Novel Miniaturized Planar Low-Cost Multiband Antenna for Industry 4.0 Communications

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Abstract—This research presents a novel integrated multiband antenna system manufactured and tested for Smart Industries applications. The proposed system consists of a miniaturized planar antenna with multi-arms conceived to cover the most required frequency bands in industry 4.0 such as GPS Band, UMTS Band, ISM Band, LTE Bands, and WiMax Bands. The manufactured design was verified using Arduino programmable circuit board interfaced to SIM900 module and digital sensors for data collection. Depending on the commands received through the human machine interface (HMI) from the end-user, the developed algorithm within the Arduino controls the SIM900 to select the adequate wireless technology to transmit the data and thus reconfigures the antenna to radiate at the target frequency band. The proposed system is easy to deploy inside industrial machines and cost-effective for large scale use. The paper first introduces the main challenges and benefits of miniaturized low-cost antennas systems for Smart Industries and Internet Of Things. Further the parametric study and final dimensions of the design and simulation results are discussed. The proposed design is fabricated, and the measurements of the radiation pattern and return loss are performed. The antenna, with measured maximum gain up to $10\,\mathrm{dBi}$ and measured S_{11} up to $-20\,\mathrm{dB}$, exhibits excellent performance for all the frequencies required in Smart Industries such as $1.6\,\mathrm{GHz}$, $1.8\,\mathrm{GHz}$, $2.3\,\mathrm{GHz}$, $2.4\,\mathrm{GHz}$, $2.6\,\mathrm{GHz}$, $3.5\,\mathrm{GHz}$, and $5.8\,\mathrm{GHz}$. The proposed antenna system was implemented and tested inside an industrial machine for Yogurt and Milk production and compared to existing commercial solutions. This study shows that the proposed antenna system is suitable for smart factories since it is miniaturized for internal integration, and it has self-frequency-adaptation and low power consumption, allowing the end-user to remotely control and monitor machines and smart devices.

1. INTRODUCTION AND MOTIVATION

Advanced data transfer middle-ware is only one part of the chain in order to successfully transmit data. Another important aspect is the quality of the wireless communication channel. This quality is strongly influenced by external factors (e.g., environment that is shielding signals, other signals causing interference), but can be improved through optimized antennas that take into account the environment in which the constrained device will be deployed. One of the sectors that relies strongly on efficient wireless communication is Industry 4.0.

Nowadays, Optimized Industry 4.0 data transmission is one of the fundamental pillars with major importance to achieve a successful Industry 4.0 [1, 2]. The optimization of Industry 4.0 data transmission is a rough task as it requires antennas that are low cost (e.g., structure cost, power consumption) and efficient (e.g., total radiation efficiency) at the same time [3]. Most antenna technologies required for

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such systems are the IoT bands and 4G technology (e.g., LTE, WIMAX) [3]. The closeness of carrier frequencies shows how difficult is the designing of an antenna capable of working in each of those systems. Therefore, novel media devices need other technologies such as UMTS, LTE, and Wimax in order to send industrial data combined with other management data to backend-servers.

There has been recently important research progress about IoT antennas. An excellent comparison between microstrip patch, helical, and conical spiral antennas is developed in [4]. In [5], Zhou et al. designed a good multiband antenna that works for GSM, LTE, and UMTS, but the GPS band is missing, and the antenna cannot be implemented inside low profile machines. A miniaturized implantable array antenna was proposed in [6, 7], and both the array designs cover the GPS bands perfectly, but both designs do not cover LTE bands and present big size. Liu et al. proposed a miniaturized antenna for GPS applications in [8], but the proposed antenna is difficult to manufacture and does not cover UMTS or LTE bands. Also using a low profile miniaturized antenna in [9], the authors present a good antenna that covers LTE bands, but GPS band is not covered. In [9] a built-in antenna works perfectly in GPS and ISM band, and the antenna is built with complex materials. It is suitable for wearable devices such as smart watch.

We aim to design a low-cost integrated multiband antenna that operates in GPS1600, UMTS1800, LTE2300, ISM2400, LTE2600, WIMAX3500, WIMAX5800, and ISM5800. The antenna must exhibits excellent performance in terms of return loss, gain, and radiation patten inside the machine which will be deployed inside industrial machines (metallic structure) at all the specified frequencies.

Further, we explain and discuss parametric study of the proposed antenna and the influence of each parameter on the antenna performance in terms of return loss.

2. REQUIREMENTS AND SPECIFICATIONS

In this section, we introduce the specifications that our antenna must meet and the conditions under which it will be deployed.

2.1. Industry 4.0 Evolution and Standards

Industry 4.0 is the new generation of automation and data exchange in manufacturing technologies. It includes smart systems, the Internet of things, cloud computing, and cognitive computing [1]. Industry 4.0 is generally referred to as the fourth industrial revolution technology as shown in Figure 1.
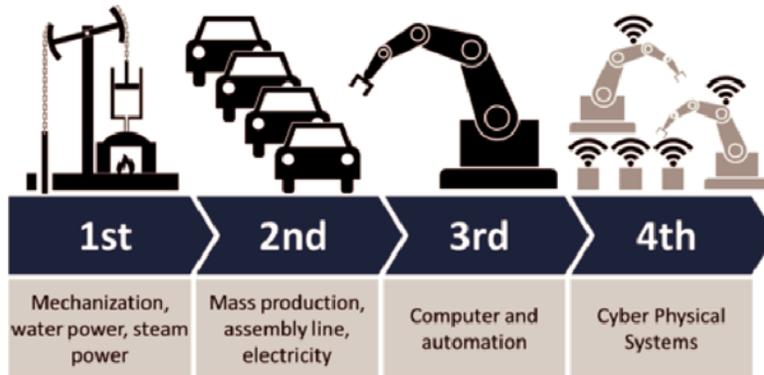
Figure 1. The evolution of the industries to Industry 4.0.

Industry 4.0 makes what has been called a "smart factory" possible starting from Industry 1.0 as shown in Figure 2. Contrary to classic automation systems which serves and works in the operational layer, the Industry 4.0 serves the manager and works in the management layer. Over the Internet of Things, it gives the manager real-time industrial data services.
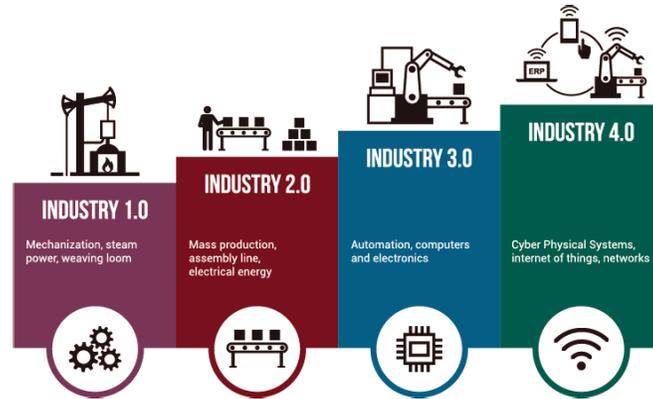
Figure 2. Internet of things in service of Industry 4.0.

2.2. Antenna Requirements

With numerous standards deployed in the market, spread over multiple frequency bands and using different communication protocols, choosing the right wireless connectivity technology for an IoT application can be quite challenging.

We aims to design a miniaturized antenna having a planar structure and easy to manufacture, such antenna is very suitable for small form-factor devices. The antenna should have cost as low as possible and easy to deploy inside the industrial machine intelligent component such as programmable logic controller (PLC). The antenna must fit inside the industrial machine presented as 3rd component in Figure 2. Implementing the antenna inside the machine protects the antenna from vandalism, but it makes the wireless communication much difficult within an industrial environment where the communication path is strongly influenced by the shielding of metal machines. Since the machine already contains conductive PCBs (such as PLCs, Servo-Drive, and other components), the antenna must be non-grounded to avoid interference and mutual coupling.

To ensure a general use case of the antenna, we select the famous common bands in which our terminal should radiate. The target bands are listed in Table 1.

Table 1. Frequency specification of the antenna.

Frequency (GHz)	Bandwidth (MHz)	Comments
1.6 GHz	1559 1610	GPS Band
1.9 GHz	1920 2170	UMTS Band
2.3 GHZ	2305 2400	LTE2300 Band
2.4 GHz	2400 2500	ISM2400 Band
2.6 GHz	2500 2690	LTE2600 Band
3.6 GHz	3605 3650	WIMAX3600 band
5.8 GHz	5750 5850	ISM5800 band
5.8 GHz	5725 5825	WIMAX5800 band

Regarding this frequency bands specification, the antenna will ensure the IoT data acquisition through the IoT band and the Data transmission through UMTS/LTE/WIMAX bands. The ISM bands can be used for local data transmission and enable the Internet Of Things (communication with other devices).

3. PROPOSED DESIGN

3.1. Configuration and Parametric Study

We start from a planar off-the-shelf antenna in order to obtain a low-cost design. We first design a simple dipole Figure 3 Arm (3) which ensures the WiMax band using the correlation between frequency and wavelength. Afterward we design the other arms step by step also based on wavelength and taking into account that each new arm must not interfere in terms of frequency band with the neighbor arm and must fit to the sizing specifications of the antenna. In each designing step, we observe and study the current distribution in each frequency in order to adjust and optimize the structure.

Figure 3 shows the four basic arms used in the conception of the design. Each arm coupled with another arm represents a target band, and in each step of the conception there are many simulations and iterations performed to obtain the best return loss. In Figure 4 we show the S_{11} result of each step and how the antenna resonates with each configuration. The final results show additional frequencies obtained due to the mutual coupling between the arms of the antenna. Configuration (a) refers to the coupling between Arm (1) and Arm (2), and it gives 1.6 GHz and 1.8 GHz bands, whereas Configuration (b) refers to the coupling of Arm (1) and Arm (3) ensuring 5.8 GHz band.
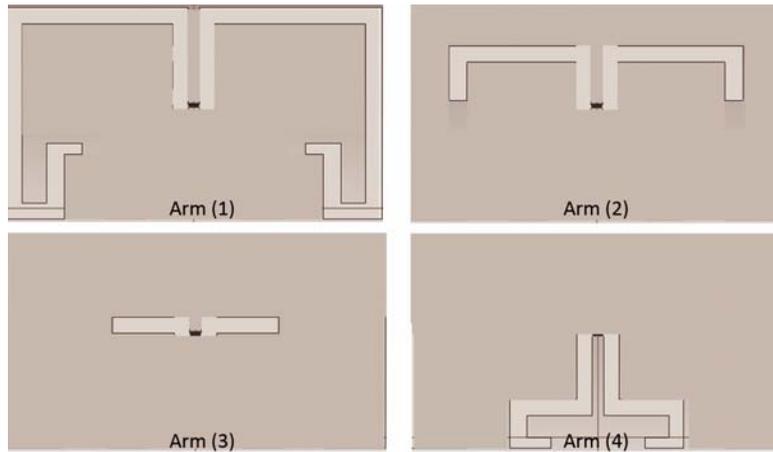
Figure 3. Design conception steps.
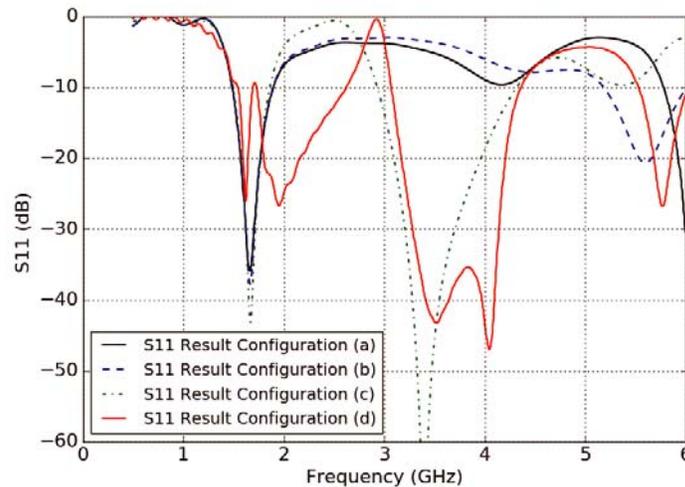
Figure 4. S_{11} simulation result for each configuration.

Configuration (c) is the coupling of Arm (1) and Arm (4) giving a wide band from 2.7 GHz to 4.5 GHz. Finally, Configuration (d) is the setup of all the Arms (1), (2), (3) and (4) as shown in Figure 5, giving an additional important band from 1.8 GHz to 2.7 GHz.

For all the simulations, we use the 3D finite-difference time-domain (FDTD) method as implemented in the software platform of the CST Studio.

3.2. Final Design

The final dimensions of the proposed antenna are $37 \times 67 \, \text{mm}^2$ with line width 2 mm. The substrate made of FR4 material has a relative permittivity of 4.3 and a dielectric tangent loss up to 0.02, and it sizes $35 \times 65 \times 1.6 \, \text{mm}^3$. The soldering spaces are modeled as PEC surfaces sizing $2 \times 4 \, \text{mm}^2$.
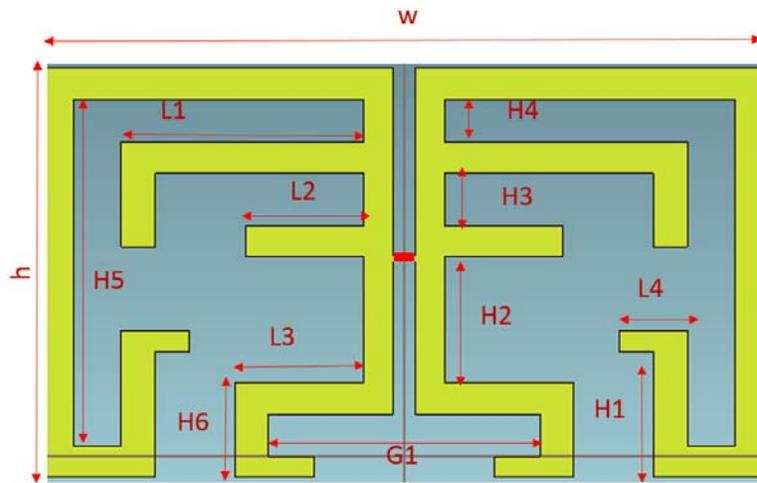
Figure 5. Antenna conception parameters. Each length is a parameter for the antenna conception.

Table 2 summarizes dimensions of the proposed antenna design and gives the value in mm of each parameter of the structure of the design shown in Figure 5.

Table 2. Dimensions of the proposed antenna.

Parameter	Value	Parameter	Value
L	37 mm	$H1$	4 mm
W	67 mm	$H2$	7 mm
$L1$	24 mm	$H3$	3 mm
$L2$	13 mm	$H4$	4 mm
$H5$	33 mm	$H6$	9 mm
$H7$	1 mm	$G1$	28.8 mm
$L3$	5 mm	Thickness	1.6 mm
$L4$	32 mm	Gap	2 mm

4. MANUFACTURING AND MEASUREMENT RESULTS

To investigate the performance of the design, we manufactured the antenna and then performed the S_{11} measurements and radiation pattern measurements.

4.1. Manufacturing

We manufactured the proposed antenna model using the LPKF ProtoLaser S systems which can process even highly complicated tasks with printed circuit boards (PCBs). The machine is very efficient for cutting assembled PCBs, flexible PCBs, and cover layers. The manufactured antenna shown in Figure 6 was printed on an FR4 substrate, where the characteristics are listed in Table 2, and cut using the Maestro3 Machine.
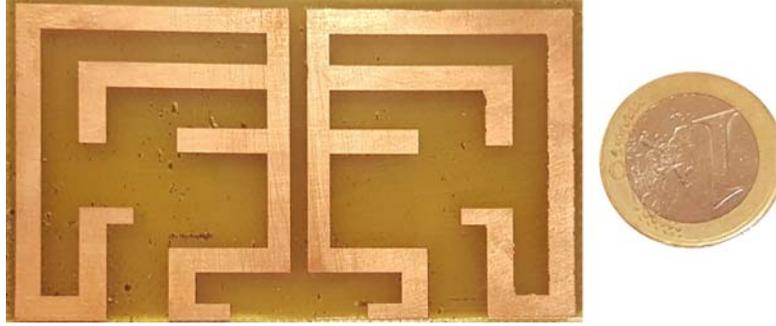
Figure 6. Manufactured antenna design.

4.2. Measurement Setup

To measure S_{11} of the antenna, we used the Vector Network Analyzer (VNA) Agilent N3383A 300 kHz-9 GHz calibrated in each simulation with the Agilent 85033E 3.5 mm Calibration Kit. The antenna was attached to the VNA through a Keysight 8121-0027 Cable.

To perform the radiation pattern measurements, we used the Double-Ridged TEM Horn Antenna with Lens GZ0226DRH intended for indoor and outdoor ultra-wideband applications. The radiation measurement setup is described in Figure 7.
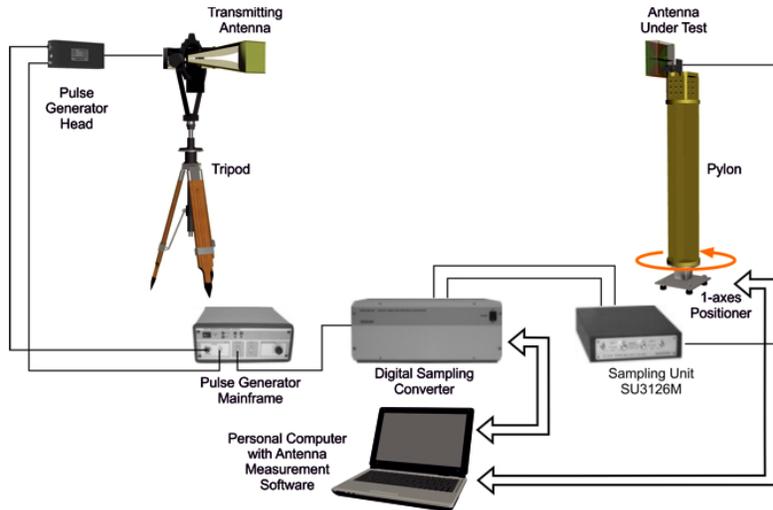
Figure 7. Measurement setup for the radiation pattern.

Far Field Antenna Measurement Systems principle of operation is based on Pulse measurement technique (Time-Domain measurements TD). This system is applicable to most types of antennas and carries out measurements at distances R between Antenna Under Test (AUT) and measuring antenna larger than far field criteria $R = 2D^2/\lambda$, where D is the section (aperture) of antenna and λ the wavelength.

As main measurement instrument, a Digital Sampling Converter is used. Its characteristics are optimized according to system parameters. An Ultrashort-Pulse Electrical Generator serves as measurement signal source. The systems are built for frequency ranges 6 GHz, 12 GHz, 18 GHz, 26 GHz, and 40 GHz.

4.3. S_{11} Measurement Results

Figure 8 describes and compares the results of simulations to the obtained measurements results in free space in terms of S_{11} with respect to 50 ohms. We observe that in free space, the simulation results correspond to the measurement ones with no offset in the resonant frequency except that the measurement results show better performance in terms of bandwidth. One of the possible reasons explaining the larger bandwidth obtained in measurements is the multipath effect obtained by the environment where we performed the measurements and which was absent in the simulations.
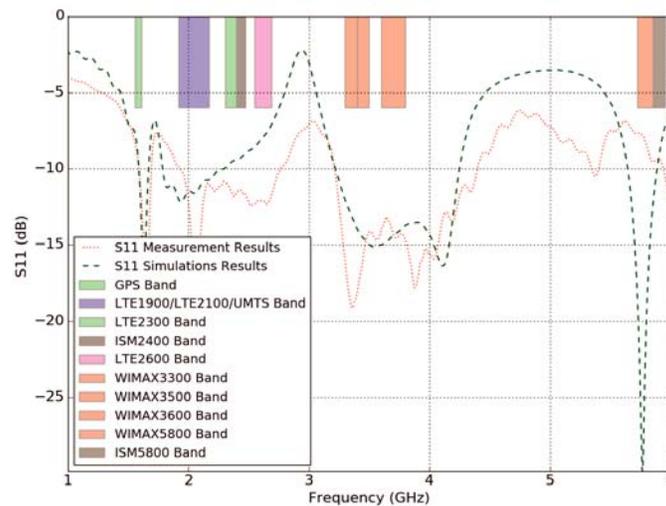
Figure 8. S_{11} simulation vs measurements results.

The results prove that the antenna meets the requirements perfectly in all the frequency bands discussed previously.

4.4. Radiation Result

The radiation pattern of the gain in 2D plot (Phi = 0 and Phi = 90) is presented for each frequency at azimuth view in Figure 10, and at elevation view in Figure 9. From the results plotted in Figure 9 and Figure 10, we observe that the antenna is approximately omnidirectional, and it exhibits a higher gain than the cited references for all the specified frequency bands. The best result is obtained for 2.3 GHz and 2.4 GHz where the antenna is clearly omnidirectional, and the gain varies between 4 dBi and 9 dBi. The antenna is more directive at 5.8 GHz with a maximum gain up to 8 dBi.

Figure 11 shows the variation of the measured maximum gain in dBi in function of the frequency. We notice that the minimum gain is 7.4 dBi obtained at 1.6 GHz, and the maximum gain is 10 dBi at 2.3 GHz and 3.5 GHz, which means that the antenna has a high maximum gain over all the target frequency bands.

4.5. Influence of the Machine Result

After evaluating the reflection and radiation measurements of the antenna in free space, we investigated the impact of an industrial automaton of the machine on the performance of the antenna in terms of
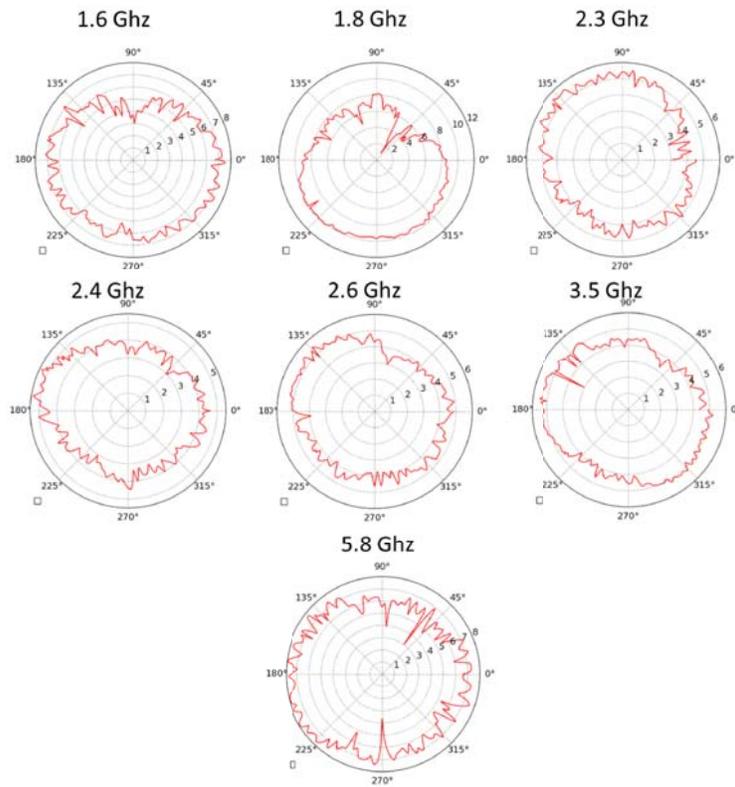
Figure 9. Elevation of the radiation pattern measurements results in each frequency.
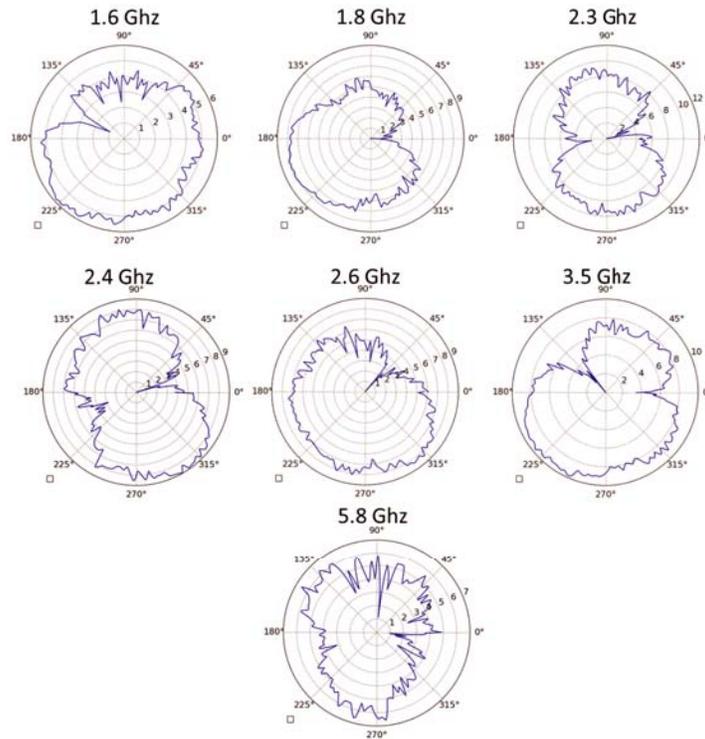
Figure 10. Azimuth of the radiation pattern measurements results in each frequency.
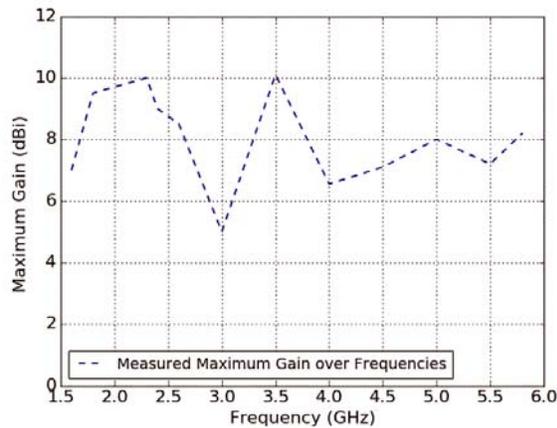
Figure 11. The maximum gain measurements over frequency.
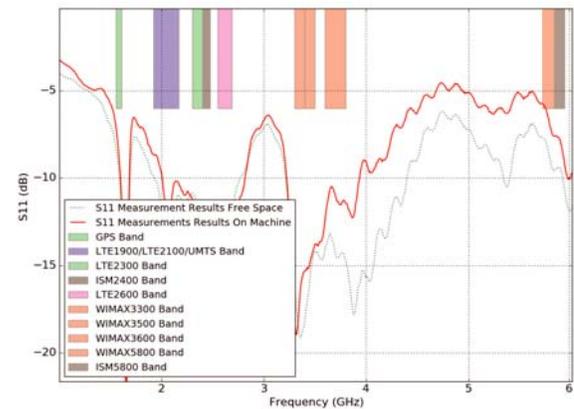
Figure 12. Influence of the machine automaton on the antenna in term of S_{11}.

S_{11}. In this experiment, the radiation was not concerned since the automaton is a dielectric box with a relative permittivity of 2.3, thus it does not prevent or reflect the propagation of the antenna waves.

Figure 12 shows the influence of the cover of the machine automaton on S_{11} parameter of the antenna. We compare the S_{11} result of the antenna inside the machine automaton to the S_{11} result of the antenna in free space. We selected Two positions of the antenna for this comparison: 0 mm (antenna attached to the cover of the machine automaton) and 8 mm separation of the antenna to the cover considered as free space. As shown in Figure 12, we observe that when the antenna is attached to the cover, the measured S_{11} of the antenna is increased dramatically, but all the targeted frequency bands remain covered. Starting from 1 mm as a separation, the S_{11} results get close to the free space results. This explains why we should keep a gap between the antenna and the cover of the machine automaton.

5. CONCLUSIONS

In this paper, we present a novel embeddable miniaturized antenna customized for Industry 4.0 applications. The antenna with its simple low-cost planar structure allows manufacturer to save considerable amount of money accounting of billions of antennas required in such applications in the world wide. We started presenting the existing propositions of similar antennas and how this new design is distinguished by its simplicity, ease of deployment, and excellent performance. We simulated the radiation pattern and return loss of the antenna, and the results confirm the simulations and show that the antenna resonates and radiates in all the specified technology bands GPS1600, UMTS1800, LTE2300, ISM2400, LTE2600, WIMAX3500, WIMAX5800, and ISM5800 required and sufficient for the industry 4.0 management. The proposed antenna system was implemented and tested inside an industrial machine for Yogurt and Milk production and compared to existing commercial solutions. This work shows that the proposed antenna system is suitable for smart factories since it is miniaturized for internal integration, and it has self-frequency-adaptation and low power consumption, allowing the end-user to remotely control and monitor machines and smart devices.

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