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January 2011

Technical Report # DISI-11-101

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Abstract

The integration of smart antennas in wireless sensor networks is a challenging and very attractive technical solution to improve the system capacity, the quality of service, and the power control. In this paper, some benefits coming from such an integration are experimentally assessed dealing with a set of test scenarios. Finally, some conclusions are discussed in order to point out current potentialities and limitations of the smart antennas integration to envisage future and possible advances.

Key Words - Wireless Sensor Networks, Smart Antennas, Self-Configuring Architectures.

1 Introduction

A Wireless Sensor Network (*WSN*) consists of a large number of small sensor nodes with sensing, data processing, and communication capabilities able to realize a distributed and remote monitoring/control of the environment. In several applications, the network nodes are randomly deployed, therefore the whole wireless architecture should be characterized by a highly-dynamic and reconfigurable topology with self-organizing capabilities to guarantee an energy-efficient transmission of the information on the scenario under test. Such a behavior is mainly concerned with the strategy of the medium access control (*MAC*) at the network layer as well as with the smart management of the physical layer to extend the node/network lifetime and to exploit the space selectivity. In this context, the adoption of a smart system (or smart antenna) [1][2] at the communication interface is certainly an optimal solution not only to reduce the *RF*-energy consumption, but also in order to maximize the efficiency of the data exchange among the network nodes. In such a way, it is possible to increase the network coverage and connectivity as well as to implement additional functionalities useful to enhance (at the physical layer) both the *WSN* security and privacy.

Early researches in *WSN*s typically considered the use of omni-directional (or isotropic) radiators at each node of the network architecture in order to avoid complex and expensive control systems. However, because of the potentialities of a "smart" solution in dealing with a time-varying scenario, there has recently been a growing interest in developing ad-hoc and heterogeneous networks where some nodes are equipped with directional and adaptive antennas [3]. As a matter of fact, directional antennas (i.e., radiators able to define preferential directions of communications) have several advantages in ad-hoc networking over omni-directional radiators. For instance, they allow an enhancement of the network throughput because of a better spatial reuse of the frequency spectrum. Moreover, such systems generally provide higher signal-plus-interference-to-noise ratios (*SINR*s) by steering the beam pattern towards the direction of the desired signal and by placing radiation nulls along the interferers [4].

The theoretical capabilities of fully-adaptive linear or planar arrays have been analyzed in [5][6] focusing on the effectiveness of such a solution for the medium access control. However, it should be pointed out that active smart solutions (e.g., controlled phased arrays) have costs and requirements in terms of both dimensions and complexity that seem to prevent their use in today sensor networks.

On the other hand, passive switched beam systems allow a good compromise between potentialities and costs for a profitable integration. As a matter of fact, they can be built using fairly inexpensive components and need of a reduced amount of space in the node structure. For such reasons, current integrations of smart antennas into sensor nodes are yielded by considering a set of multiple directional antennas with a switch control to allow the communication only in the direction identified by the activated antenna. For instance, *Yang* et al. proposed in [7] the use of four independent semi-directional antennas installed on the four sides of each node and controlled by a switching network. Another solution has been described in [8]. The "*smart*" behavior has been obtained by placing two wire antennas at the opposite corners of the node structure, thus obtaining a two-element switched beam array. Although limited compared to "fully-adaptive" implementations, such approaches turn out to be a feasible and reliable alternative able to emulate a smart system in a limited and discrete set of working configurations.

In this paper, the integration of parasitic switched beam antennas in a *WSN* is analyzed and validated through a set of experimental studies aimed at envisaging the effectiveness and potentialities of such a solution. In particular, two different cases-of-study are discussed by presenting some preliminary experimental results. The former deals with the interference rejection for *WSN* security/privacy purposes, while the latter considers the node localization issue in order to enable location-based functionalities.

2 An Example of the Integration of Smart Antennas into a Wireless Sensor Network

Let us consider a heterogeneous *WSN* that employs the $2.4\,GHz$ ZigBee standard for the wireless communication and where some "*smart*" nodes are equipped with switched beam parasitic [(1)] antennas, while the remaining ones (indicated as "*standard*" nodes) use omnidirectional quarter-wave radiators. As far as the smart node is concerned, the switched beam parasitic antenna [9] is a planar reconfigurable structure composed by a central active element

[(1)] Smart antenna systems can be roughly categorized in *actively driven* (i.e., the control is obtained by varying the currents on the array antenna elements) and *parasitic* (i.e., the beam pattern is synthesized/modified by using passive elements around a single driven source).

and a radial array of P electronically-reconfigurable passive elements (Fig. 1). The beamforming is carried out by acting on the electronically-driven *RF* switches controlled by the binary weights β_p, $p = 1, ..., P$ (i.e., $\beta_p = 1$ when the p-th switch is on, $\beta_p = 0$ otherwise). Thus, the gain function Γ of the antenna is adaptively tuned by setting a suitable configuration of the weight array $\underline{\beta} = \{\beta_p;\, p = 1, ..., P\}$ (i.e., controlling the state of the parasitic elements).

Let us now refer to a communication between a "*desired*" standard node and a "*smart*" device, which is working as the network gateway (*master* node), in the presence of M "*undesired*" standard nodes. With reference to Fig. 2, the node equipped with the smart antenna receives, at a generic time-instant t, the following signal

$$r(t) = g\left\{\theta_d(t),\, \underline{\beta}(t);\, t\right\} d\left\{\rho_d(t),\, \theta_d(t);\, t\right\} +$$

$$+ \sum_{m=1}^{M} g\left\{\theta_{u(m)}(t),\, \underline{\beta}(t);\, t\right\} u_m\left\{\rho_{u(m)}(t),\, \theta_{u(m)}(t);\, t\right\} + n(t) \tag{1}$$

where d denotes the signal transmitted at t by the desired node located at $\{\rho_d(t),\, \theta_d(t)\}$, $u_m\left\{\rho_{u(m)}(t),\, \theta_{u(m)}(t);\, t\right\}$ is the m-th undesired signal, n is the unknown background noise, and $g\left\{\theta,\, \underline{\beta}(t);\, t\right\} = \sqrt{\Gamma\left\{\theta,\, \underline{\beta}(t)\right\}}$.

The total power Φ_r received by the "*smart*" node is equal to

$$\Phi_r(t) = \Phi_d\left\{\theta_d(t),\, \underline{\beta}(t);\, t\right\} + \sum_{m=1}^{M} \Phi_{u(m)}\left\{\theta_{u(m)}(t),\, \underline{\beta}(t);\, t\right\} + \Phi_n(t) \tag{2}$$

where

$$\Phi_d\left\{\theta_d(t),\, \underline{\beta}(t);\, t\right\} = \Gamma\left\{\theta_d(t),\, \underline{\beta}(t)\right\}\left[d\left\{\rho_d(t),\, \theta_d(t);\, t\right\}\right]^2 \tag{3}$$

and

$$\Phi_{u(m)}\left\{\theta_{u(m)}(t),\, \underline{\beta}(t);\, t\right\} = \Gamma\left\{\theta_{u(m)}(t),\, \underline{\beta}(t)\right\}\left[u_m\left\{\rho_{u(m)}(t),\, \theta_{u(m)}(t);\, t\right\}\right]^2 \tag{4}$$

are measurable quantities.

In order to find the most suitable configuration of the antenna-beam at t, the optimal configuration of the weight coefficients $\underline{\beta}_{opt}$ is determined by maximizing the *SINR* function of the link between the *smart* node and the *desired* one

$$SINR\left\{\underline{\beta}\left(t\right);\,t\right\}=\frac{\Phi_{d}\left\{\theta_{d}(t),\,\underline{\beta}\left(t\right);\,t\right\}}{\sum_{m=1}^{M-1}\Phi_{u(m)}\left\{\theta_{u(m)}\left(t\right),\,\underline{\beta}\left(t\right);\,t\right\}+\Phi_{n}\left(t\right)}. \tag{5}$$

The direct maximization of (5) is not possible, since neither $\Phi_{u(m)}$, $m = 1, ..., M$, is known nor it can be easily measured at the receiver. Nonetheless, it can be demonstrated that the function

$$\Delta\left\{\underline{\beta}\left(t\right);\,t\right\}=\frac{\Psi_{d}\left\{\theta_{d}(t),\,\underline{\beta}\left(t\right);\,t\right\}-\Phi_{n}\left(t\right)}{\sum_{m=1}^{M-1}\Psi_{u(m)}\left\{\theta_{u(m)}\left(t\right),\,\underline{\beta}\left(t\right);\,t\right\}} \tag{6}$$

has a maximum for the same $\underline{\beta}_{opt}$ as (5). In (6), Ψ_d is the signal strength (*RSS*) measured at the receiver [11] according to the guidelines in [10] and given by

$$\Psi_{d}\left\{\theta_{d}(t),\,\underline{\beta}\left(t\right);\,t\right\}=\Gamma\left\{\theta_{d}\left(t\right),\,\underline{\beta}\left(t\right)\right\}\left[d\left\{\rho_{d}\left(t\right),\,\theta_{d}\left(t\right);\,t\right\}+n\left(t\right)\right]^{2}. \tag{7}$$

Moreover, $\Psi_{u(m)}$ is the the m-th received interference strength (*RIS*) [11]

$$\Psi_{u(m)}\left\{\theta_{d}(t),\,\underline{\beta}\left(t\right);\,t\right\}=\Gamma\left\{\theta_{u(m)}\left(t\right),\,\underline{\beta}\left(t\right)\right\}\left[u_{m}\left\{\rho_{u(m)}\left(t\right),\,\theta_{u(m)}\left(t\right);\,t\right\}+n\left(t\right)\right]^{2}. \tag{8}$$

In order to maximize (6), the *smart* node tunes the binary weights β_p, $p = 1, ..., P$ according to the PSO control logic described in [12][13]. More specifically, in order to reach the best condition of the inter-node communication, the *smart* node dynamically determines the orientation of the radiation pattern of the smart antenna. Towards this end, the actual value of Δ is measured and the more suitable among the P different orientations of the radiation pattern in Fig. 3 is chosen to obtain the lowest and the highest attenuation along the direction of the desired signal and of the interferers (i.e., towards *undesired* nodes), respectively.

By exploiting the reconfiguration capabilities of the smart antenna, two main issues of *WSN*s can be profitably addressed. For instance, the security level of the communication between the *master* node and the *desired* one can be enhanced by rejecting/attenuating the interfering signals coming from the (others) undesired nodes (*Defence against Interferences*). Moreover, the neighboring nodes of the *master* one can be localized and tracked (*Sensor Node Positioning*).

3 Experimental Analysis

In this section, the use of a *smart* node in a *WSN* architecture is discussed and the envisaged applications preliminary analyzed by considering a set of simplified, but illustrative, configurations.

3.1 *"Defense against Interfering Signals"* Scenario

Let us consider the case of a communication between a *smart* node ($P = 18$) with another *desired* node in the presence of other active nodes acting as interferers for the communication link under test. With reference to Fig. 4(*a*), the *control* node is placed at the origin of the coordinate system, while the *desired* node is located at $\theta_d = 0^o$. The signals coming from the undesired nodes ($M = 3$) impinge on the control node from the directions $\theta_{u(1)} = 180^o$, $\theta_{u(2)} = 260^o$, and $\theta_{u(3)} = 40^o$, respectively. Both desired and undesired nodes operate at the same frequency (i.e., co-channel interference) and radiate with the same intensity at different time-instants (τ_k, $k = 1, ..., K$; $K = 3$). As far as the experimental validation is concerned, the following configurations have been considered: (*1*) $u_1(\tau_1) = d(\tau_1)$, $u_2(\tau_1) = u_3(\tau_1) = 0$; (*2*) $u_1(\tau_2) = u_3(\tau_2) = 0$, $u_2(\tau_2) = d(\tau_2)$; (*3*) $u_1(\tau_3) = u_2(\tau_3) = 0$, $u_3(\tau_3) = d(\tau_3)$ [Fig. 4(*a*)]. Moreover, the measurements have been carried out in a non-controlled environment and Φ_n has been measured in the quiescent configuration [i.e., $u_m(\tau_0) = d(\tau_0) = 0$, $m = 1, ..., M$].

The obtained results are summarized in Fig. 5 where the behavior of the system, in terms of measured Δ values, is described. For comparison purposes, the same result for a WSN equipped with a standard control node is reported. As expected, the smart architecture allows a non-negligible enhancement of the link quality with an improvement of about $10\,dB$.

3.2 *"Sensor Node Positioning"* Scenario

The second scenario deals with the situation where the *master* node needs some information on the location of another moving sensor node to re-configure the management of wireless resources. Such a scenario is sketched in Fig. 4(*b*) where the moving node is located at [$\rho_d(\tau_k)$, $\theta_d(\tau_k)$], $k = 1, ..., K$, with respect to the *smart* control node. At each time-step τ_k, $k = 1, ..., K$, the localization of other nodes (in this simplified case, only one indicated as *slave* node) is carried out by exploiting the flexibility of the smart antenna and according to the following procedure:

- the *smart* node determines the antenna setting [i.e., the optimal configuration $\underline{\beta}\left(\tau_k\right)$] that allows the reception of the maximum level of signal from the *slave* node. Since both the transmitted power and the gain function of the omnidirectional antenna of the *slave* node are known quantities, the distance $\hat{\rho}_d$ between the two nodes is determined according to the Friis' relationship [14]. Moreover, the control node also stores the angular position of the maximum of its own radiation pattern to give an estimate of the angular location $\hat{\theta}_d'\left(\tau_k\right)$ of the moving node;
- in order to improve the estimation of $\theta_d\left(\tau_k\right)$, the *smart* node tunes the orientation of the reference pattern (Fig. 3) around $\hat{\theta}_d'\left(\tau_k\right)$ by looking for the position of the null $\theta_n\left(\tau_k\right)$ that minimizes the level of the signal received by the *slave* node.

In order to assess the feasibility and reliability of such a solution, the experimental validation has been performed by considering a set of $K=5$ time-steps. The results are reported in Tab. I in terms of the location errors defined as

$$\varepsilon_\theta\left(\tau_k\right)=\frac{\left|\hat{\theta}_d\left(\tau_k\right)-\theta_d\left(\tau_k\right)\right|}{\theta_d\left(\tau_k\right)}\times 100 \qquad (angular\ error) \tag{9}$$

and

$$\varepsilon_\rho\left(\tau_k\right)=\frac{\left|\hat{\rho}_d\left(\tau_k\right)-\rho_d\left(\tau_k\right)\right|}{\rho_d\left(\tau_k\right)}\times 100 \qquad (distance\ error). \tag{10}$$

As it can be noticed, despite the presence of a background noise, the angular coordinate of the *slave* node has been carefully estimated [$\varepsilon_\theta\left(\tau_k\right)\leq 12$ - Tab. I], while greater errors verify in the distance estimation [$\varepsilon_\rho\left(\tau_k\right)\leq 35$].

4 Conclusions

In this paper, some advantages and potentialities of the integration of smart antennas in a *WSN* architecture have been envisaged and preliminary assessed by means of a set of experiments dealing with test configurations. Although concerned with simplified scenarios, the obtained results confirm the feasibility and relevance of such an integration. Let us consider the "*WSN topology control*" (Sect. 3.2), it is certainly of great importance and suitability when monitoring dynamical scenarios (e.g., landslips or avalanches). As a matter of fact, the free-of-charge (i.e., without the use of a position sensor) detection of the location of each node of the network might be profitably employed in automatic alert systems for civil protection.

Besides these positive effects, the integration of "*intelligence*" at the physical layer of the network architecture allows one the development/improvement of a large number of other functionalities currently of high interest in both *WSN* researches and, in general, wireless networks. As a matter of fact, some trivial benefits coming from such an integration turn out to be: (*a*) an efficient spatial management of the radiated energy for RF energy-saving purposes as well as to improve the network coverage and connectivity; (*b*) an efficient and adaptive (e.g., based on the environmental conditions) reuse of wireless links to significantly increase the network throughput and solve coexistence problems coming from the integration with other wireless standards/technologies (i.e., *RFID* or *UWB*).

On the other hand, it should be pointed out that, some improvements in both flexibility and impact of the adaptive antenna on the *WSN* node are needed to properly address the most demanding requirements arising in large scale and realistic applications. As an example, let us consider the presence of fully-adaptive antennas (instead of switched beam devices). It would strongly improve the efficiency of each node as well as of the whole network architecture when dealing with the detection and suppression of intentional network attacks devoted to alter or/and destroy data links. Because of a wider number of degrees of freedom (compared to that of a switched-beam system) in adapting the radiation pattern to the electromagnetic environment, there would be the possibility of synthesizing a radiation pattern with the main lobe directed towards the direction of arrival of the signal of interest and with nulls along the interference directions. Unfortunately, up till now, complexity, size, and energy consumption prevent their current implementation in *WSN*. Future researches will be aimed at properly addressing such an issue.

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Figure Captions

- **Figure 1.** Prototype of the *smart* node.
- **Figure 2.** Smart *WSN* architecture.
- **Figure 3.** Reference radiation pattern of the *smart* node [θ_n: angular null position].
- **Figure 4.** Geometry of the (*a*) “*Defence against Interferences*” Scenario and of the (*b*) “*Sensor Node Positioning*” Scenario.
- **Figure 5.** ”*Defence against Interferences*” Scenario - Behavior of Δ in correspondence with different configurations.

Table Captions

- **Table I.** “*Sensor Node Positioning*” Scenario - Error figures.

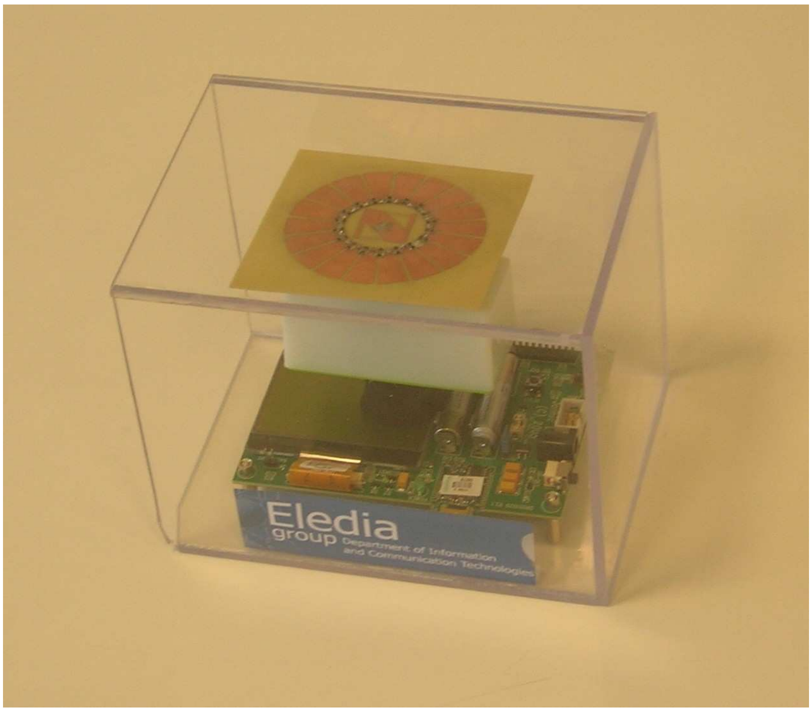


Fig. 1 - F. Viani *et al.*, "Exploitation of parasitic smart antennas in ..."

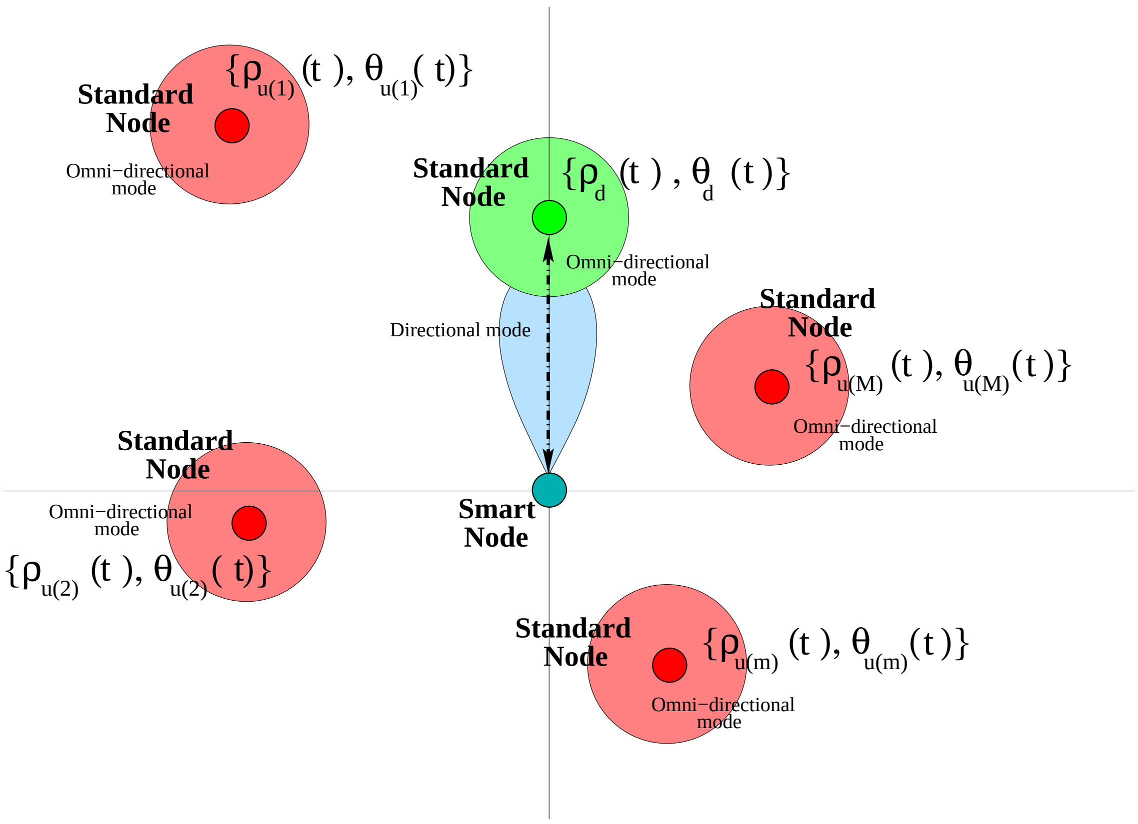


Fig. 2 - F. Viani *et al.*, "Exploitation of parasitic smart antennas in ..."

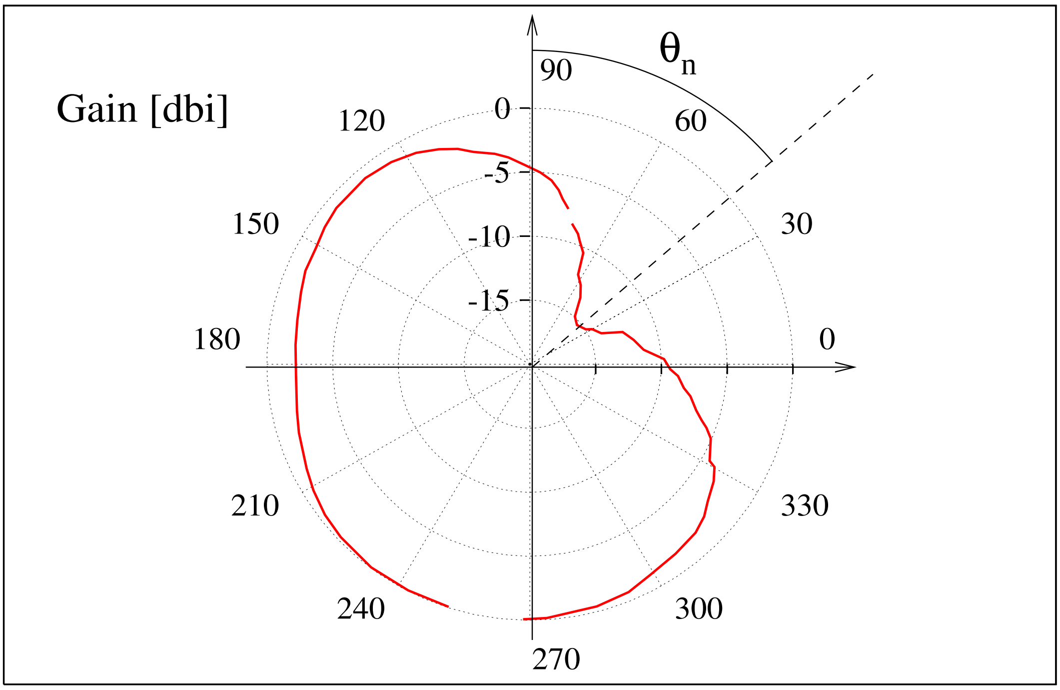
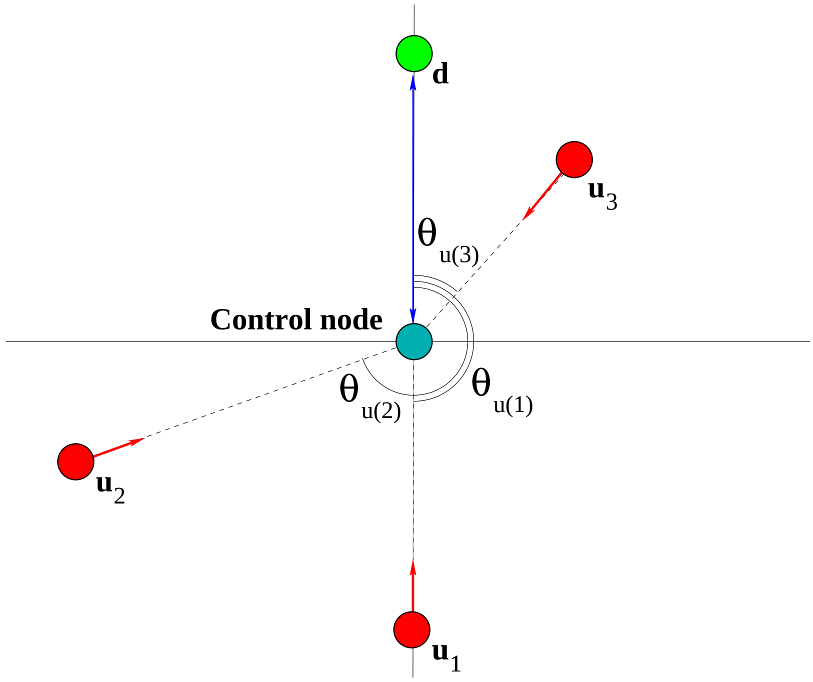
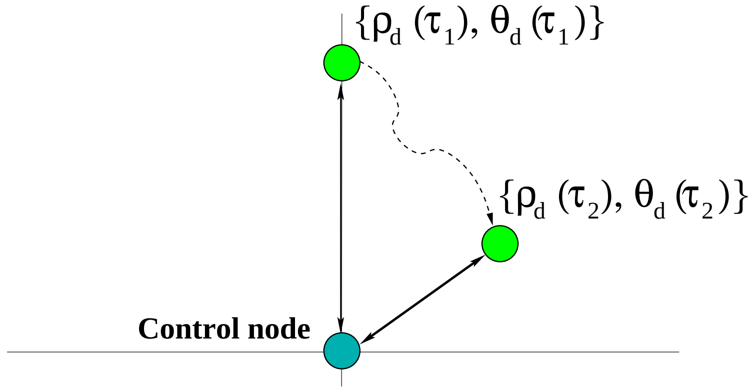


Fig. 3 - F. Viani *et al.*, “Exploitation of parasitic smart antennas in ...“



(*a*)



(*b*)

Fig. 4 - F. Viani *et al.*, "Exploitation of parasitic smart antennas in ..."

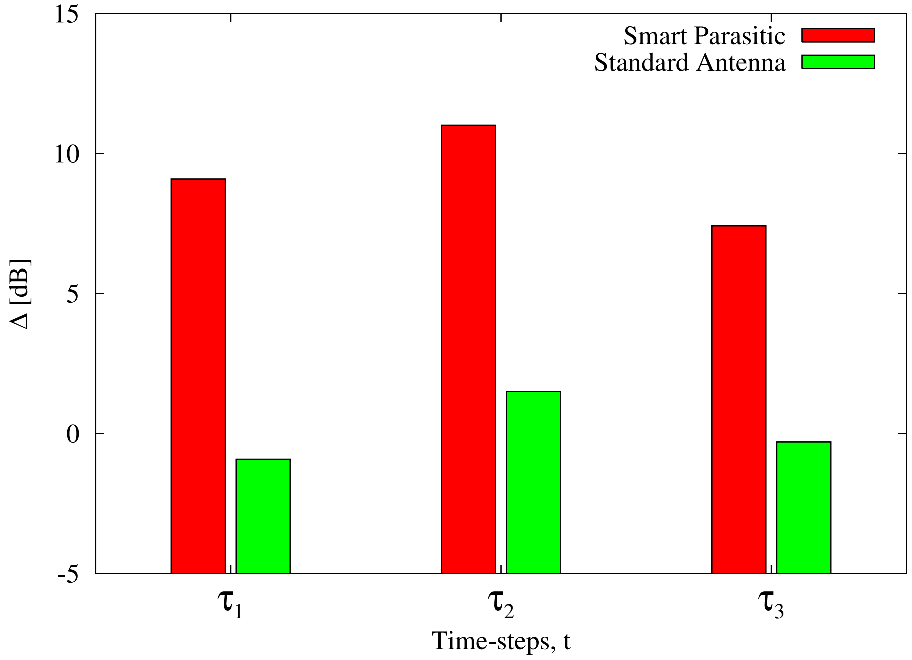


Fig. 5 - F. Viani *et al.*, "Exploitation of parasitic smart antennas in ..."

k	$\theta_d(\tau_k)$ $[deg]$	$\rho_d(\tau_k)$ $[m]$	$\varepsilon_\theta(\tau_k)$	$\varepsilon_\rho(\tau_k)$
0	0^o	6.30	2.2	5.2
1	50^o	4.75	12.0	24.0
2	180^o	5.50	5.0	11.8
3	240^o	4.30	6.2	32.0
4	260^o	7.50	7.7	28.9

Tab. I - F. Viani *et al.*, "Exploitation of parasitic smart antennas in ... "