RFID-grid Systems: the Electromagnetic Way to Ubiquitous Computing

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Abstract- **Ubiquitous Sensing and Distributed Computing could be achieved in the next Future by a non conventional re-engineering of the Radiofrequency Identification Technology, when a multitude of tags, or more in general multi-chips systems, eventually doped with material defects will be designed as unique interconnected networks of passive devices glued by near-field electromagnetic interactions. Recently demonstrated improvements in energy scavenging, new kinds of measurable fingerorints, inter-tag communications, as well as sensitivity to changing objects, now suggest the idea of an approaching generation of "disappearing" computers, suitable to be integrated into the environment and having size, processing power and capability, fully scalable according the specific problem. This paper reviews in a unitary way the concept of RFID Grids, their amazing properties and their realistic and futuristic potential-ities to achieve sensing smart-skins, self-authenticated devices, distributed wireless-access memory membranes and, in a word, "localized intelligence".**

I. INTRODUCTION

Years ago, engineers moved from single antennas to clusters of radiators fed in phase coherence with the purpose to increase radiation gain and to shape the beam. The concept of array factor generated a rich set of ideas and methodologies merging the traditional Electromagnetic background together with Signal Processing and Optimization expertise. Modern applications of array technology, such as adaptive and MIMO systems, even encompass the original paradigm.

One of the most disturbing side effect of packing many antennas in a limited space is the electromagnetic coupling among elements that, in the denser layouts, demands for special and more challenging mathematical models and above all of ad-hoc implementation tricks.

There is no reason why a similar evolution for the *single* to the *multitude* does not apply to the RadioFrequency Iden-tification (RFID) context, even if with different and specific implementations.

As known, RFID devices are now wide-spreading as aug-mented, wireless version of objects' labels, with many ad-vantages over bar codes. Beside applications to logistic, new pioneering experiments begin addressing the sensing of things and environments. In any cases, the universally accepted paradigm is *one tag per thing*, e.g. the RFID tag is perceived as a standalone device and each tag is not aware of the even close presence of other tags. The alignments of tagged objects, for instance over a shelf or within a fashion retail store, is a potentially source of trouble due to collision of responses and to inter-tag coupling that modifies in a nearly unpredictable way the tag response with respect to an ideal isolated condition, with the risk to make the things' labeling less robust and stable, eventually even unreliable.

Very recently, the author introduced the concept of RFID-Grid as the RFID analog of array concept, e.g. a multi-tude of tags, or even a single tag with multiple microchip transponders, that may interact among themselves by means of the electromagnetic coupling which now becomes a kind of short-range channel allowing the tags to generate completely new overall effects. Among them, the most interesting and fascinating ones are the improvement in energy scavenging capabilities, measurable fingerprints that result invariant over the interrogation modalities, the sensitivity to geometrical deformations and the theoretical possibility to achieve a true tag-to-tag communications, as in more conventional networks of active nodes.

This contribution reviews the above phenomena in a unitary way and discusses some new possible applications of the RFID interacting coalitions which could have an interesting role in the pervasive and distributed computer architecture of the next future.

II. RFID GRID: REPRESENTATION

The phenomenology of coalitions of tags is here described by a very general mathematical model which permits to derive many interesting properties, most of them already experimental verified. To preserve the generally, an RFID grid can be considered as a multi-port loaded scatterer (Fig.1), whose termination impedances are asynchronously changed to achieve the backscattering modulation. The grid's terminals, where the microchips of impedances $Z_{C,n} = R_{C,n} + jX_{C,n}$ are connected, act as the ports of the grid. The reader unit interrogates the grid and collects the backscattered signals. This system is not an array in the strict sense since the antennas input/output ports are not directly interconnected by a beamforming network. Moreover the direct link and the reverse link obey to completely different rules. In particular in the direct link all the microchips collect power from the remote reader in a coherent way. In the reverse link, instead, due to anti-collision protocols, the microchips modulate their internal impedance to add information to the reflected wave at different times and hence the coherence is completely lost.
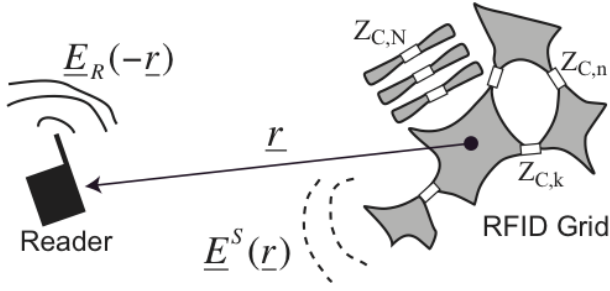
Figure 1. RFID grid and interrogating reader

The response of the the Grid may be therefore efficiently described by introducing an *N-port system* analog (Fig.2) modeled by the $N \times N$ matrix $\mathbf{Z} = \mathbf{R} + j\mathbf{X}$ accounting for the electromagnetic interactions among the various parts, and by equivalent Thevenin open-circuit voltage generators V_n^{OC} accounting for the interrogating reader. This model, enable a full characterization of the RFID phenomena (see [3] for all the details).
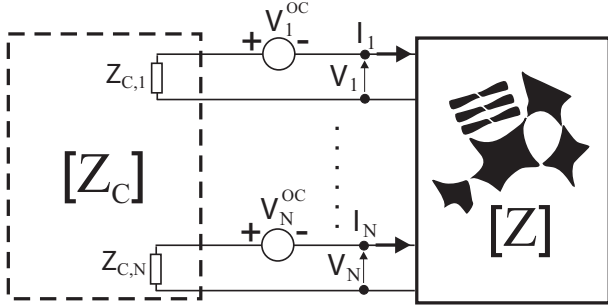

Figure 2. Thevenin network model of the RFID-Grid where the incident field coming from the reader is accounted for by means of open circuit voltage generators V_n^{OC}. $\mathbf{Z}_C$ and $\mathbf{Z}$ are respectively the impedance matrix of the terminations and of the N-port system.

A. Energy Scavenging

The power scavenged by the nth port can be formally rewritten as in the single microchip case:

$$P_{R \leftarrow Tn} = P_{in} G_R \left(\frac{\lambda}{4\pi r} \right)^2 \tilde{G}_n \qquad (1)$$

having introduced the *embedded realized gain* of port nth:

$$\tilde{G}_n = 4\eta_0 R_{C,n} \left| [\mathbf{Y}_G]_n \cdot \mathbf{g} \right|^2 \qquad (2)$$

with $\mathbf{g}$ the column vector of normalized ports' gains and $\mathbf{Y}_G = \mathbf{Z}_G^{-1}$ and $\mathbf{Z}_G = (\mathbf{Z}_C + \mathbf{Z})$. The function $\tilde{G}_n$ is therefore the parameter to be taken into account within a multi-chip antenna optimization problem and it is possible to demonstrate that power scavenging properties better than those of standalone tags could be theoretically achieved if the mutual resistances become negative since a portion of the power scattered by each port will be recaptured by adjacent ports, as already experimented MIMO systems. For examples

Fig.4 shows two specifically-designed coupled tags in comparison with the performances of a single tag in standalone configuration [4]. In this case the improvement on the realized gain is

$$\tilde{G}_n(two - port)_{max} / \tilde{G}(one - port)_{max} = 1.4$$

which definitely enlarges the maximum read distance of 20%.

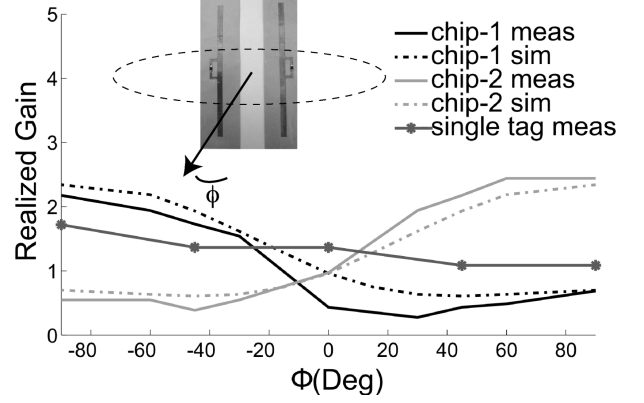Figure 3. Measured and simulated realized gains for the coupled tags with respect to a single tag of same size

B. Fingerprint

It is useful to combine the forward and backward powers at the particular *turn-on condition*, e.g. at the minimum power $P_{in} \equiv P_n^{to}$ entering into the reader's antenna for which the nth port's microchip wakes up and begins to perform actions. In this case the power collected by such a port equals the microchip sensitivity $p_n \equiv P_{R \rightarrow Tn}$. The following a-dimensional parameter is therefore derived

$$AID_n \equiv \frac{p_n}{2\sqrt{P_{R \leftarrow Tn} \, P_n^{to}}} = R_{C,n} |Y_{G,nn}| \qquad (3)$$

The left side member includes power quantities which are known (p_n is declared by the microchip's manufacturer), or measurable by the reader (P_n^{to}, $P_{R \leftarrow Tn}$). So the equation (3) gives a unique feature of the nth port and may be considered as a kind of *Analog Identifier* of that port which complements the Digital Identifier included in the microchip memory. It is greatly remarkable that AID_n is an invariant with respect to gains and with respect to distance and mutual orientation between reader and tag. If we put together the AID and the digital identifier (IDn) of each chip, a new heterogeneous data structure is obtained, the *grid's Fingerprint*

$$\mathbf{F}(\omega) = [AID_n(\omega), ID_n]_{n=1..N} \qquad (4)$$

that is a multi-dimensional structural property, independent on the particular interrogation modality and on the nearby environment, and is expected to be greatly relevant to RFID sensing and security.

C. Tag to Tag communications

Electromagnetic coupling, as discussed previously, is the glue of the RFID grid so that the response of a chip includes, in some way, the effect of the presence of other tags. In this sense, coupling is a kind of weak communication channel among elements.

Anyway, a more direct communication way among tags within a coalition could be possible provided that a *listener* tag is enabled to decode the backscattered field emerging from a close tag, acting as *talker*. This idea was originally introduced in [2] and then mathematical investigated in [6]. What is only required is just an *illuminator* radiating a continuous wave able to power up the tags. They could hence communicate through backscattering modulation of such a CW carrier (Fig.4). Actually, passive UHF RFID protocols do not support this kind of interaction since the microchips usually receive an ASK-modulated signal from the reader while they backscatter according to an FSK modulation. Nevertheless, this envisaged new technology could open new frontiers in distributed processing such as ubiquitous interaction for person to person, person to object and object to object paradigms as well as collaborative pervasive sensing.
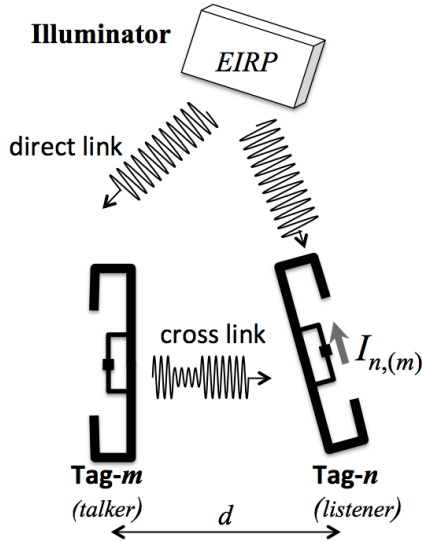

Figure 4. Scheme of tag to tag communication wherein the required power for the cross link is provided by and external illuminator.

The key-parameter of so established cross-link is the *modulation depth* between the nth listener tag and the mth talker tag which describes the distance between the two ON/OFF electrical states. For the particular case of ASK modulation with proper match in one of the two states and total reflection in the other, $Z^{ON} = Z_{C,n}$ and $Z^{OFF} = \infty$, it is possible to demonstrate [6] that the modulation depth reduces to

$$\tilde{m}_{n,(m)} = \frac{|Y_{G,mn}|}{|Y_{G,mm}|} \left| \frac{[Y_G]_m \cdot \mathbf{g}}{[Y_G]_n \cdot \mathbf{g}} \right| \qquad (5)$$

The smaller is $\tilde{m}_{n,(m)}$, the more tricky the discrimination of the data-bit for the listener will be. Just for example, the

modulation depth of two equal-size and parallel dipole tags is simply

$$\tilde{m}_{1,(2)} = \tilde{m}_{2,(1)} = \frac{|Z_M|}{|Z_S + Z_C|} \qquad (6)$$

where Z_M and Z_S are the mutual and self impedance of the two-tag system. Such a modulation depth strongly decay along with increasing tag to tag distance (Fig.5) but may be improved by an Hermite-like impedance matching $Z^{in} \equiv Z_S + Z_M = Z_C^*$. In this case the modulation depth stays higher than 50% up to inter-tag distance d=0.25λ, roughly corresponding to {7cm, 8cm} at the US and European RFID frequencies, respectively.
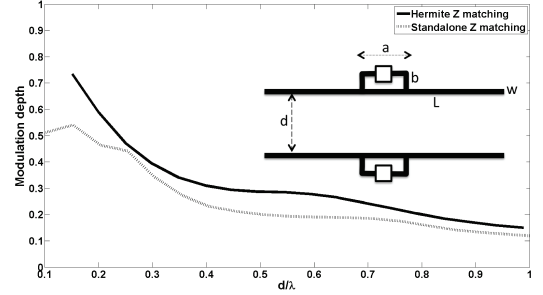

Figure 5. Two T-match tags with different kind of impedance matching: modulation depth vs. antenna separation. Wavelength corresponding to frequency f=870MHz. Size (in [mm]): w=2; Conjugated matching: $L = 148$, a=20, b=8. Hermite matching $L = 156$, a=20, b=10.

An example of circular grid of eight T-match tags is shown in Fig.6. The antennas are uniformly angularly spaced by 45° increments and the resulting grid exhibits a rotational symmetry. According to the study in [3], the corresponding impedance and admittance matrices are circulant and under the assumption of broadside and circular-polarized illumination the modulation depths are simply

$$\tilde{m}_{n,(m)} = \frac{|Y_{G,mn}|}{|Y_{G,S}|} = \tilde{m}_{m,(n)} \qquad (7)$$

where $Y_{G,S}$ is the self network admittance of the system. Fig.6b shows the values $\tilde{m}_{n,(1)}$ in case the tag m=1 is acting as talker. Any other configuration is simply an angular shifted replica of the m=1 case.
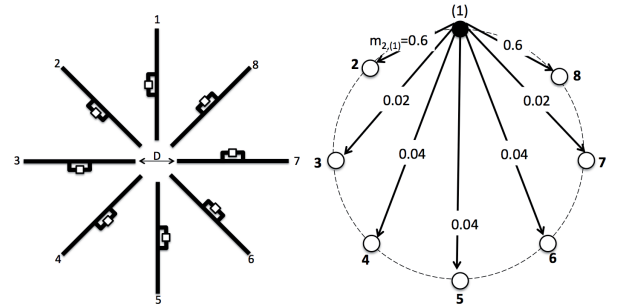

Figure 6. A circular grid of equal dipoles with distance D=40mm. right) Modulation index $\tilde{m}_{n,(1)}$ when the tag m=1 is talking.

Not all the tags will receive data signals with enough modulation depth (>50%) to decode the message from the talker, but a multi-hop routing protocol could be implemented to have all the tags interconnected in an indirect way by a percolation-like effect. For instance the connection among tag 1 and tag 5 may be achieved by a first link between tag 1 and tag 2 and hence by a second jump from tag 2 to tag 3, then from tag 3 to 4 and finally from 4 to 5.

III. ACTUAL AND FUTURE APPLICATIONS

Some possible applications of the RFID Grid are listed in the following paragraphs. A few of them have been already demonstrated but a great work is still needed to achieve really working prototypes. Other ideas have to be instead considered as just embryonic, but nevertheless fully affordable by means of current manufacturing technology.

A. Deformation Sensing skin

It is well known that the input impedance of antennas placed at a close distance suffers from mutual coupling effects. For instance the mutual resistance and reactance of a couplet of half-wavelength parallel dipoles are oscillating functions dumping to zero as the inter-antenna distance increases. However, as the distance is less than about $\lambda/2$, the relationship between mutual impedance and distance is monotonic. Hence a remote estimation of the variation of coupling could establish the basis for sensing surface deformation, provided that a grid of strongly coupled antennas is considered all over the interesting part of the infrastructure.

So a ribbon or an elastic skin hosting a highly coupled RFID tags attached on top may communicate the deformation of a surface throughout the measurement of the grid fingerprint. It was verified in [7] that such a system is potentially able to sense linear and quadratic deformations, including the presence of an anomaly-like crack on the wall. For instance Fig.7 shows the evolution of the RFID fingerprint, represented as bars, of an elastic ribbon of equally spaced dipole tags. The ribbon is constrained out of its center by a zero-strength point, for instance a crack. When subjected to a tractive force the ribbon deforms according to a linear strain and the inter-antenna distances will change as indicated by the position of the bars. By observation of the fingerprint evolution along with the strain it is visually possible to localize the position of the anomaly.
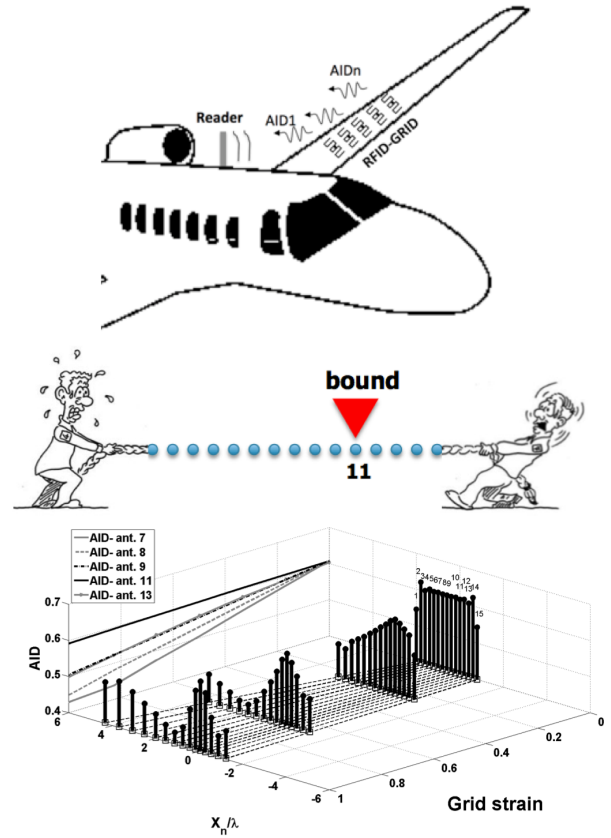

Figure 7. Example of simulated fingerprint of a 1D RFD grid of dipoles when subjected to an increasing quadratic deformation (linear strain) with a bound, for instance a crack, placed out of center of the grid.

B. Lab on Antenna

By doping an antenna with a chemical paint it is possible to make the antenna response sensitive to the presence of particular gases which interacts with the paint and produces a change of the antenna characteristics. Examples have been recently presented in [8] and in [9] for what concerns carbon nanotubes that are sensitive to ammonia and conductive polymers reacting to humidity absorption. The same idea could be extended to a *skin* of densely packed RFID tags to form a grid in order to enable a spatial monitoring of many different volatile or liquid compounds originating a kind of *chemical lab on Antenna* suitable to envelope things, plants and even animal. The grid fingerprint is again the tool to achieve a multi-dimensional image of the time varying chemical phenomenon, independently on reading modality.
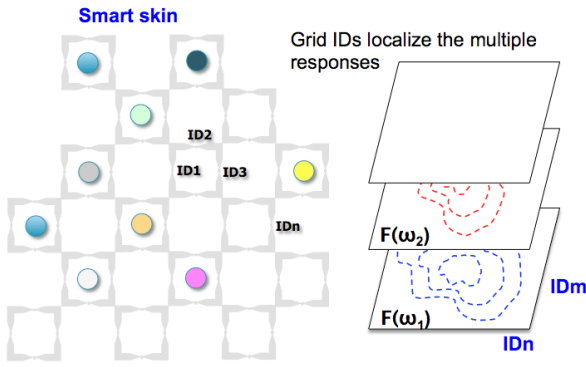
Figure 8. Idea for a sensitive skin able to collect the presence and amount of chemical species.

Figure 10. Grid for a distributed memory

C. Security and Authenticity

On covering a grid with random defects like metal and dielectrics materials (see Fig.9) it is possible to achieve a physical unclonable function [12] e.g, the whole grid fingerprint may provide a unique analog-digital identification code useful to prove the authenticity of a tag.
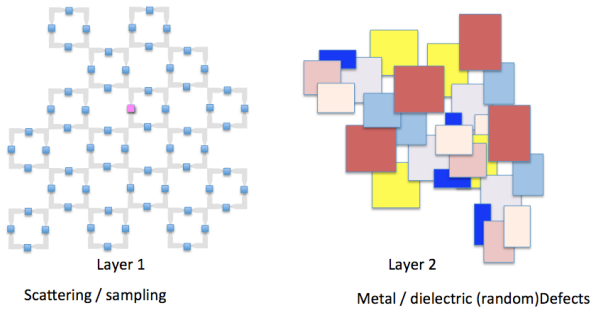

Figure 9. Grid loaded by a random distribution of dielectric and metallic objects to provide the grid with a unique electromagnetic fingerprint useful to demonstrate its authenticity.

D. Distributed memory with wireless access

A complex information (images, sounds, may be splitted into small packets and saved into the user memory of the grid. An *index node* will store the allocation table to correctly recompose the information after reading. In this way a distributed memory with wireless access is obtained. The device could be placed in the environment and over objects and will be suitable to be expanded just by added elements, like a Lego toy.
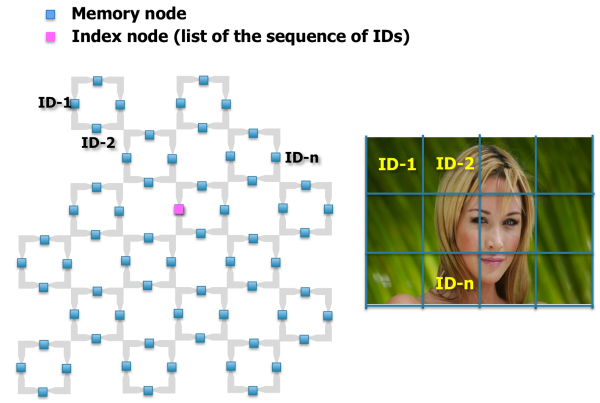
E. Amorphous computer

All the previous ideas may be put together to form an electromagnetic implementation of the amorphous computer e.g. "a plethora of simple identical computational units spread randomly over a given area" [10]. Within a limited radius the units can communicate wirelessly with their neighbors via a single-channel radio. Their new instances integrate sensing, data processing and wireless communication capabilities. The grid could be obtained as the integration of specialized regions for sensing, data storage, physical or logical actuators. Sensed and processed information will flow from a point to another by percolation according to passive tag to tag communication, and finally collected by aggregation points which have in charge the direct communication with an external nomadic reader. Actuators could be real electromechanical or chemical devices, controllable by electromagnetic interactions, or more simply a set of rules, written in the microchip user memory, which tell the reader what to do in case a specific condition occurs over the sensed data [11].

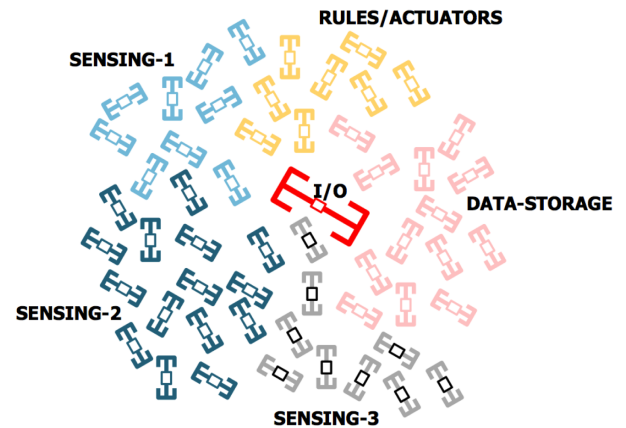A structure like this could be fully scalable a self adapting to difference needs.

Figure 11. Grid for amorphous computing.

IV. Conclusion

Out of logistic applications, RFID may provide the enabling technology for new families of computational devices, spread all around the environment, by learning how to master heterogeneous coalitions of very simple elemental objects. Although some experiments have been already reported, there are amazing opportunity for further investigation and improvement. On looking ahead with the imagination, provided that the form factor of tags may be scaled down to sub-millimeter sizes, for instance by moving to high frequency and using nano materials, there will be the opportunity to conceive and fabricate "digital skins" able to work, in a same time, as sensors, memory, radio and actuators.

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