A Smart Glove for Near-Field UHF RFID Applications

Andrea Michel, Rajesh Kumar Singh, Giuliano Manara, and Paolo Nepa

Abstract – In several applications of radio-frequency identification (RFID) systems, the distance between the reader antenna and the tag antenna is comparable or even shorter than one wavelength; thus, the typical Friis equation or radar equation cannot be used for link budget and tag detection estimation. In this article, a possible key performance indicator, namely, power transfer efficiency, is used to analyze the performance of a specific near-field RFID application at UHF band, consisting of a textile reader antenna integrated onto a smart glove.

1. Introduction

Today, the Internet of Things (IoT) paradigm is used largely to connect things and people to the Internet and digital world, thus providing access from everywhere. Among other technologies used to create these connections, radio-frequency identification (RFID) technology represents one of the most interesting candidates for identification [1]. RFID systems are extensively used in various applications, such as access control, electronic toll collection, waste management, tracking, IoT-based personal health care, item-level tagging, security, and so on. A number of frequency bands are assigned to RFID: low frequency (LF, 125 KHz), high frequency (HF, 13.56 MHz), and ultra-high frequency (UHF, 865–868 MHz, European band). When compared to LF or HF RFID systems, UHF RFID technology gives a much larger read range and achieves higher data rates.

In logistics and retail applications, UHF RFID devices have been proposed in past decades to help human operators in detecting tagged objects and collecting information during inventories or recognition processes. RFID technology is a more reliable and fast technology with respect to the bar code, also remembering that the latter requires optical visibility and a line-of-sight link between the bar code and the reader. Operators often use portable/handheld UHF RFID readers. These devices allow for a good detection of tagged items up to a distance of a few meters. The integrated antenna is a circular polarized antenna with a typical 1–2 dBic gain [2] at the UHF band. Moreover, data collected from tagged items (e.g., the electronic product code of the tag or data from sensors integrated into the RFID tag) are sent to the infrastructure and management systems through a Bluetooth or wireless local area network connection.

However, inventory done by means of a portable reader might cause an uncomfortable situation because users have only one hand to perform their own tasks. For this reason, wearable devices have been developed to automate identification and data collection during normal human operator activities. A wearable and portable RFID reader helps the user reduce effort compared to holding the reader by one hand when performing a related task. This is the case, for example, when a wearable RFID reader is integrated into a hand glove to obtain a smart glove. By integrating RFID readers into smart gloves, humans will not face any inconvenience due to the presence of the reader.

Smart gloves have already been extensively used in various domains, such as medical and industrial applications, since they are lightweight and comfortable to wear [3–5]. RFID technology that is integrated into protective gloves is suitable for helping workers during their activities, minimizing human effort and the risk of accidents. A UHF RFID smart glove [6, 7] is required to detect tagged items that are close to the hand (Figure 1) yet avoids the detection of tags placed a few tens of centimeters beyond (false-positive events). Given the typical space available to a glove for antenna integration, we observe that the far-field region starts beyond 70–80 cm, which means that the tag and smart glove reader antennas are in the near-field region of each other [8].

Thus, conventional far-field antenna parameters, such as radiation pattern and antenna gain, cannot be considered as effective figures of merit [8]. In some articles, the electric and magnetic field distributions are considered as key performance parameters to optimize the near-field antenna, but they are not directly related to the characteristics of the tag antenna, which can be of different shapes and sizes. For these reasons, new parameters have been proposed, such as power transfer efficiency (PTE). As demonstrated in [9], PTE is a good candidate to qualitatively predict the received signal strength indicator (RSSI) distribution and then the overall system performance. PTE can be estimated by means of numerical tools, and it depends on the reader and tag antenna shapes as well as on the surrounding environment.

In this article, PTE is used to qualitatively estimate the performance of a UHF RFID near-field reader antenna when integrated into a smart glove. Specifically, the textile reader antenna design is briefly presented in Section 2 together with some numerical and experimental results on a real prototype. Then, in Section 3, some numerical results are shown in terms of

Manuscript received 29 December 2021.

Andrea Michel, Rajesh Kumar Singh, Giuliano Manara, and Paolo Nepa are with the Department of Information Engineering, University of Pisa, Via G. Caruso 16, I-56122 Pisa, Italy; e-mail: andrea.michel@unipi.it, rajesh.singh@dii.unipi.it, giuliano.manara@unipi.it, paolo.nepa@unipi.it.

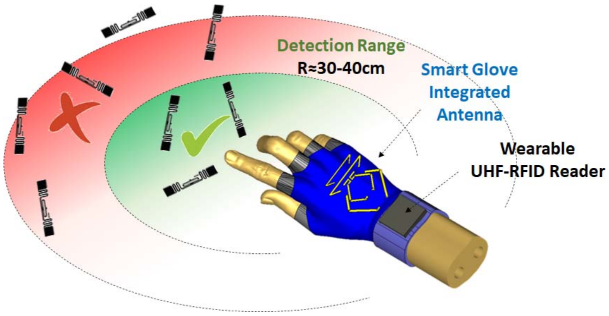

Figure 1. Schematic representation of the detection area of a UHF RFID smart glove.

PTE when considering a commercial tag close to the wearable reader antenna on the smart glove. Results in terms of measured RSSI are also presented and discussed.

2. Smart Glove Reader Antenna: Layout and Performance

The design of the wearable reader antenna must take into account some constraints not related to electromagnetic aspects. In particular, the material used to fabricate the antenna must be washable and stretchable to follow the hand's movements. Moreover, the position of the antenna must be chosen in order to maximize the ergonomics of the antenna while minimizing discomfort in wearing it. In this article, a Yagi-like antenna is proposed and designed on the back of the hand [6], which represents the area less affected by hand movements. Typically, a Yagi-Uda antenna consists of a single driven element (a dipole or a folded dipole), a reflector, and one or more directors. Since the application focuses only to detect tagged objects close to the human hand (inside the antenna near-field region), thus avoiding the detection of tags placed beyond the target region, a modified layout has been designed to maximize the fields in proximity to the smart glove and to limit the radiation in the far field. In particular, the feeder is represented by a square-shaped folded dipole, while two other parasitic folded dipoles are used as directors (Figure 2). A 3D-printed material has been used to fabricate the antenna, giving elasticity and comfort. Stretchable fabric is used as a dielectric material, and metallic parts are made on this fabric. The plain conductive fabric has a finite resistivity of 0.6 Ω/sq, allowing for better stability of the antenna parameters. The antenna is fed through a coaxial balun. Snap buttons are attached to the antenna instead of soldering. Specific absorption rate (SAR) has been also calculated, considering the European limit of 2 W/kg averaged over 10 g of tissue. The SAR-compliant transmission power is hence calculated to be 27.8 dBm. Experimental tests use a reader power of 16.5 dBm, which is well below the allowed limit. Further simulated and measured results have been presented in [6].

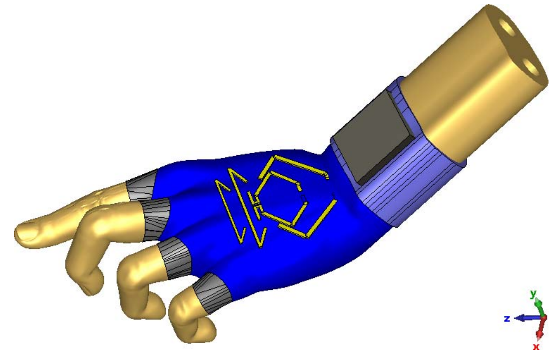

Figure 2. Numerical model of the glove-integrated antenna worn on the hand.

3. PTE Analysis

As discussed in Section 1, the distance between the reader antenna and the tagged objects in the application under discussion is usually smaller than one wavelength at ETSI UHF RFID band (i.e., about 34.5 cm). This means that classic assumptions, such as free-space propagation and local plane wave illumination, cannot be considered to numerically estimate the UHF RFID system performance in terms of reading range and read rate.

Consequently, novel coupling models must be developed to devise new system and antenna requirements. It is worth noting that the configuration analyzed here is different from what is found in the HF band, where the magnetic field is dominant around the reader antenna, thus representing the main agent for energizing the tag. At the UHF band, both electric and magnetic energy density distributions exhibit one or more peaks in the near-field region of the reader antenna. Therefore, at the UHF band, a more complex model is needed, accounting for both electric and magnetic coupling.

Without loss of generality, the overall system can be fully characterized and described by means of a two-port equivalent network that considers the reader and tag antenna characteristics as well as the surrounding environment, including the presence of the human body. In other words, the tag and the reader antennas and the space between them have been considered as a linear two-port network. The numerical evaluation of the entries of the impedance matrix Z has been performed through the commercial numerical tool CST Microwave Studio.

Commercial tag layouts have been separately imported into the numerical model together with the proposed antenna. Thus, the wireless PTE between the reader and the tag has been computed to qualitatively estimate the power delivered to the tag chip when varying the tag position. PTE is defined as the ratio between the power delivered to the microchip, P_T, and the power entering the input port of the reader antenna, P_R,

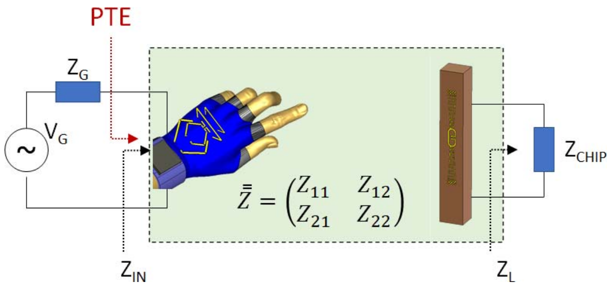

Figure 3. Schematic representation of a near-field UHF RFID system consisting of a reader antenna and a tag antenna connected to the RFID chip.

$$\mathrm{PTE} = \frac{P_\mathrm{T}}{P_\mathrm{R}} = \frac{1/2\,\Re\{Z_\mathrm{L}\}|I_2|^2}{1/2\,\Re\{Z_\mathrm{in}\}|I_1|^2} = |Z_{21}|^2\,\frac{\Re\{Z_\mathrm{L}\}/\Re\{Z_\mathrm{in}\}}{|Z_\mathrm{L}+Z_{22}|^2} \tag{1}$$

where Z_in is the input impedance of the two-port network when the second port is connected to Z_L. As apparent from (1), PTE expression is given by the square of the mutual impedance amplitude (proportional to the open-circuit voltage at the tag antenna) multiplied by a coefficient that includes the tag load.

To validate the effectiveness of PTE for a qualitative estimation of the tag detection performance of the reader antenna, numerical simulations have been carried out by varying the reciprocal distance between the tag and the reader antenna (Figure 4a). Specifically, a commercial LabID UH100 tag has been placed on a plane (x-z plane) at a distance of 2 cm from the palm of the hand and is moved along an axis (z-axis in Figure 4a) whose origin is placed in correspondence with the glove-antenna phase center. The tag is aligned with the x-axis.

Such PTE values have been used to estimate the power received by the tag when the power transmitted by the reader antenna is set to 20 dBm. A sample of numerical results is shown in Figure 4b, where the power received by the microchip is plotted as a function of the z coordinate (red continuous line).

In particular, an asymmetric behavior is observed. Indeed, a better coverage is obtained in front of the hand with respect to what happens in the back side. This latter behavior is due to the asymmetry in the Yagi-like structure of the glove antenna, determined by the presence of the two directors. This tendency is confirmed by RSSI measurements obtained by means of a commercial UHF RFID reader (CAEN RFID Ion, Model R4301P), again when the power transmitted by the reader antenna is set to 20 dBm.

PTE can then be used to compare the performance of different tag typologies or reader antenna layouts. By referring to the same geometry depicted in Figure 4a, a comparison between the estimated power received by three tag layouts (button tag, LabID UH101, and LabID UH414) is shown in Figure 5 as a function of the distance between the reader antenna and the tag (z-axis in Figure 4a). The button tag is a circular UHF RFID tag

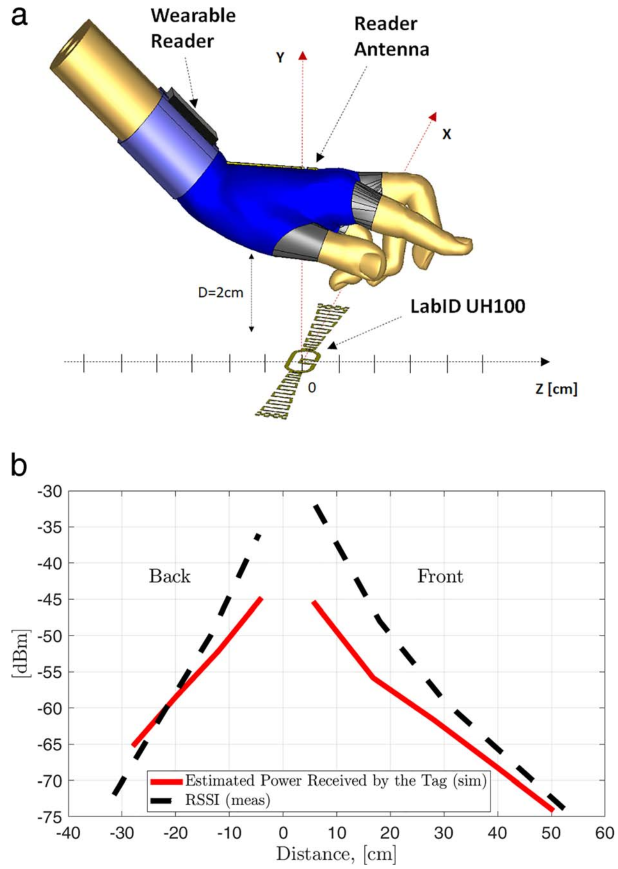

Figure 4. (a) Sketch of the experimental setup. (b) Estimated power received by the tag (solid red curve) as a function of the distance from the antenna center ($z = 0$). RSSI measured data are also reported in the figure (dashed black line).

with 1 cm diameter. It is typically used for short read range applications. Given its small size, the read range is limited, and the behavior of the estimated received power reflects the measured RSSI trend. On the other

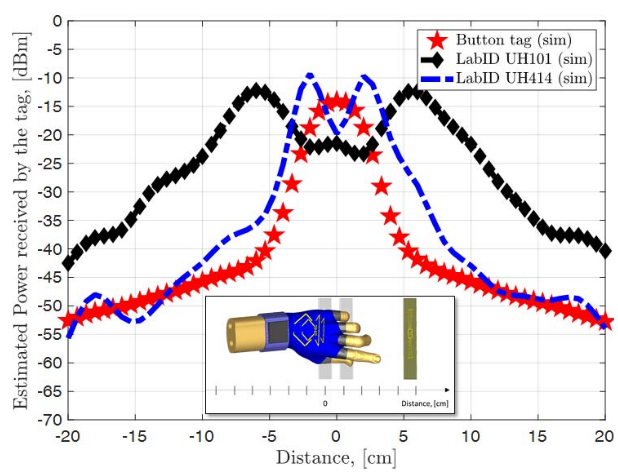

Figure 5. Comparison of the power received by three tag typologies as a function of the distance between the reader antenna and the tag. A transmitting power of 20 dBm is considered.

hand, the LabID UH101 is a 9 cm long dipole-like tag and is used for long read range applications. From Figure 5, it can be observed that the estimated power received by the microchip has a slower decreasing rate with respect to the other two tags. The LabID UH414 tag represents a trade-off between the others, as also confirmed by the related curve. An interesting phenomenon can be observed by looking at the received power curves pertinent to the UH101 and UH414 tags. When the tag is close to the reader antenna, a decrease of the received power is observed, even though the distance becomes smaller. This might be due to the electric and magnetic field distributions in the near-field region of the reader and tag antenna, both of which responsible for the coupling mechanism at the UHF band.

4. Conclusion

A novel model has been proposed to overcome the specific near-field conditions often occurring in RFID systems. Indeed, when the RFID reader and tag antennas are placed at a small distance (e.g., few centimeters), the classic Friis or radar equation cannot be used to estimate the RFID system performance in terms of tag detection and read range. Thus, new parameters should be defined and considered, such as PTE. To overcome the definition of PTE, future work will be focused at introducing a complete model for both the downlink and the uplink between the reader and the tag.

5. References

1. X. Jia, Q. Feng, T. Fan, and Q. Lei, "RFID Technology and Its Applications in Internet of Things (IoT)," 2012 Second International Conference on Consumer Electronics, Communications and Networks (CECNet), Yichang, China, April 21-23, 2012, pp. 1282-1285.
2. R. Caso, A. Michel, M. Rodriguez-Pino, and P. Nepa, "Dual-Band UHF-RFID/WLAN Circularly Polarized Antenna for Portable RFID Readers," *IEEE Transactions on Antennas and Propagation*, **62**, 5, May 2014, pp. 2822-2826.
3. K. P. Fishkin, M. Philipose, and A. Rea, "Hands-On RFID: Wireless Wearables for Detecting Use of Objects," Ninth IEEE International Symposium on Wearable Computers (ISWC'05), Osaka, Japan, October 18-21, 2005, pp. 38-41.
4. D. J. Patterson, D. Fox, H. Kautz, and M. Philipose, "Fine-Grained Activity Recognition by Aggregating Abstract Object Usage," Ninth IEEE International Symposium on Wearable Computers (ISWC'05), Osaka, Japan, October 18-21, 2005, pp. 44-51.
5. T. Chouhan, A. Panse, A. K. Voona, and S. M. Sameer, "Smart Glove With Gesture Recognition Ability for the Hearing and Speech Impaired," 2014 IEEE Global Humanitarian Technology Conference—South Asia Satellite (GHTC-SAS), Trivandrum, India, September 26-27, 2014, pp. 105-110.
6. R. K. Singh, A. Michel, P. Nepa, A. Salvatore, M. Terraroli, et al., "Compact and Wearable Yagi-Like Textile Antennas for Near-Field UHF-RFID Readers," *IEEE Transactions on Antennas and Propagation*, **69**, 3, March 2021, pp. 1324-1333.
7. R. K. Singh, A. Michel, P. Nepa, and A. Salvatore, "Wearable Dual-Band Quasi-Yagi Antenna for UHF-RFID and 2.4 GHz Applications," *IEEE Journal of Radio Frequency Identification*, **4**, 4, December 2020, pp. 420-427.
8. A. Michel, P. Nepa, X. Qing, and Z. N. Chen, "Considering High Performance Near-Field Reader Antennas: Comparisons of Proposed Antenna Layouts for Ultrahigh-Frequency Near-Field Radio-Frequency Identification," *IEEE Antennas and Propagation Magazine*, **60**, 1, February 2018, pp. 14-26.
9. A. Michel, M. Rodriguez Pino, and P. Nepa, "Reconfigurable Modular Antenna for NF UHF RFID Smart Point Readers," *IEEE Transactions on Antennas and Propagation*, **65**, 2, February 2017, pp. 498-506.