“A study on performance of RF channel between ultra miniature devices composed of up-to-date components”

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Outline

- Concept of wireless sensor nano-network :
  - *Definition and properties ;*
  - *Why do we need nano-networks?*
- Key paradigms of nano-network based on RF communication :
  - *The primary problems of nano-robot design ;*
  - *Statistical behavior of the channel at nano-level ;*
  - *Nano-networking challenges ;*
- Simulations of channel between up-to-date miniature RF nodes ;
- Conclusion ;

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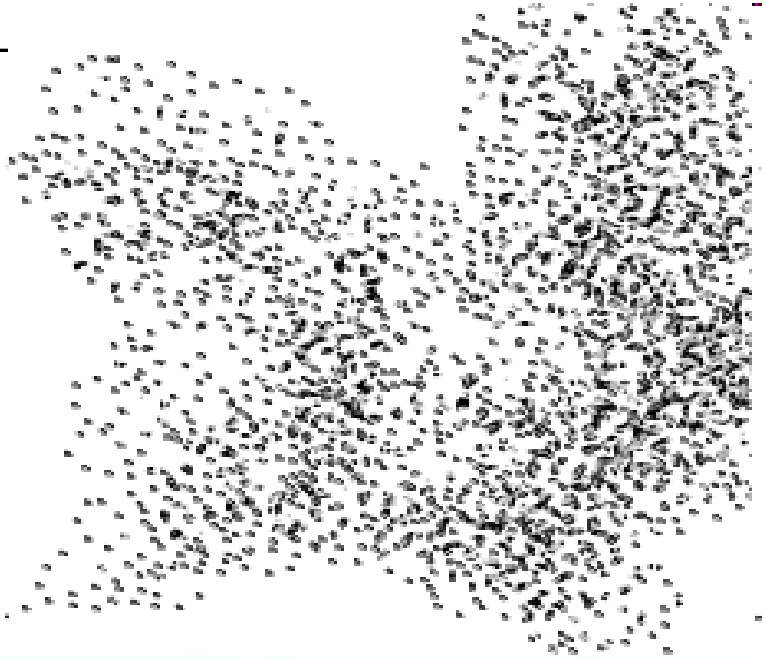
Sensor nano-network: definition and properties

- **Sensor nano-network** has been consisted of a large number ("swarm") of ultra miniature sensor devices (i.e., nano-robots).
- **Primary tasks of sensor nano-network are** detecting phenomena or events of environment, collect and process data, and transmit sensed information to interested users (e.g., an external macro-scale receiver).

Sensor nano-network properties are…

- *Very short-lived ;*
- *Wireless data transmission ;*
- *Multi-hop ;*
- *Randomly deployed ;*
- *Self-organizing ;*
- *Decentralized ;*
- *No fixed infrastructure ;*



Sensor nano-network: active interest

1. A growth of sensing performance is a critical enabler for new services and products in present “sensor applications” ;

2. A further need to miniaturize node size: a diversity of dramatic applications is unreachable with dimensions of off-the-shelf sensor nodes ;

3. The first step to create full-fledged nano-scale devices: a typical sensor nano-robot will be able to perform only very simple tasks; however, its architecture might be used as a base to create more complex devices at nano-level (e.g., molecular assembler/disassembler) ;

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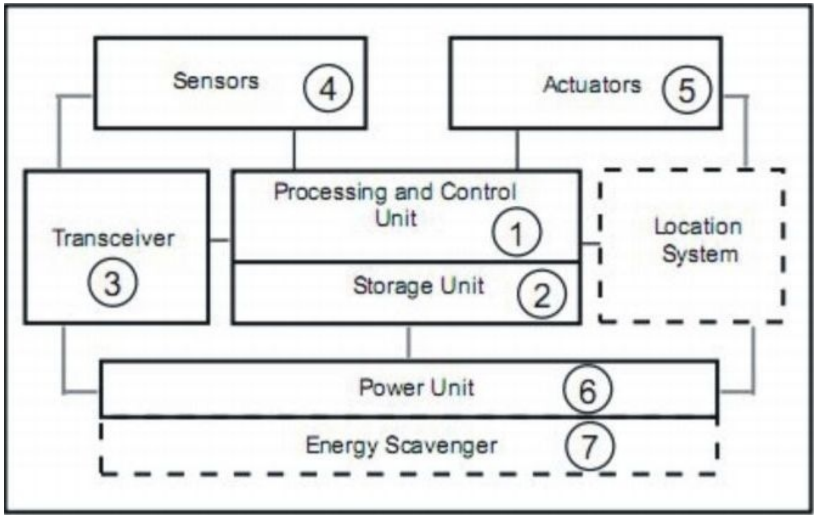
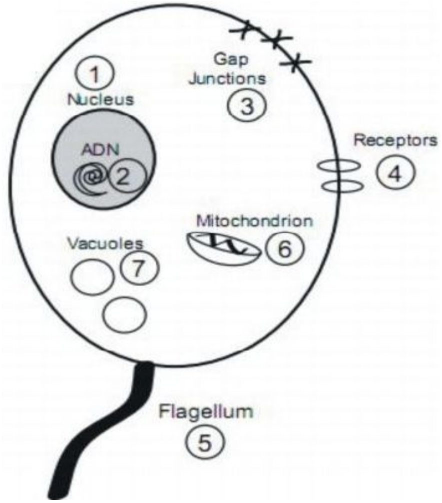
Nano-robot architecture

Traditional node architecture



"Bio"-architecture of a node

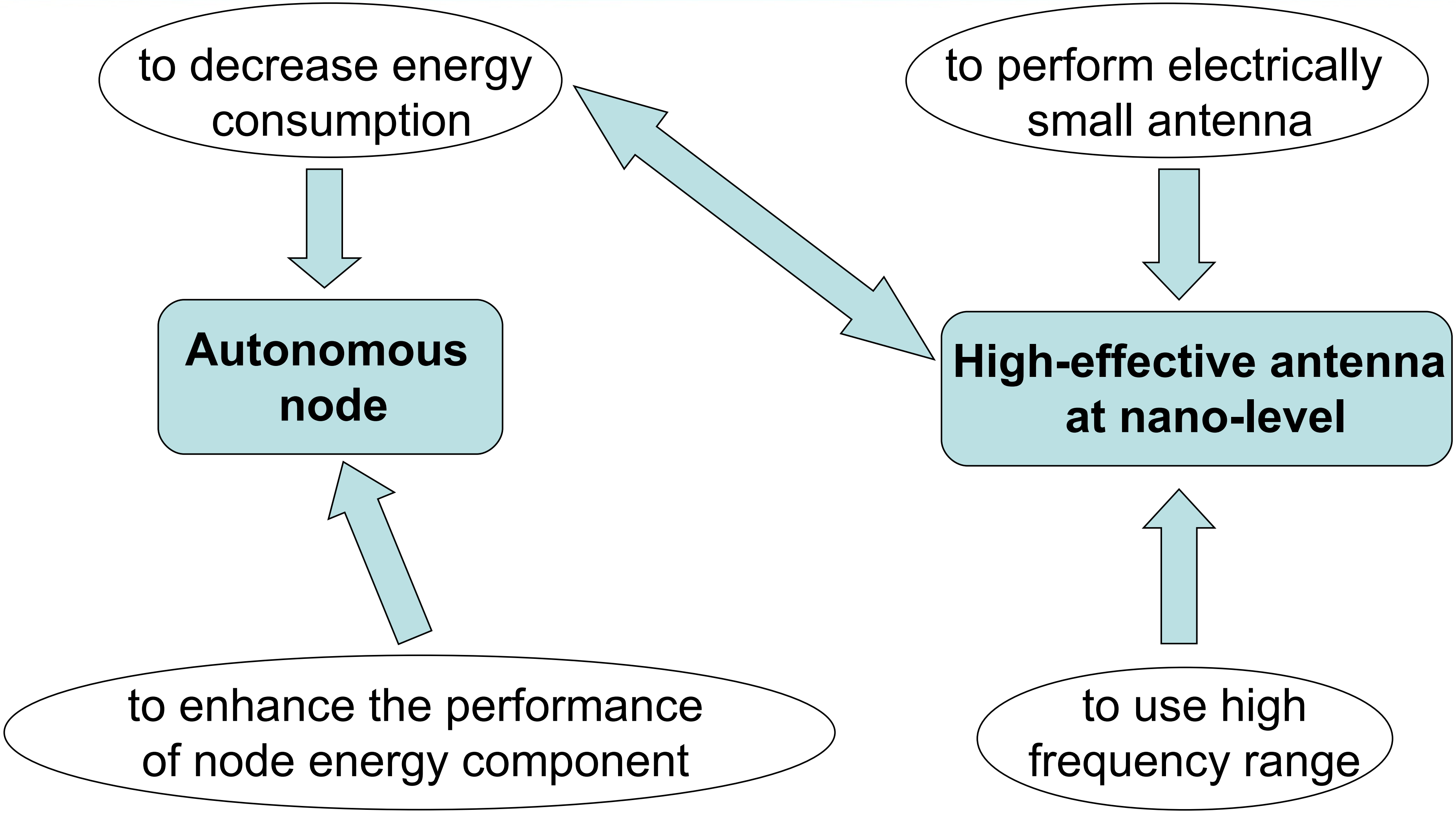


Node components:

Primary : processor (1); sensor/actuators (4,5); energy supply (6,7); transceiver (3);

Secondary (optional): memory (2), motor and etcetera;

Performing a feasible nano-robot



Capability of energy sources

F S. Roundy, D. Steingart and et al., “Power sources for wireless sensor networks” , 2004

Power Source	P/cm³ (µW/cm³)	E/cm³ (J/cm³)	P/cm³/yr (µW/cm³/Yr)	Secondary Storage Needed	Voltage Regulation	Comm. Available
Primary Battery	-	2880	90	No	No	Yes
Secondary Battery	-	1080	34	-	No	Yes
Micro-Fuel Cell	-	3500	110	Maybe	Maybe	No
Ultra-capacitor	-	50-100	1.6-3.2	No	Yes	Yes
Heat engine	-	3346	106	Yes	Yes	No
Radioactive(^{63}Ni)	0.52	1640	0.52	Yes	Yes	No
Solar (outside)	15000 *	-	-	Usually	Maybe	Yes
Solar (inside)	10 *	-	-	Usually	Maybe	Yes
Temperature	40 *	-	-	Usually	Maybe	Soon
Human Power	330	-	-	Yes	Yes	No
Air flow	*380*	-	-	Yes	Yes	No
Pressure Variation	*17*	-	-	Yes	Yes	No
Vibrations	200	-	-	Yes	Yes	No

Table – Comparison of various potential power sources for wireless sensor networks. Values shown are actual demonstrated numbers except in two cases which have been italicized.

* Denotes sources whose fundamental metric is power per **square** centimeter rather than power per **cubic** centimeter.

Current battery and capacitor technology store approximately 1 joule per cubic mm (0,27 mW*hour)

The most power density technology is solar cells provide 1 joule per day per square mm in sunlight (outdoors) and 1 to 10 millijoules per day per square mm indoors.

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State-off-the-art in transceiver manufacture

RF transceiver = Electronic circuit + Antenna

	Circuit size (m^3)	Antenna size (m^3)	System size
Hitachi	1E−14	1E−08	1E−08
UCI CNT Radio	1E−23	1E−05	1E−03
France-Telecom	1E−09	1E−09	1E−09
Smart Dust	3.125E−09	1E−06	1E−06
SMS	NA	NA	1E−06
BioRasis	NA	NA	5E−09
ISSYS	NA	NA	1E−06
Potential single-chip radio			1E−14
Volume of single cell			1E−18
Potential nano radio			1E−21

These are estimates only, as most literature does not specify complete system volume

Circuit size versus Antenna size (based on off-the-shelf technology)

P. J. Burke, C. Rutherglen, "Towards a single-chip, implantable RFID system: Is a single-cell radio possible?" *Biomedical Micro-devices,* in press (**2009**)

- Typical high-efficiency antennas should be built close to size multiples of λ /4 ;
- The size of nano-scale antenna is incomparably less than the RF wavelength (cm) ;

⇓

There is no high-efficiency antenna at nano-level yet

THz communication link: advantages

A use of higher frequency range (THz) decays a free-space wavelength → increases the efficiency of nano-antennas.

- THz communications have the potential for increased bandwidth capacity compared to microwave systems ;
- THz communications are inherently more directional than microwave or millimeter links due to less free-space diffraction of the waves ;
- Under certain weather conditions and for specific link length requirements THz can enable reliable communication where IR based systems would fail.
- For THz radiation, scintillation effects are smaller than for IR radiation ;
- The THz frequency range is largely unregulated (e.g., above 275 GHz is available for communications) ;

N.B.: Components for communication systems (like planar integrated circuits, amplifiers, antenna arrays) do not exist above 125 GHz: the chip performance is S=10 Gb/s, D=800 m.

THz communication links: challenges

Primiry goal of THz band – to develop a mathematical model taking into account all attenuation sources in the channel:

• Spreading loss – depends only frequency and distance ($L = const \cdot f^2 d^2$) ;

• Absorption loss – the terahertz channel is typically very frequency-selective because molecular absorption will affect and determine the usable bandwidth (to find a "frequency window") ;

• Multi-path fading – characterize the reflection coefficients from materials found in the envisaged scenarios; use scattering models from rough surfaces;

• Nano-particle scattering – The scattering by particles much smaller than the signal wavelength is known as Rayleigh scattering ;

• Interactions of THz radiation with nano-scale biological entities needs to be studied.

* Development of miniature THz sources within the atmospheric transmission windows as well as compatible high sensitivity detectors and modulation software.

Electrically small antenna designs

A use of electrically small antenna (the largest dimension of the antenna is no more than one-tenth of a wavelength)

- **Coating a wire with a layer of dielectric:** resonance is quite sharp (narrow frequency range) and antenna is very frequency-selective as well, a search of favorable antenna design taking into account real-life materials and handling possibilities at nano-level ;

- **Better use of the volume occupied by antenna:** The antennas based on this principle have sophisticated design. In this wise it's extremely hard to manufacture them at nano-level ;

- **A use of near field:** a maximizing the electrical or magnetic coupling is the primary design goal, the communication very depends on antennas positions, more critical approach for a real-life dynamical sensor network at na

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<u>"RFID" design</u>
small size, no energy supply ;
restricted applicability ;

VS.

<u>"typical" design:</u>
large size, need energy supply ;
full applicability ;

Crucial miniaturization problem of RF nano-robot

- Node has to be autonomous: There is no possibility to replace a battery in nano-robots ;
- Very limited amount of energy stored in the node: Capabilities of up-to-date energy sources at nano-level are drastically bounded + very poor performance of up-to-date energy scavenging techniques ;
- High power consumption level: the transceiver based on radio frequency becomes incredibly hungry power consumption component in nano-robot ;

The main goal is to bridge power demands of sensing, computing and wireless technologies for a node with capabilities of energy component

Statistics in the nano-channel

The features of nano-channel :

- *It is hardly to manipulate and to handle nano-scale devices* :
  - The communication distance ;
  - The statistics of polarization losses ;
  - The statistics of directivity losses (i.e., associated with antenna direction pattern) ;
  - The statistics of antenna gain because of manufacture tolerance ;
- *The energy component preferably should harvest energy * :*
  - The output power because of scavenging technique ;

** N.B.* - If the application is very short-lived, we will be able to use a battery element as the nano-robot energy component as well ;

Nano-network: pros and cons

- Nano-network can be more robust than conventional wireless networks because of their non-hierarchical distributed control and management mechanisms: however, a need to develop medium access control, routing protocols (i.e., ICT contributions) is arisen ;
- Multi-hop in nano-network can reduce the power consumption of wireless devices: For N-hop transmission the power advantage is:

$$\eta = N^{\alpha - 1}, \text{ where } \alpha - \text{pathloss exponent};$$

N.B. - A finding of trade-off number of hops: power consumption of node components VS. advantage of multi-hop transmission ;

- Because of short communication links radio emission levels can be kept low. This reduces interference levels and increase security level as well as spectrum reuse efficiency (in addition, it is possible to use unlicensed unregulated frequency bands as well).

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The expression for transmitted power

$P_R^{real} = P_T \left[\frac{G_T G_R \lambda^2}{16\pi^2 R^2} \right]$ - Friis equation for free space

$P_R^{min} = E_0^{bit} N_0 S$ - in order to get an acceptable bit-error-probability

$\Rightarrow P_R^{real} \geq P_R^{min}$;

where S is date rate, N_0 is noise spectral density (= -174 dBm),

E_0^{bit} is energy-per-bit : * $E_0^{bit} \geq 7dB$ <=> Bit-Error-Probability $\leq 10^{-3}$

* The data is for the most energy-conserving modulation scheme - BPSK;

⇓

$$P_T^{min} = \frac{16\pi^2 E_0^{bit} N_0 R^2 S}{G_T G_R \lambda^2} \quad ;$$

Attenuations between antenna and generator/amplifier are specified in G_T and G_R

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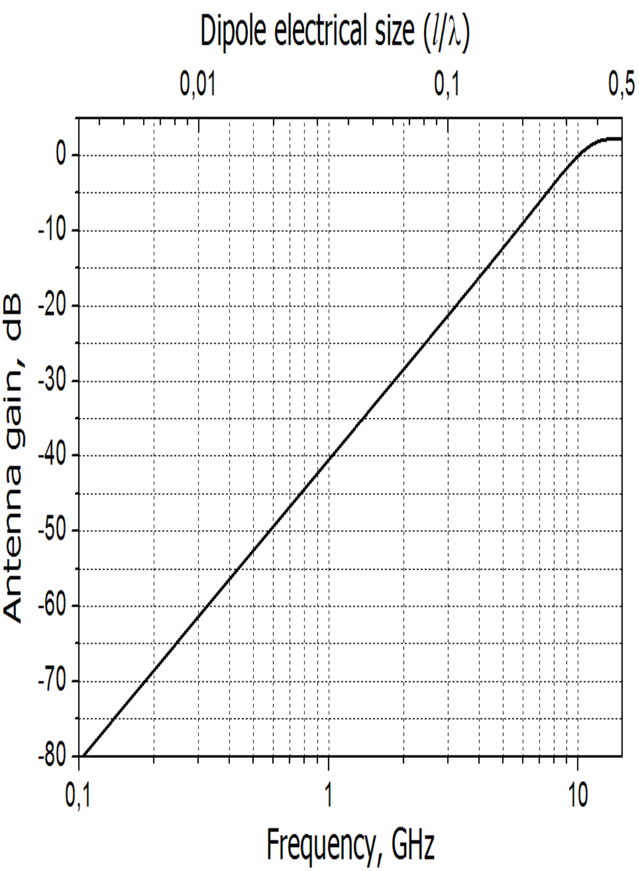
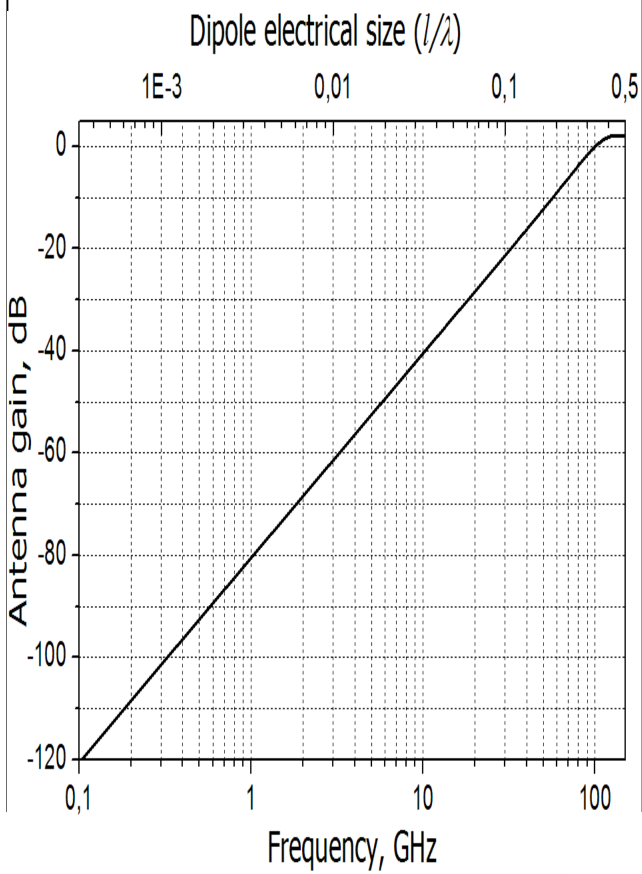
Antenna gain calculations

The antenna is dipole with length l *and radius* l */10:*

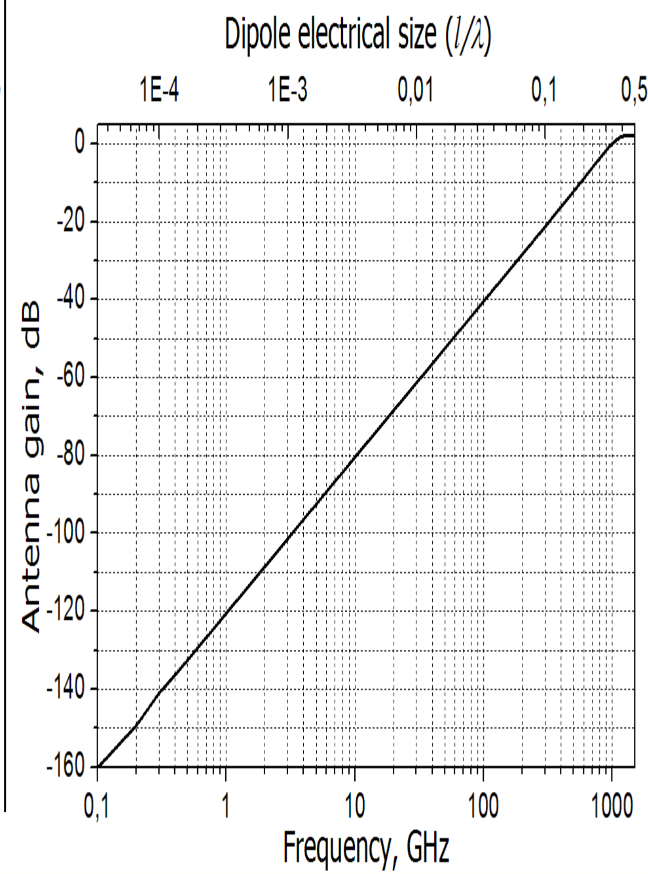
l = 1 cm



l = 1 mm

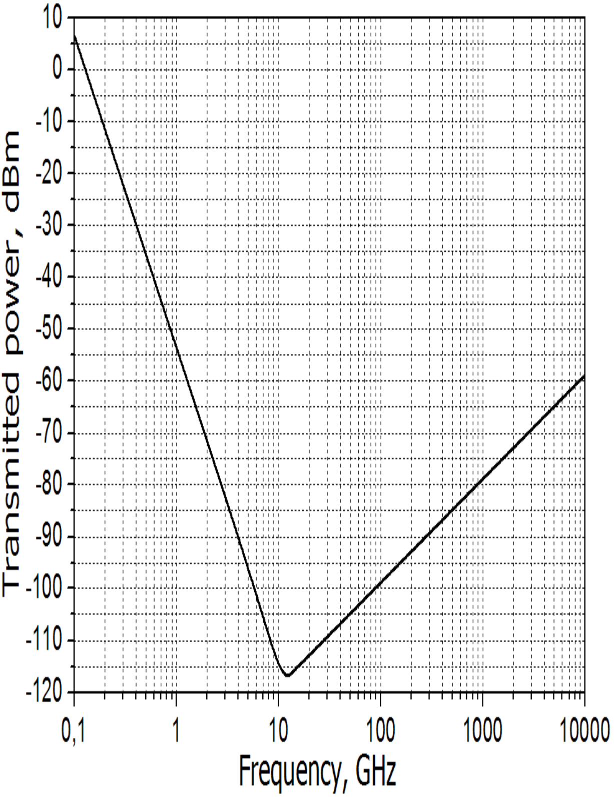


l = 100 μm

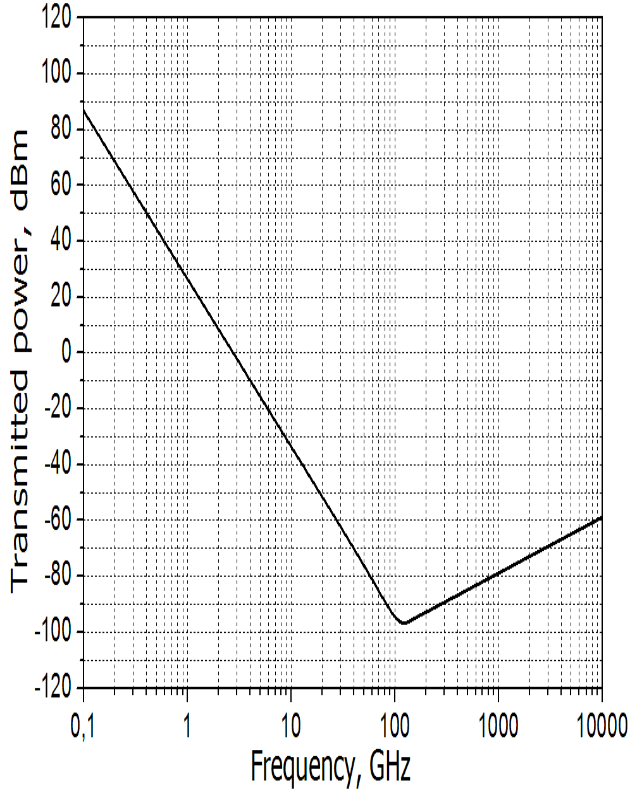


Calculations of transmitted power for S=100 bit/sec and R=10 cm

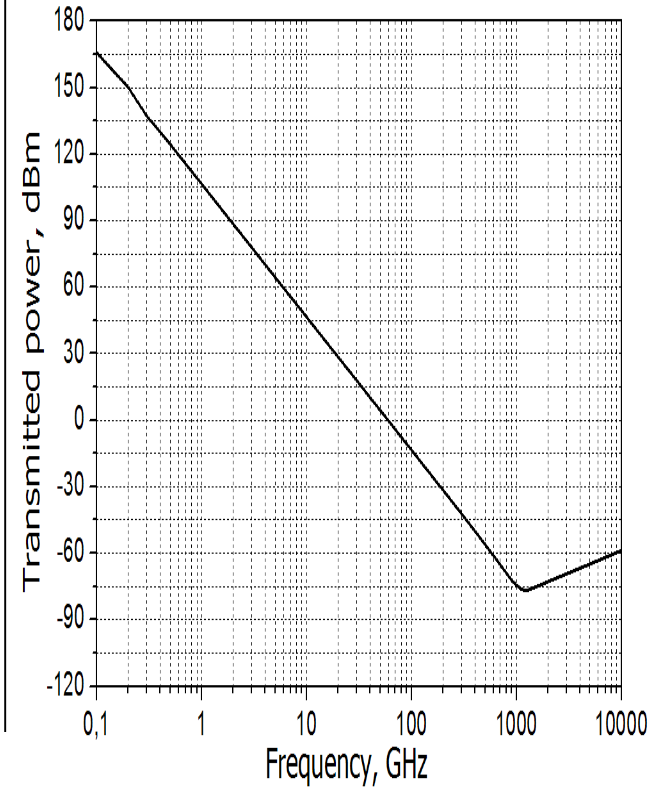
l = 1 cm



l = 1 mm



l = 100 μm



To increase/decrease the data rate in 10 times ⇔ add/subtract 10 dB;

To increase/decrease the distance in 10 times ⇔ add/subtract 20 dB ;

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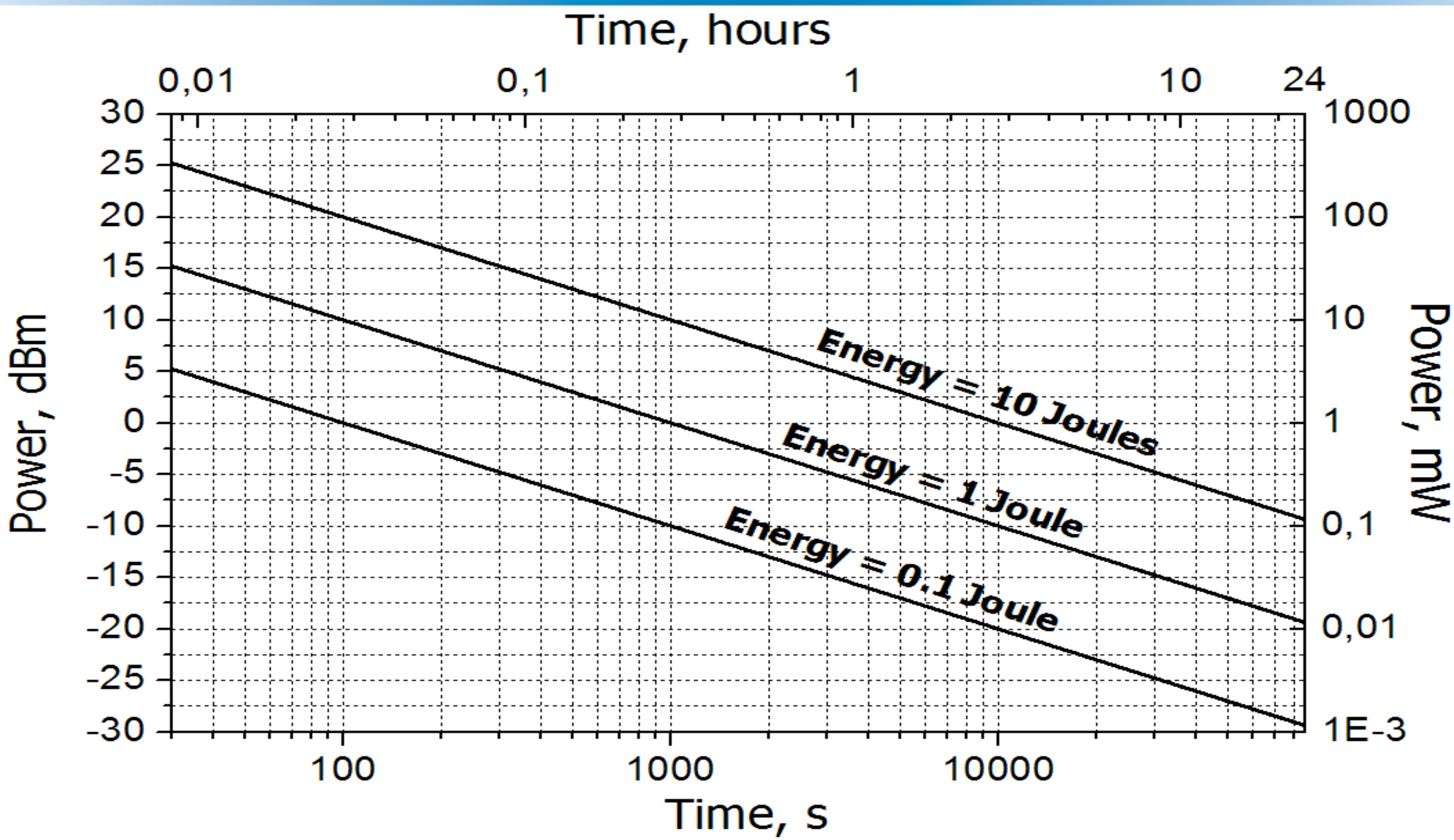
Energy needs vs. power consumption



Present technologies store approximately 1 joule per cubic mm

Example of specification of channel statistics - 1

Through mathematical manipulations and approximations received power is expressed :

$$P_R = \frac{900 l^4 k^2 \varepsilon \mu \, |A|^2 \cos^2 \alpha}{8 \cdot \mathrm{Re}(Z_0) \cdot R^2} = C \cdot X = \begin{cases} C = \dfrac{900 l^4 k^2 \varepsilon \mu}{8 \cdot \mathrm{Re}(Z_0) \cdot R^2} & \text{is the deterministic component} \\ X = |A|^2 \cos^2 \alpha & \text{is the statistics multivariate component} \end{cases}$$

***A* is the source amplitude :**

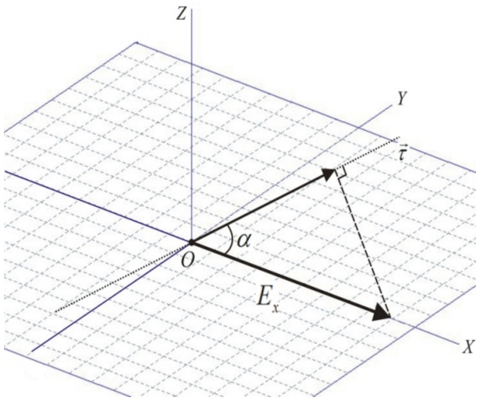
density function of A:

$$f(A) = \frac{1}{A_m} \quad in\ the\ range\ [0, A_m]$$

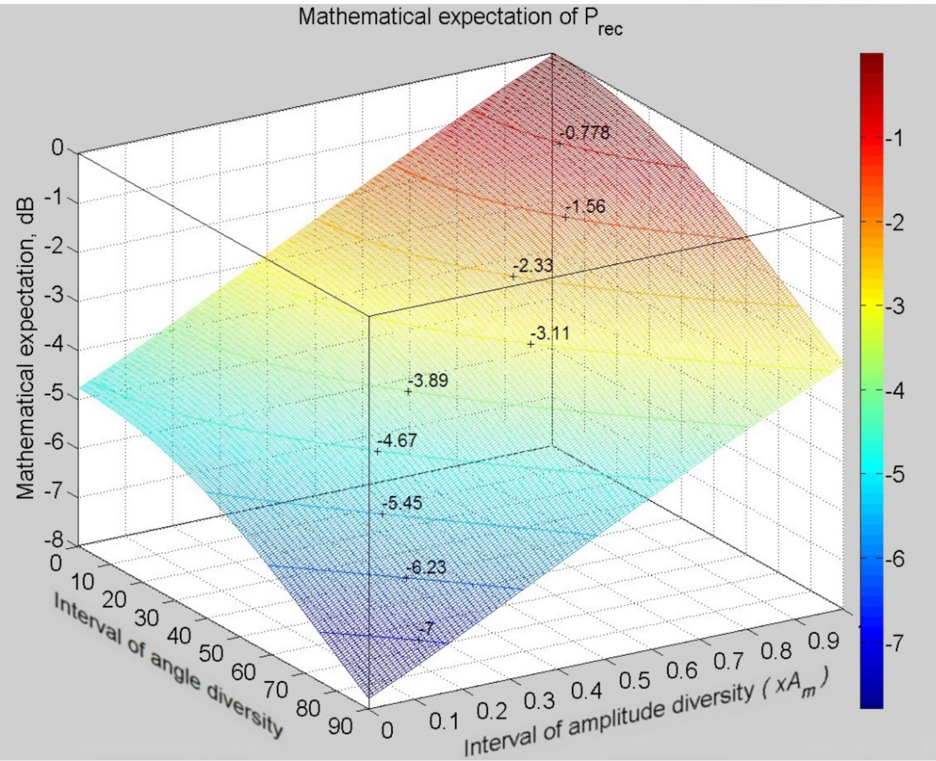
***α* is the angle between antennas :**

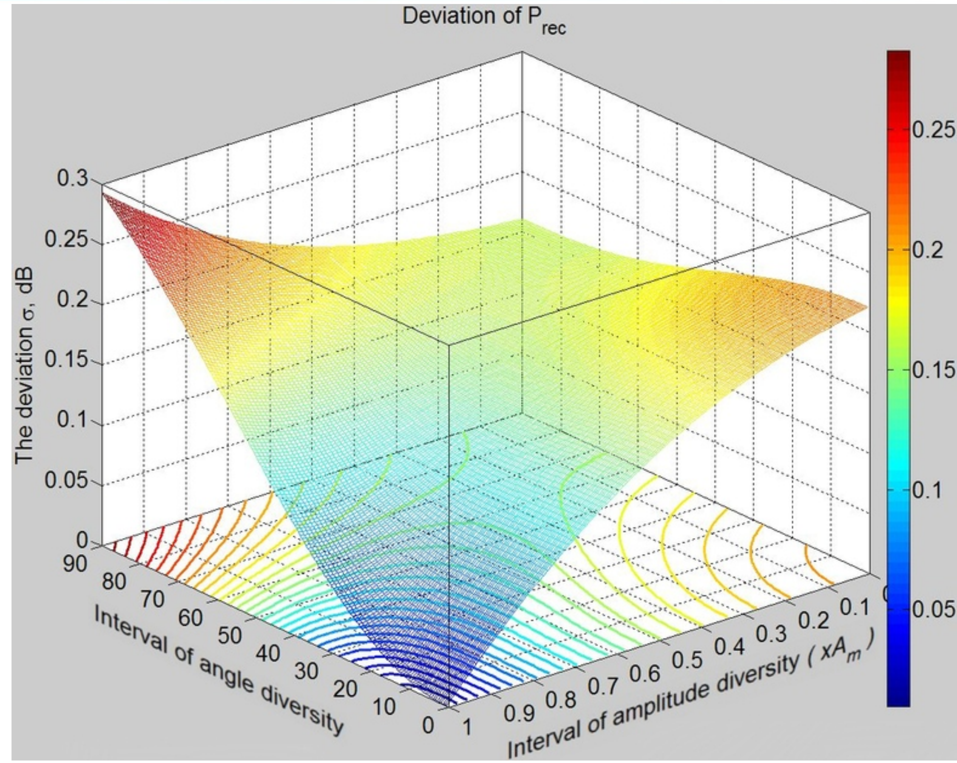
density function of α :

$$f(\alpha) = \frac{1}{\pi/2} \quad in\ the\ range\ [0, \pi/2]$$



Example of specification of channel statistics - 2





$$\langle P_R \rangle = \langle CX \rangle = P_R^{\max} M(X), \; where \;\; P_R^{\max} = \frac{900 l^4 k^2 \varepsilon \mu \, |A_m|^2}{8 \cdot \mathrm{Re}(Z_0) \cdot R^2};$$

The value of received power is also decreased because of statistics in the channel: for instance, a decay of almost 8 dB is found out under the aforementioned conditions.

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Conclusion

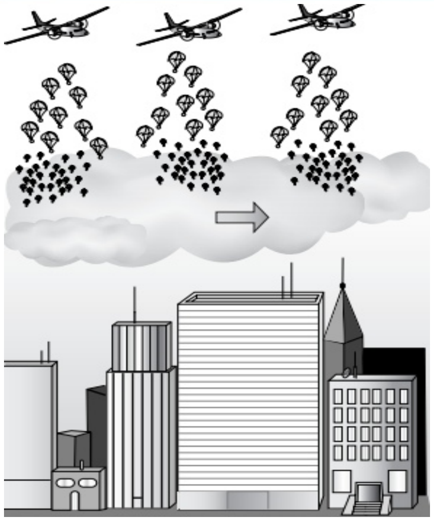
- To support the five-minute data transfer (on THz frequencies) using the miniature transceiver (i.e., micron dipole antenna + nano-generator) we need one Joule of energy: the performance of modern energy supply sources should be increased in billion times (i.e., under the assumption that 1 μm^3 energy element is able to provide the node with 1 Joule of energy);
- In order to make feasible nano-robot we should…

  - To enhance the capabilities of energy supply sources ;

  - To make a miniature antenna more efficiency: a use of high frequency range + electrically small antenna techniques ;

  - Take into account possible specific attenuation sources (e.g., very frequency-selective terahertz range, channel statistics ...) ;

Thank you for your attention



P.S. One of the real possible application for nanonetworks is a tracking of chemical plumes

Which application directly associated with nano-communication do you know ???

QUESTIONS ?