A smart suitcase with overmolded inkprinted dual-band antennas

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***Abstract*—Nowadays, the Internet of Things is continuously expanding, with more and more objects connected. The seamless integration of wireless communication systems into smart objects is possible thanks to ink-printed antennas. A smart suitcase is manufactured, where ink-printed antennas are overmolded into the plastic shell of the suitcase, during its production process. The result is a smart object where the antennas are fully integrated inside the material, including printed transmission lines, which interface to a small printed circuit board by means of a dedicated interposer board. The radiation patterns of the suitcase are measured into the anechoic chamber and its performance is analyzed.**

***Index Terms*—IoT, localisation, printed antennas, smart objects**

I. Introduction

The Internet of Things interconnects an unprecedented number of devices, revolutionizing society [1]. Low-Power Wide-Area Networks (LPWAN), provided by technologies such as LoRa and Sigfox, allow connections at low power but at a large range. LPWAN technologies play an important role in industry automation, agriculture, smart grids and logistics tracking [2]. Airline operators can also exploit this technology for luggage tracking. Luggage is currently being tracked by means of optical systems, barcodes, radio frequency identification (RFID), or manual checks [3].

A problem with RFID is the dependence on private infrastructure throughout the luggage handling trajectory, which is a large investment for the operators [4]. Other possibilities are Bluetooth or short message services (SMS). Suitcase tracking could be improved in terms of cost, coverage, reliability, and interoperability by relying on the new LPWAN networks, such as LoRa and Sigfox. Therefore, we propose a scheme employing a combination of the Sigfox Monarch localization service [5] and WiFi [6].

Arriving at a foreign airport, a smart suitcase takes advantage of the available WiFi networks to triangulate its position within tens of meters. The Sigfox Monarch feature is able to identify the country or territory [5] where the suitcase is located, serving as a fall-back solution for WiFi sniffing. Once the location is determined, the suitcase reports its whereabouts through the Sigfox network, which is rolled out on a worldwide scale.

The antennas used for this communication are fully integrated, owing to the proposed integration technique involving the design of antennas printed on thin polymer sheets [7] and overmolded into plastic objects during the injection molding process of the suitcase shell.

In a novel design-for-integration cycle, antennas are designed, simulated, implemented, measured, overmolded, and remeasured. The shift in properties due to overmolding is compensated for by means of a redesign, such that the second similar design cycle results in a properly working overmolded antenna. This paper focuses more on the manufacturing process of the smart suitcase, whereas a more detailed analysis of the antenna design procedure was published in [8].

The antenna is realized in a single ink-printed metal layer, which is seamlessly integrated into the plastic surface of a suitcase hardshell. The planar platform allows for large antennas to be realized while occupying virtually no real estate, leading to highly efficient, wideband designs. Previously, the authors of [9], [10] overlaid an RFID tag and an IRUWB antenna on a suitcase shell, resulting in increased robustness and reusability compared to the currently used disposable RFID tags.

Major hurdles are the frequency detuning and communication link impairment caused either by the electromagnetically unpredictable nature of the smart device materials or by objects surrounding the smart device. In [11], an alternative is proposed by building substrate-independent antennas that rely on an air-filled cavity-backed antenna directly fabricated in the smart device. Unfortunately, such structures are too thick for integration into a suitcase shell. Finally, the work in [12] copes with detuning by adopting a large design margin on the impedance bandwidth.

Antennas have been integrated into objects before, but this integration often did not unify the antennas with these objects to the same degree as is possible with current large-scale manufacturing technologies. Here, by taking the influence of the suitcase material into account during the design stage, two antenna topologies are proposed with a -10 dB impedance bandwidth covering, with ample margins, the Sigfox [862–928] MHz band and the WiFi ISM [2.4–2.5] GHz band, having percentile bandwidths of 26% and 15%, respectively, and achieving in-band simulated total efficiencies of at least 94% and 88%, respectively.

The paper is further organized as follows. The manufacturing process of the smart suitcase is described in Section II, the antenna design in section III, and the radiation performance in Section IV. Finally, the conclusion follows in Section V.

Fig. 1. Overmolding printed antennas at the suitcase factory.

Fig. 2. Suitcase with overmolded antennas and solar panels.

II. THE OVERMOLDING PROCESS

In literature, many applications are described where antennas are integrated into clothing or objects by attaching extra layers on top of the base material. For smart suitcases, such an approach has the disadvantage of a higher fragility since they are often handled roughly, not only on the outside, but also on the inside, by inserting items in a hurry. Hence, antennas glued on either side of the suitcase shell are expected to detach early in the lifecycle of the suitcase, or at least be scratched, deteriorating their performance. We present an innovative approach of antenna integration, where the antennas are first printed in silver ink on thin thermoplastic sheets, made of either polypropylene or polyethylene. In the Samsonite® suitcase factory, the suitcase shell is produced by means of a high-pressure injection molding process. The mold is made of very solid metal, to withstand the enormous pressure, as visible in Fig. 1. The plastic sheet with the printed antennas is inserted into the mold and properly fixed by mechanical supports. After that, the mold is closed, leaving only the fairly thin empty space, which is filled with plastic to manufacture the suitcase shell.

When the hot molten plastic is injected into the mold, the pressure is known to range from 10000 to 20000 psi, which corresponds to 689-1379 Bar. This enormous pressure makes the substance flow immediately around the antenna sheet, on both sides. Given both the high pressure and temperature, at the interface, the plastic of the shell fuses with the plastic of the antenna sheet, resulting in a seamlessly integrated antenna system, as visible in Fig. 2. The texture of the suitcase shell near the antennas is exactly the same as for a standard shell without antennas, such that a thin paintwork is enough to completely hide the antennas. Additionally, the suitcase shell responds well to bending, with the antennas showing no sign of detachment from the suitcase material. In the picture, also solar panels were integrated in a similar way. Therefore, clear plastic was chosen. When only antennas are integrated, the plastic can of course be opaque. In the experiments, it appeared that despite the clear polymer, the solar panels suffered an efficiency degradation because of the transparent layer covering them. However, as shown in the next sections, for the antennas, no degradation was observed. The plastic causes only a shift in resonance frequency, but this can be compensated for at the antenna design stage.

III. ANTENNA DESIGN

Both antennas are manufactured via the same process, using silver-based ink with conductivity $\sigma = 6.8 \cdot 10^6 S/m$, printed in a layer of 4 μm thickness, on polypropylene (PP) sheets of 150 μm thickness. The PP sheets are covered with a thin polyurethane (PU) layer to improve the adhesion of the ink [8]. The ink was cured in an oven at $135°$C after printing. Supply of materials and printing were performed by Quad Industries (see acknowledgement).

A. *Monopole for* 868 *MHz*

The suitcase is intended to establish a wireless link to 868 MHz LoRa or Sigfox networks and to 2.45 GHz WiFi networks. For the lowest frequency, a monopole antenna architecture was chosen, because of its fairly compact size, compared to a patch antenna. A photograph of the overmolded monopole is displayed in Fig. 3, with its dimensions annotated.

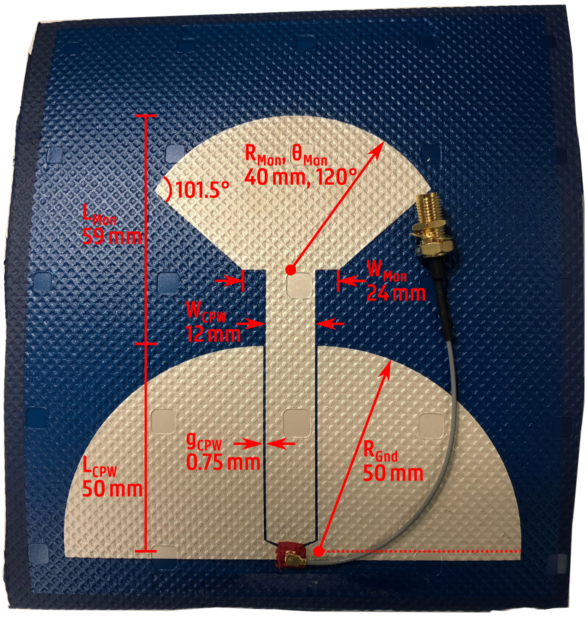

Fig. 3. Annotated picture of the overmolded monopole antenna.

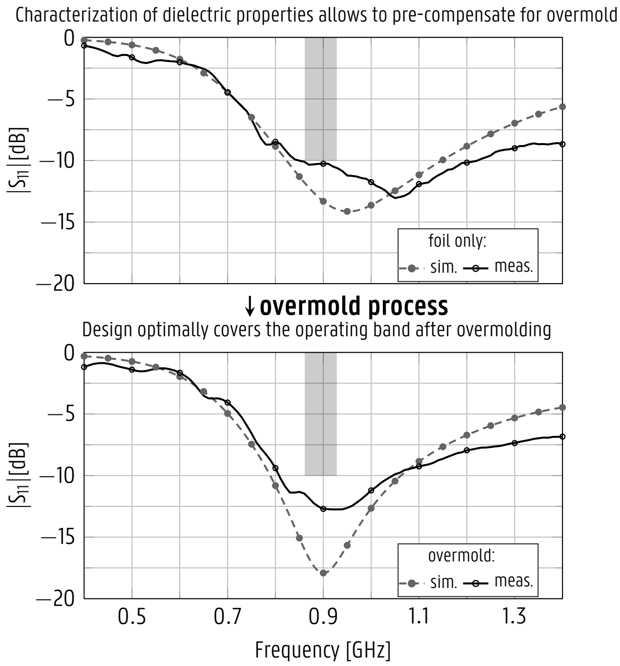

Fig. 4. Impedance bandwidth of the monopole antenna.

The antenna operates as a top-loaded monopole, excited by a coplanar waveguide, attached to a ground structure that consists of two quarter disks with radius approaching a quarter wavelength. The center conductor, which is the radiating element, widens at the top, forming a capacitive top load. This allows to shorten the length of the radiating element, without sacrificing too much bandwidth or radiation efficiency. The design was simulated and finetuned in CST Microwave Studio. Dielectric losses in the thin polymer appear insignificant compared to the losses caused by the limited conductivity of the ink, also after overmolding and integration into the suitcase shell.

The simulated and measured $|S_{11}|$ curves of the monopole are shown in Fig. 4. The top plot shows the response before overmolding, whereas the bottom plot visualizes the antenna behavior after overmolding. Note that measurement and simulation agree fairly well. Although some differences are visible, the main behavior is certainly predicted well by the simulation. The polymer surrounding the antenna has a higher dielectric permittivity than air, which causes the resonance frequency to shift downwards. This effect was compensated for during the design of the antenna, in order to achieve the desired center frequency, after overmolding. The bottom plot clearly illustrates how the antenna's resonance is nicely centered around the band of interest. Additionally, for the whole band of interest, the $|S_{11}|$ is around -12 dB. The bandwidth for which a $|S_{11}|$ of -10 dB or lower is achieved is large enough to provide some margin for detuning caused by objects around the antenna or by manufacturing tolerances, such as variations in the suitcase material's thickness and properties.

B. Patch antenna for 2.45 *GHz*

For the 2.45 GHz band, an inset-fed patch antenna is chosen, because of its well-known performance in this frequency band.

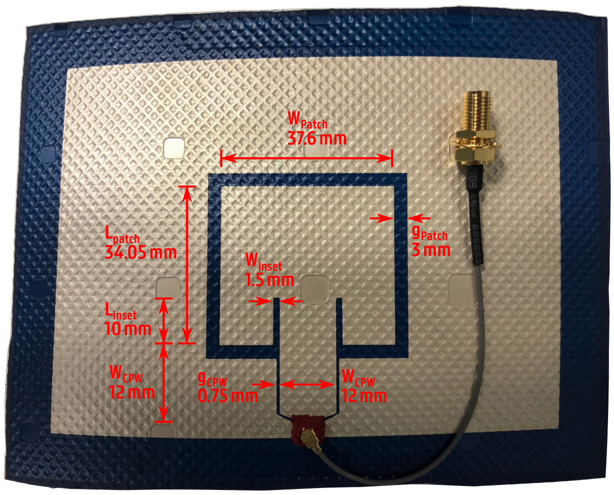

Fig. 5. Annotated picture of the overmolded patch antenna.

The wavelength is now only 12 cm, which also enables a compact design. The inset-fed patch antenna design is displayed in Fig. 5. The radiating patch is excited with respect to the outside conducting rectangle, which operates as a ground plane. This design was also optimized in CST Microwave Studio and adjusted by precompensating for the frequency shift caused by overmolding.

The simulated and measured $|S_{11}|$ curves of the patch antenna are plotted in Fig 6. Again, some deviations between the simulation and measurement exist, but the general behavior is adequately captured by the simulation. Importantly, after overmolding, the downward shift positions the resonance

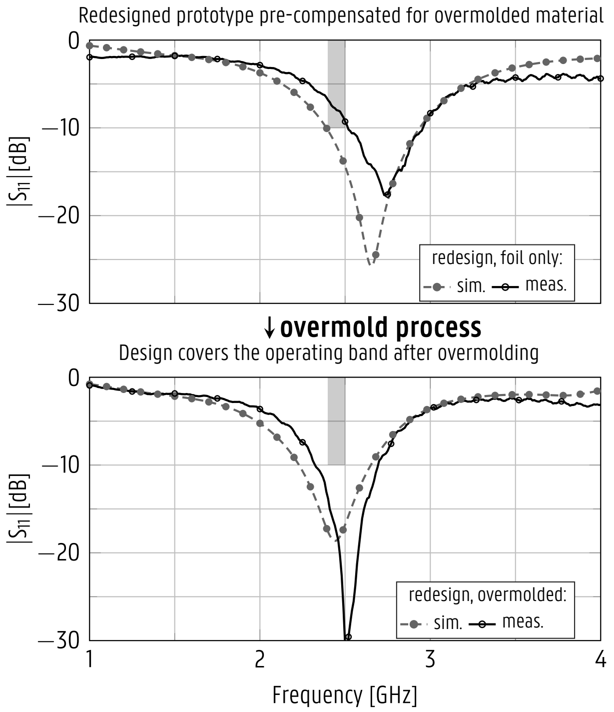

Fig. 6. Impedance bandwidth of the patch antenna.

frequency within the desired band, this time with a $|S_{11}|$ that is below -15 dB for the whole band of interest. The large -10 dB bandwidth provides ample margin for detuning due to objects in the environment, or for manufacturing tolerances and slight discrepancies not accounted for at the design stage, such as the deformation of the antenna to conform to the suitcase shell.

IV. Radiation patterns of the smart suitcase

The performance of the antenna system after seamless integration into the smart suitcase is tested in the anechoic chamber. In this setup, the antenna designs described earlier are both printed on a large polypropylene sheet and overmolded together in the same suitcase shell. To determine the radiation patterns displayed in Fig. 7, the complete suitcase shell is mounted on the rotary system in the anechoic chamber, as shown in Fig 8. Note that the printed design also includes planar transmission lines, such that both antennas can be excited at the center bottom area of the antenna section. The antennas interface to a small printed-circuit board (PCB), housed in the logo plate of the suitcase, where also the solar panels from the bottom half of the suitcase are connected. In this way, both antennas and solar panels can be conveniently interfaced to the same small unit, containing all the electronics, near the center of the suitcase. To measure the radiation patterns, the antennas are connected to a network analyzer via a dedicated interposer PCB, interfacing to the planar printed transmission lines via goldfinger contacts.

The measurement results in Fig. 7 display both co-polar and cross-polar radiation patterns. The radiation patterns can only be scanned over the frontal hemisphere of the antenna. The reason for this is that because the suitcase is so large, it can only be attached to the heavy rotating arm, which is normally used for a horn antenna. Using this arm, as seen in the picture, we suffer from shadowing by the rotary system's construction if we rotate the arm too far. However, due to the nature of the antennas, which are single-layer designs, the radiation pattern is practically symmetrical. The metallic structures of each antenna act as either a reflector or director for the other, tilting the radiation patterns away from $\theta = 0°$ as can be observed for the monopole in the xz-plane and for the patch antenna in the yz-plane. Additionally, radiation by the feedline for the monopole causes asymmetry in its radiation pattern in the yz-plane. The monopole's frontal hemisphere 3 dB beamwidth equals $87°$ in the xz-plane, with a maximum gain of 2.8 dBi. For the patch antenna, the beamwidth is $114°$, with a maximum gain of 1.5 dBi in the xz-plane. Significant cross-polarized components are also present, due to the bending of the antennas along the curved surface of the suitcase shell.

V. Conclusion

A dual-band antenna system was seamlessly integrated into a suitcase shell, by means of overmolding a printed monopole and patch antenna in its injection molding manufacturing process. The overmolding caused a downward shift in the resonance frequency of the antennas, due to the higher dielectric permittivity of the polymer added by this process. This effect was taken into account during the design of the monopole and patch antenna in CST Microwave Studio, by precompensating for the resonance frequency shift. Return loss measurements of the overmolded antennas correspond well to the performance predicted by the simulations. The 895 MHz monopole and 2.45 GHz patch antennas were printed together on a single polypropylene sheet, interconnected by printed planar transmission lines. The radiation patterns of the complete suitcase shell with fully integrated antennas and transmission lines were measured in an anechoic chamber. The maximum gains of the monopole and patch antennas were 2.8 dBi and 1.5 dBi, respectively. The frontal hemisphere beamwidths equal $87°$ and $104°$ in the xz-plane, respectively. This antenna system is part of a traceable suitcase relying on Sigfox and WiFi, achieving a new level of antenna integration into smart objects. Owing to the overmolding process, the antennas are not only seamlessly integrated, but also mechanically protected by the suitcase material which fully covers them on both sides.

Acknowledgment

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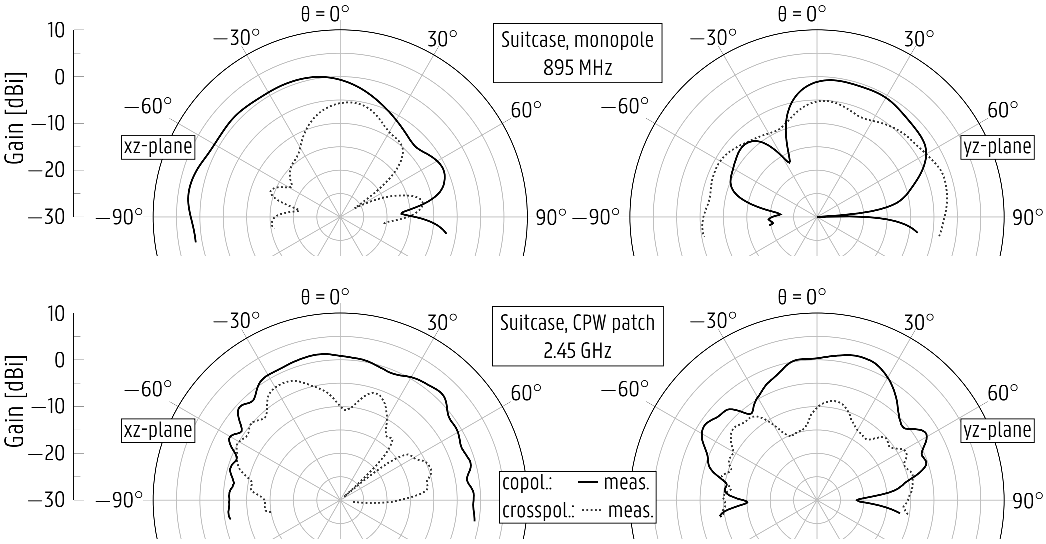

Fig. 7. Radiation patterns of the antennas integrated into the suitcase.

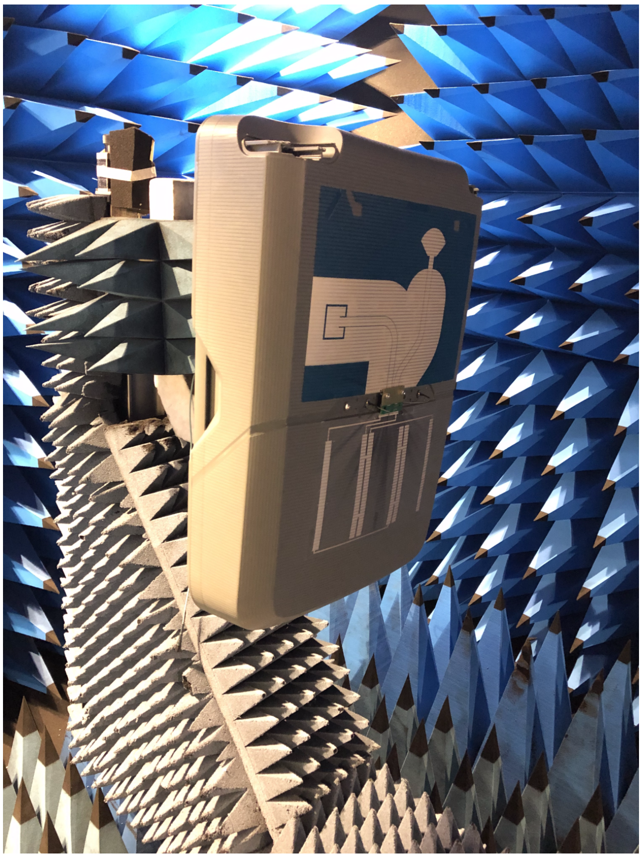

Fig. 8. Suitcase with overmolded printed antennas in anechoic chamber.

REFERENCES

[1] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low Power Wide Area Networks: An Overview," *IEEE Communications Surveys Tutorials*, vol. 19, no. 2, pp. 855–873, 2017.

[2] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A Comparative Study of LPWAN Technologies for Large-Scale IoT Deployment," *ICT Express*, vol. 5, no. 1, pp. 1–7, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2405959517302953

[3] A. de Juniac, "IATA Annual Review 2019," Int. Air Transport Assoc., Seoul, Tech. Rep., Jun. 2019. [Online]. Available: https://www.iata.org/contentassets/c81222d96c9a4e0bb4ff6ced0126f0bb/iata-annual-review-2019.pdf

[4] Y. Rouchdi, A. Haibi, K. El Yassini, M. Boulmalf, and K. Oufaska, "RFID Application to Airport Luggage Tracking as a Green Logistics Approach," in *2018 IEEE 5th International Congress on Information Science and Technology (CiSt)*, 2018, pp. 642–649.

[5] A. Mineo, M. Palesi, D. Patti, and V. Catania, "Cloud-Based Energy Efficient Scheme for Sigfox Monarch as Asset Tracking Service," in *2020 International Conference on Omni-layer Intelligent Systems (COINS)*, 2020, pp. 1–6.

[6] Y. Li, J. Barthelemy, S. Sun, P. Perez, and B. Moran, "A Case Study of WiFi Sniffing Performance Evaluation," *IEEE Access*, vol. 8, pp. 129 224–129 235, 2020.

[7] P. Pongpaibool, P. Rattanawan, M. Kitjaroen, W. Wallada, and S. Siwamogsatham, "An Ink-Reducing Printed Rectangular CPW Antenna Design via Selective Area Thickening," in *2016 International Symposium on Antennas and Propagation (ISAP)*, 2016, pp. 674–675.

[8] I. Lima de Paula, H. Rogier, and P. Van Torre, "Conformal integration of efficient conductive-ink-printed antennas in smart suitcases for LPWAN-based luggage tracking," *Sensors*, vol. 22, no. 11, p. 4077, May 2022. [Online]. Available: http://dx.doi.org/10.3390/s22114077

[9] C. R. Medeiros, J. R. Costa, and C. A. Fernandes, "Passive UHF RFID Tag for Airport Suitcase Tracking and Identification," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 123–126, 2011.

[10] A. Zaric, V. S. Matos, J. R. Costa, and C. A. Fernandes, "Viability of Wall-Embedded Tag Antenna for Ultra-Wideband Real-Time Suitcase Localisation," *IET Microwaves, Antennas Propagation*, vol. 8, no. 6, pp. 423–428, 2014.

[11] K. Y. Kapusuz, S. Lemey, and H. Rogier, "Substrate-Independent Microwave Components in Substrate Integrated Waveguide Technology for High-Performance Smart Surfaces," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 3036–3047, 2018.

[12] H. F. Khalili, S. Lemey, O. Caytan, T. Deckmyn, S. Agneessens, D. V. Ginste, and H. Rogier, "Biodegradable Dual Semicircular Patch Antenna Tile for Smart Floors," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 2, pp. 368–372, 2019.