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This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:
Paolini, G., Fazzini, E., Trovarello, S., Amato, D., Masotti, D., Costanzo, A. (2024). An Innovative Multi-Port LoRa-Based Wireless Node for Railway Signaling and Positioning. IEEE JOURNAL OF RADIO FREQUENCY IDENTIFICATION, 8, 618-626 [10.1109/JRFID.2024.3411814].

Availability:
This version is available at: https://hdl.handle.net/11585/974100 since: 2024-07-10

Published:
DOI: http://doi.org/10.1109/JRFID.2024.3411814

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19 February 2025

An Innovative Multi-Port LoRa-Based Wireless Node for Railway Signaling and Positioning

G. Paolini, *Member, IEEE*, E. Fazzini, S. Trovarello, *Graduate Student Member, IEEE*, D. Amato, D. Masotti, *Senior Member, IEEE*, and A. Costanzo, *Fellow, IEEE*

***Abstract*—This work presents the design and validation of a compact wireless system, adopting a modular wireless system composed of three co-located antennas operating in the 2.4 GHz band. The system is designed to be exploited for positioning purposes in secondary railway lines where the European railway traffic management system (ERTMS) is not available. An omnidirectional antenna, cross-polarized with respect to the other two, is used for transferring positioning data among the train and intelligent poles placed along the railway, while two directional radiating elements are arranged back-to-back, to perform wagon-to-wagon communication for train integrity purposes. The omnidirectional antenna has a radiation efficiency of 97.8% and a gain of 4.2 dBi, whereas the directive ones have 79.3% and 5.4 dBi, respectively. The data communication is established by using LoRa systems, enabling low-power, long-range communication with acceptable latency for the application purpose. Due to possible adverse environmental conditions, such as presence of dust or ice, a suitable enclosure of the system is designed to be as much as possible electromagnetically transparent. The whole system has been tested both in laboratory environment and on board of the moving train, inside and outside the wagon, demonstrating the successful communication between wagons and with the poles located along the railway. The highest bit error rate monitored was $2.08\cdot10^{-4}$ in the worst testing configuration.**

***Index Terms*—antennas, bit error rate, ERTMS, localization, LoRa, packet error rate, positioning, railway, RFID, train integrity, transportation.**

I. Introduction

THE railway security and monitoring issues have always been one of the most challenging topics in the transportation sector. Innovative solutions based on wireless technologies are currently being investigated to provide agile and secure solutions to the problems of train integrity and localization. Some recent examples are the use of the global navigation satellite system (GNSS) which has been recently assessed with the aim of facilitating the detection of virtual balises [1], and it has been adopted inside the European railway traffic management system (ERMTS). In Fig. 1, a schematic representation of the ERTMS terrestrial architecture is shown, which ensures all trains to be consistently and reliably self-monitored by sending data about their integrity [2], [3], and instantaneous positioning [4], [5]. Recently, an innovative alternative use of the GNSS system has been demonstrated combining satellite communication with live data retrieved from kinematic sensors, such as the trains' current speed [6].

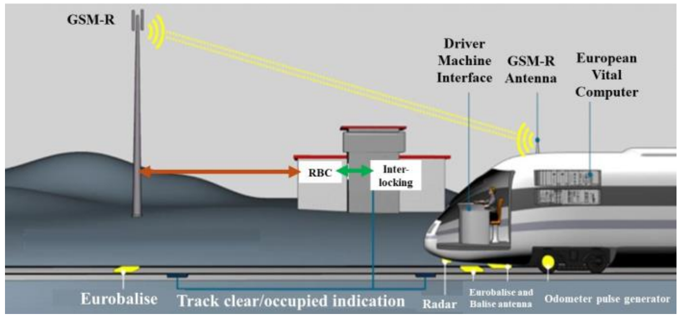


Fig. 1. Current scenario for high-speed networks for railway signaling and positioning following the European railway traffic management system/European train control system (ERTMS ETCS), denoting with GSM-R the global system for mobile communication in railways, and with RBC the radio block center.

Other interesting solutions to improve efficiency, reliability, and security of GNSS-based train localization systems are reported in [7], [8], where localization data coming from GNSS are combined with inertial navigation systems, with the manifold goal of enabling redundancy by using on-board sensor data to increase positioning accuracy and detecting GNSS signal faults.

Without dwelling on satellite communications, solutions able to be applied in the railway sector can be restored from the vehicle-to-everything (V2X) world for localization and train integrity. Researchers have been working with different wireless communication technologies for defining a reliable architecture for various applications in the field of V2X communication, such as Long Range (LoRa), Zigbee, Wi-Max, and 4G. In [9], an analysis of every wireless communication protocol has been conducted, highlighting LoRa as one of the most promising technologies in intelligent transportation systems due to its long-range and low-power properties. Despite the increasing popularity of research in LoRa, little is known about its performance when it is involved in V2X communication scenarios. In [10], several

This work has been partly funded by the European Union and the Italian Emilia-Romagna Region through the POR-FESR 2014-2020 project entitled "Innovativo Sistema di Segnalamento Ferroviario".

Giacomo Paolini, Enrico Fazzini, Simone Trovarello, Diego Masotti, and Alessandra Costanzo are with DEI "Guglielmo Marconi", University of Bologna, 40136 Bologna, Italy (e-mail: giacomo.paolini4@unibo.it, enrico.fazzini2@unibo.it, simone.trovarello2@unibo.it, diego.masotti@unibo.it, alessandra.costanzo@unibo.it). Davide Amato is with Sadel S.p.A., 40013 Castel Maggiore (Bologna), Italy (e-mail: davide.amato@sadel.it).

LoRa schemes with different parameter configurations have been selected and then their bit error rate (BER) performance has been simulated under a typical V2X communication scenario, showing that this protocol presents the potential to satisfy the growing demand for the longer range and larger amount connectivity in vehicular communication networks. To overcome the limit of the simulation, in [11] a real-world scenario has been evaluated to propose a low-power and reliable architecture with LoRa and evaluate it with vehicles on the move. In [12], the first tentative utilization of the LoRa protocol in the railway sector has been presented, with the aim of creating high-speed channels that allow communication between the moving LoRa gateway on the train with sensors and devices distributed along the railway road.

LoRa performance has been extensively characterized in different harsh conditions, such as the movement of the devices during its operation. In [13] and [14], the feasibility of the adoption of the LoRa protocol in V2X communications is reported. Literature demonstrated how LoRa technology exhibits significant versatility across various applications such as enhancing traffic safety, facilitating vehicle networking, and controlling area networks. Moreover, its affordability in hardware makes it a practical and potentially widespread solution for implementation at scale. Due to the outdoor positioning of the devices, also the feasibility of the 2.4 GHz radio link in harsh weather conditions needs to be taken into account. In [15], the correlation between meteorological factors and the performance of the 2.4 GHz network is reported. It is also reported that, although the performance of the radio link is influenced by different weather conditions, the choice of the 2.4 GHz operating frequency remains a valid alternative to the more classic operating frequencies, such as 433 or 868 MHz.

Moreover, recently the low-power communication protocol LoRa has been demonstrated to successfully support real-time kinematic (RTK) messages broadcasting to numerous linked devices, to provide high-accuracy localization data while simultaneously constraining power consumption [16].

In [17], an antenna system design, consisting of three co-located antennas has been presented, to be combined with such low-power nodes. In this work, this system has been experimentally tested and adopted as the radiating front-end inside a novel, stand-alone wireless network architecture for wagon-to-wagon and wayside railway communications. The goal is to enable simple, low-cost, and accurate solutions for monitoring train integrity and train positions in secondary railways, which are not equipped with GNSS and ERMTS architectures. In Section II, the network architecture is described, and the targeted scenarios are considered. Section III contains an extensive numerical and experimental characterization of the three-element antenna system, both in free-space conditions and accounting for environmental conditions, including the presence of large metal obstacles representing the train wagons, together with the design of an ad-hoc plastic case. Section IV is dedicated to the LoRa network characterization and describes the results obtained during realistic measurement campaigns, carried out with the train moving in a secondary railway path. Section V contains the conclusions on the proposed solution which turns out to be an excellent compromise between the required need for localization accuracy, security level, and essentiality of the sensors on board the train and along the railway tracks.

II. LoRa Network Architecture: Wagon-Wagon and Wagon-Poles Network System Architectures

Considering the Italian situation, only about 1000 km (4.8% of the total) are covered by a high-speed network exploiting ERTMS ETCS Level 2 (Fig. 1) as a command control system, and radio block center (RBC) for train spacing. This is mainly due to the high costs correlated to the installation, management, and maintenance of these kinds of lines. For this reason, it is increasingly urgent to monitor and preserve the subsidiary, low-traffic lines with unexpensive and robust solutions able to guarantee a reliable localization of all the trains along the railways, thus their spacing.

The goal at the basis of this project is to design a network architecture which is able to provide a precise tracking of the trains along secondary lines, and at the same time looking for their integrity. In that sense, the envisioned scenario previews the adoption of low-power and low-cost sensor nodes placed on each train's wagon and on intelligent poles that are placed wayside on single-tracked railway lines every 250 m.

As regards the current designed study (Figs. 2, 3), the convoy can consist of a number of wagons ranging from one to four. Further studies will be carried out for longer trains (up to ten wagons). The length of the considered railway is about 30 km, with the possibility of placing an intelligent pole every 250 m, thus with the presence of 120 poles for localization, each equipped with the same node of the wagons. The key idea is to allow two or more trains to run simultaneously on the same secondary railway, differently from now due to the lack of information coming from these trains regarding their precise localization.

Thanks to the low power consumption and robustness given by its intrinsic high sensitivity (detectable input signal levels as low as −129 dBm), the LoRa protocol operating at 2.4 GHz has been chosen to support communication between the wagons, for train integrity purposes (Network 1), between the train and intelligent poles placed along the railway (Network 2A), and between different types of intelligent poles (Network 2B) for localization purposes.

To ensure train integrity, the primary goal of Network 1 (Fig. 2) is to provide communication across wagons in the same train. The first wagon in the train will have a LoRa node installed, acting as a "Master", and all the other carriers will be recognized as "Slaves". The industrial, scientific, and medical (ISM) band, here at 2.4 GHz, is the selected operating band for the operations of the LoRa protocol; this choice has been made to limit the overall dimensions of the prototype, and in particular of its radiating elements. Despite the fact that electromagnetic (EM) waves at this frequency are subjected to a more severe path loss with respect to protocols employing lower frequencies, such as 433 or 868 MHz,

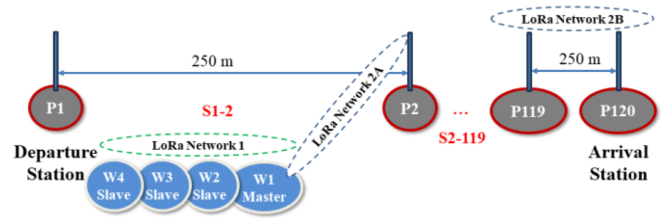


Fig. 2. Schematic diagram for the architecture of Network 1, 2A, and 2B in normal conditions.

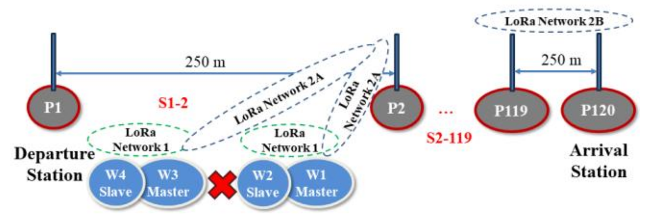


Fig. 3. Schematic diagram for the architecture of Network 1, 2A, and 2B in case of train integrity loss between W2 and W3, with consequent generation of a new Network 2A with two Masters.

for the presented application the predicted signal-to-noise ratio (SNR) is as high as 30 dB, as it has been demonstrated by the measurements reported in Section IV; thus, there are no problems with the demodulation of the signals since LoRa can also demodulate signals which are –7.5 to –20 dB below the noise floor.

Regarding Network 1 radiating elements, each wagon will be equipped with two horizontally polarized directive patch antennas (ports P2 and P3 in Figs. 4(b, c)), labelled WWDAs (Wagon-Wagon Directive Antennas); the first is used for communication with the preceding wagon, and the other with the following one. The antennas can be placed either inside the train or outside it.

Network 2A involves the communication of the Master device located inside the train (W1) with the type-A intelligent poles, which are also equipped with a LoRa node, for the purpose of locating the train (Fig. 2). Since the direction of the train is not known a priori, it is necessary to equip both devices with omnidirectional antennas (Port P1 in Fig. 4(b)) guaranteeing adequate communication in terms of BER, for example keeping this value below 10^{-3}.

In this case, a monopole antenna (vertically polarized, and cross-polarized with respect to the WWDAs) which presents an omnidirectional radiation pattern in the *xy* plane (see reference axes in Fig. 4(b)), named WPOA (Wagon-Pole Omnidirectional Antenna), will be adopted and will work in the same LoRa band of the aforementioned Network 1 antennas.

This architecture foresees, in case of loss of train integrity condition, that the first wagon of the detached convoy will assume the role of Master and will communicate itself with the intelligent pole. As an example, presented in Fig. 3, the separation between W2 and W3 is considered. In this scenario, W3 and W4 will be separated from the original Master device placed in W1; therefore, W3 will take on the role of Master for the second convoy and will communicate itself with the type-A intelligent poles.

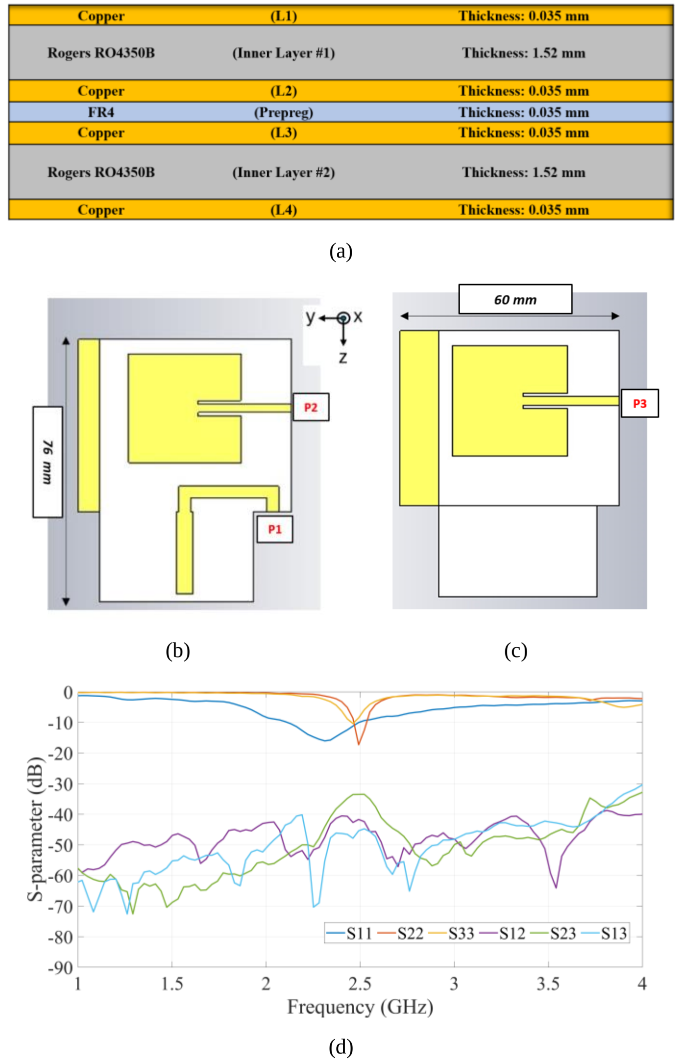


Fig. 4. (a) Stack-up of the prototype; layout of the (b) front and (c) back layers; (d) measured S-parameters of the multi-antenna prototype in free space.

Finally, Network 2B involves communication between type-A and type-B intelligent poles. For this network, it was chosen to adopt an omnidirectional antenna (as in the case of Network 2A) for the type-A intelligent poles, and a directive one for the type-B intelligent poles (which are conveyors of information coming from a number of type-A poles, and are typically positioned near the stations), given that they will always have to receive/send information from/to type-A poles whose location is known. However, it is foreseen the possibility for the same type-B intelligent poles to communicate with the wagons of a convoy when the train is in the station and the type-B pole is the closest pole to the train.

III. Tri-Port Antenna Design and Evaluation of Possible Adverse Environmental Conditions

A. *Tri-Port Antenna Prototype Design*

For the multi-port LoRa transceiver, a double-layer stack-up with dimensions of 76 mm x 60 mm has been derived on a Rogers RO4350B substrate (ε_r = 3.66, thickness: 1.52 mm), as illustrated in Fig. 4(a). The radiating elements are arranged in two layers: the top layer displays the WPOA (monopole antenna, Port 1: P1) and the first of the WWDA (patch antenna, Port 2: P2), while the bottom layer contains the second WWDA (patch antenna, Port 3: P3). Figs. 4(b) and 4(c) show the front and bottom views, respectively. To connect the two Rogers laminates, a prepreg of FR4 having a thickness of 35 μm has been adopted.

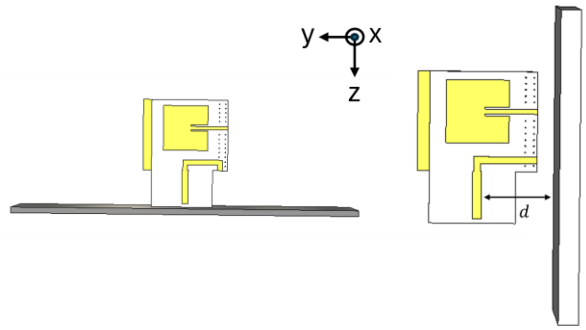
To verify the design and the simulations performed using the EM simulation software Computer Simulation Technology (CST) Microwave Studio, an S-parameters characterization and radiation patterns measurements have been conducted in free space and are reported in [17]. It is worth noting that the back-to-back arrangement of the two patch antennas (P2 and P3) has been chosen in order to maximize the decoupling between the two horizontally polarized antennas that are working at the same frequency; in fact, the maximum measured value of the S_{23} transmission coefficient resulted to be equal to –33 dB at 2.46 GHz (see Fig. 4(d)).

B. *Positioning of the Prototype near Metal Plates*

Given the application, it results mandatory simulating the radiating architecture in a real environment, for considering undesired and unwanted effects or performance dropping. As can be supposed, the tri-ports module working at 2.45 GHz with LoRa protocol is intended to operate outside of the moving train, for obtaining the best scenario in terms of line-of-sight (LoS) both for the elements of Network 1 (WWDAs) and Network 2 (WPOA). On the other hand, the environment where the module is located influences the performance of the module itself. The most disturbing element that can interfere with the ideal behavior of the radiating elements is the presence of metallic plates emulating the wagons of the train. A strong and invasive effect is expected most of all on the performance of the monopole antenna given its ungrounded nature. On the contrary, the patch antennas are expected to be less influenced by the wagon's walls, given the presence of metallic ground that behaves as a shield, offering a more robust solution.

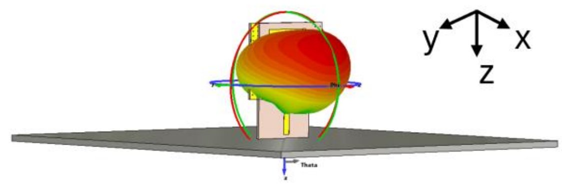
To estimate the effect of this phenomenon qualitatively and quantitatively, simulations of the tri-ports antenna module considering the presence of metallic layers replicating the behavior of the walls of the wagon, have been performed. A plate realized in perfect electric conductor (PEC) of 120 x 120 x 4 mm^3 has been considered in two operating conditions, presented in Figs. 5:

1. Considering the module placed on the top of the wagon, therefore with the plate below it, as depicted in Fig. 5(a).
2. Considering the module placed on the lateral wall of the wagon, therefore with a plate next to it, as depicted in Fig. 5(b).

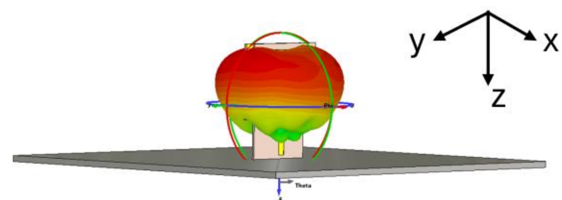


(a) (b)

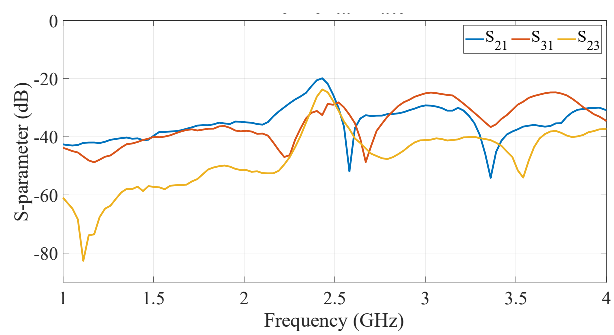
Fig. 5. (a) Simulation setup with the module on the top of the wagon; (b) simulation setup with the module next to the wagon.



(a)



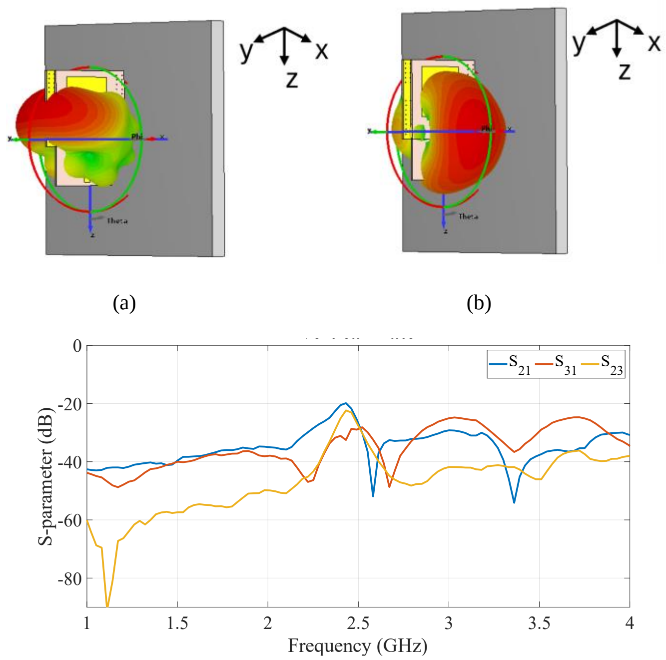
(b)



(c)

Fig. 6. Tridimensional radiation surfaces (realized gain) of (a) P2 and (b) P1, and (c) measured transmission coefficients for the prototype placed on the top of the metal plate.

The results of the simulation for the patch antennas (WWDAs) of Network 1 show that the presence of the PEC plane deflects the maximum of the radiation surface, presented in Fig. 6(a), of 30° in elevation in a direction opposite to the metal plate, with a radiation that presents a maximum gain of 8 dBi and 50° of half power beam width (HPBW), offering therefore an efficient solution for train integrity; since in broadside (where in LoS condition the link is established) the gain results approximately 5.3 dBi, hence higher than the ideal case presented in [17].



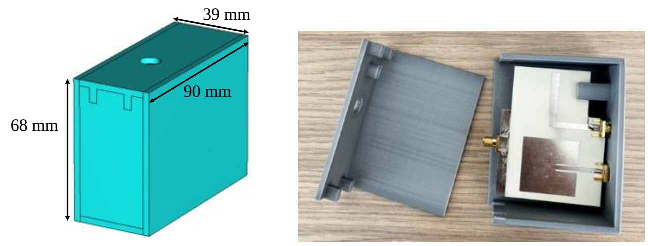
(a) (b) (c)

Fig. 7. Tridimensional radiation surfaces (realized gain) of (a) P1 and (b) P2, and (c) measured transmission coefficients for the prototype placed alongside the metal plate.

On the other hand, the presence of the PEC layer majorly influences the performance of the monopole, eliminating the radiation in the half-space below the plate, obtaining a maximum realized gain of 5.7 dBi with a deflection of 40° in the elevation plane and a HPBW of 43°. This is still an efficient solution since this antenna communicates with intelligent poles whose antennas are positioned at higher heights than the top of the wagons. The radiation surface (realized gain) for the WPOA is presented in Fig. 6(b).

Several configurations based on the distance *d* of the module from the lateral wall of the wagon have also been tested, since, especially for the monopole antenna, the presence of a PEC plate parallel to the vertical axis of the WPOA could represent a very important disturbance if not correctly positioned. As it is known from the EM theory, it has been verified that the best setup and performance occurs when this distance is fixed to a quarter of wavelength ($d = \frac{\lambda_0}{4}$) such that the wall behaves as a perfect reflector halving the radiation pattern of the WPOA in the useful half-plane where the link is meant to be established. The radiation surface, presented in Fig. 7(a), presents a deflection in the elevation plane of approximately 30° (particularly useful considering the nature of Network 2), with a maximum gain of 8.8 dBi and a HPBW of 44°.

The results of the simulation for the patch antennas of Network 1 show that the PEC plane does not affect their 3D radiation pattern, presenting a standard radiation orthogonal to the patch plane with a maximum gain of 6.3 dBi and HPBW of 97°, as shown in Fig. 7(b).



(a) (b)

Fig. 8. (a) 3D view of the simulated case with its dimensions, and (b) photo of take apart fabricated prototype.

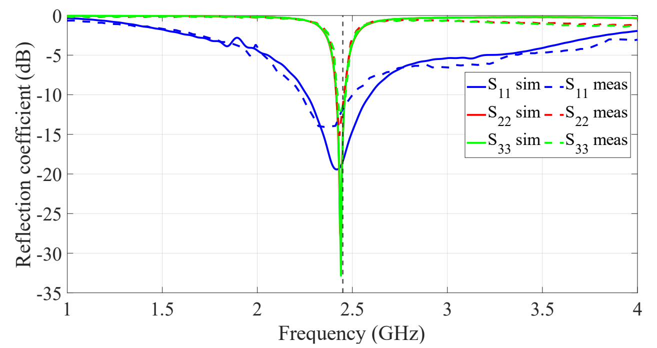


Fig. 9. Comparison between simulated and measured reflection parameters of the tri-port antenna system protected by the PLA-case.

Comparing the two solutions, a partial conclusion can be drawn. Speaking about the WWDAs, responsible for the train integrity whose link foresees two directional patch antennas one in front of the other, the best solution is represented by placing the module laterally with respect to the wagon wall, since the radiation presents a broadside characteristic with higher gain if compared to the other solution in the same direction. For what regards the WPOA, responsible for the connection with the intelligent pole whose position is higher than the wagon, efficient and robust solutions have been found in both cases, with higher flexibility in the first configuration, since the connection can be established on the left and the right with respect to the train running direction, whereas when the module is placed on the lateral wagon wall it can speak with the devices located only in one half-space. However, for ease of installation, configuration 2 has been adopted, and the corresponding on-field measurements will be provided in Section IV.

C. *Design of the Plastic Case and Weathering Impact*

Given the outdoor positioning of the antennas, atmospherically agents such as rain, dust, and ice can impact the performance of the antenna system, resulting in a degradation of the matching between the antennas and the LoRa device and/or a degradation of the radiating patterns of the modular tri-antenna. For this reason, a plastic case is adopted to protect the antenna system.

The protective cover is made of polylactic acid (PLA), a material often used in 3D printing. For case prototyping, the Ultimaker 3 Extended 3D printer has been used. The EM characteristics were characterized using the T-resonator technique [18] from 10 kHz to 6 GHz. The EM simulations of the case use a dielectric constant ε_r of 2.64 and a *tan(δ)* of 0.018 at 2.4 GHz. The case design was performed while enclosing the 3-port antenna system: for this reason, different PLA thicknesses were analyzed: a 3 mm thickness was chosen to provide adequate mechanical robustness and low impact on the radiation properties of the antenna system. The case has been designed in such a way that it can be opened and closed through interlocking joints and three holes have been prepared for the insertion of RF cables for the correct connection of the antennas to the LoRa device.

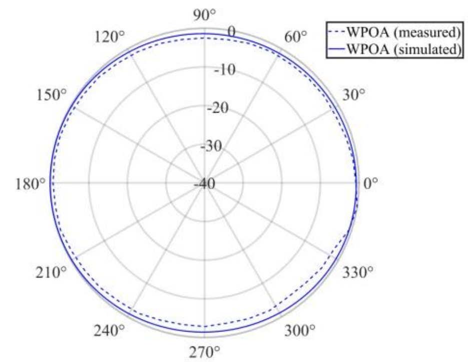
Figs. 8 show the 3D view of the simulated PLA-case and the fabricated one by means of 3D printing techniques. The total dimensions of the case are 68 x 90 x 39 mm^3, and guarantee the correct protection of the antenna, leaving the performance of the system unchanged.

The antenna placed inside the fabricated case is measured using the Agilent N9923A FieldFox vector network analyzer (VNA) and Fig. 9 shows the comparison between the EM-simulated and the measured results in these conditions.

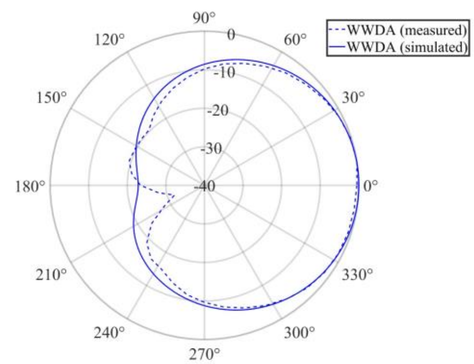
Measurements show a small difference between the experimental patch antenna reflection coefficient and the simulated one, with a measured peak of –14 dB at 2.45 GHz, while the monopole antenna is more affected by the presence of the case. In fact, the peak of the reflection coefficient undergoes a shift of approximately 140 MHz, while still maintaining return loss values greater than 10 dB in the band of interest. Similar consideration can be made for the tri-port transmission coefficients, which are not shown for brevity's sake. A small variation in the gain of the three antennas is observed between the case-free system and the protected antennas. In particular, 0.2 dB and 0.4 dB of degradation occur for the WPOA and WWDA, respectively.

The radiation patterns of the three antennas have been measured in free space and the normalized radiation patterns for the WPOA (Port 1) and WWDA (Port 2) are presented in Figs. 10 and compared with the simulated results. The maximum realized gain of the WPOA is 4.2 dBi for an elevation angle of 25° with respect to the *xy* plane, whereas for the WWDA is 5.4 dBi in the broadside direction.

In order to further validate the correct design and functioning of the case made of plastic material, an analysis in presence of different types of atmospheric agents is taken into consideration. The strong impact on the case-free antenna behavior of external agents has been discussed in [17], where the need for a protective case has been raised. Here, it is assumed that the modular tri-antenna system inside the plastic case must be used both in conditions where dust settles on the carriage and in extreme winter conditions, where several millimeters of ice can be deposited on the case. Both the dust and ice electrical properties are extracted from the literature [19], [20].



(a)



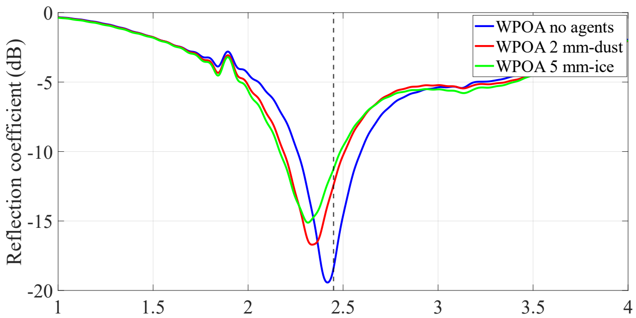
(b)

Fig. 10. Normalized radiation patterns of (a) WPOA (for an elevation angle of 25° with respect to the *xy* plane) and (b) WWDA (in the *xy* plane).

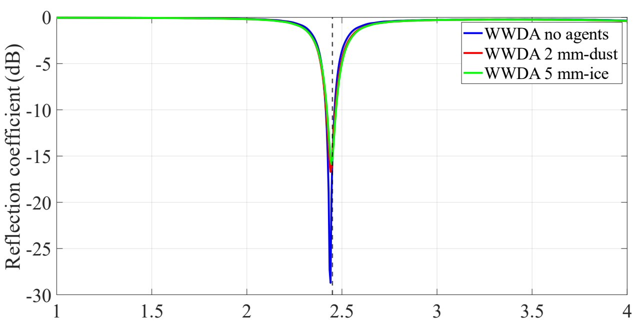
In particular, the adopted dust complex permittivity (at 2.45 GHz) is 4.4–j·0.204, whereas the complex permittivity of fresh ice used for EM simulations is 3.31–j·0.11. Figs. 11 shows the simulated comparisons between the modular system with PLA case with and without dust or ice deposited. The thickness of the dust and ice accumulations are set to 2 mm and 5 mm respectively, to recreate a realistic scenario where the antenna module is positioned outside the train wagons.

Simulations demonstrate how the designed case can limit performance degradation due to the accumulation of dust or ice resulting from atmospheric agents. For the omnidirectional antenna, a shift of the return loss peak from 2.42 GHz to 2.37 GHz is observed in the worst case (5 mm ice thickness), while maintaining good matching conditions (reflection coefficient of approximately –15 dB at 2.45 GHz).

Patch antennas are more robust to disturbances due to the accumulation of impurities on the surface of the case. In fact, the frequency shift is negligible, while a worsening of the minimum reflection coefficient, which shifts from –28 dB to –15 dB, is detected at the working frequency of 2.45 GHz.



(a)



(b)

Fig. 11. (a) Reflection coefficient of the monopole antenna, and (b) reflection coefficient of the patch antennas, whether there are dust or ice agents deposited on the surface of the case.

Comparable analysis can be conducted for the tri-port transmission coefficients; however, they are excluded for brevity reasons. The gain performance reports a slight decrease as the thickness of snow or ice accumulation varies. The worst case is observed when the accumulation of ice is equal to 5 mm, for which the simulated patch antennas report a decrease in the main lobe gain equal to 0.52 dB, compared to the situation without accumulation of weathering agents on the antenna's case.

IV. Validation Measurements of the Prototype on Board the Train

At the end of the design and simulation phases, an experimental measurement campaign was conducted using the tri-port module for both Network 1 (wagon-to-wagon communication) and Network 2 (type-A intelligent pole-train communication). The setup consists in using the antennas for Network 1 and 2 as transmitters and receivers, both connected to LoRa modules (two end-devices working at 2.45 GHz, one of which acts as a Gateway) for the evaluation of the received signal strength indicator (RSSI) values at different distances and considering different environmental conditions.

The measurements were conducted on the Modena-Sassuolo railway line, and in particular, the Modena-Formigine sub-section was considered.

Fig. 12. Positioning of the 2.45 GHz antenna module with PLA case outside the cockpit.

The train on which the tests were conducted is the Pop model, an electric train built by Alstom Ferroviaria, with 3 wagons for a total length of approximately 75 meters. In order to characterize the behavior of Network 1 antennas, during the first Modena → Formigine run, two prototypes (equipped with case) were positioned outside the window of the front and rear cockpit (Fig. 12), to test the feasibility of train integrity in the worst case (3 carriages, approximately 75 m). The devices themselves are continuously connected to a DC power supply guaranteed within the train.

The measurements highlighted the feasibility of this connection: in fact, during the measurement, which lasted approximately 29 minutes, 276 packets were detected with an average RSSI of –69.1 dBm and a loss of 3 packets.

The first return journey Formigine → Modena was always dedicated to verifying the possibility of guaranteeing communication between different carriages, but inside the compartments and with the presence of passengers.

To this end, three different application scenarios were evaluated, which proved to be feasible to guarantee the integrity of the train:

1. Remote connection with a 3-wagon distance: measurement duration: 260 seconds, 49 packets detected, 2 packets lost, average RSSI: –84.8 dBm.
2. Remote connection with a 2-wagon distance: measurement duration: 198 seconds, 50 packets detected, 0 packets lost, average RSSI: –77.2 dBm.
3. Remote connection with a 1-wagon distance: measurement duration: 197 seconds, 51 packets detected, 0 packets lost, average RSSI: –58.3 dBm.

To characterize the behavior of the Network 2 communication, during the second Formigine → Modena trip, the 2.45 GHz antenna module of the Gateway was positioned outside the front cockpit window, while the end-device with the relevant antennas (including the Network 2 monopole) was fixed to a pole at a height of 2 meters at Baggiovara station, in order to test the possibility of train communication with a type-A intelligent pole. Measurements have highlighted the possibility of receiving packets sent by the Gateway up to a

TABLE I
AVERAGE RSSI, SNR, PER, AND BER FOR NETWORK 1 WITH DIFFERENT LINK CONDITIONS

Communi-cation Link	Antennas Position	Average RSSI (dBm)	SNR (dB)	PER	BER
Network 1 (3 wagons)	Outside Train	–69.1	50.9	0.0109	$5.69 \cdot 10^{-5}$
Network 1 (3 wagons)	Inside Train	–84.8	35.2	0.0392	$2.08 \cdot 10^{-4}$
Network 1 (2 wagons)	Inside Train	–77.2	42.8	0	0
Network 1 (1 wagon)	Inside Train	–58.3	61.7	0	0

distance of about 350 meters between the driving cab and the pole positioned in the station, with a minimum received RSSI of –86 dBm both far from the station and in approaching it, and with an average RSSI of –58.9 and –56.7 dBm, respectively, detected during the train's run.

Table 1 reports the summary of the abovementioned measurements with the indication of packet error rate (PER) and BER calculated as follows:

$$BER = 1 - (1 - PER^{1/n}) \quad (1)$$

where n is the number of bits per packet (here, 192); each packet includes a 4-byte payload and an overhead due to addressing (12 bytes), preamble, and LoRa synchronism. In this case (spreading factor: 12; bandwidth: 200 kHz; coding rate: 4/5), time on air for each packet resulted to be 690.64 ms.

Moreover, in Table 1 the SNR values for the presented measurements are reported, considering a typical noise floor of –120 dBm for the employed device (Semtech SX1280).

The morphology of the terrain during the trip was entirely flat, and a maximum speed of 59 km/h was reached by the train. The average speed, considering only the sections where the train is detected in motion, resulted to be 21.8 km/h. Three different environments have been considered during the trip, i.e., urban area, extra-urban area, and tunnel; in that sense, Fig. 13 represents the RSSI retrieved with respect to the different environments that have been crossed by the train during the first run (antennas positioned outside the train with 3-wagon distance).

The results that have been achieved allow to affirm that it is possible to adopt this solution for train integrity, making the connection between wagons feasible without noticeable information losses, and placing the antenna module both inside and outside the train. Moreover, the distance covered by LoRa communication at 2.4 GHz for Network 2 (between trains and intelligent poles) is sufficient to establish a stable connection in case of poles spaced by 250 m, in order to precisely localize a convoy within a secondary line and to preview the possibility of locating more trains along the same railway.

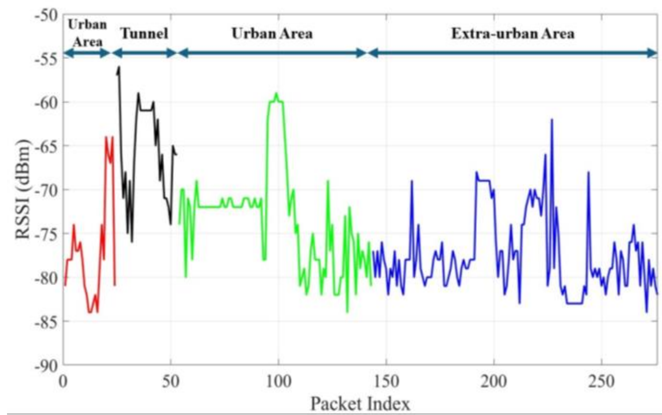


Fig. 13. Retrieved RSSI with respect to the different environments that have been crossed by the train, with the two modules placed outside it at a distance of about 75 m.

V. CONCLUSION

This work presented the design and characterization of an innovative and low-cost architecture designed for poorly equipped secondary railway lines, for train signaling and positioning purposes, and is based on the LoRa protocol at 2.4 GHz. The overall architecture of Networks 1 and 2 have been presented, intended for train integrity and localization purposes, respectively, and a modular system comprising of three different antennas has been conceived and realized. This allows each wagon to communicate with the previous and following one(s), as well as to establish a connection between the train and the intelligent poles up to a distance of 350 m. Also, several weather conditions have been considered, and for this purpose, an ad-hoc case in plastic 3D printable material has been conceived and realized to protect the antenna module against harsh environmental conditions.

REFERENCES

[1] O. G. Crespillo et al., "Local GNSS Threat Detection Methods for Virtual Balise Placement in Railway Applications," in *16th ITST*, Lisboa, Portugal, 2018, pp. 1-7.

[2] J. Mendizabal, J. Goya, G. De Miguel, L. Valdivia, S. Arrizabalaga, and I. Adin, "Virtual testing of the on-board ETCS with GNSS based Train integrity determination," in *15th ITST*, Warsaw, Poland, 2017, pp. 1-7.

[3] S. Oh, Y. Yoon, K. Kim, and Y. Kim, "Design of train integrity monitoring system for radio based train control system," in *12th ICCAS*, Jeju, South Korea, 2012, pp. 1237-1240.

[4] J. Liu, B. Cai, D. Lu, and J. Wang, "Integrity of GNSS-based Train Positioning: From GNSS to sensor integration," in *ENC*, Lausanne, Switzerland, 2017, pp. 48-56.

[5] S. Spinsante and C. Stallo, "Hybridized-GNSS Approaches to Train Positioning: Challenges and Open Issues on Uncertainty," *Sensors*, vol. 20, no. 7, p. 1885, Mar. 2020, doi: 10.3390/s20071885.

[6] D. Mikhaylov et al., "Toward the Future Generation of Railway Localization Exploiting RTK and GNSS," *IEEE Trans. Instrum. Meas.*, vol. 72, Art no. 8502610, pp. 1-10, May 2023, doi: 10.1109/TIM.2023.3272048.

[7] A. Schütz, D. E. Sánchez-Morales, and T. Pany, "Precise positioning through a loosely-coupled sensor fusion of GNSS-RTK, INS and LiDAR for autonomous driving," in *IEEE/ION PLANS*, Portland, OR, USA, 2020, pp. 219-225.

[8] Y. Zhou, Q. Chen, and X. Niu, "Kinematic Measurement of the Railway Track Centerline Position by GNSS/INS/Odometer Integration," *IEEE Access*, vol. 7, pp. 157241-157253, Oct. 2019, doi: 10.1109/ACCESS.2019.2946981.

[9] A. A. Brincat, F. Pacifici, S. Martinaglia and F. Mazzola, “The Internet of Things for Intelligent Transportation Systems in Real Smart Cities Scenarios,” in *IEEE 5th WF-IoT*, Limerick, Ireland, 2019, pp. 128-132.

[10] G Y. Li, S. Han, L. Yang, F. -Y. Wang, and H. Zhang, “LoRa on the Move: Performance Evaluation of LoRa in V2X Communications,” in *IEEE IV Symposium*, Changshu, China, 2018, pp. 1107-1111.

[11] K. F. Haque, A. Abdelgawad, V. P. Yanambaka, and K. Yelamarthi, “A LoRa Based Reliable and Low Power Vehicle to Everything (V2X) Communication Architecture,” in *IEEE iSES*, Chennai, India, 2020, pp. 177-182.

[12] J. Soares, M. Luís, and S. Sargento, “Mobile LoRa Gateway for Communication and Sensing on the Railway,” in *IEEE ISCC*, Gammarth, Tunisia, 2023, pp. 499-502.

[13] P. A. Torres, C. B. D. Silva, and H. T. Filho, “An Experimental Study on the Use of LoRa Technology in Vehicle Communication,” *IEEE Access*, vol. 9, pp. 26633-26640, Feb. 2021, doi: 10.1109/ACCESS.2021.3057602.

[14] J. Gozalvez, M. Sepulcre, and R. Bauza, “IEEE 802.11p vehicle to infrastructure communications in urban environments,” *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 176-183, May 2012, doi: 10.1109/MCOM.2012.6194400.

[15] D. Bri, M. Fernandez-Diego, M. Garcia, F. Ramos, and J. Lloret, “How the Weather Impacts on the Performance of an Outdoor WLAN,” *IEEE Commun. Lett.*, vol. 16, no. 8, pp. 1184-1187, Aug. 2012, doi: 10.1109/LCOMM.2012.060812.120090.

[16] P. Mayer, M. Magno, A. Berger, and L. Benini, “RTK-LoRa: High-Precision, Long-Range, and Energy-Efficient Localization for Mobile IoT Devices,” *IEEE Trans. Instrum. Meas.*, vol. 70, Art no. 3000611, pp. 1-11, 2021, doi: 10.1109/TIM.2020.3042296.

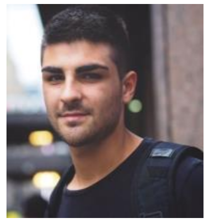
[17] G. Paolini, E. Fazzini, S. Trovarello, D. Amato, D. Masotti, and A. Costanzo, “A 2.4 GHz Modular Antenna System for Train Integrity and Localization Purposes,” in *IEEE 13th RFID-TA*, Aveiro, Portugal, 2023, pp. 221-224.

[18] A. Costanzo, F. Donzelli, D. Masotti, and V. Rizzoli, “Rigorous design of RF multi-resonator power harvesters,” in *EuCAP*, Barcelona, Spain, 2010, pp. 1-4.

[19] X.-Y. Dong, H.-Y. Chen, and D.-H. Guo, “Microwave and Millimeter-Wave Attenuation in Sand and Dust Storms,” *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 469-471, May 2011, doi: 10.1109/LAWP.2011.2154374.

[20] A. M. Semmling et al., “Sea-Ice Permittivity Derived From GNSS Reflection Profiles: Results of the MOSAiC Expedition,” *IEEE Geosci. Remote Sens. Mag.*, vol. 60, Art no. 4302416, pp. 1-16, 2022, doi: 10.1109/TGRS.2021.3121993.

Giacomo Paolini (Member, IEEE) received the M.Sc. Degree in Biomedical Engineering and the Ph.D. Degree in Electronics, Telecommunications, and Information Technologies Engineering from the University of Bologna, Italy, in 2016 and 2021, respectively. He joined the Interdepartmental Center for Industrial Information and Communication Technologies Research (CIRI ICT) of the University of Bologna as a research fellow within the EU-supported HABITAT (Home Assistance Based on the Internet of Things for the AuTonomy of everybody) project in 2016. He is currently working as a junior assistant professor at the Department of Electrical, Electronic and Information Engineering “G. Marconi” (DEI) of the University of Bologna. His research interests include microwave radar systems for biomedical applications, indoor positioning exploiting RFID technologies, far-field wireless power transfer (WPT), and simultaneous wireless information and power transfer (SWIPT) systems.



Enrico Fazzini received the M.Sc. degree in Telecommunications Engineering from the University of Bologna, Bologna, Italy, in 2020. He is currently pursuing the Ph.D. degree in Electronics, Telecommunications, and Information Technologies Engineering. In 2020, he joined the Department of Electrical, Electronic and Information Engineering “G. Marconi”, University of Bologna, as a Research Fellow within the framework of the PRIN WPT4WID (“Wireless Power Transfer for Wearable and Implantable Devices”) project. His research interests include the design of wireless power transfer systems operating at microwaves and millimeter waves with focusing on smart power transmitter, especially time modulated and frequency diverse arrays.

Simone Trovarello (Graduate Student Member, IEEE) received the M.Sc. degree in Electronics and Telecommunications Engineering from the University of Bologna, Cesena, Italy, in 2020. He is currently pursuing the Ph.D. degree in Electronics, Telecommunications, and Information Technologies engineering. In 2021, he joined the Department of Electrical, Electronic and Information Engineering “G. Marconi”, University of Bologna, as a Research Fellow with the EU Project “NANO-EH”. His research interests include energy harvesting at microwaves and mm-waves, ferroelectric materials for silicon-integrated reconfigurable applications, and non-invasive microwave sensors.

Davide Amato received the M.Sc. degree in electronics engineering and the Ph.D. in system engineering from the University of Bologna, Bologna, Italy, in 1998 and 2002, respectively. He is currently an employee at Sadel S.p.A., Bologna, Italy, a market leader company in passenger information systems (PIS), wireless and wired communication networks in the railway sector. His research work focuses on innovative technologies for the evolution of railway signalling, high accuracy/precision localization, LoRa and UWB wireless networks and cybersecurity. He is an active member of several IEC TC9 working groups, such as WG43 for Train Communication Networks (TCN), WG46 for On-Board Multimedia and Telematic Systems (OMTS) and PT63452 for the cybersecurity in railway applications.

Diego Masotti (Senior Member, IEEE) Diego Masotti received the Ph.D. degree in electric engineering from the University of Bologna, Italy, in 1997. In 1998 he joined the University of Bologna where he now serves as an Associate Professor of electromagnetic fields. From 2021 he has the role of coordinator of the Telecommunications Engineering Master Degree course. His research interests are in the areas of nonlinear microwave circuit simulation and design, with emphasis on nonlinear/electromagnetic co-design of integrated radiating subsystems/systems for wireless power transfer and energy harvesting applications. He authored more than 90 scientific publications on peer reviewed international journals and more than 190 scientific publications on proceedings of international conferences. Dr. Masotti is member of the IEEE MTT-25 Wireless Energy Transfer and Conversion Technical Committee and serves in the Editorial Board of Electronic Letters, of the Maximum Academic Press journal of Wireless Power Transfer, of IEEE Access, of the IEEE Journal of RFID, and is a member of the Paper Review Board of the main Journals of the microwave sector.

Alessandra Costanzo (Fellow, IEEE) is full Professor at the University of Bologna, Italy, since 2018. She is IEEE Fellow, class 2022, for contribution to "nonlinear electromagnetic co-design of RF and microwave circuits".

Her current research activities are dedicated to the design of entire wireless power transmission systems, for several power levels and operating frequencies. She has developed efficient design procedures based on the combination of electromagnetic and nonlinear numerical techniques, adopting both far-field and near-field solutions, thus creating the bridge between system-level and circuit-level analysis techniques of RF/microwave wireless links. She has accomplished this goal by means of a general-purpose approach combining electromagnetic (EM) theory, EM simulation inside the nonlinear circuit analysis, based on the Harmonic Balance Technique. She is currently the principal investigator of many research and industrial international projects at microwave and millimeter wave dedicated to Industrial IoT, and smart mobility. She has authored more than 300 scientific publications on peer reviewed international journals and conferences and several chapter books. She owns four international patents. She is past associate editor of the IEEE Transactions on MTT, of the Cambridge Journals IJMWT and JWPT. She is past Vice-President for publication of the IEEE CRFID and has been conference chair of EuMC 2022 and of IEEE WiSEE 2023. She is co-chair of the Steering Committee of the IEEE WPTCE. She is independent member of the Board of Directors of Rai Way S.p.A.