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RF Energy On-Demand for Automotive Applications

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***Abstract*—This work proposes the design of a Wireless Power Transfer (WPT) system in the 2.4 GHz band, suitable for remotely energizing low-power wireless sensors located in highly complex environments from the electromagnetic propagation point of view. This is the case of many industrial scenarios such as industrial machineries or automotive engines, to enable remote monitoring, predictive maintenance and components diagnosis. A co-designing method was used to obtain a system of independent RF sources embedded in the complex environment, with the aim of being at the same time miniaturized for easy integration into the environment, and of having the ability for providing energy wirelessly in a pervasive way. The validation of the project shows that even wireless sensors located in critical and NLOS (Non-line-of-sight) positions, placed in key points of the engine compartment and in contact with parts that need to be monitored, can be successfully energized by the proposed approach. This enables battery-less sensors to be powered and to simultaneously communicate with a gateway in order to monitor vital engine parameters. A communication among the gateway and a number of battery-less sensor nodes is demonstrated exploiting low-power LoRa (Long Range) nodes working in the same frequency band of the RF powering system.**

***Keywords*—Wireless Power Transfer, automotive, Wireless Sensor Networks, predictive, maintenance, radiofrequency.**

I. INTRODUCTION

Currently, there is an always increasing interest in the implementation of the paradigm of industrial IoT (Internet of Things) to enable connections of critical machines and sensors in high-stakes industries such as aerospace, automotive and healthcare for predictive maintenance to avoid emergency situations. Over these last years, the IoT typical technologies, such as Radio Frequency Identification (RFID), Wireless Sensor Networks (WSN) and Artificial Intelligence (AI), have been always increasingly associated with Wireless Power Transfer (WPT), in order to develop energy autonomous sensor systems [1] able to avoid the use of batteries and wired power connections.

In the automotive sector, there has been an even more frequent interest of both scientific community and companies on new systems to provide solutions for monitoring engine components with sensors [2] and for feeding them with WPT techniques [3], always taking account of the potential biological effects of high-power microwaves [4].

This work presents the design and the operation of a WPT system working in the 2.4 GHz ISM band, making use of an optimized number of suitable designed RF sources ("illuminators"), for the present case two, that can be optimally placed in the engine compartment of a car to wirelessly energize a set of battery-less smart wireless sensor tags attached to key parts of the car engine, whose characteristics have to be monitored during a trip. For instance, the temperature of the radiator and the movement (i.e., the acceleration) of the pump drive belt should be worthy of special attention in order to ensure car functionalities intact for a long time and to predict maintenance before failure.

In Fig. 1, an illustrative example of the envisioned scenario is represented.

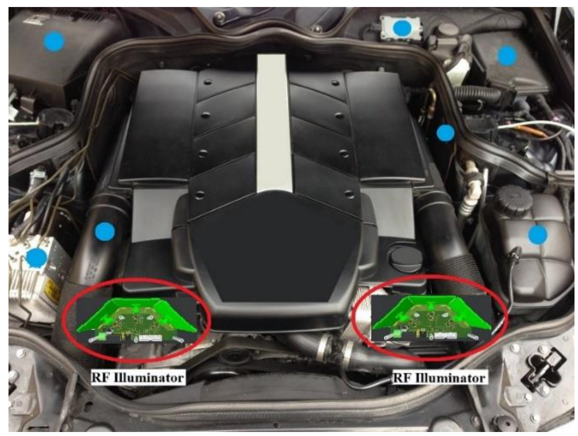

Fig. 1. Envisioned scenario for a system with wirelessly powered sensor nodes (in cyan) in a car engine compartment. The RF sources, including their transmitting antennas and the corresponding feeding circuitries, are circled in red.

II. RF ILLUMINATORS PROJECT AND BEST POSITIONING PREDICTION SIMULATIONS

In order to achieve a successful powering of the sensor nodes located in the engine compartment, a RF source (named illuminator) has been designed, realized and tested. By reason of the fact that the environment where the WPT system is placed is strongly harsh from the electromagnetic point of view, and can be different from car to car and within the same car, a customized 3D layout for the illuminator has been designed consisting of a set of independent active patch antennas arranged constituting a portion of a polyhedron. For the present purpose, successful operations have been demonstrated by using three different patch antennas, incoherently fed by three separated identical paths, and subsequently rotated by 45° in order to ensure the adequate coverage of every part of the engine. Moreover, each antenna element is circularly polarized (CP), in order to face possible changes of the electromagnetic wave polarization that can easily happen in a metallic

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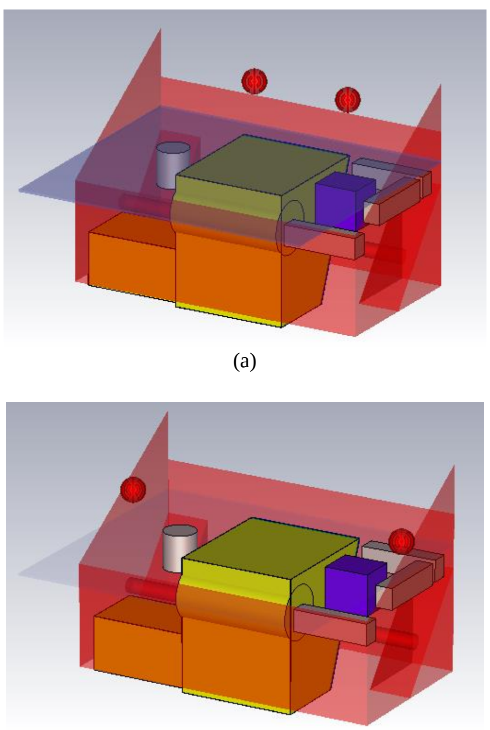
environment, such as the one addressed in this work, due to multi-path propagation, as fading, shadowing, etc.

A. *Integral Solver 3D Scenario Layout*

In order to establish the optimum illuminators positioning, a simplified representation of the whole car engine environment has been electromagnetically simulated by means of a customized method exploiting the reciprocity theorem [5] to estimate the received power at the tag location: the main goal is to evaluate the power received at the tags in order to select the optimal positions of the RF sources.

The benefit of such approach, with the help of Integral Equation solver (IE) [6], is to minimize the simulation problem size, hence allowing faster (about two times) simulations, and more accurate results than a standard full-wave approach because of the complexity of the scenario. This agile tool has been exploited to select the most effective position of the couple of illuminators adopted in the test phase.

A schematic representation of the harsh environment to be computed is shown in Fig. 2, representing a generic small size hatchback car model with a 1248cc engine measuring 62×54×60 cm^3 inserted in a closure (shown in light red) that measures 76×143×95 cm^3. Simplified representations of the engine parts are shown, such as battery, air filter, and metal holders for the motor body. Fig. 2(a) represents the simulated scenario corresponding to the final (and measured) placement of the two illuminators, while Fig. 2(b) depicts an alternative setting that has been simulated.



(a)

(b)

Fig. 2. Tri-dimensional representation of the modelled scenario with the main parts included inside the motor closure shown in light red, the surface Σ in light blue, and the illuminating RF sources represented as red spheres; (a) shows the position that has been realized for measurements, while (b) is another simulated scenario with the sources placed in lateral positions.

The numerical method based on IE solver, rigorously exploits the reciprocity theorem without the simplified assumption of far-field, which cannot be always valid in the scenario under test; once the illuminator/tags positions have been defined, a virtual surface (Σ) in between the transmitting and receiving parts is placed inside the electromagnetic project. From the numerical evaluation of the electromagnetic fields generated by the transmitting illuminator (E_I, H_I) and by the receiving tag (E_T, H_T) on a point $P \in \Sigma$, the expression of the Norton equivalent current on the receiving tag load (R_0) can be straightforwardly evaluated through:

$$J_{eq} = \frac{1 + R_0 Y_T(\omega)}{U} \cdot \hat{n} \iint_{\Sigma} [E_I(P) \text{x} H_T(P) - E_T(P) \text{x} H_I(P)]\, d\Sigma \quad (1)$$

where Y_T is the receiving tag antenna input admittance, $\hat{n}$ is the unit vector orthogonal to the Σ surface and pointing at the tags side, and U is a sinusoidal voltage source whose internal impedance is R_0.

In the present case, the virtual surface Σ is a plane interposed between the tags and the illuminators (see the blue plane in Fig. 2(a,b)) in order to best intercept the produced fields.

This procedure allows to accurately evaluate the current produced in each receiving tag, whatever the polarization and the incoming direction of the involved fields; once the current is evaluated with (1), the available power in the receiving tag location is then evaluated by:

$$P_T(\omega) = \frac{|J_{eq}|^2}{8Re(Y_T(\omega))}. \quad (2)$$

The simulations have been carried out with the electromagnetic simulation software CST Microwave Studio, installed on a 2 GHz-Intel processor on a machine with 32 GB of RAM. While the traditional Frequency Domain (FD) method takes 14 hours to complete, the IE takes approximately 6 hours in total, equal to 4 hours for tags simulation and 2 hours for the evaluation of the illuminators fields on the surface Σ.

The numerical results suggest that the two selected positions of the illuminators (Fig. 2(a,b)) are almost complementary in terms of power delivered to eight tags placed in different parts of the engine (as detailed in Section III): the final choice of the illuminators has then been the one depicted in Fig. 2(a), because of the slightly higher power budget and of the simpler positioning in the test phase.

B. *RF Illuminators Design and Realization*

The illuminator circuitry has been realized by using off-the-shelf components, namely Maxim MAX2750 Voltage Controlled Oscillators (VCO), one for each antenna, having an output power of -3 dBm in the 2.4 GHz ISM band; this frequency band selection has been made in order to have small size antennas both at the illuminator and at the sensor node side.

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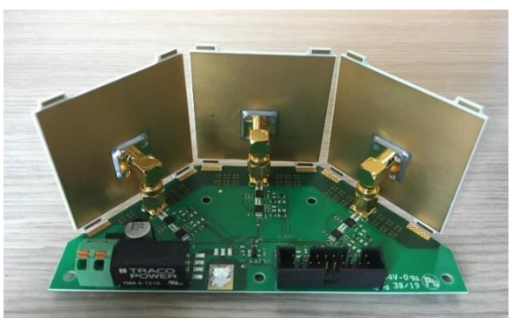
The adoption of a VCO allows to dynamically select the illuminators operating frequency in order to enable frequency division between the powering and the communication operations. The VCO tuning voltage input is given by a voltage control element (Linear Technology LT6650) that is set in order to have a signal at 2.45 GHz; this choice has been made in order to have sufficient distance in the spectrum between the WPT signal and the LoRa communication signal (at 2.401 GHz).

The other key elements of the illuminator are the three RF amplifiers incoherently feeding the antennas: the selected component is the Skyworks SE2598L, having a gain of 26 dB and therefore able to ensure an output power of 23 dBm at the transmitting CP patch antennas; hence, having measured a 4 dB-gain for the antennas, the total Effective Isotropic Radiated Power (EIRP) for each illuminator channel is 27 dBm, compliant with the current regulations.

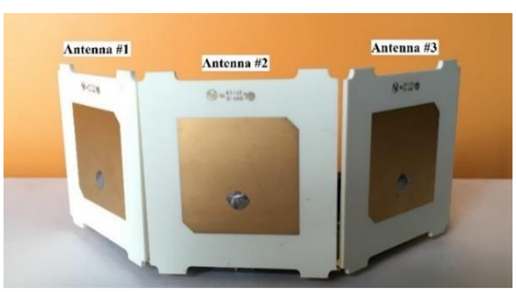
The chosen substrate for the board is Rogers RO4360G2 (thickness: 0.610 mm, with ε_r=6.15, tan(δ)=0.0038), in order to have a reduced microstrip line width of 0.9 mm for a 50 Ω impedance and at the same time low dielectric losses, with respect to a standard FR-4 substrate (ε_r=4.3, tan(δ)=0.025).

On the other hand, the three CP patch antennas are reached by a right-angle coaxial connector and realized on a thicker and less dense Rogers RO4350B (thickness: 1.524 mm, with ε_r=3.48, tan(δ)=0.0037)

The entire board of the RF source is shown in Fig. 3, including the three CP antennas rotated by 45°, one from each other. The overall dimensions of the illuminator prototype are 13×6×5.54 cm^3.



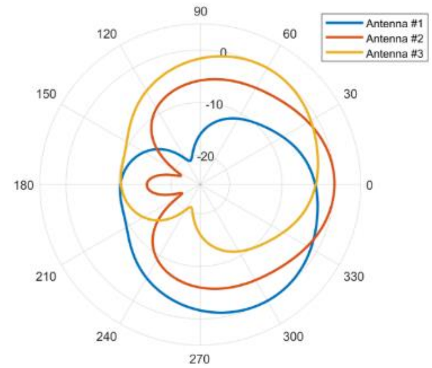
(a)



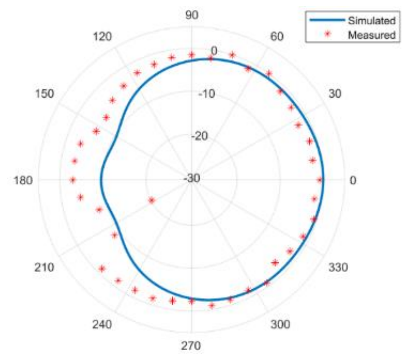
(b)

Fig. 3. (a) Photograph of the illuminator feeding circuitry working in the 2.4 GHz band. (b) The front view with the three coaxial-fed CP patch antennas is represented.

Fig. 4 shows the simulated normalized radiation patterns of the self-standing three antennas (Fig. 4(a)) and the normalized total radiation pattern (measured and simulated) due to the incoherent and simultaneous feeding strategy of the antennas (Fig. 4(b)), both in the horizontal plane.



(a)



(b)

Fig. 4. (a) Normalized simulated polar patterns (in dB) of the self-standing three illuminator CP patch antennas and (b) normalized simulated and measured polar patterns of the entire RF illuminator, both in the horizontal plane.

III. Measurement Campaign and Results for the WPT System

The measurement campaign has been finally conducted in a real scenario, adopting the engine compartment of a car, and registering typical values of the WPT system, such as voltage and power at the output of the rectifier and the charge time of the storage capacitor.

The antenna at the tag side for energy harvesting is a squared patch antenna, whose dimensions have been minimized by adopting a shorting plate mechanism and are 2.5×3 cm^2, with a realized gain of 1.84 dB, whereas for the Power Management Unit (PMU), Texas Instruments bq25570 has been adopted as power boost charger and buck converter in order to store a total amount of energy of 5.12 mJ, widely sufficient for the execution of a single operation scheduled by the protocol and achieved by the microcontroller and the transceiver.

Eight positions of the wireless sensor nodes in the abovementioned environment have been tested, tagging the most important parts that require parameters monitoring over

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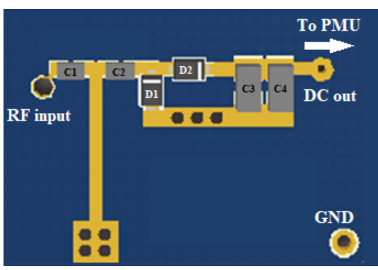
time, such as acceleration and temperature, that can be detected by the tag.

The presented system is going to operate in a harsh environment, also in terms of temperature. The main components of the prototypes offer storage and operating temperatures high enough (i.e., MAX2750 oscillator storage temperature: 150°C; bq25570 operating temperature: 125°C), whereas others (i.e., SE2598L amplifier) recommend operating temperature conditions below 85°C. For this reason, both the illuminators and the tags will be included in cases made of thermoplastic materials characterized by low thermal conductivity (*k*), e.g. PU (Polyurethane) or ABS (Acrylonitrile Butadiene Styrene), whose *k* are 0.025 and 0.25 W/(m·K), respectively, in order to minimize the circuits heating.

Moreover, the illuminators and the tags are subject to vibrations that have to be considered in real scenarios: however, they result to bring about negligible changes on the overall system operations.

In Table 1, the minimum distance of the sensors from the illuminators and the mean rectified output power (P_{out}) are reported: these power values allow the capacitor to charge between few seconds and about four minutes, in the worst case.

For what concerns the harvesting part of the battery-less node, a full-wave rectifier has been adopted, with a voltage doubler (two Skyworks SMS7630-079LF diodes, D1 and D2) and a matching network consisting of one 0.3 pF capacitor (C1), and a shorted stub (width: 0.51 mm; length: 5.70 mm) instead of a lumped component to reduce losses, as depicted in Fig. 5.



Component	Value
C1	0.3 pF
C2	20 pF
C3	10 pF
C4	10 pF
L_{stub}	5.70 mm
W_{stub}	0.51 mm

Fig. 5. Layout of the full-wave rectifier designed for the battery-less nodes.

Table 1. Mean harvested DC power, and distance from the closest illuminator for eight sensors placed in correspondence of parts of the engine compartment.

Monitored Part	Mean P_{out} at the Rectifier	Illuminator Min. Distance
Battery	240 μW	28 cm
Engine Head	1320 μW	20 cm
Engine Support	83.1 μW	42 cm
Radiator	133.7 μW	39 cm
Air Filter	61 μW	20 cm
Hydraulic Oil Tank	55.3 μW	36 cm
Fuse Box	170.3 μW	36 cm
Radiator Fan	40.8 μW	54 cm

With respect to the estimated results (corresponding to the available power at the tag antenna location, thus not taking into account the rectifier efficiency), the measurements are in good agreement: in particular, it is worth noting that the real (more complex) scenario allows to increase the power budget of the most critical positions, thus assuring the feasibility of the proposed energizing approach.

In Fig. 6, one out of eight tested scenarios is shown, with highlighted the two illuminators and the sensor node placed over the engine support.

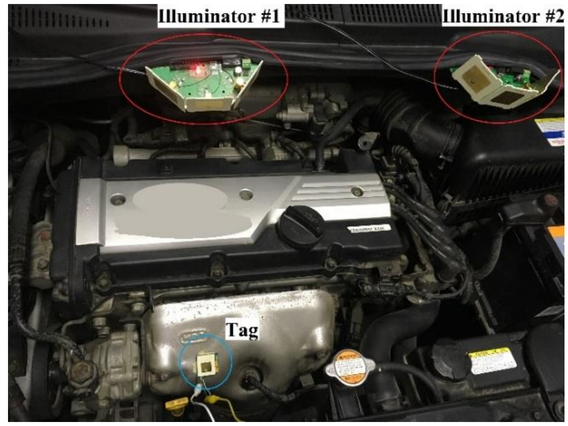


Fig. 6. Front view of the environment under test. The two RF illuminators and the sensor placed at the base of the engine are represented.

IV. Conclusion

In this work, a novel WPT system at 2.4 GHz for specific automotive applications has been developed and tested.

The RF source, named illuminator, has been designed with three CP patch antennas in order to cover approximately a 170°-aperture. Its position has been determined by means of Integral Equation solver-based simulations assuring accurate results within a reasonable time.

A measurement campaign was conducted in a real car engine compartment scenario and demonstrated the effectiveness of the whole WPT system, with available DC power and storage capacitor charging times adequate for the requirements of the proposed monitoring system for automotive applications.

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