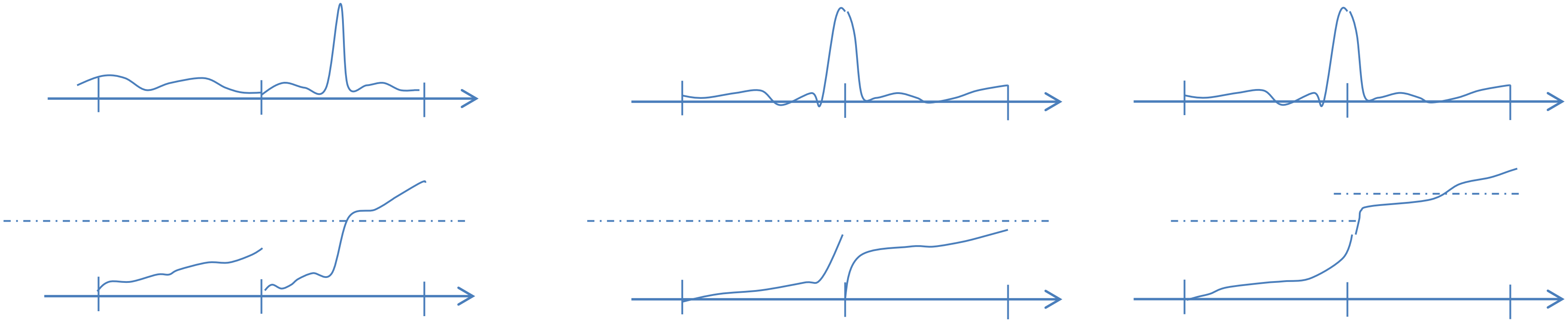
- Frequency Synchronization properties of the receiver:
  - Usual receivers:



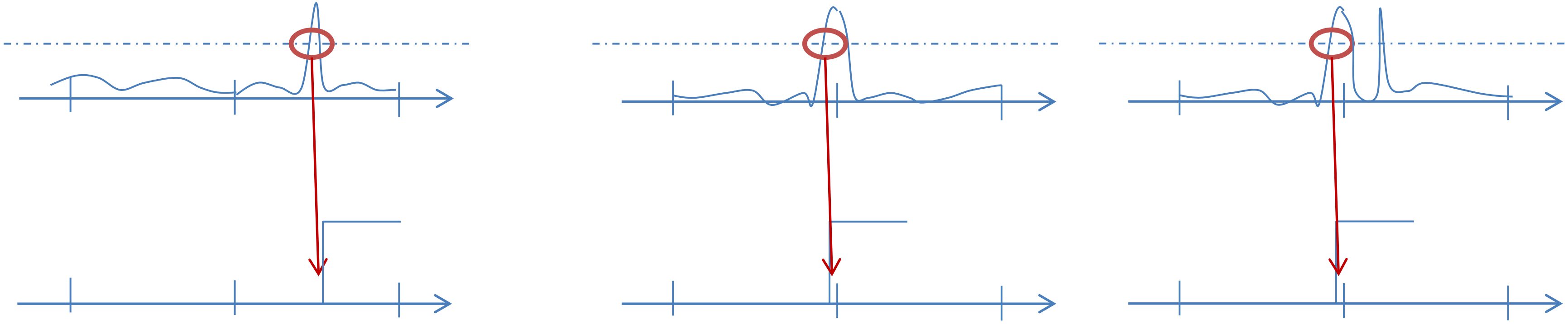
  - Our Receiver

Symbol Time Synchronization Scheme

- Frequency Synchronization properties of the receiver:
  - Usual receivers:



  - Our Receiver



Symbol Time Synchronization Scheme

- Frequency Synchronization properties of the receiver:
  - Slotting a time interval into K sub-intervals, the relation between the error probabilities for logical “0”s and “1”s are:

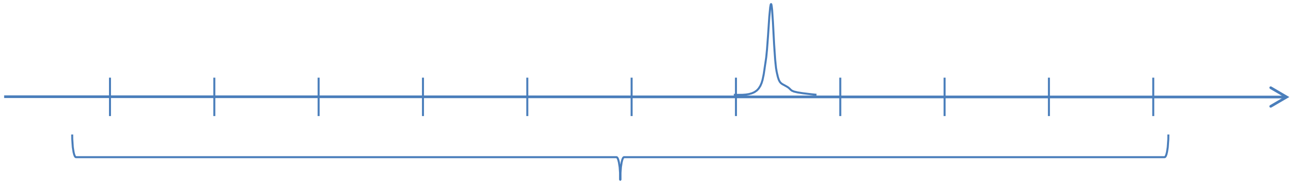


Fig. 21 – Property of subinterval slotting

    - We successfully receive the a logical “0” if every subinterval is decoded as “0”

$$P_{\epsilon|s=0} = 1-(1-p_0)^K \approx Kp_0$$

    - We receive an error if in the reception of a logical “1” if there is an error in the “1” and the rest time intervals are kept as “0”

$$P_{\epsilon|s=1} = p_1(1-p_0)^{K-1} \approx p_1$$

Symbol Time Synchronization Scheme

- Frequency Estimation
  - To estimate the frequency we count number of periods between pulses:

Fig. 22 – Relative frequencies example

  - As shown in the example: Receiver 1 detects a T_s of 5 sampling periods
  - Receiver 2 detects a T_s of 4 sampling periods

  - We refer this as Relative Frequencies
  - To improve the performance in the estimation, we have information *a priori* about the received frequency

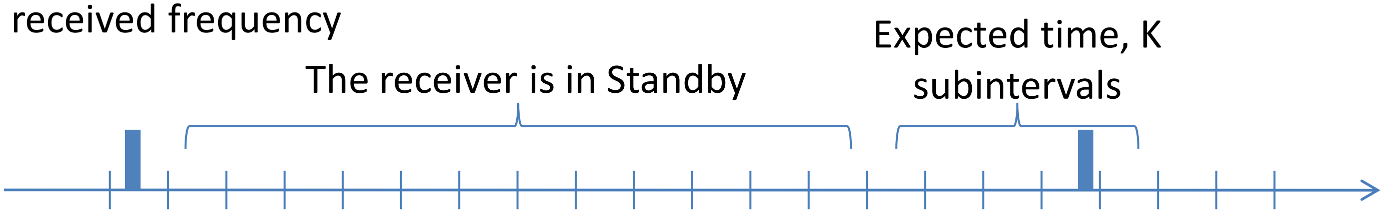
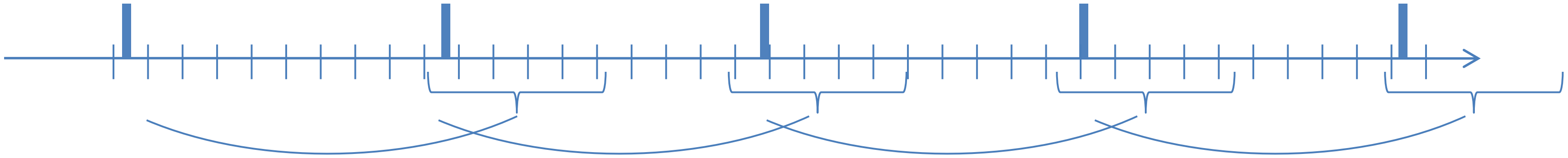


Fig. 22 – Standby - Reading time

Symbol Time Synchronization Scheme

- Frequency Estimation:
  - There is an error in this estimation. The receiver can count only an integer numbers of periods
  - We propose the use of a synchronization preamble:



$N_0 = 11$, $N_i = \{9,9,10,9\}$

Fig. 22 – Example of the frequency estimation process

$$\hat{N} = \sum_{i=1}^{N_{synch}} N_i \,/\, N_{synch} = N + \epsilon$$

$$|\epsilon| < \frac{1}{N_{synch} - 1}$$

  - Using this estimation, there is always an error that the receiver must be able to handle

Symbol Time Synchronization Scheme

- Adaptive Frequency Correction
  - During the transmission, the receiver must be able to cope handle the estimation errors and possible frequency drifts
  - “1”s Provide synchronization information
  - “0”s Provide uncertainty

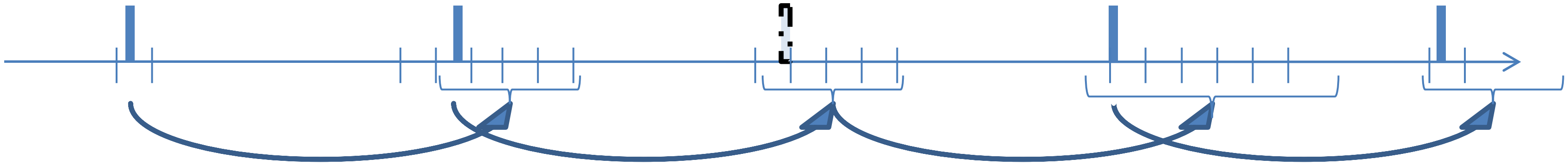


Fig. 22 – Example of the adaptive frequency correction algorithm

Symbol Time Synchronization Scheme

- Optimum Number of Subintervals
  - It must Guarantee that the next pulse is inside the time interval
  - It must be kept as small as possible to reduce the error probability

$$K_{i+1} = \left\lceil (n_{zeros}+1)(\hat{N}_s+\epsilon)+1/2 \right\rceil - \left\lfloor (n_{zeros}+1)(\hat{N}_s-\epsilon)-1/2 \right\rfloor$$

  - The average number of subintervals is:

$$\bar{K} = \sum_{n=0}^{\infty} p_n E[k_n] = 2\left(1+\frac{\epsilon_{max}}{P_{s=1}}\right)$$

  - Where:
    - Pn : probability of receiving n consecutive "0"
    - E[kn] : average number of subintervals when the receiver has received n consecutive "0"
    - E : maximum error accepted
  - Then, there are 2K-1 zero subinterval per each one subinterval, thus we approximate the Packet Error Rate as:

$$PER = 1-(1-P_{\epsilon|s=1}/2-P_{\epsilon|s=0}/2)^{N_{bits}}$$

$$P_{\epsilon|s=0} \approx \frac{\bar{K}}{2\bar{K}-1} SER(2K-1)$$

$$P_{\epsilon|s=1} \approx SER(2K-1)$$

Symbol Time Synchronization Scheme

- Preamble Evaluation
  - There is a probability that the error is kept inside the maximum error accepted.
  - This maximum error depends on the number of pulses for synchronization
  - Probability estimated in terms of the channel degradation

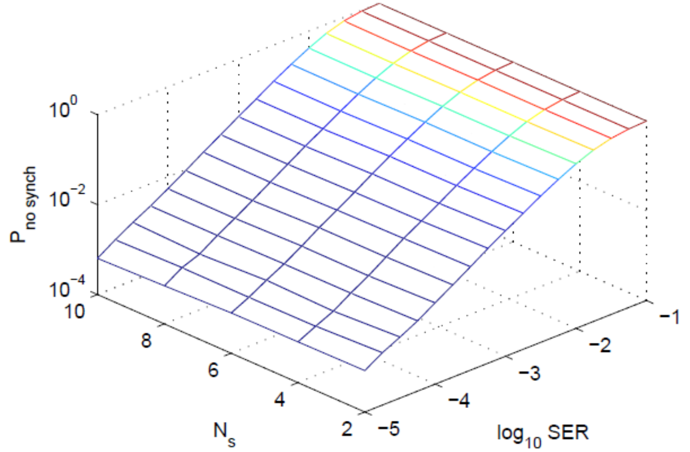


Fig. 22 – Probability of no synchronization in terms of the SER and the synchronization preamble length

- Frequency correction evaluation
  - We have simulated the adaptive algorithm proposed.
  - We observe that unbalancing probabilities we obtain a minimum in the Packet Error Rate estimation

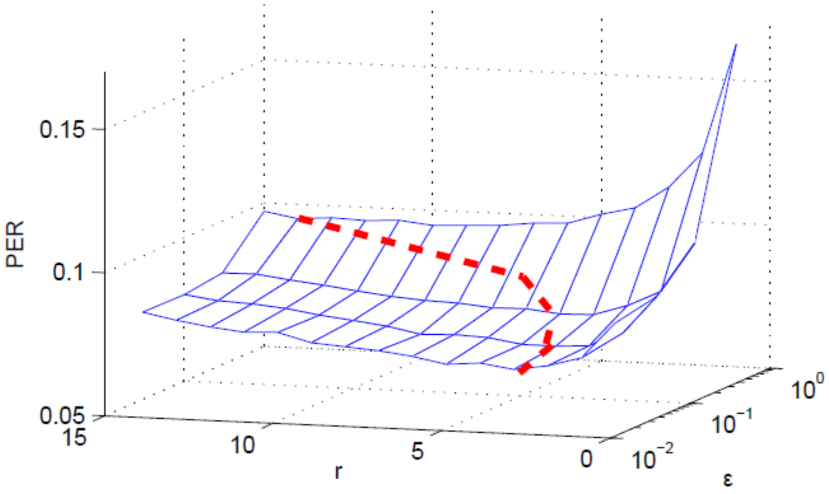


Fig. 23 – Evaluation of the frequency correction. PER in terms of the maximum error and unbalancing parameter

Symbol Time Synchronization Scheme

- Frequency correction Evaluation
  - We evaluate the expression for the Packet Error Rate in terms of the channel degradation and we compare the results with the simulation results for the algorithm
  - Appropriately unbalancing probabilities

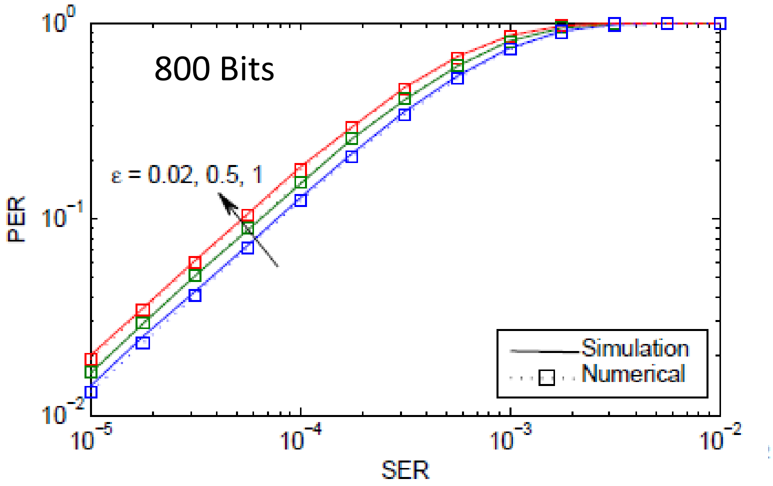


Fig. 24 PER comparison. Numerical model vs. Simulation

- Benefits of this frequency correction
  - We compare the Packet error rate with:
    - Ideal synchronization
    - Non frequency correction
  - We outperform in one order of magnitude

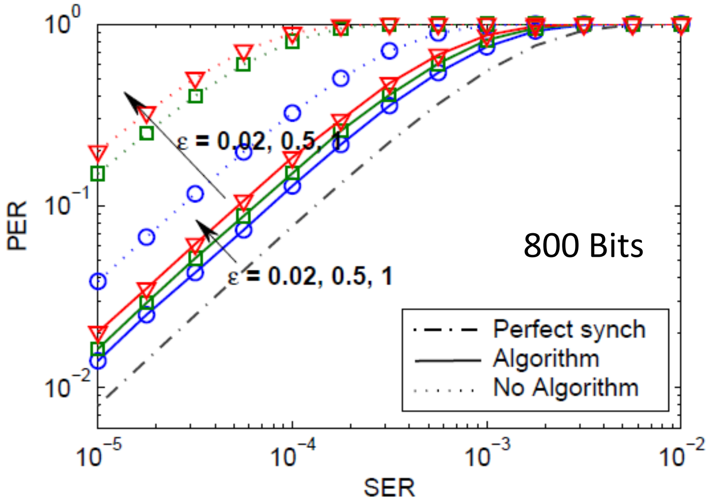


Fig. 25 PER comparison. Numerical model vs. Simulation

Symbol Time Synchronization Scheme

- How many pulses must be sent to synchronize frequencies?
  - A few number of pulses increases the PER, increases the time interval but reduces overhead
  - Large number of pulses improves PER, reduces time interval but increases overhead.
  - We define:

$$tput = \frac{\left(N_{bits} - N_{synch} / P_{s=1}\right)\left(1 - PER_{synch}\right) p_{synch}}{N_{bits}\left(1 - PER_{I}\right)}$$

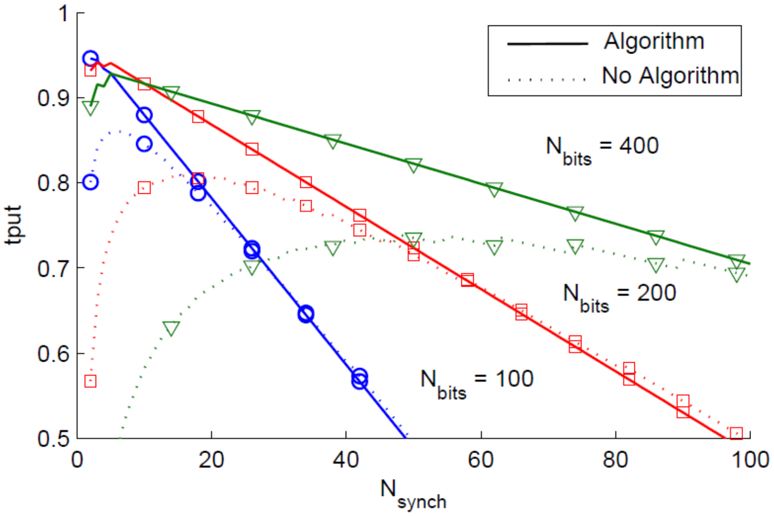


Fig. 26 Optimum synchronization preamble length

- Less than 10 pulses are needed to synchronize if the adaptive algorithm is being used
- Alternatively, without the algorithm some tens of pulses are needed.

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Wake-Up Receiver for EM Nanonetworks

- Goal:
  - We provide an asynchronous synchronization scheme to detect new transmissions that:
    - is based on a wake-up receiver
    - We evaluate its functionality over the ALOHA protocol
- Properties:
  - Asynchronous synchronization
  - It is capable of rejecting packets before the receiver wakes up if the receiver is not the target of this packet

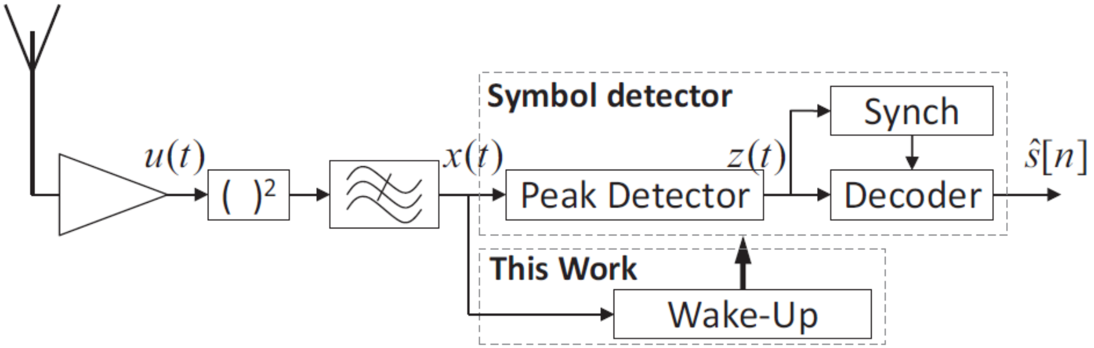


Fig. 27 – Context of the Wake-Up module

Wake-Up Receiver for EM Nanonetworks

- Motivation:
  - Due to power restrictions, a receiver node can only decode some tens of packets of 200 bits each minute.
  - The rest of the time, the receiver must be sleeping to save energy.
  - It is too expensive (in energy) for the receiver to decode any packet not targeted to it.
  - Due to clock drifts, duty cycled synchronization schemes do not apply

Wake-Up Receiver for EM Nanonetworks

[15] Ye, W.; Heidemann, J. & Estrin, D. An energy-efficient MAC protocol for wireless sensor networks. In *Proc. of the IEEE Computer and Communications Societies. INFOCOM, 2002*

- Duty cycled synchronization schemes
  - Nodes wake up periodically to sense the channel, in case any node is transmitting
  - When a node is transmitting, it sends a synchronization preamble. If the receiver decodes the packet, the receiver switches to reception and the transmitter sends the packet
  - Suitable For carrier communications
  - Power Consumption proportional to:

$$P = \frac{T_1}{T_1 + T_2}$$

- EM Nanonetworks
  - TS-OOK: Carrierless
  - **We consider frequency drifts**
  - Some tens of nanosecond long packets per minute
  - The energy constraints limit the duty cycle to be very reduced.
  - **Maximum drifts of nanoseconds allowed**

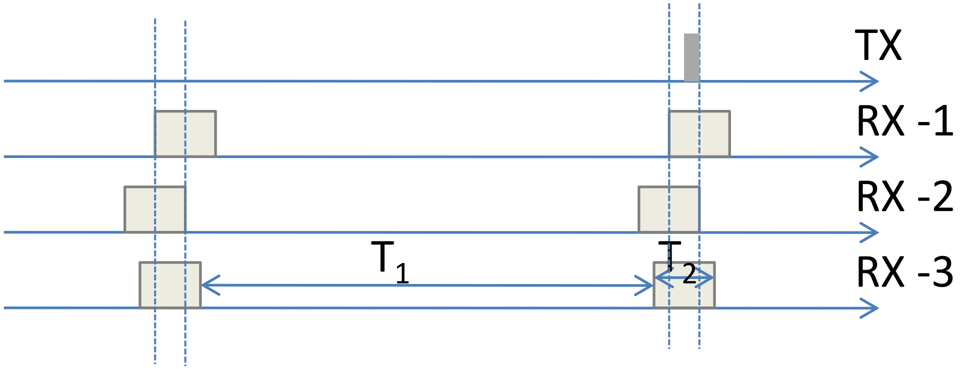


Fig. 28 – Example of duty cycled synchronization schemes

Wake-Up Receiver for EM Nanonetworks

[16] S. Marinkovic and E. Popovici. Nano-power wake-up radio circuit for wireless body area networks. In *Proc. of IEEE Radio and Wireless Symposium,* January 2011.

- Wake-Up Receiver
  - We need an asynchronous scheme to synchronize the nanodevices
  - A wake-up receiver needs to constantly sense the channel but using less power [16].
  - The wake-up signal must be easier to decode.
  - In particular, authors in [16] they use a second frequency to synchronize

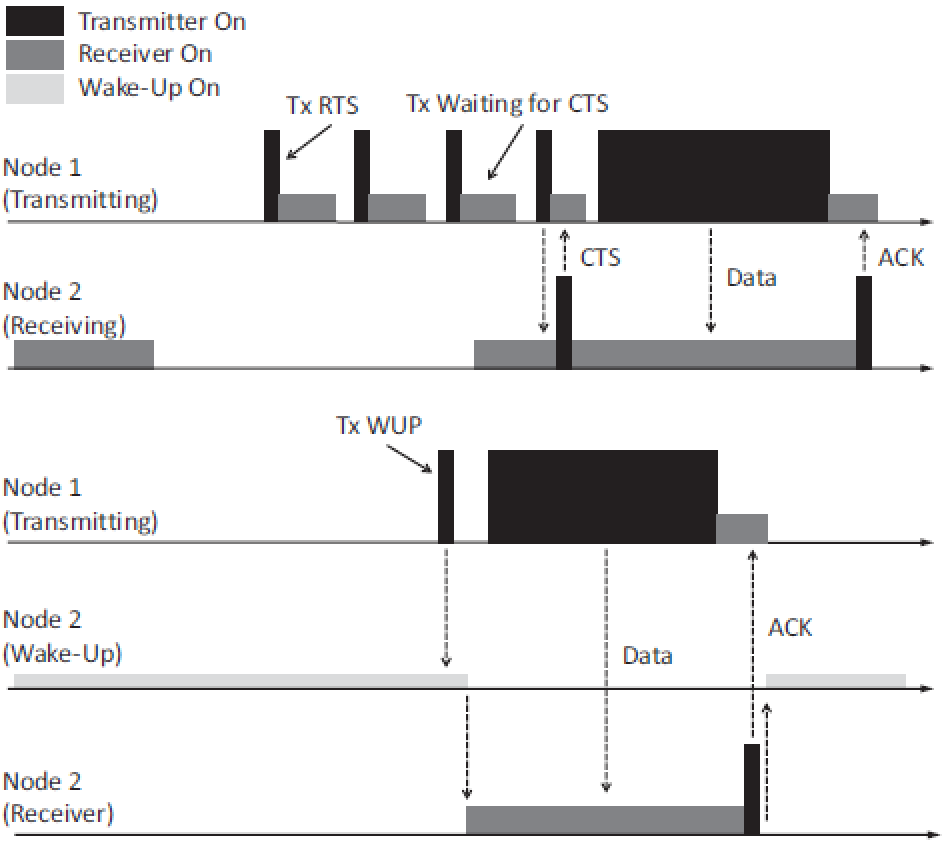
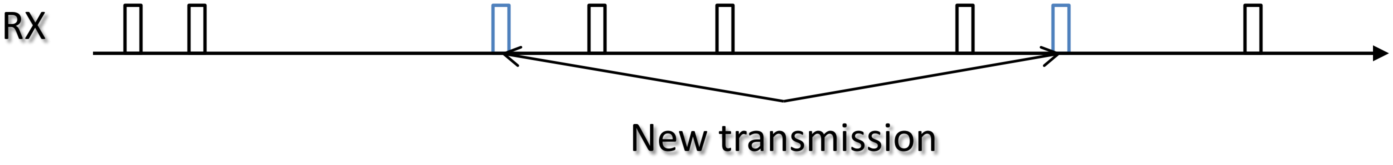


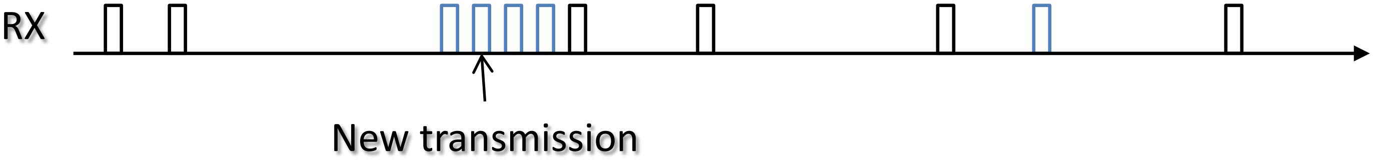
Fig. 29 – Comparison between duty cycled and wake-up synchronization schemes

Wake-Up Receiver for EM Nanonetworks

- Wake-Up Signal
  - The medium is shared with other users.
  - The pulses are spread in time
  - The receiver cannot try to synchronize every pulse it detects.
  - The Wake-Up signal cannot be a preamble of pulses



  - We propose the use of pulse bursts.



Wake-Up Receiver for EM Nanonetworks

Detection of a Pulse Burst

- We model this pulse burst as N_B independent pulses.
    - This detection can be done with power detectors, detecting a minimum power during a minimum time
- To provide robustness, we suppose that not all of the pulses are needed to detect a burst.

$$P_D = \sum_{i=0}^{N_B - N_b} \binom{N_B}{N_b + 1} (1 - p_d)^{N_b + i} P_d^{N_B - N_b - i}$$

- Additionally, it is also valid for when a neighboring node starts a transmission.

Effect of noise and Interference

- We model noise and interference as Poisson arrival.

$$\lambda = \lambda_n + \lambda_i$$

$$\lambda_n = p_0 / T$$

$$\lambda_i = N \lambda_{TX}$$

- We model the behavior of the wake-up module in presence of noise as a M/D/c/c queue

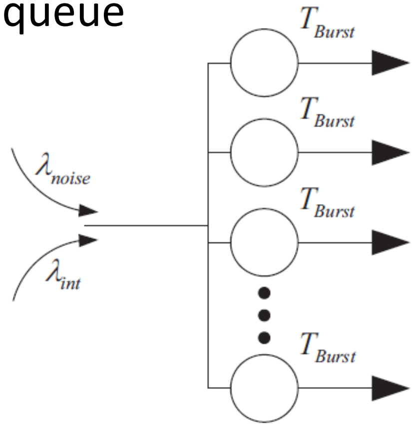


Fig. 30 – M/D/c/c queue model

Wake-Up Receiver for EM Nanonetworks

- Orthogonal Burst Preamble
  - As the number of neighboring nodes increases, the number of false alarms is increased.
  - To be energy consistent, the nanodevice has to wake-up only if this is the target of this packet

  - We propose time ortogonality between two consecutive pulses

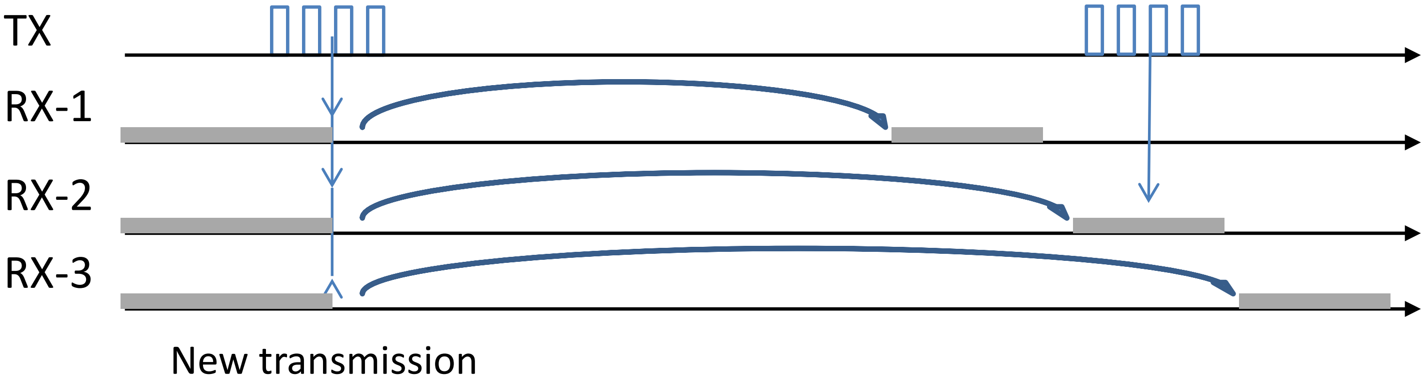


Fig. 31 – Example of Orthogonal Burst Preamble

Wake-Up Receiver for EM Nanonetworks

- Protocol Description
  - We propose to build this synchronization scheme on top of the ALOHA protocol

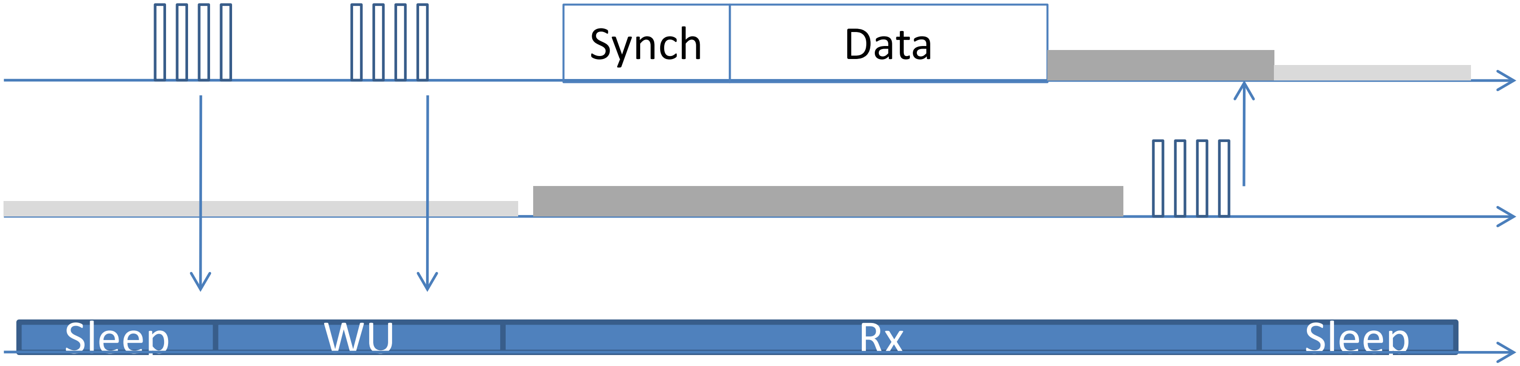


Fig. 32 – Protocol descritption. Current states and power consumption

  - A nanodevice sends a packet whenever it needs to send it.
  - The receiver aknowledges the packet by using a burst acknoledgment (BACK).
  - If the transmitter does not receives the BACK, it sends again the packet.

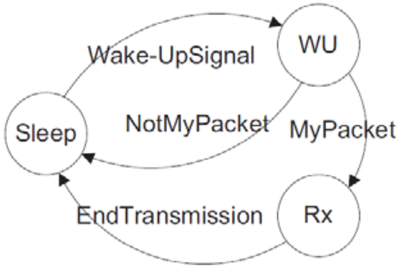


Fig. 29 – Receiver state diagram

Wake-Up Receiver for EM Nanonetworks

- False alarm
  - We refer as a false alarm as starting the reception due to neighboring nodes, interference or noise

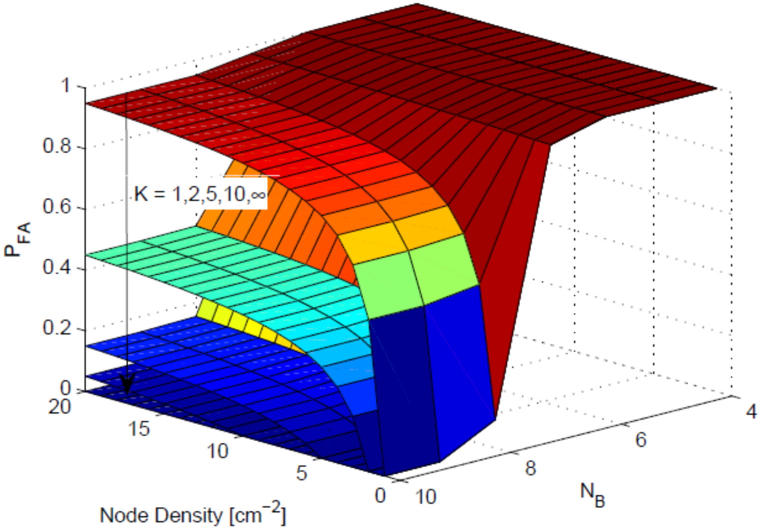


Fig. 33 – False alarm probability in terms of the node density

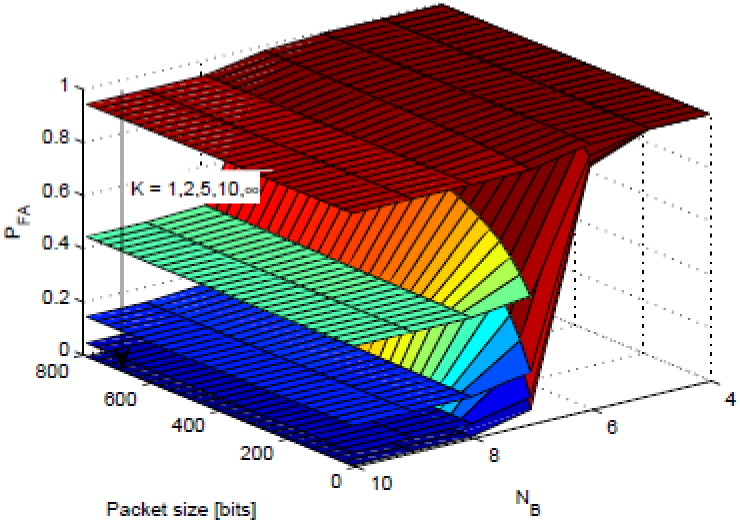


Fig. 34 – False alarm probability in terms of the packet size

- When the pulse burst is short:
  - The false alarm is mainly affected by noise
- When the pulse burst is large:
  - The false alarm is mainly affected by interferences and neighboring nodes
- When using orthogonal preambles, the node is not affected

Wake-Up Receiver for EM Nanonetworks

- Loss Probability
  - Losing a packet due to the protocol depends on the number of neighboring nodes
  - However this loss probability is very low. The system is highly scalable

- Energy Consumption
  - We model the energy consumption in terms of the stateflow.
  - The energy to receive a pulse is fixed to 0.1 pJ while the power in wake up is fixed to 0.7 pW

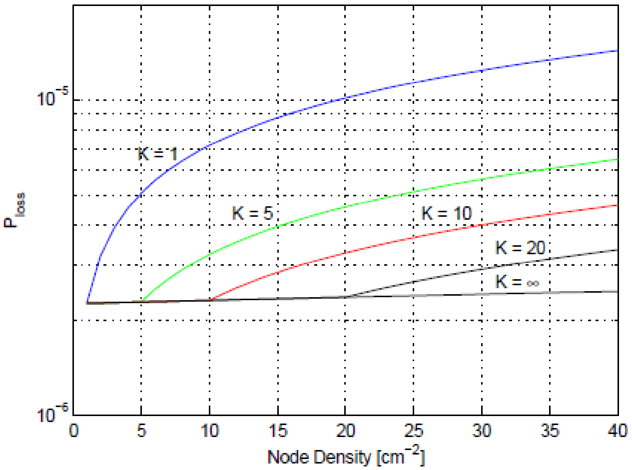


Fig. 35 – Loss probability in terms of the node density

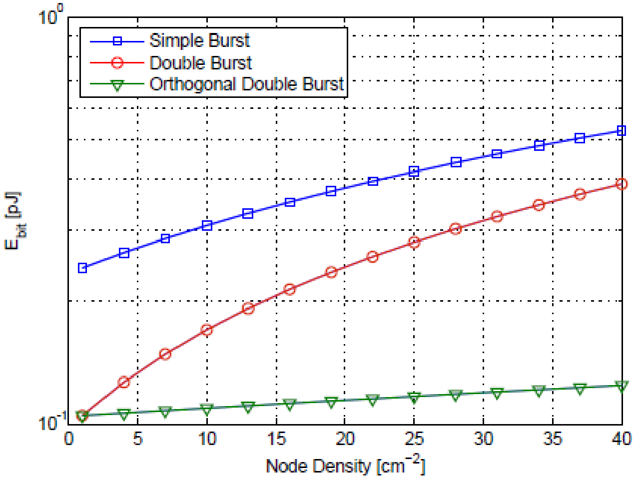


Fig. 36 – Energy consumption in therms of the node density

Table of Contents

- Introduction
- Transceiver Architecture for EM Nanonetworks
- Symbol Time Estimation
- Wake-Up Receiver
- ***Conclusions and Open Issues***

Conclusions and Open Issues

- Conclusions:
  - We provide a bridge between the antenna and the future network protocols. For this:
  - We propose a low complexity transceiver architecture, which provides better performance in terms of Symbol Error Rate and simplifies the frequency synchronization designed on top.
  - We propose a low complexity frequency synchronization scheme to guarantee the successful packet delivering. This is evaluated in terms of Packet Error Rate.
  - We propose an asynchronous synchronization scheme based on a wake-up receiver for nanodevices to enable the communication among nanodevices.

Conclusions and Open Issues

- Open Issues:
  - Simulation and implementation of the transceiver architecture over a specific technology.
  - Integration of the transceiver architecture results and frequency estimation in a network simulator
  - Network protocols designed built on top of our Wake-Up transceiver architecture.

Thank you very much for your attention!