CENTRO RICERCHE FIAT

Wireless and Powerless Sensor:

Technical Aspects and Indoor Communication Techniques

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Outline

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- Process monitor – from wires to wireless
- Wireless system @ CRF – requirements & design
- Wireless system
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  2. V/F device
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- Multi path routing protocol

Process monitor – from wires to wireless

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The current state-of-technology is characterized by systems based on sensors (photodiodes, cameras, microphones, ….) connected to the data acquisition device **by wires**

wires as medium for data transferring → drawbacks:

- difficulties of wires placement
- wires cost
- installation cost
- maintenance cost

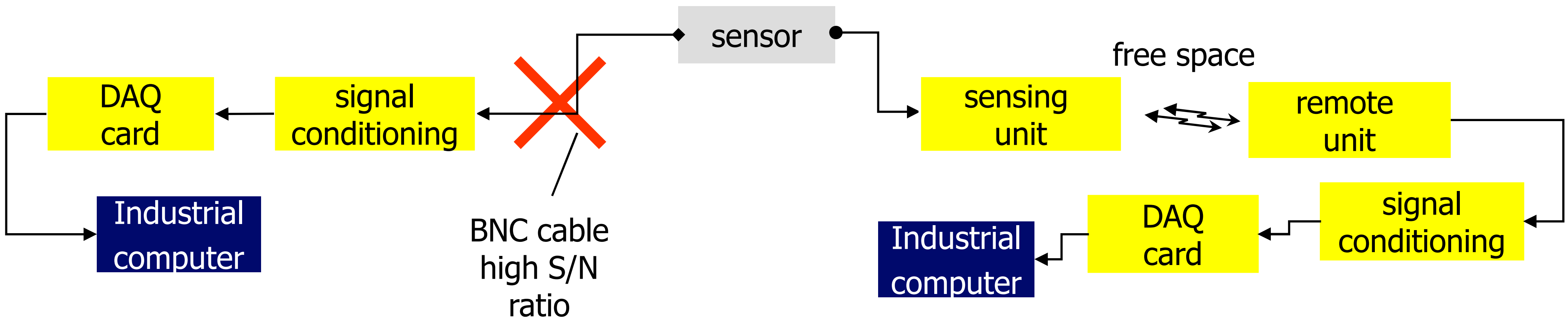
wireless technology as medium for data transferring, available due to:

- increment of functionality capabilities of components
- cost reduction of components

→ advantages:

- elimination of wires cost
- make connections not feasible previously
- retrofit more measurement points cost effectively

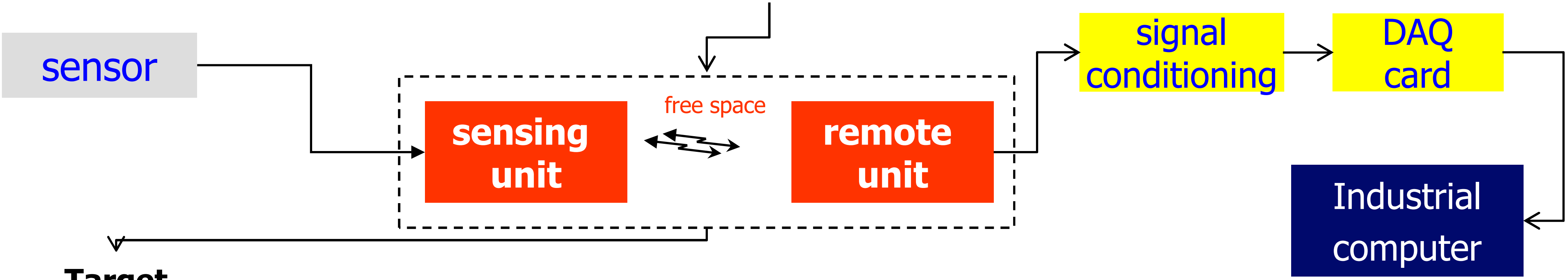
wireless communication technology can be considered as a cost and reliable alternative for cabled systems



Wireless system @ CRF – requirements & design

The system, consists of

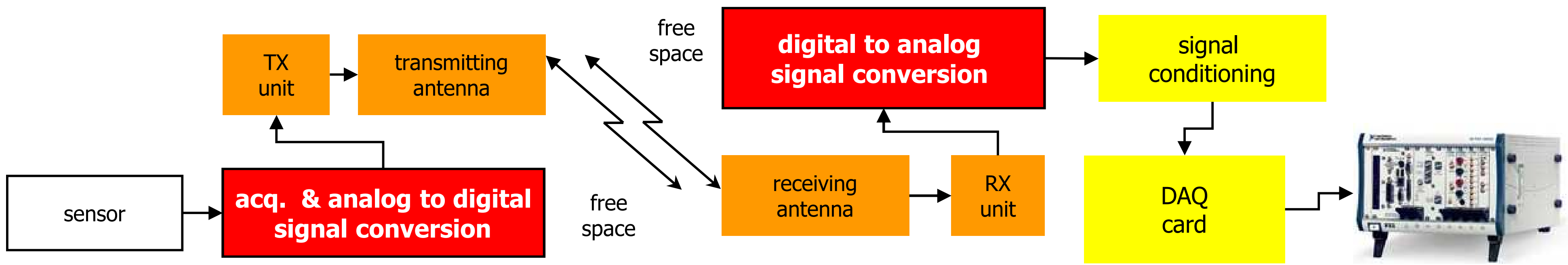
- sensing unit, to **sample and transmit** the process data
- remote unit, to **receive and send** the data to DAQ card



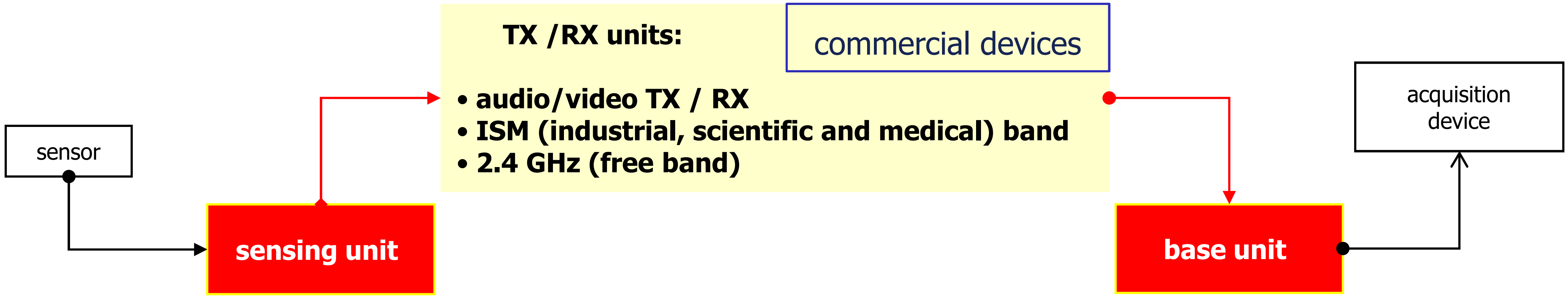
Target

- ✓ compact & robust for industrial environment
- ✓ cheap
- ✓ able to transmit the data in real time (sample & transmit)
- ✓ adaptable for different sensors (different dynamics)
- ✓ **max. sampling frequency 65536 Hz**

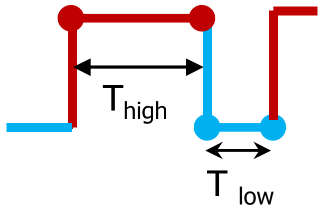
CRF solution | **Patent: EP 1634672A1 - US 712063B2**



Wireless system – data conversion (1/2)



- sensing and base units communicate through the video channel which transmit pulse shaped digital signals
- video channel, @ 2.4 GHz, transmit pulses with the minimum pulse duration = 800 ns
- maximum frequency pulse rate calculation: $T_{high} \geq 800$ ns, $T_{low} \geq 800$ ns



$$f_{max} = 1/(T_{high} + T_{low}) \leq 625 \text{ kHz } (\approx 1.25 \text{ Mpulse/sec})$$

Wireless system – data conversion (2/2)

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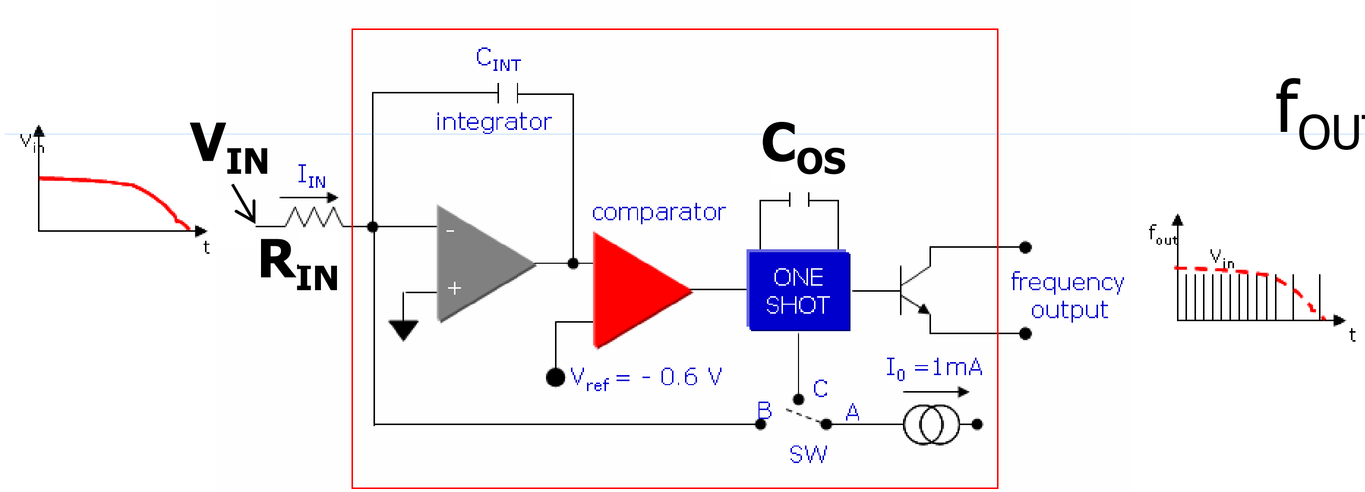
circuit based on a simple voltage-to-frequency / frequency-to voltage converter

the voltage to frequency converter (VFC) is a device which accepts at its input an analog voltage signal and provides at its output a digital signal at a frequency precisely proportional to the applied input voltage

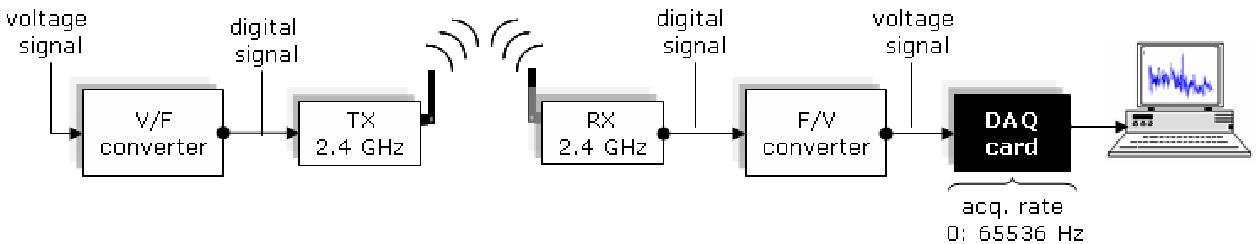


$$f_{OUT} = f(V_{IN}, R_{IN}, C_{OS})$$

The external components (R_{in} ,C_{INT} and C_{OS}) have been chosen considering that the system must be connected to different type of sensors, as well as the constraints on the max. frequency pulse rate

- acq rate range = 0:65536 Hz
- max. frequency pulse rate $f_s \leq 625$ KHz

$$65536\,\text{Hz} < f_{OUT} < 625\,\text{kHz}$$



Wireless system – V/F device

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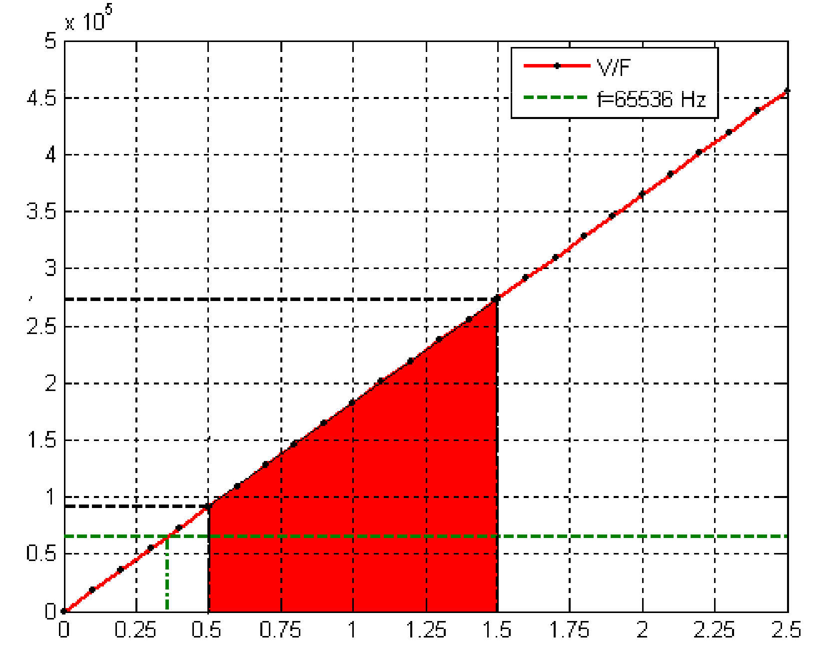
The signals oscillates between -0.5 V and 0.5 V. We have used a voltage regulator for getting the minimum signal voltage > 0.36 V. We used an offset of 1 Volt:

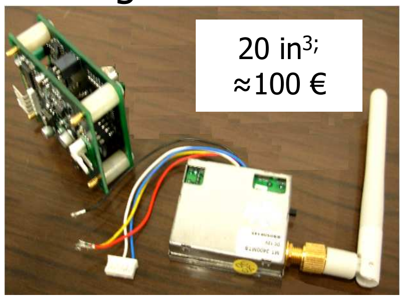


$$f_{out} = \frac{1}{T_1 + t_{os}} = 0.15\frac{V_{in}}{R_{in}}\left(\frac{1}{C_{os} + 4.4 * 10^{-11}}\right)$$

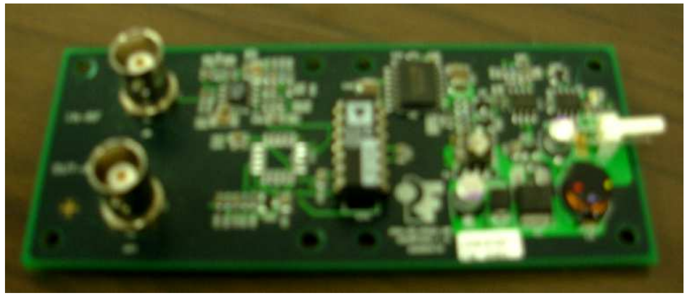
R_{in} = 2.2 kΩ
C_{int} = 1.5 nF
C_{OS} = 330 pF

signal between 0.5 V: 1.5 V
f_{out} between 100 kHz : 280 kHz
1 Hz → 5.5 μV

sensing unit



base unit



Patent: EP 1634672A1 - US 712063B2

Indoor radio propagation model

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In the development of a wireless communications system,
an accurate radio channel for indoor communications is needed

building structure

operating frequency

The propagation behavior in any in-building environment is a difficult to predict phenomenon

the presence of many obstacles leads to multi-path signals and shadow fading

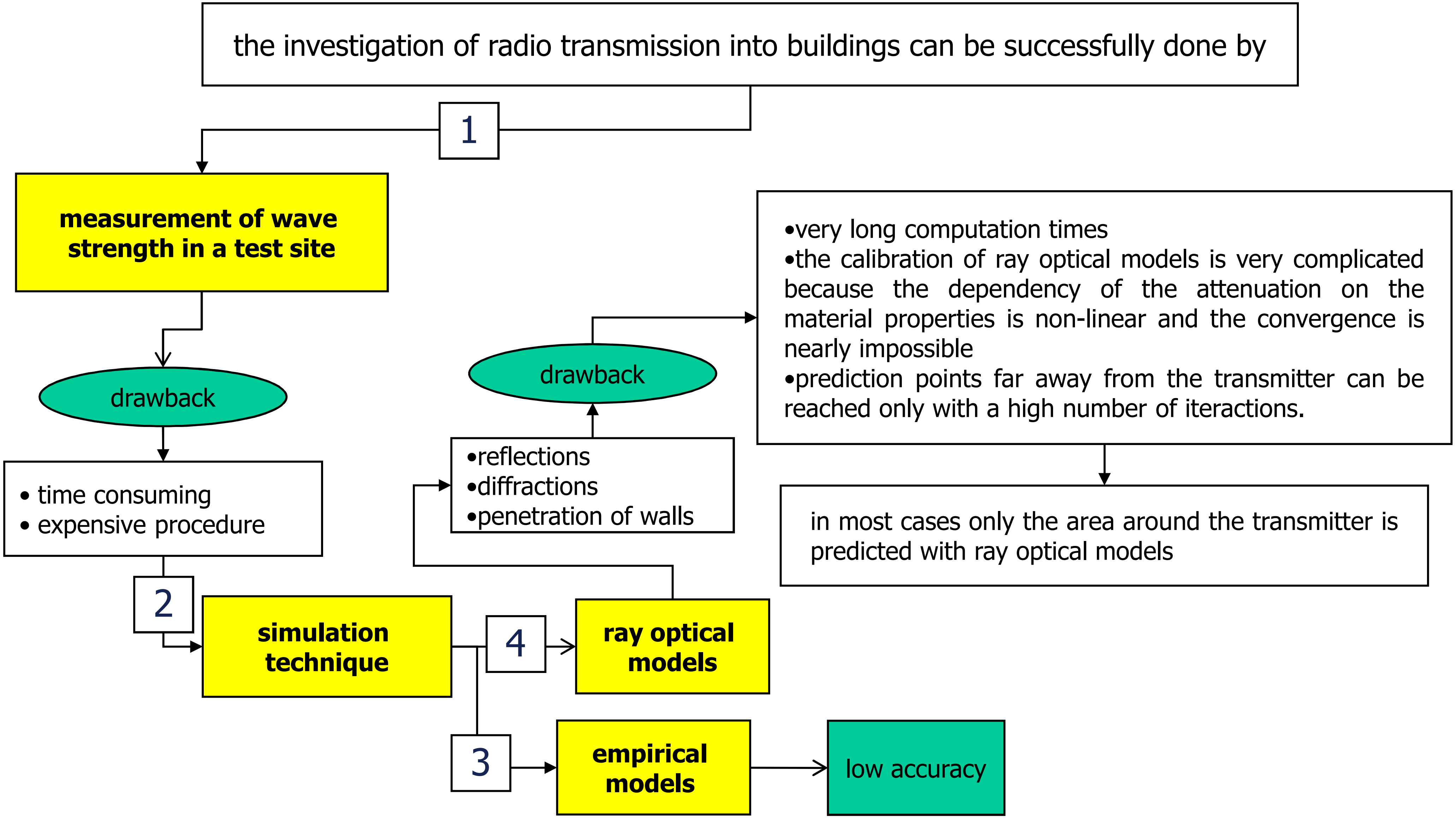
reduced coverage region of the signal

dispersion due to delay spread

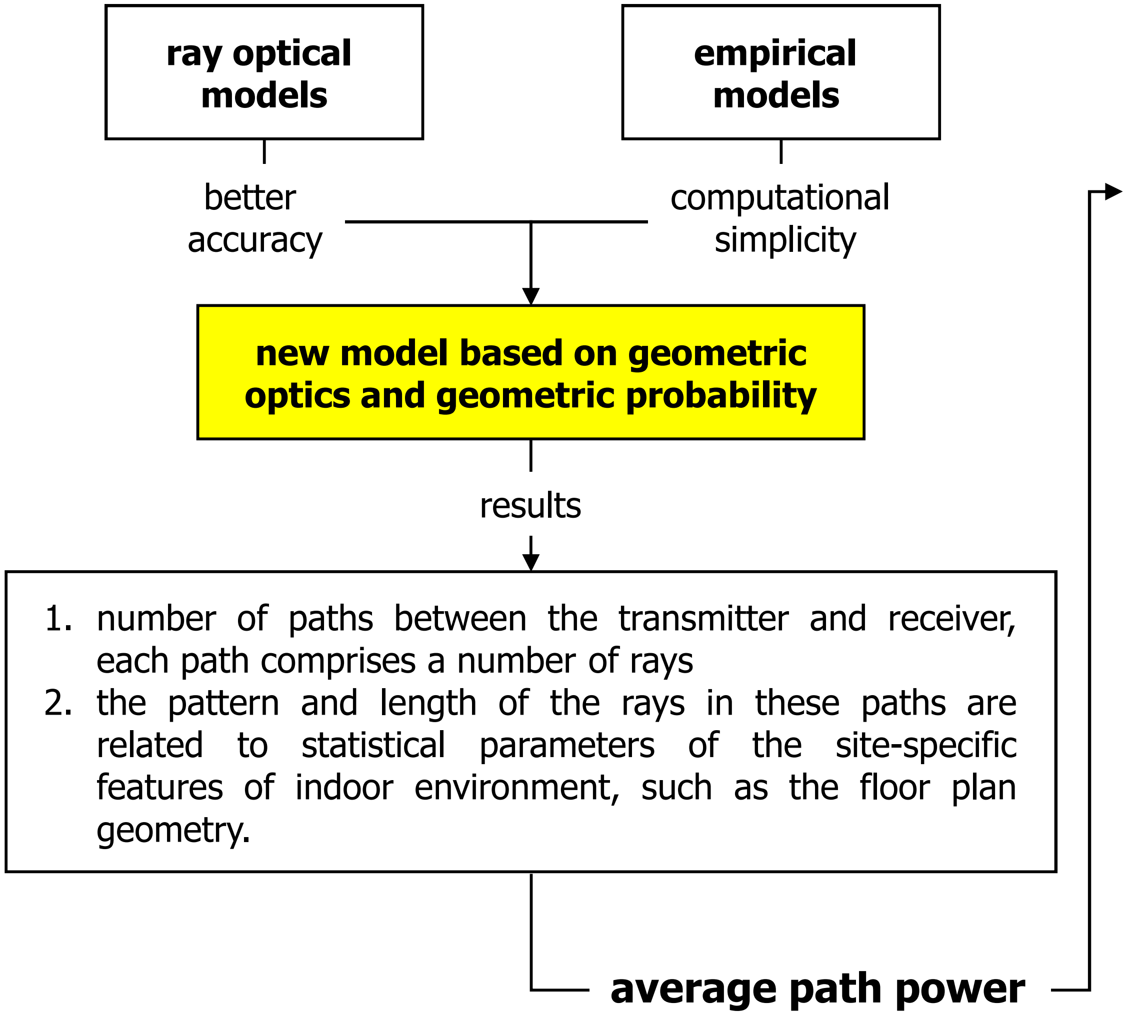
limits the maximum data rate that can be achieved in a wireless indoor channel

Indoor radio propagation model

Why do we need a new indoor radio propagation model?



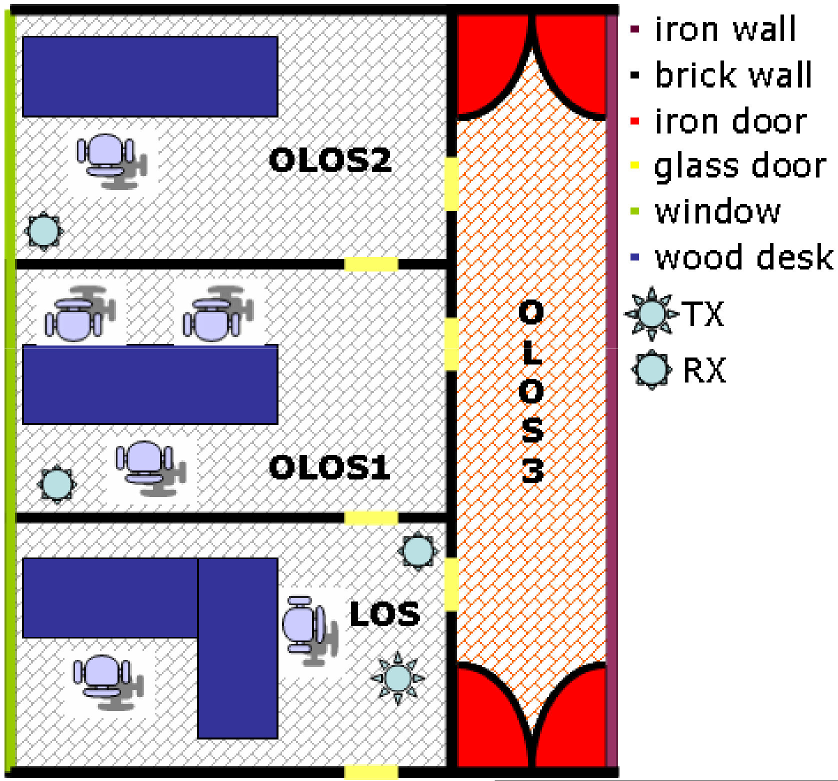
Indoor radio propagation model



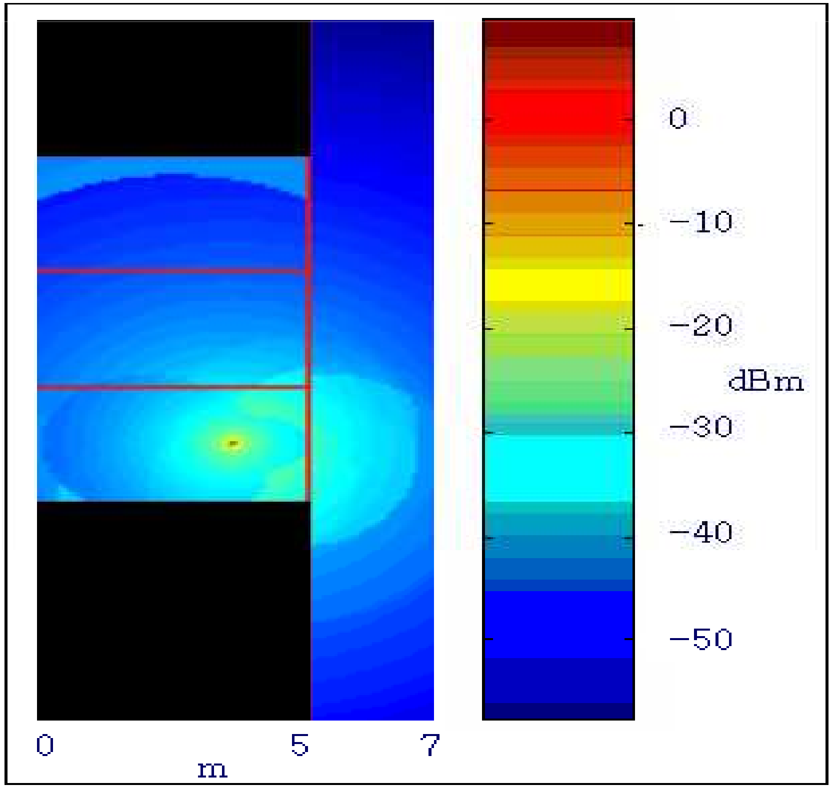
$$P(l) = P_0 \left(l^{-2} \cdot e^{\frac{\lambda l \, (T^2 + R^2)}{2}} \cdot e^{\frac{\lambda l \, (T^2+R^2) \cdot \, e^{\frac{-\Delta\lambda}{2}}}{2}} + \\ - L^{-2} e^{-\lambda L \left(1 - T^2 \right)} + \sum_{i=1}^{n} L^{-2} T_i^2 \right)$$

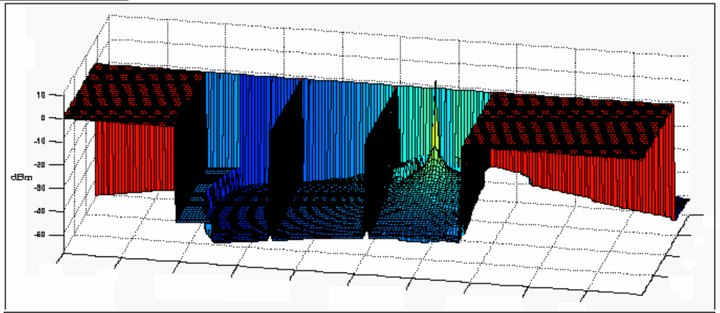
- l: traveling meters from the transmitter (T_x), undergoing n intersections (m reflections and (n-m) transmissions)
- P_0: free-space power at distance 1 meter (Friis equation)
- 1/λ: mean free distance between two intersections, which depends on the floor layout Mean Free Distance
- R, T: mean "voltage" reflection and transmission coefficients
- Δ: the difference between the total path length and transmitter–receiver distance and L denotes Tx – Rx distance, l = L + Δ distance

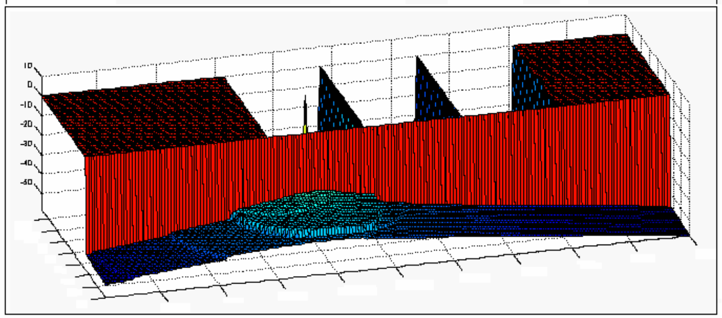
Indoor radio propagation model - simulation



a) operating frequency (2.4 GHz)
b) transmitter power Pt (= 0.1 W)
c) transmitting antenna type : short vertical dipole
d) irradiation efficiency η of the transmitting antenna TX =0.5
e) irradiation efficiency η of the receiving antenna RX =0.5
f) receiving antenna specification: short vertical dipole







Indoor radio propagation model - measurements

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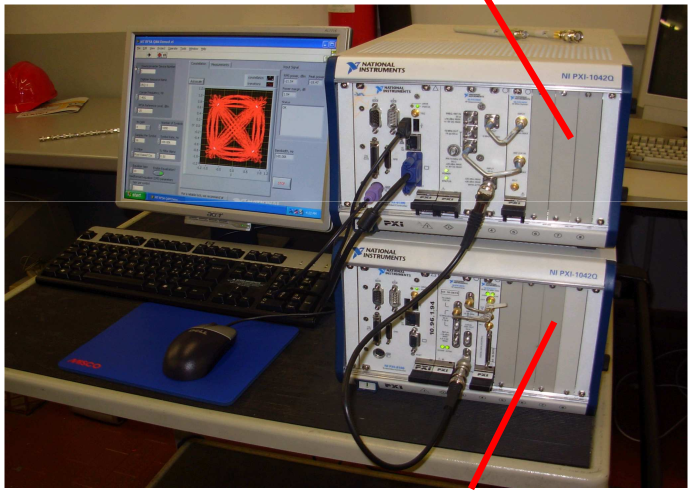
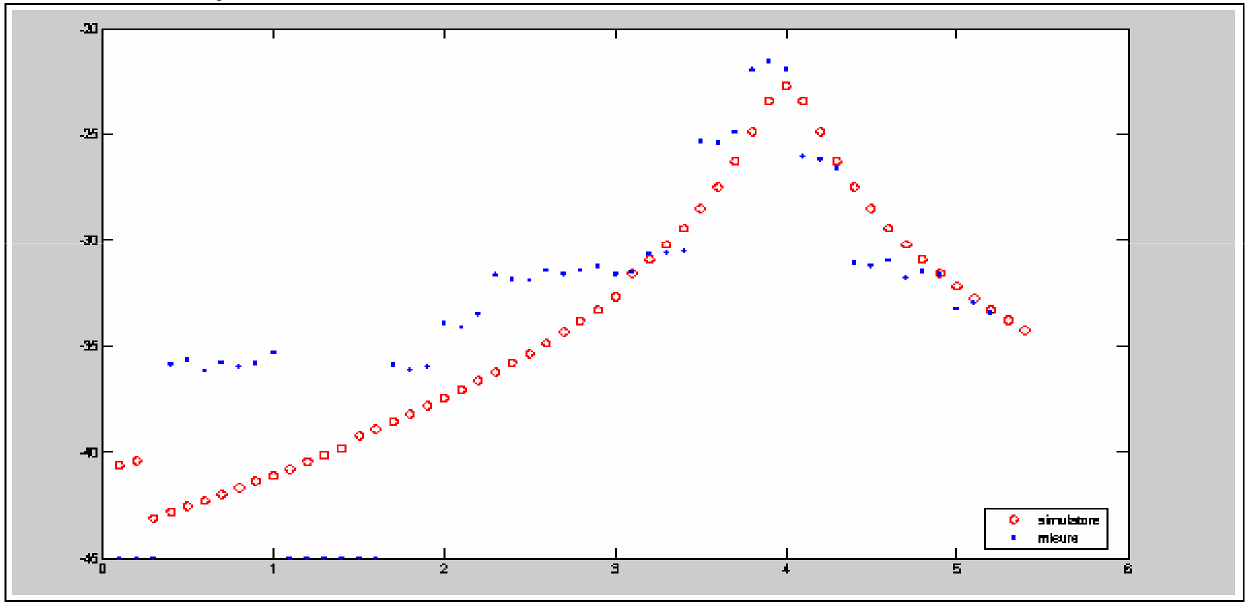
NI PXI-5671- 2.7 GHz RF Vector Signal Generator with Digital Up-conversion



NI PXI-5661- 2.7 GHz RF Vector Signal Analyzer with Digital Down-conversion

Comparison between models and measurements



Small differences have been noticed due to the diffraction effect

from the obtained results we can say that the proposed model effectively help us on the positioning of transmitting and receiving antennas in a short period compared to one to be spent by using ray tracing models or directly measuring the wave strength in a test site

Wireless system - application

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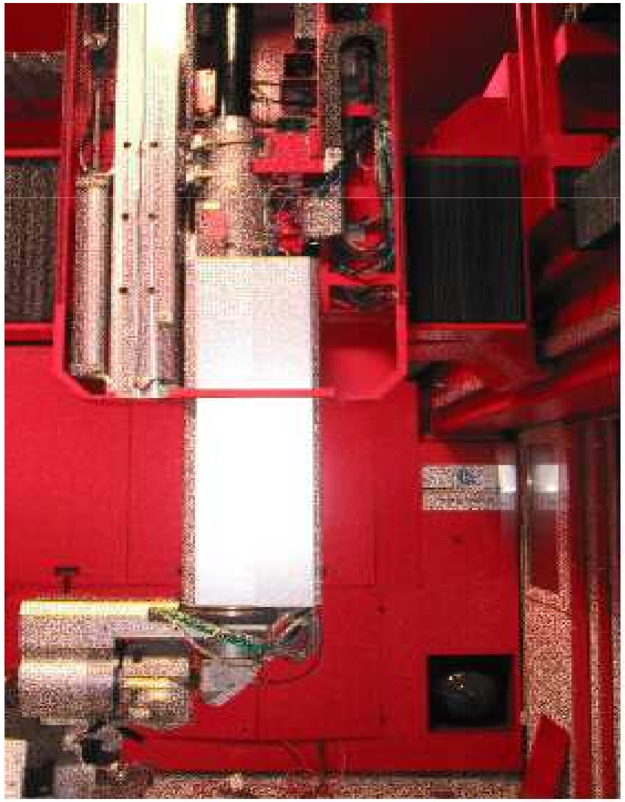
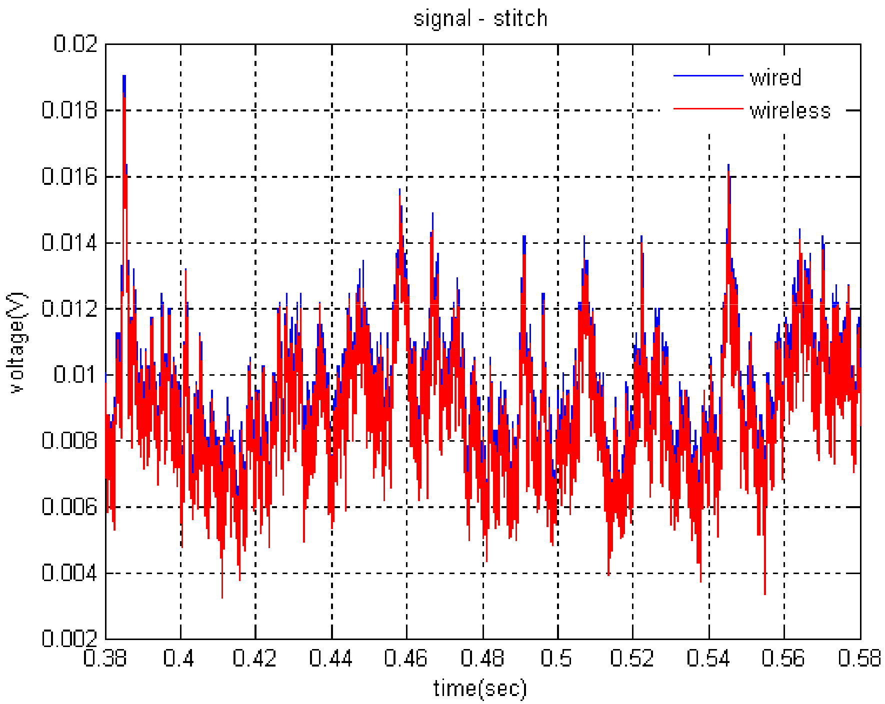
The system has been applied to monitor the laser welding of car doors by
RWS AGILASER – COMAU



1. the sensor has been mounted on the optical head behind a plane pinhole mirror (Φ≈1 mm), which has replaced the last bending mirror. It has been optically coupled to the process radiation by a small focusing lens and an optical filter for selecting a specific wavelength. An adjustable aperture is used to select the relevant field of view
2. the sensor has been connected to the sensing unit, by a short BNC cable placed along the z-axis
3. the base unit has been placed at a distance of 10 meters
4. the walls surrounding the welding machine are made by aluminum except one (sliding doors) made by a combination of aluminum and Plexiglas

Wireless system - wires vs wireless



- signals acq.rate = 65536 Hz
- DAQ card resolution = 24 bit

1. the signal transmitted by wire is a little bit higher than one transmitted wireless. These differences will become irrelevant if the signals are acquired by DAQ cards with lower resolution (12 – 16 bit)

2. the wireless weld monitor has been tested moving the base unit around the welding station (max distance 30 meters). The signal has been transmitted without disturbances in front the sliding doors, whereas behind the aluminum wall the signal has been heavily attenuated, as expected.

Wireless system - application

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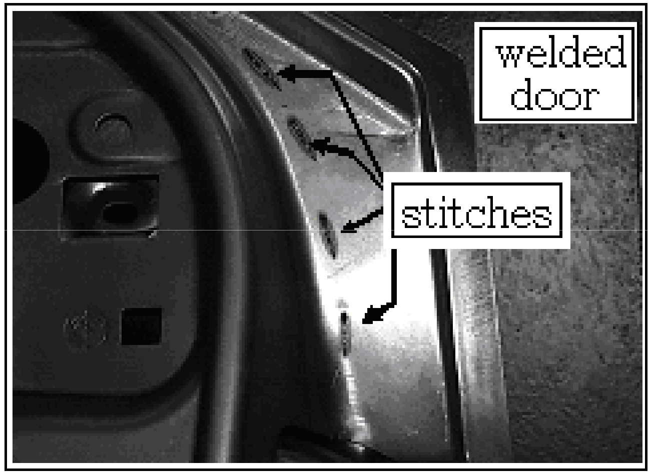
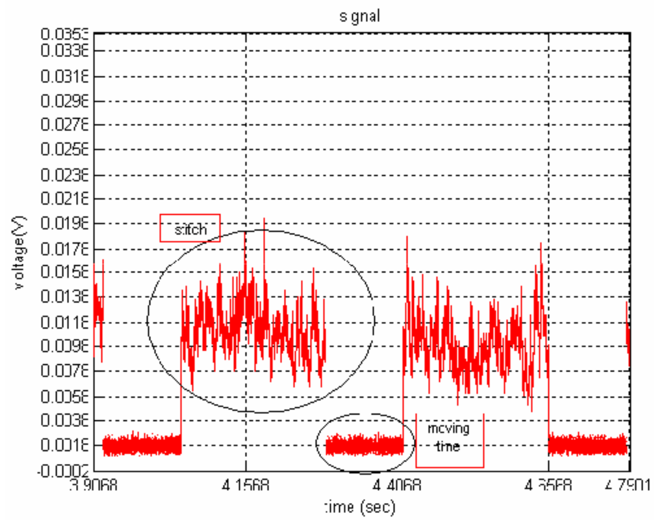
The wireless weld monitor has been tested, at COMAU lab, on about 300 doors (≈ 11100 stitches)

Laser power	3.5 kW
Welding speed	5 m/min
Shielding gas	N2
N. stitches x door	37
Length of each stitch	20 mm
Moving time between 2 stitches	.15 sec





- During the welding process, the data have been acquired at 65536 Hz. For each stitch 7867 samples are detected and transmitted to the base unit
- The received data have been acquired by a DAQ card with an FPGA on board
- For each stitch, the FPGA (3 Mgate) elaborates the received data in 0.1 sec. by a complex algorithm. Taking into account the moving time between two stitches, the FPGA, thanks to its fast computation capability, allows for representing the process results stitches by stitches.

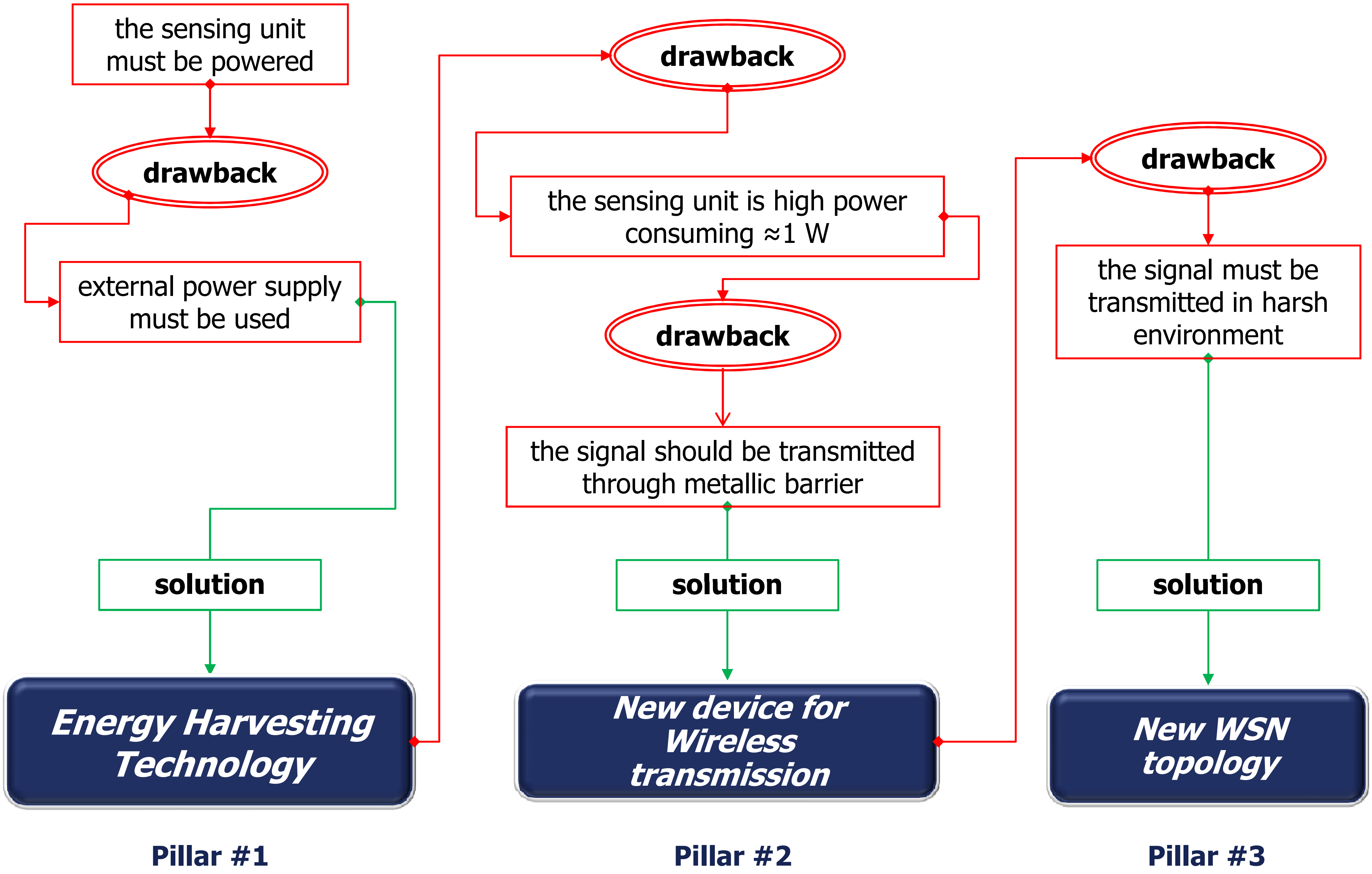
the first results were classified ***"encouraging"***

→ make the sensor autonomous

→ Transmit the information in harsh environment

→ Try to transmit signal through thin metal barrier

Wireless & Powerless: development



Communication transceiver module

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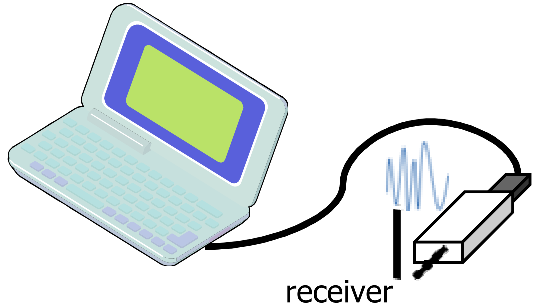
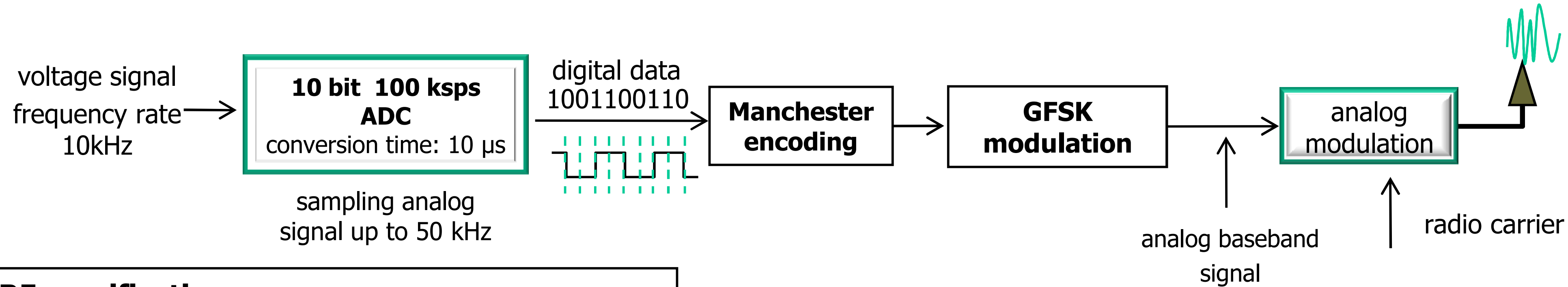
Low power Multiband Transceiver/MCU/ADC

Communication **Single Chip 433/868/915 MHz Transceiver (nRF9E5 – Nordic)**

EM pulse communication module, in response to the sensor output (voltage signal), **generates electromagnetic pulses**, to deliver the signal to the data acquisition terminal

5 mm x 5mm x 0.8 mm





RF specification
- 430 – 435 MHz / 862 – 870 MHz / 902 – 928 MHz
- 100 kHz channel resolution @ 433 MHz
- 200 kHz channel resolution @ 868/915 MHz
- GFK modulation for efficient output spectrum

• Supply Voltage:	**1.9 V - 4 V**
•Transmitting Current:	**10 mA @ 10dbm**
• Receiving current	**12.5 mA**
• Low MCU supply current	**3mA at 16MHz @4volt**

power supply - TXmode
~ 40 mW

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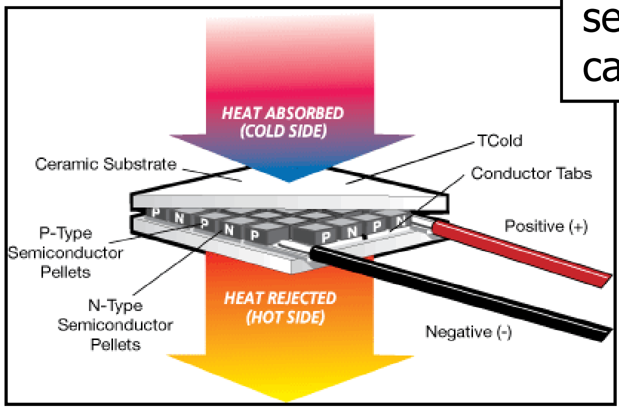
Energy Harvesting Technology

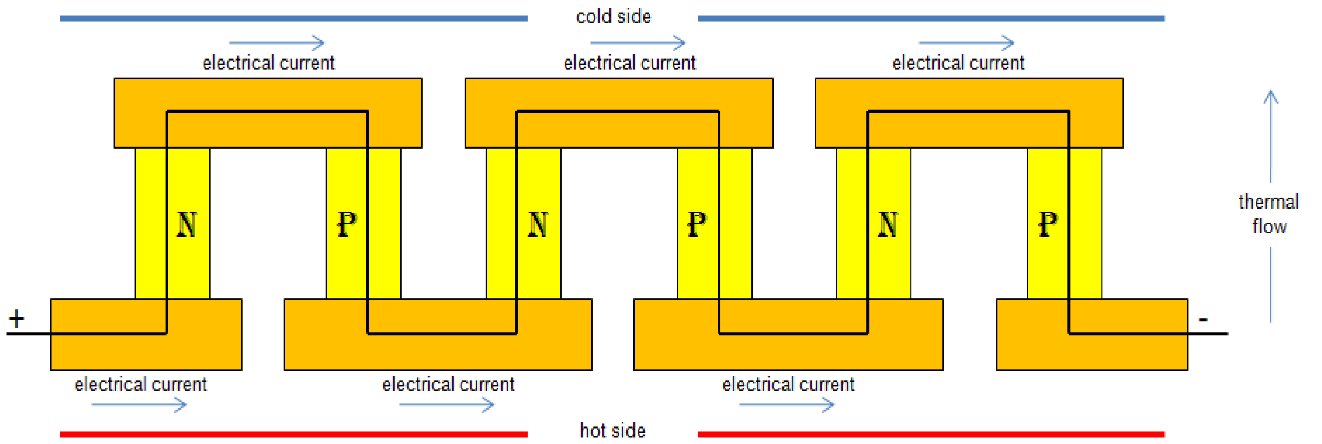
self-power generator consists of a thermoelectric module which, employing the Seebeck effect, **converts heat energy to electricity**.

- ✓ the **Seebeck effect** is a phenomenon in which a **temperature difference between two dissimilar** electrical conductors or **semiconductors** produces a **voltage difference between the two substances**
- ✓ when heat is applied to one of the two conductors or semiconductors, heated electrons flow toward the cooler one. If the pair is connected through an electrical circuit, direct current (DC) flows through that circuit. When a load is properly connected, electrical current flows

➢ ***the temperature gradient, created between the mirror heated by the laser beam and some cold part, is responsible for the electric power generation***

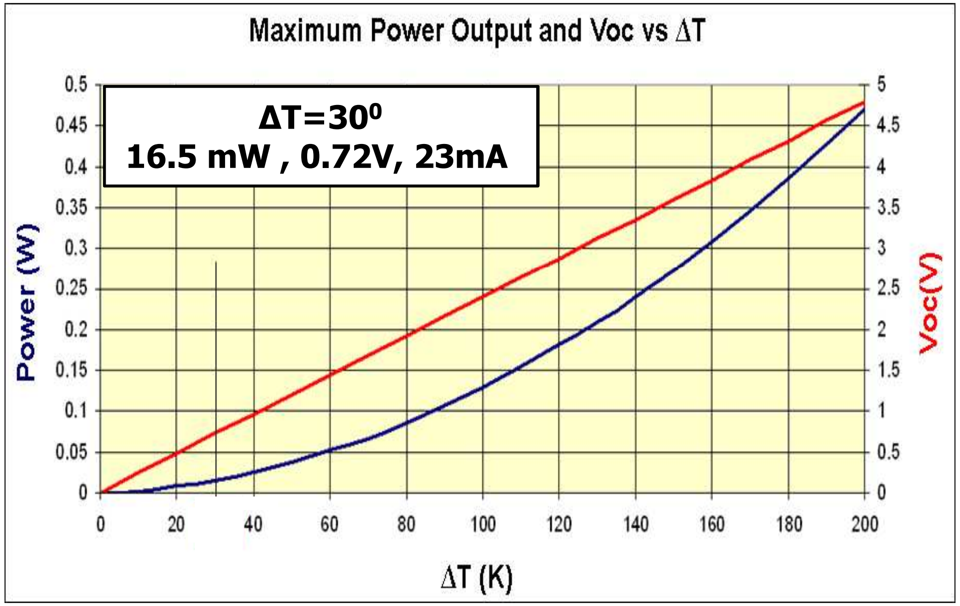
thermoelectric generator (TEG) consists of an array of Bismuth Telluride semiconductor pellets that have been "doped" so that one type of charge carrier – either positive or negative – carries the majority of current



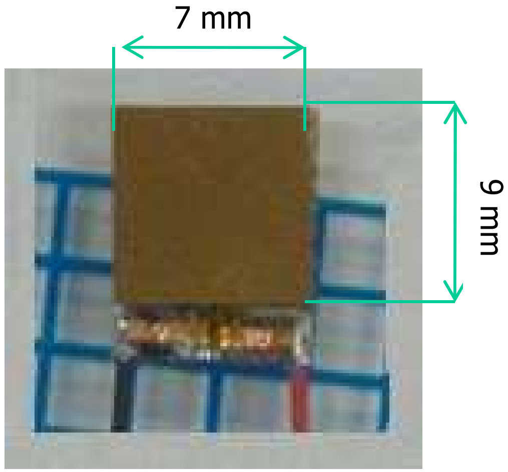


Energy harvesting device

TEG HV56 - NEXTREME



overall transceiver **<u>power consumption</u>** of the EM pulse communication
40mW @ 2V, 20mA



TEG developed on CRF request *(prototype)*

4 TEG in series

ΔT=30⁰
~46 mW @ 2.2V, 23mA

We would like to exploit the **temperature gradient**, created between ***the mirror heated by the laser beam*** and "***something around the mirror***" **for generating electric power**

measurement of temperature in a test site

model for evaluating the thermal behaviour of mirror heated by laser beam

Lab tests

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copper mirror was used as the test optic

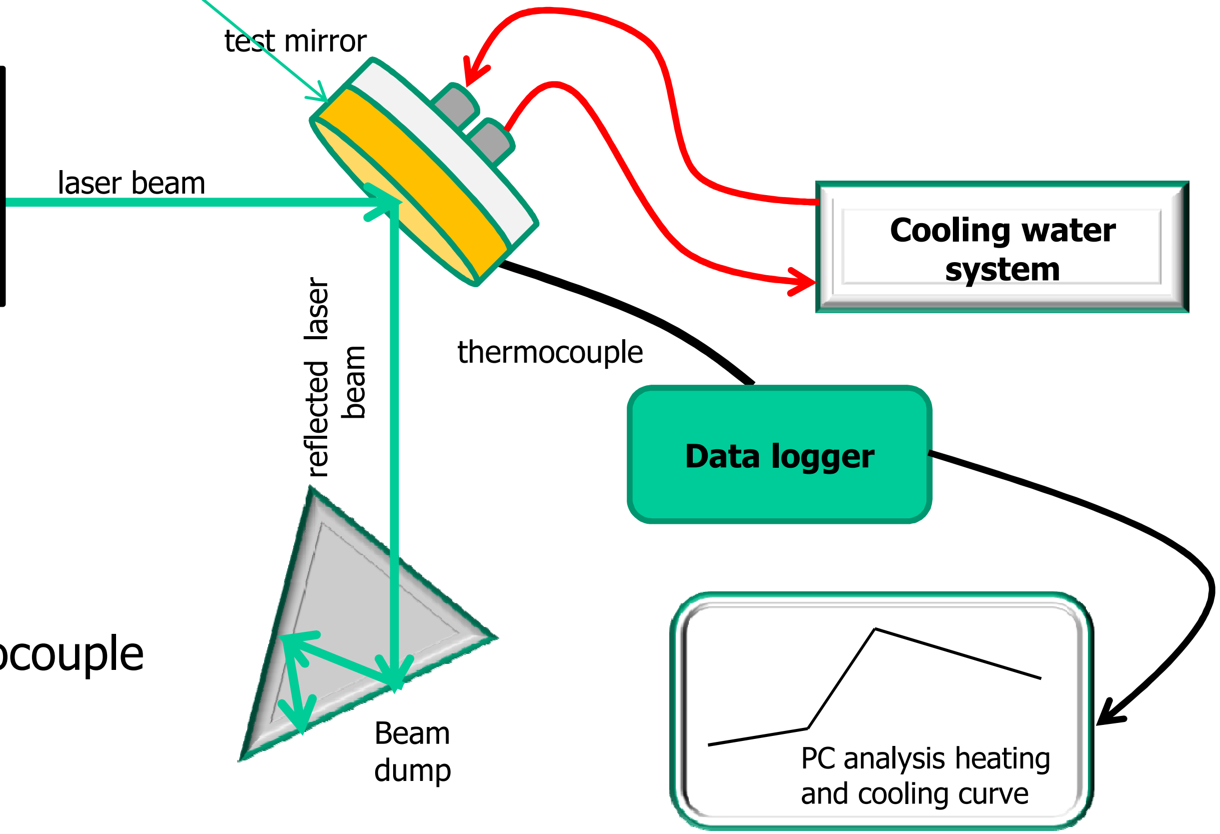
- o **Diameter** 76.21 mm
- o **Edge thickness** 6.35 mm

A= 3 %

R= 97% (measured)

ROFIN – SINAR laser DC035

Laser power	3.5 kW
Wavelength	10.6 µm
Raw beam diameter	30 mm
Beam quality - K	0.9
Power density	495 W/cm^2



Test condition:

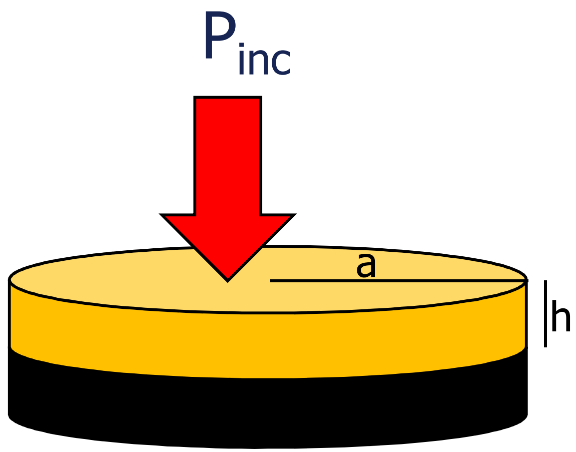
✓ mirror tested after 200 hours

temperature measured by thermocouple

$\Delta T \sim 40^0$ C

Analytical model

copper mirror was used as the test optic



a= 76.2/2	mirror radius [mm]
h=6.35	mirror thickness (mm)
Ass=0.04	mirror absorption
K= 392	copper conductivity [W/mm C]
P=3500	laser power [W]
w= 1	beam waist (mm)
rl=15	laser beam radius (mm)
sigma= 5.67*10^-8	Boltzman constant [W/m² C⁴]
eps=0.025	copper emissivity
Text=23	external temperature [C]
Tw=19	cooling water temperature [C]
H=1000	convection coefficient [W/m²C]

$K\Delta T = 0$ ------------------------ Fourier eq. with no internal generation

$T(r,z) = T_{ext} + T_{\infty}(r,z)$ ----------------- Steady state solution

boundary conditions:

$$K\frac{\partial T_{\infty}}{\partial r}(a,z) = -\sigma\varepsilon\left(T_{\infty}^4(a,z) - T_{ext}^4\right)$$

$$K\frac{\partial T_{\infty}}{\partial r}(r,h) = Ass * I(r) - \sigma\varepsilon\left(T_{\infty}^4(r,h) - T_{ext}^4\right)$$

$$K\frac{\partial T_{\infty}}{\partial r}(r,0) = H\left(T_{\infty}(r,0) - T_w\right)$$

Wireless Sensor Network for harsh environment

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In order to benefit of the potential advantages resulting from the deployment of WSNs, a robust protocol must be considered.

The research on wireless sensor networks has to face the following challenges

- the area of interest is large and "complex"
- the production chain covers a length of hundreds of meter
- industrial machineries and obstacles of various nature

the environment where the WSN operates has a topology which is spatially inhomogeneous and therefore may cause a subsequent variation in the network topology

there may be interferences, due to the presence of several wireless technologies in the same unlicensed frequency band, and to possible EMC emissions from specific processes

the lifetime of the WSN node and thus the use of low power algorithms should be envisaged.

the implementation and set-up of a WSN in industrial environments represents a complex problem, which cannot be solved by using traditional Wireless Sensor Networks

Multi path routing protocol

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multiple paths could represent the right way to increase the reliability of delivery

Different multi-path routing protocols can be found in the literature

drawback

Most of them are negatively affected by ***long latency and high overhead***, which greatly decreases the applicable value of them

Our goal is to realize a multi-path routing protocol which can discover multiple paths with short latency and low overhead

Assumptions

- the WSN is composed of a base station (BS) and a set of sensor nodes which are scattered in an area A
- each sensor node is energy constrained and has the knowledge of its energy
- each node has a unique identifier (ID) and can directly communicate with its immediate neighbors.
- a link layer protocol ensures this communication.
- every link between two nodes is bidirectional

Multi path routing protocol

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Double Routing Trees Construction - two trees must be constructed

query tree rooted at sink node

sink node broadcasts *query* messages

once one node receives a *query* message, it enters the *query tree*

T_0 - time when the construction of two trees begins

search tree rooted at source node

source node broadcasts *search* messages

once one node receives a *search* message, it enters the *search tree*

- ✓ the construction of two trees ends at the same time
- ✓ the period of construction is pre-assigned, which determines the size of two trees
- ✓ after two trees have been constructed, there are some nodes which belong to both of two trees, called *shared nodes*.
- ✓ the longer the construction period of two trees is, the more the *shared nodes* are

Route Discovery - multiple paths from source node to sink node will be discovered.

1. in double routing trees constructed in the first phase, for each *shared node*, one and only one path can be discovered from source node to this *shared node* then to sink node.
2. one *shared node* can determine one path.
3. since there are multiple *shared nodes*, multiple paths can be discovered.

Data Transmission

when source node has collected sensing data, it sends the data along multiple paths discovered in the previous phase to sink node

Multi path routing protocol

1. the delivery speed of *query* and *search* messages is the same, and that the delivery speed of the messages in diverse directions is the same.
2. *query* and *search* messages form two circles whose centers are sink node and source node respectively
3. as time goes, the two circles are larger and larger
4. When they intersect, the *shared nodes* emerge
5. the construction period of two trees determines the size of the two circles, thus determines the number of s*hared nodes.*
6. the distance between two centers, i.e. the distance between sink node and source node, is D
7. the two circles intersect and form a central angle of φ
8. it is assumed that the density of nodes in the network is ρ

the protocol is evaluated by three parameters:

1. the latency
   - time of double routing trees construction
   - time of route discovery
2. the number of paths
3. the overhead:
   - total number of messages transmitted in network.