Stand-Alone Smart Wireless Sensor Nodes Providing Dynamic Routing by Means of Adaptive Beamforming

Roberto Caso[1], Rosario Garroppo[1], Stefano Giordano[1], Giuliano Manara[1],
Andrea Michel[1(✉)], Paolo Nepa[1],
Luca Tavanti[1], Marco Magnarosa[2], and Guido Nenna[2]

[1] Department of Information Engineering, University of Pisa, Pisa, Italy
{r.caso,r.garroppo,s.giordano,g.manara,
a.michel,p.nepa,l.tavanti}@iet.unipi.it
[2] CUBIT s.c.a.r.l., Pisa, Italy
{marco.magnarosa,guido.nenna}@cubitlab.com

Abstract. In this paper, the feasibility of a single integrated autonomous device equipped with WiFI capability is analyzed, discussing its potentiality in the framework of the Internet of Things and Cyber Physical Systems. By equipping photovoltaic panels with sensors and antennas, it is possible to obtain a single stand-alone wireless network node. Specifically, integration of a number of antennas in a large solar panel is suitable to obtain an integrated antenna array. Thus, beamforming techniques can be implemented to electronically orient the array maximum gain radiation, so improving the point-to-point network link.

Keywords: Integration · Slot antennas · PV panel · Solar cells · Stand-alone systems · Wireless sensor networks

1 Introduction

The interest on connecting systems and devices to a whole and unique network is the main topic of a large number of research activities in the last decades. Wireless Sensor Networks (WSNs) have been widely studied and used to create networks of physical devices and systems equipped with sensors and electronics which are able to share data with the other nodes. That is, the Internet of Things (IoT). Such networks allow objects and devices to be remotely monitored and controlled by means of the existing network. Shared data such as temperature, real-time status of electronic devices, humidity can be collected and processed to extract information on the network status. More recently, Cyber-Physical Systems (CPS) have been created. Devices and systems are connected together creating a wide network, and feedback loops are also provided to drive the single nodes. In this way, actuators can be activated to face with environment and system issues. It is clear that these systems have a huge potential from an economic and societal point of view, and investments are being done.

Even though CPS have been largely discussed in the scientific literature, some of the desirable features of a single network node are here summarized:

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- stand-alone, equipped with green power sources such as wind turbines or solar panels;
- equipped with integrated sensors and antennas to provide wireless link in the network;
- dynamic routing capabilities to make the network flexible, reconfigurable and self-healing.

A specific attention has to be paid to the dynamic routing capabilities. Even if the static routing (Fig. 1a) is still used in networks since it is secure, easy to implement in small networks and no routing algorithms are required, dynamic routing (Fig. 1b) is preferable because it makes the network almost scalable and flexible.

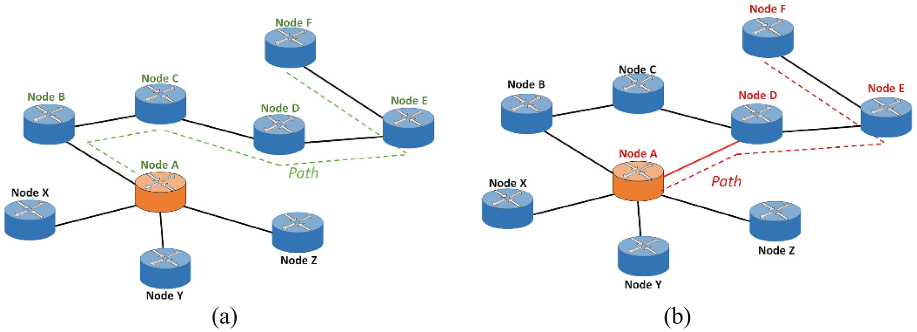


Fig. 1. Schematic wireless sensor network with (a) static and (b) dynamic routing.

However, changing the route could be demanding, especially for stand-alone wireless sensor network nodes. Indeed, in outdoor scenarios the links among network nodes are provided by antennas with a specific radiation pattern. If the position of nodes is fixed and known *a-priori*, directional antennas can be used to implement a high-quality radio link. Nevertheless, directional antennas are characterized by a narrow radiation pattern, and

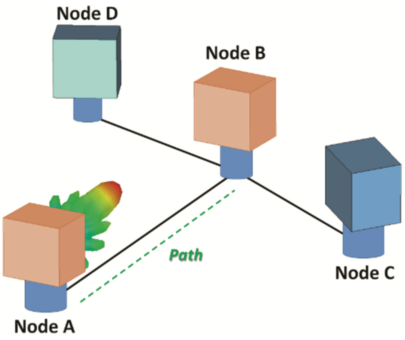


Fig. 2. In a static routing, the wireless link between two nodes can be optimized by using specific directional and high-gain antennas, since the relative position of the two nodes is a-priori known.

point-to-point links must be carefully set-up – a slight misalignment between the transmitting and receiving antennas could lead to a reduced radio link performance. Thus, static routing can be implemented by means of directional antennas. (Fig. 2).

On the other hand, if the nodes are not fixed (*e.g.* cars or drones could be nodes of a wireless sensor network), dynamic routing is preferable since the network topology changes. However, directional antennas are not suitable anymore – the position of nodes is not known *a-priori*. Thus, omnidirectional antennas are typically used, even though they are characterized by a fairly low gain. To improve the wireless link performance, directional antennas could be used and beamforming algorithms can be implemented to orient the maximum gain toward a specific direction. For example, Node A in Fig. 3 can scan the azimuthal plane and orient the radiation pattern toward Node C (Fig. 3a) or Node D (Fig. 3b), creating new paths set by dynamic routing.

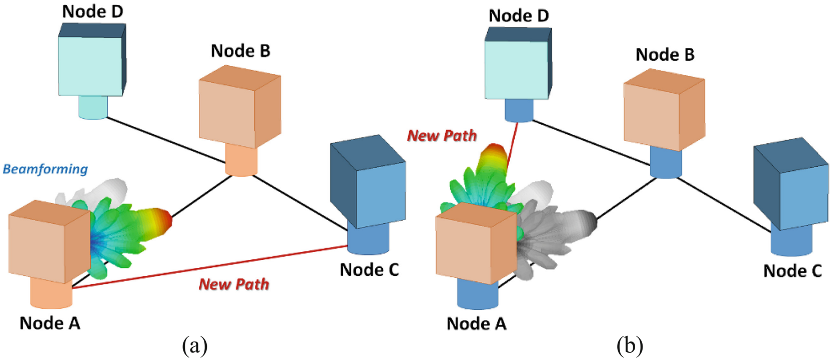


Fig. 3. In a dynamic routing, the wireless link between two nodes is not a-priori set. Therefore, beamforming capabilities can be implemented in order to orient the antenna maximum gain direction toward a diverse node.

The beamforming capability can be obtained by equipping the network node with an array of antennas and by setting a proper input current phase for each radiating element. Thus, phase shifters are needed. Microcontroller or microprocessors are also required to be remotely controlled in order to select the currents phase. Since the wireless nodes could be arranged in rural scenarios where wired feeding networks are not available, stand-alone power sources must be considered for each single node. For example, wind turbines or photovoltaic panels are effective in providing power to the network nodes.

In particular, photovoltaic (PV) energy is widely used in autonomous communication system due to its eco-friendliness and reliability. In 2009 it was estimated that at the end of this century the solar power generation will account for more than 60 % of world's totally [1]. To date, solar panels are used in some stand-alone wireless communication systems, especially in isolated environments. However, PV panel, sensors and antenna are separate elements of the same system, causing relatively great space employment, engineering and design problems. Therefore a compromise in the utilization of the limited available space is needed and sensor and antennas integration in PV panel is desirable.

Several studies have been carried out in order to assess the possibility of integrating antennas in solar cells and photovoltaic panels. For example, researchers are interested in innovative transparent antenna, made by TCOs (Transparent Conductor Oxides) [2, 3]. These antennas may represent a good integrated solution because they can be easily integrated in after-market solar cell. However these TCOs are still relatively expensive and with the existing technological capabilities is not easy to obtain a 90 % sunlight transparency, needed for the proper functioning of the solar cell [3].

Since solar cells are fabricated with conductive materials, they may be used as a radiating patch [4] or as a coupled patch [5–7]. However, in these cases the cell dimensions are strictly related to the operating frequency band, restricting the possible applications. Regardless of a solar panel efficiency reduction, solar cells may be used also as a ground plane for an upper patch element [8–11]. Finally, slot antennas have been integrated among the solar cells [12–15] or obtained by properly etching of them [16]. The latter affects the solar panel efficiency, but for high frequency applications the antenna size is small and the integration in a PV panel results to be simpler.

Anyway, antenna integration in photovoltaic panels is possible, providing the panel with new features. Since small photovoltaic panels are used in consumer products such as battery recharger, access points or other personal devices (Fig. 4), antennas and sensors can be distributed in a large number of electronic items. In some of these systems, sensors can be used to get information on humidity, temperature, geographical position, etc. Hence, all the information can be transmitted to a base station and collected to remotely monitor both the single devices and the overall network. Mesh networks could be design by using all these devices, creating a wide wireless sensor network.

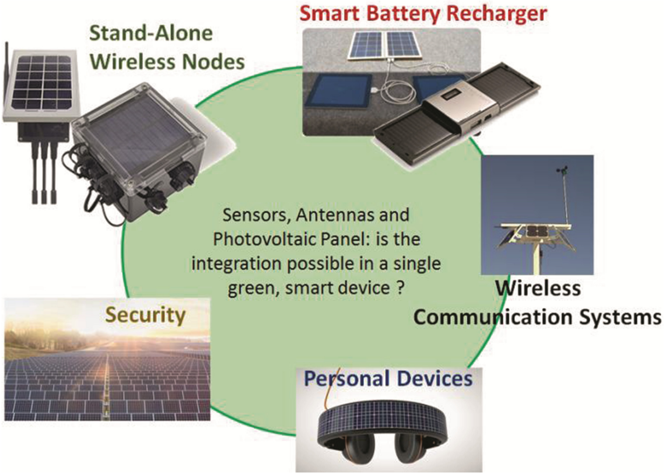
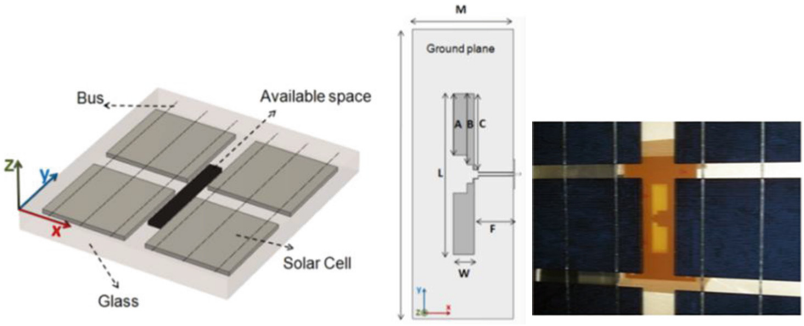


Fig. 4. Examples of applications in which sensors, antennas and photovoltaic panels could be integrated in a unique device.

In this paper, the potentiality of a Wireless Sensor Network composed by autonomous nodes equipped with integrated sensors and antennas is investigated. To improve the link quality, smart PV panels can be equipped with more than one antenna. Indeed, exploiting the available space between the solar cells, a planar array can be obtained, providing the PV panel with beamforming capabilities. As a result, the maximum gain direction can be oriented by means of phase shifters, pointing toward the network node selected by dynamic routing algorithms.

2 Preliminary Results on the Integrated Array

In the previous section, some PV panel integrated antennas are described. In order to obtain a low-cost antenna solution without affecting the PV panel solar efficiency, the integrated antennas are designed to exploit the available space among adjacent solar cells where only a cover glass layer is present above the radiating element. A typical commercial PV panel has been considered for the antenna design. It is composed by 36 156-mm-side monocrystalline silicon (m-Si) square solar cells, which are incorporated between two ethylene vinyl acetate (EVA) layers. The cells plane is covered on the top and bottom side by two glass layers, for an overall thickness of about 8 mm. The solar cells are separated from a distance of 25 mm each other. In Fig. 5a, a potential position of a slot antenna among square solar cells is shown (dark color). The top view of the proposed antenna is also shown in Fig. 5b. This antenna is characterized by low cost materials and easy-integration in a PV panel (Fig. 5c), in order to obtain a cost limitation of the manufacturing process. The radiating element has been presented in [14, 15] and here optimized for WiFi applications. The geometrical parameters of the final design are listed in Table 1.



(a) (b) (c)

Fig. 5. The antenna presented in [14] has been here optimized for WiFi applications: (a) potential position of a slot antenna among square solar cells (b) top view of the proposed antenna and (c) antenna prototype integrated in a commercial PV panel.

Table 1.

ANTENNA DIMENSIONS, MM			
N	200	**A**	27.6
M	45	**B**	28.8
L	67.5	**C**	30.3
W	5.6	**F**	18.3

In [15], WiFi antennas have been integrated in a photovoltaic panel, and some tests have been carried out. Specifically, the slot antenna performance in terms of measured reflection coefficient, received signal power and goodput results is described and compared with that of a commercial dipole. The experimental analysis of the overall integrated system shows that the performance of the developed antenna integrated in the PV panel are no worst, or even better than the commercial antenna one.

Consequently, similar tests have been repeated by using two antennas integrated in two separate PV panels, creating a panel-to-panel WiFi link. In Fig. 6 the measurement scenario is shown.

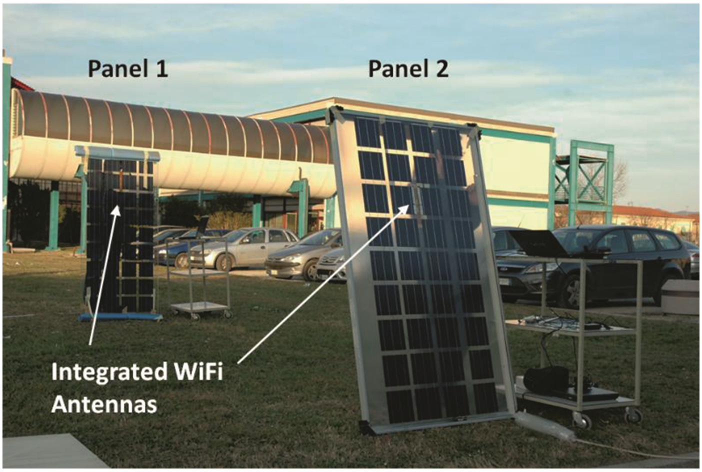


Fig. 6. The measurement setup for the panel-to-panel tests.

The two panels are equipped with two integrated WiFi antennas. Both antennas were connected to two laptops through the TL-WN722 N modules [17]. Thus, the received power and the goodput have been measured as a function of the distance between the two panels. The results are shown in Fig. 7. With only a single radiating element and a transmission power of 20dBm, the two photovoltaic panels can communicate beyond 100 m of distance, which is suitable for a large variety of applications.

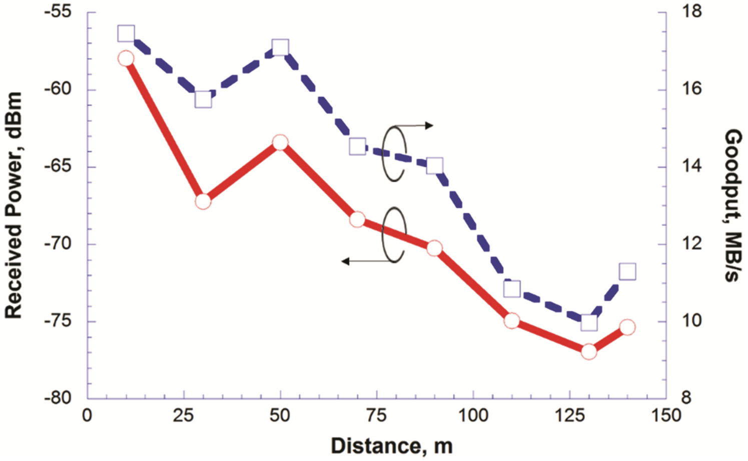


Fig. 7. Panel-to-panel WiFi link performance in terms of received power and goodput, as a function of the distance between the two PV panels.

The measured performance on the WiFi integrated antenna demonstrated that a single, integrated, photovoltaic panel can be fabricated and used as an autonomous node of a Wireless Sensor Network. However, a specific attention has to be paid on the photovoltaic panel orientation. It is clear that the solar cells must be oriented toward the sun in order to maximize the power generation. On the other hand, two communicating network nodes can be arbitrarily positioned in the open space. Moreover, if a dynamic routing is implemented or the network nodes position changes (*i.e.* mobile nodes), the smart panel has to be "smart" and able to orient the maximum gain direction toward the node position.

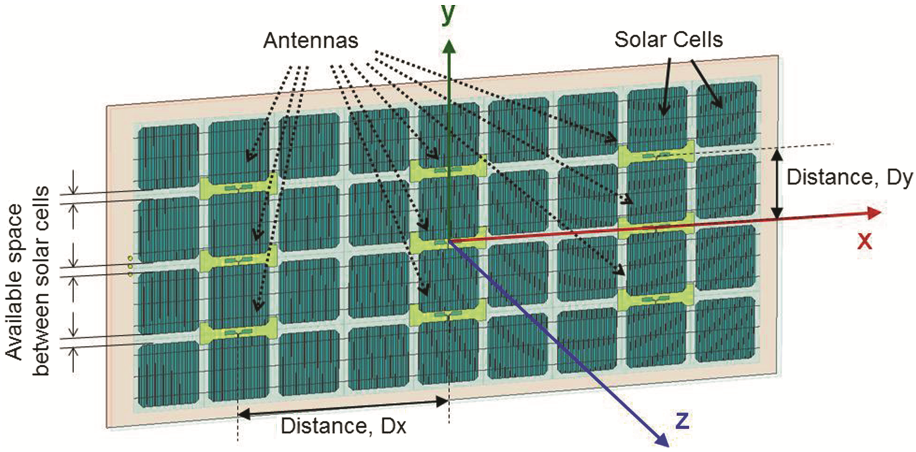


Fig. 8. WiFi antennas have been integrated in a photovoltaic panel to obtain a 3 × 3 array.

For these reasons, a number of antennas could be integrated in the same PV panel, and opportunely fed in order to orient the maximum gain toward a specific direction where other network nodes are supposed to be. That is, the PV panel integrated array provides the smart panel with beamforming capabilities.

To prove the feasibility of a PV panel integrated array, numerical simulations have been performed by using CST Microwave Studio®. As shown in Fig. 8, nine WiFi antennas have been placed between the cells of a 4 × 9 solar cells PV panels.

The maximum gain direction can be oriented by choosing a proper input phase of each radiating element. Let us consider an $M \times N$ planar array arranged on the XY plane as in Fig. 8. As usual, θ is the angle between the z-axis and the x-axis, while ϕ is the angle between the x-axis and the y-axis. In general, the current phase of the $(m,n)^{\text{th}}$ radiating element ($\alpha_{m,n}$) has to be set to

$$\alpha_{mn} = -\beta\left(x_{mn}\sin\theta_0\cos\phi_0 + y_{mn}\sin\theta_0\sin\phi_0\right)$$

where

- β is the wavenumber in free space, and it is directly proportional to the operating frequency;
- $(x_{m,n}, y_{m,n})$ represents the position of the $(m,n)^{\text{th}}$ element in the XY plane;
- (θ_0, ϕ_0) represents the direction where the gain has to be maximized.

The distance D between two adjacent radiating elements plays an important role in the array radiative performance. In particular, the higher the distance between the antennas (but lower than λ which represents the free-space wavelength), the higher is the gain. However, the distance D is also strictly related to the radiation pattern characteristics in case of beamforming (for example, for large distances D the grating lobes phenomenon could appear). Nevertheless, the distance between the radiating elements is highly affected by the presence of the radiating cells. Indeed, the available space between solar cells rows is limited and the distance between two free slots is set by the cell size. Anyway, the distance D can be chosen as a trade-off between the required array radiative performance and the physical limitations due to the presence of the solar cells.

To better assess the feasibility of an integrated antenna array, the antennas shown in Fig. 8 have been properly fed to maximize the radiation toward a specific direction. In Fig. 9 the normalized radiation patterns of the 3 × 3 array of PV panel integrated antennas for WiFi applications are shown for the XZ plane (Fig. 8), by considering a fixed frequency of 2445 MHz. In particular, the distance D_X is set to 85 mm and the distance D_Y is set to 125 mm which corresponds to the typical solar cells size. Therefore, input current phases have been computed in order to orient the main lobe direction toward $\theta_0 = 0°$, $\theta_0 = 10°$ and $\theta_0 = 30°$ - for the sake of simplicity we assumed $\varphi_0 = 0°$. When the main lobe is tilted toward $\theta_0 = 30°$, the side lobe level is not negligible ($\mathrm{SLL} = -4$ dB), and it could be not satisfactory for communication systems. Increasing the number of antennas and reducing the distance among them could allow for a lower side lobe level; however, also the number of radiating elements depends on the photovoltaic panel size.

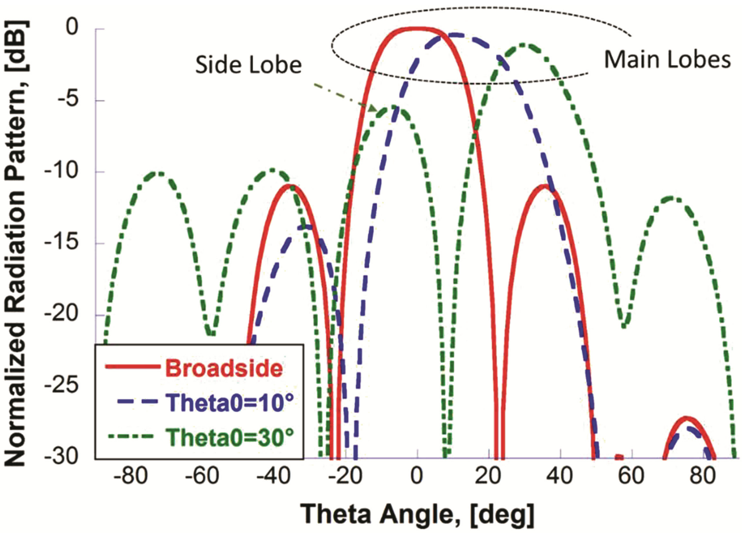


Fig. 9. Normalized radiation pattern of the 3 × 3 array of PV panel integrated antennas for WiFi applications.

3 Conclusion

Solar panels allow communication systems to be stand-alone, without the need of wired-feeding networks. That is, they can be installed and used in wild and rural environments. Arranging small devices equipped with green power sources (*e.g.* PV panels or wind turbine) in outdoor scenarios could represent a valuable solution for remote control and management of isolated areas. Moreover, wireless sensor and mesh networks can be constructed to collect and share data. Integrated sensors and antennas in the same autonomous device represent a challenge for the future Internet of Things. In this paper, the feasibility of an array of antennas integrated in a single photovoltaic panel has been investigated. Preliminary numerical results have been also presented, confirming that beamforming techniques can be implemented to orient the integrated array maximum gain direction toward a wireless network node, improving the overall network performance. This opens also to the possibility of performing dynamic routing with high directional antennas. By steering the beam in accordance with the routing decision, the maximum gain can be aligned towards the node the traffic is destined to.

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