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RFID-Grids for Deformation Sensing

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Deformation of Structures

Processes in evolution involving structural deformations

- Civil infrastructures
- Cultural heritage
- Aircrafts/ships/vehicles

Multi-point information (map) required

- Control of a large surface
- Detection of unknown defects

Post-Disaster control

Continuous Monitoring Network

Disaster Prevention

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Deformation of Structures

Structural Health Monitoring (SHM)

A structure may Fail

- Aging
- Environment
- Accidental events
- Design and manufacturing errors
- Unsatisfactory maintenance

SHM:

*"The process of implementing monitoring strategies to give, at every moment during the life of a structure, a diagnosis of the "**state**" of the constituent **materials**, of the different **parts**, and of the full **assembly** of these parts constituting the structure as a whole."*

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Deformation of Structures

In Numbers

Case	Typical Range	Resolution
Cracks in concrete Beams	1 mm	**0.1mm**
Cracks in steel reinforced concrete Beams	2-6 mm	0.5mm
Cracks in walls	2-4 mm	0.2mm
Cracks in tunnels' concrete slabs	0.1-0.2 mm	0.05mm
Deformation of foundations	1-10 mm	0.5mm
Cracks in Old and Historic buildings	1+ cm	**1-2mm**
Deformations in Ground Vibration Testing on Aerospace Structural Models	5cm	0.1mm

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Parametrization of Deformation

Stress

$$\bar{S} = lim_{A \to 0} \frac{\bar{F}}{A}$$

Displacement Vector

$$\bar{d} = u(x,y,z)\hat{i} + v(x,y,z)\hat{j} + w(x,y,z)\hat{k}$$

Therefore, a point $P(x,y,z)$ will become, after the stress is applied, a new point $P'(x+u, y+v, z+w)$.

Strain

$$\underline{\epsilon} = \begin{vmatrix} \varepsilon_x & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_y & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_z \end{vmatrix}$$

$$\varepsilon_x = \frac{\triangle dx}{dx} = \frac{\delta u}{\delta x}$$ Normal strain

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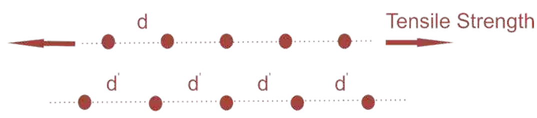
Deformation Models

Constant Strain
with Linear Displacement

- All points subjected to the same constant strain.
- Equal-size segments are scaled in a same way during the deformation
- dilatation/compression of unbounded body,
- **crack formation**

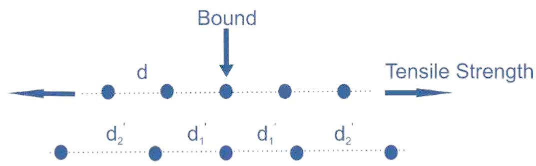


a) LINEAR DISPLACEMENT

$$u = b_0 x + b_1 y$$
$$\varepsilon_x = \frac{\delta u}{\delta x} = b_0.$$

Linear Strain
with Quadratic Displacement

- Equal-size segments may be transformed in a different way depending on the position over the body
- deformation of bounded bodies,
- **crack growth**



b) QUADRATIC DISPLACEMENT

$$u = b_0 + b_1 x + b_2 y + b_3 x^2 + b_4 xy + b_5 y^2$$
$$\varepsilon_x = \frac{\delta u}{\delta x} = 2b_3 x$$

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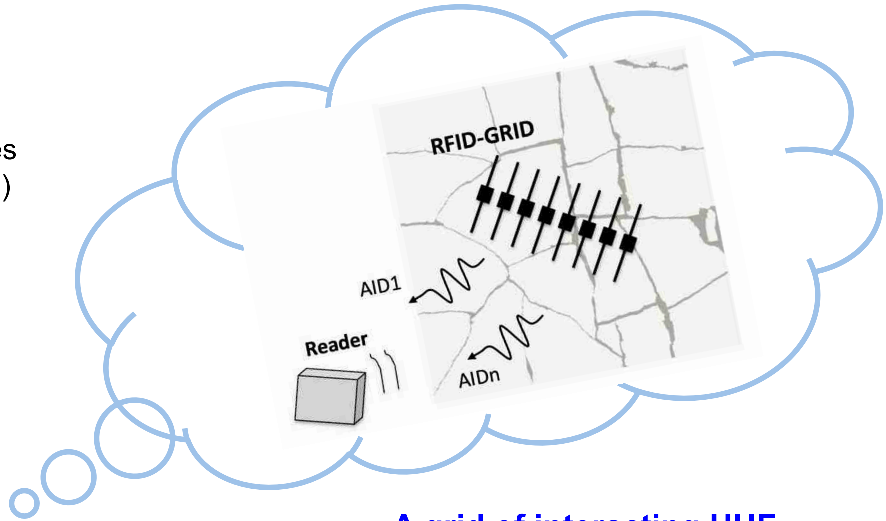
Distributed-Deformation & RFID

RFID may provide
- Wireless reading
- Fully autonomous
- Low-cost
- Deployable in multitudes (i.e. multi-point sensing)



A grid of interacting UHF RFID tags

Our vision…

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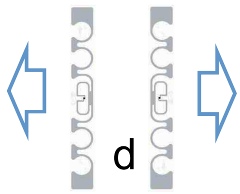
Physical rationale

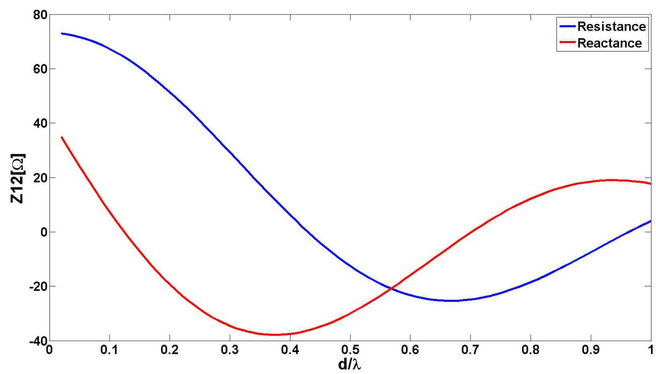
engineering em. coupling

- Change of mutual distance between two antennas caused by deformation of the surface will produce a variation of the tag's response due to **electromagnetic coupling**

- Change of **active impedance**
- Change of **embedded gain**

- Deformation are remotely detectable by a RFID reader



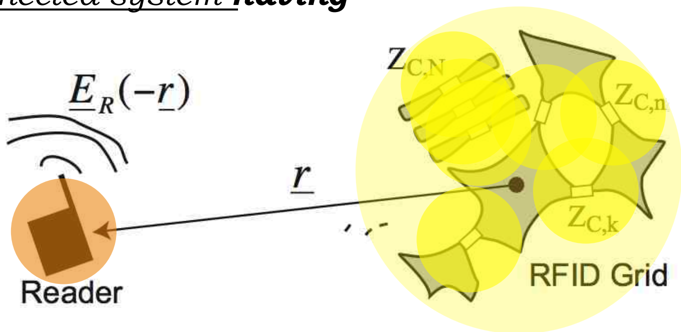


The idea may be extended to an array of tags

➔RFID Grids

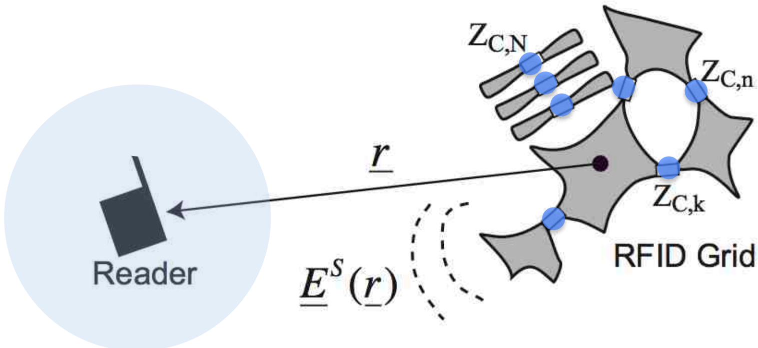
RFID Grids: multi-chip system

The close displacement of UHF RFID tags can be considered as an electromagnetic interconnected system ***having specific properties***



Direct Link (scavenging)

- A highly-coupled coherent system
- not an Array since there is no summation of received signals



Inverse Link (backscattering)

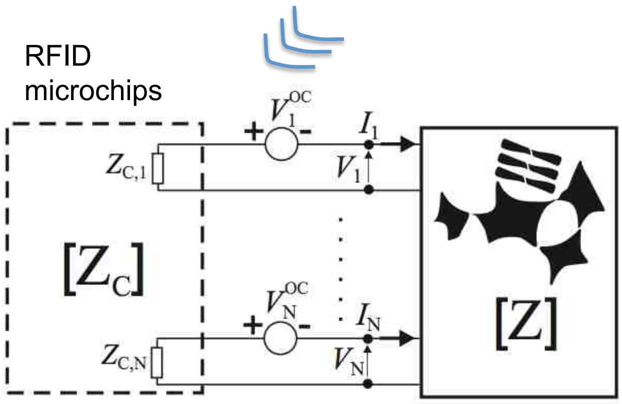
- Anti-collision protocol
- Multi-port scatterer with incoherent modulating loads

Model: Multi-port scatterer

Radiation / scattering

Embedded effective length & Gain

$$\{\underline{h}_n(\hat{r}), G_n(\hat{r})\}, \quad n = 1..N$$



Impedances

Network representation

$$\mathbf{I} = -\mathbf{Y}_G \cdot \mathbf{V}^{OC}$$

$$\mathbf{Y}_G = [\mathbf{Z} + \mathbf{Z}_C]^{-1} = [\mathbf{Z}_G]^{-1}$$

Admittance Matrix of the Grid

$$\mathbf{Z}_C = \begin{bmatrix} Z_{C,1}(t) & 0 & 0 & 0 \\ 0 & Z_{C,2}(t) & & 0 \\ 0 & & & 0 \\ 0 & & 0 & Z_{C,N}(t) \end{bmatrix}$$

G. Marrocco, "**RFID GRIDS: Part I – Electromagnetic Theory**", *IEEE Trans. Antennas Propagat,* March. 2011

S. Caizzone, G. Marrocco, "**RFID GRIDS: Part II – Experimentations**", *IEEE Trans. Antennas Propagat.* Aug.2011

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Grid's Fingerprint

Analog IDentifier (AID) of Grid's elements

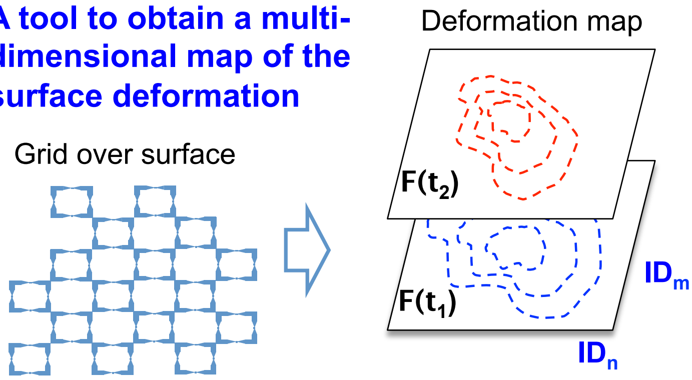
$$AID_n \equiv \frac{p_n}{2\sqrt{P_{R\leftarrow Tn} P_n^{\text{to}}}} = \alpha R_{C,n} |Y_{G,nn}|$$

- **Angle and position invariant**
- Environment invariant
- Frequency dependent

RFID-GRID fingerprint

$$\mathbf{F}(\omega) = \begin{bmatrix} \text{analog} & \text{digital} \\ AID_1(f) & ID_1 \\ AID_2(f) & ID_2 \\ & \\ AID_N(f) & D_N \end{bmatrix}$$

A tool to obtain a multi-dimensional map of the surface deformation



G. Marrocco, "**RFID GRIDS: Part I – Electromagnetic Theory**", *IEEE Trans. Antennas Propagat,* March. 2011
S. Caizzone, G. Marrocco, **"RFID GRIDS: Part II – Experimentations**", *IEEE Trans. Antennas Propagat.* Aug.2011

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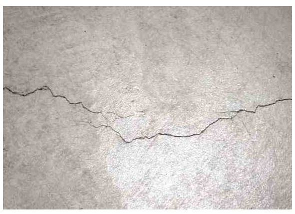
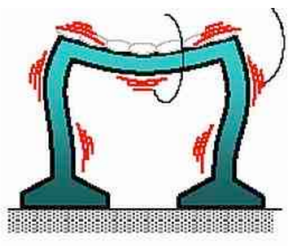
An Inverse Problem

The application of RFID-grid concept to the deformation observation requires the (measured) **variation of AID to be related to** (unknown) change of **inter-element spacing or distributed strain**



Cracks ←→ displacement

$$\vec{d} \Leftarrow f[\boldsymbol{F}(\omega)]$$



Structural deformations ←→ strain

$$\varepsilon \Leftarrow f[\boldsymbol{F}(\omega)]$$

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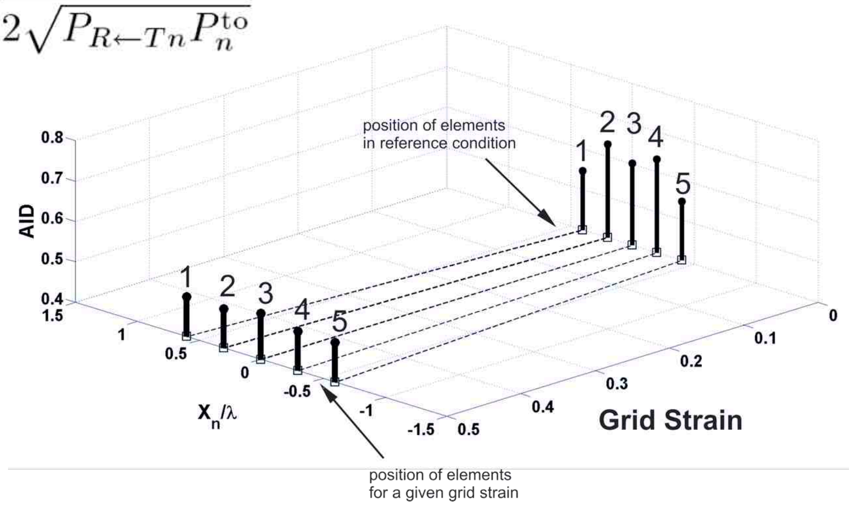
Processing The RFID Fingerprint

AID histogram pattern

$$F_n \equiv \frac{p_n}{2\sqrt{P_{R \leftarrow Tn} P_n^{\mathrm{to}}}}$$



A visual relationship between the change in the geometrical position of the tags and the corresponding modification of each AIDn as a function of the grid strain, defined as the **incremental change in the length of the whole grid**

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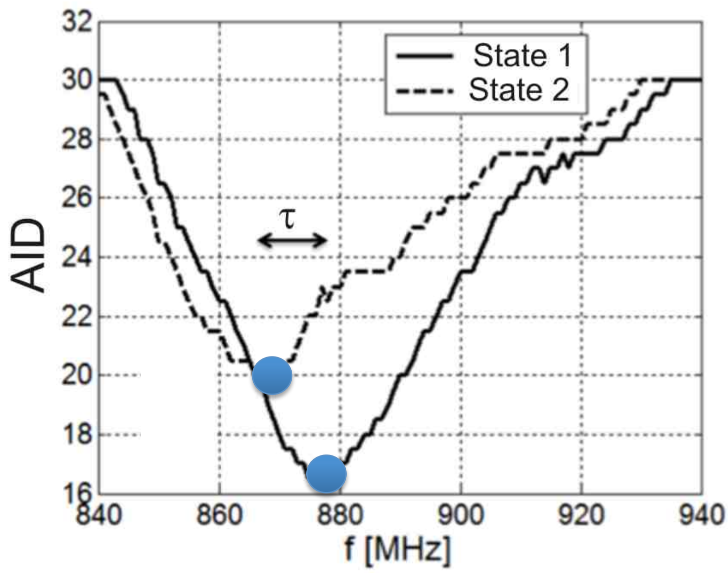
Processing The RFID Fingerprint

Frequency-domain Indicator

Frequency shift

$$\tau_n = k\Delta f \; : \sum_{m=1}^{M} AID_{nm}^{(0)} AID_{n,m-k} \text{ is maximum}$$



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GRID Model

"mathematical" dipoles

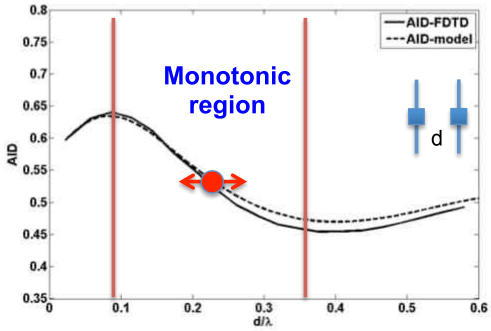
- Theoretical formulas for mutual impedance of **side-by-side dipoles**
- Self impedance of standalone configuration

$$Z = \begin{bmatrix} Z_s & Z_{12}(d_{12}) & Z_{13}(d_{13}) & .. & Z_{1n}(d_{1n}) \\ Z_{21}(d_{21}) & Z_s & Z_{23}(d_{23}) & .. & Z_{2n}(d_{2n}) \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{m1}(d_{m1}) & Z_{m2}(d_{m2}) & Z_{m3}(d_{m3}) & \cdots & Z_s \end{bmatrix}$$

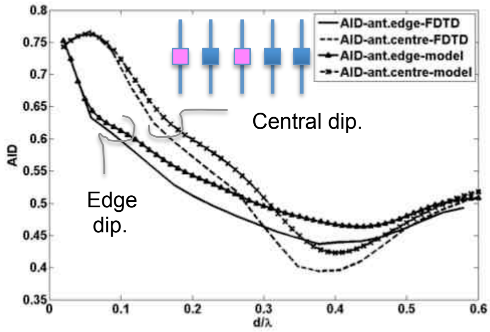
$$Z_{mn} = \frac{\eta}{2\pi}(-2E_i(ju_0) + E_i(ju_1) + E_i(ju_2))$$

E_i: Exponential function

$$AID_n = R_{C,n}\,|Y_{G,nn}|$$



a)



b)

Monotonic region

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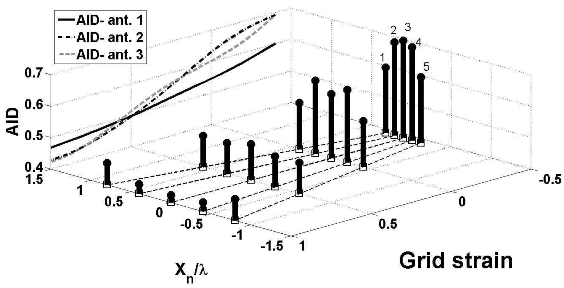
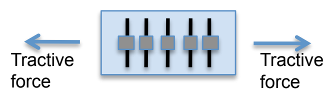
Examples:

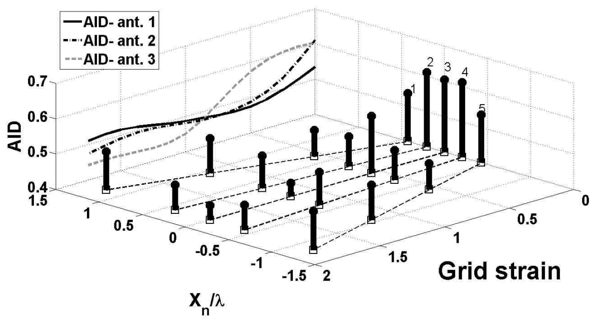
5-elements GRID ("mathematical" dipoles)

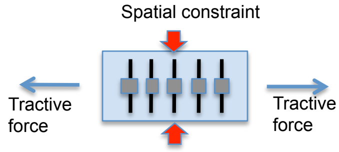




Constant strain

f=870 MHz

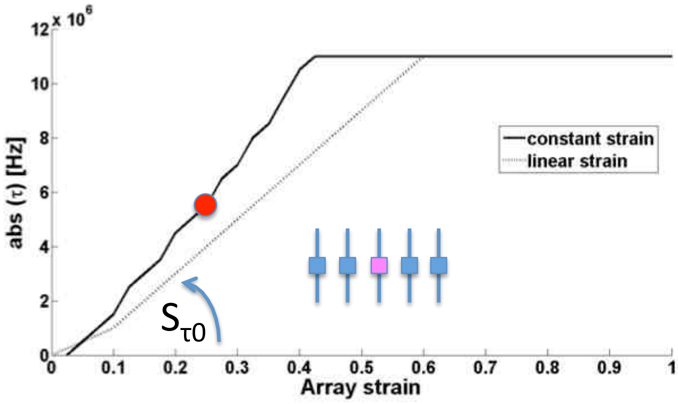




Linear strain

Examples:

5 elements GRID – frequency shift



Sensitivity (w.r.t strain)

$$S_\tau = \frac{\partial \tau}{\partial \varepsilon} \quad \text{frequency shift sensitivity}$$

$$S_{\tau_0}\,(\text{constant strain}) = 26\,MHz/\varepsilon$$

$$S_{\tau_0}\,(\text{linear strain}) = 20\,MHz/\varepsilon$$

Frequency shift of the **central element** versus **strain of the overall grid**

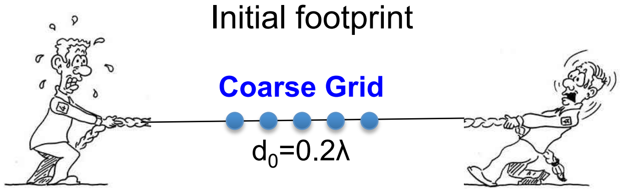
Example

A measured frequency shift of **250KHz** in the tags' response will indicate a strain of **1%** of the object (elongation of 1% of the **overall grid size**)

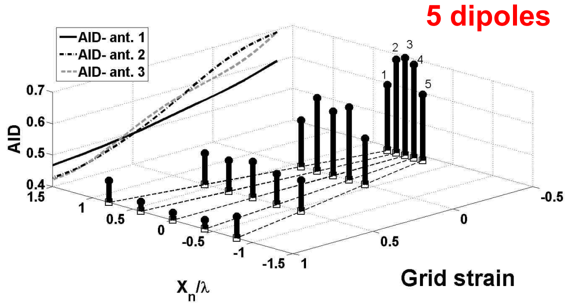
Examples:

dense and coarse grids

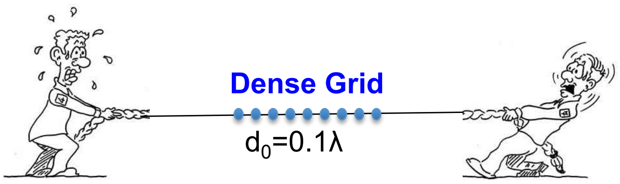
A same
Initial footprint



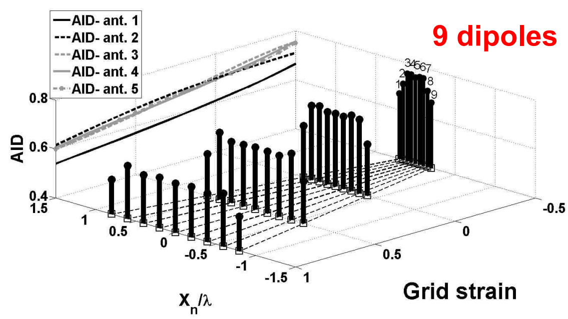
5 dipoles



f=870 MHz

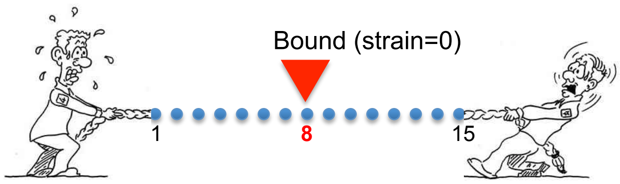


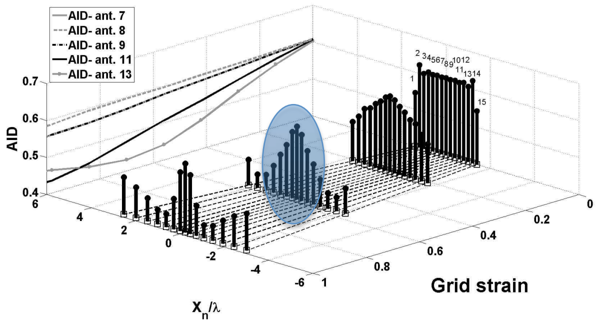
9 dipoles



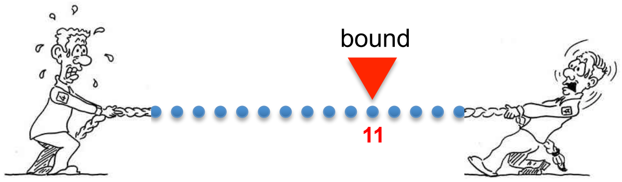
Increasing the grid density reduces the sensitivity to deformation

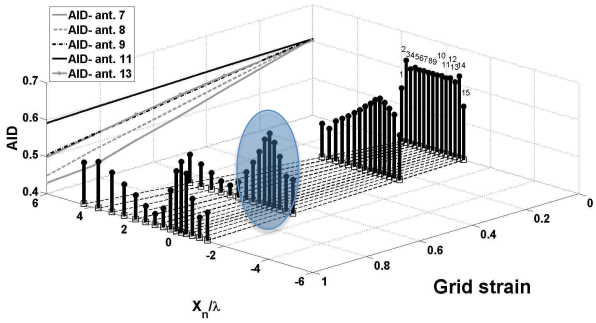
Examples:
15 elements GRID: detection of defect





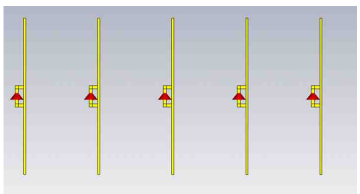
f=870 MHz d_0=0.2λ

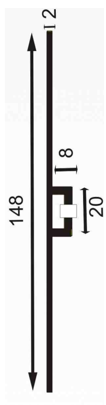




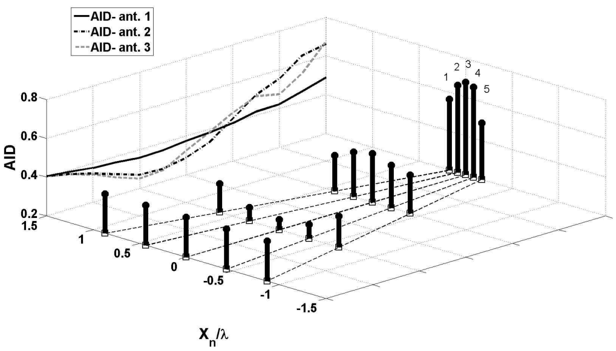
Possibility to detect the position of a crack

Examples:
T-match dipoles (FDTD)

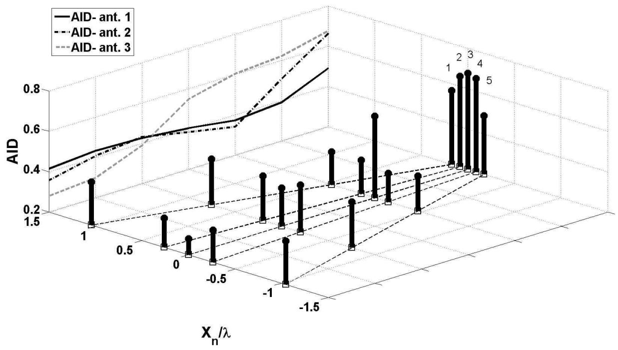




Constant strain



Linear strain



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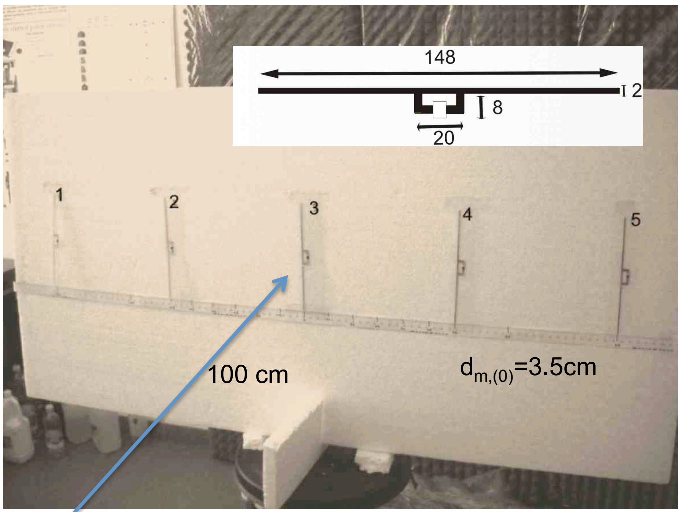
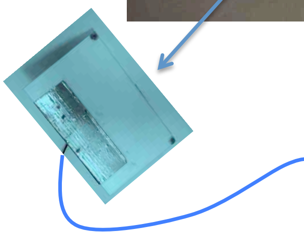
Experiment
Five T-match dipoles

- The grid lays over a foam-like substrate.
- ThingMagic M5E reader + broad band PIFA antenna in broadside orientation at distance, **L=100cm**
- The positions of the tags inside the grid **are manually changed** in order to simulate **a linear displacement** (compression and elongation).
- Initial condition (zero strain)
- inter-tag distance d_m=3.5cm (0.2λ at 870MHz).





Thingmagic M5E reader

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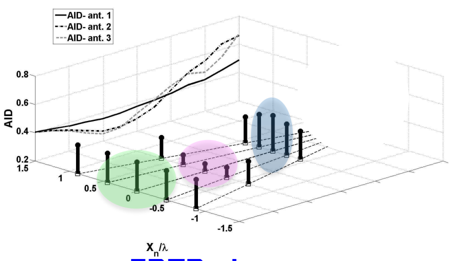
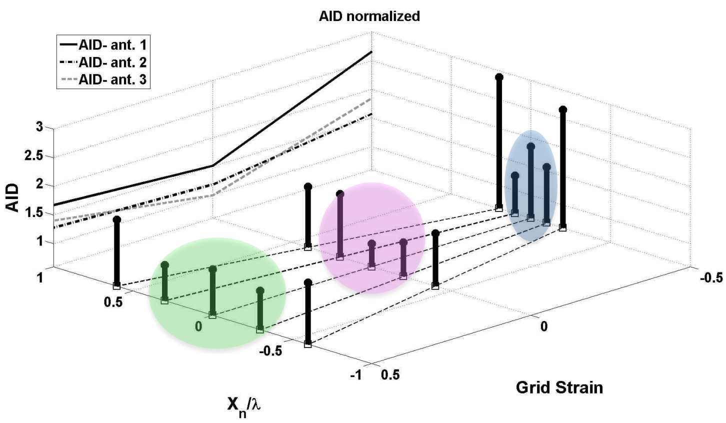
Experiment
Five T-match dipoles

AID bars



FDTD sims



Measurements

Edge elements behaves differently than simulations since FDTD model does not account for the non-linearity of microchip impedances

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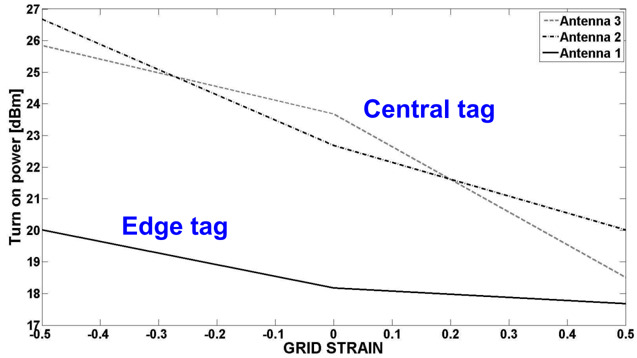
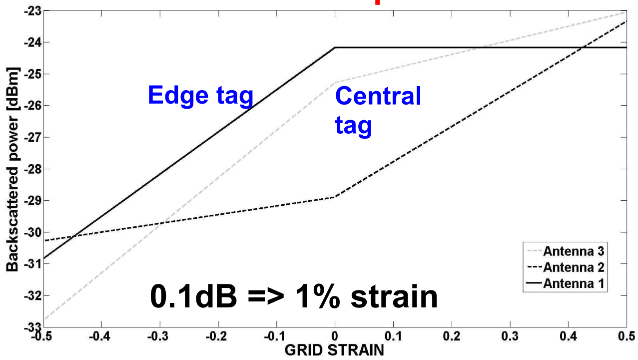
Experiment
power metrics

Turn-on power vs strain



Backscattered power vs strain



- These indicators show a remarkable sensitivity
- The response in not invariable with observation angle

Sensitivity-Central tag

$$S(backscatt) = 9.7dB/\varepsilon$$

$$S(turn-on) = 7.3dB/\varepsilon$$

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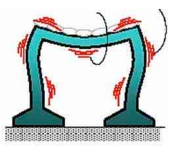
Discussion
Sensing vs. reader's resolution

Example:
N=5
d_0=5.5cm (initial inter-antenna distance)
Strain: constant

$$\Delta p_{BS,\min} \le S_{BS} \cdot \varepsilon_{\min}$$

$$\Delta p_{BS,\min} \le S_{BS} \cdot \frac{\Delta d}{d_0}$$

cracks



deformations

Achieved GRID Sensitivity

Desired system resolution	AID S_τ=25MHz/ε	Backscattering S_{BS}=10dB/ε
Δd_{min}=0.1mm Aerospace Structures, cracks in concrete	Reader resolution: Δf_{min}< 40kHz	Reader resolution Δp_{min}< 0.015 dB
Δd_{min}=1mm cracks in historical buildings	Δf_{min}< 400 kHz	Δp_{min}< 0.15dB
ε_{min}=0.1%	Reader resolution: Δf_{min}< 25 kHz	Reader resolution Δp_{min}< 0.01dB
ε_{min}=1%	Δf_{min}< 250kHz	Δp_{min}< 0.1dB

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Conclusion

- **RFID grids' fingerprint might be a promising tool to**
  - estimate the **overall amount** of surface deformation
  - provide **a local representation of the displacement**
  - identify **defects**

- Other indicators, such as **turn-on power or backscattered power, can provide bigger variation levels**, but need fixed setups

- **Grid-spacing controls the sensitivity** (coarse grids are better, provided that tags' response lay in the monotonic region)

- The Grid sensitivity may be improved by investigate **more-coupled lattices** (physically interconnected system)

- **Phase-change** may be also considered thanks to new readers

- **Sensing-oriented readers** (**$\Delta p <= 0.1 dB$**) and ad-hoc processing tools are required to form a true imaging system