Low-Cost Ink-Jet Printed RFID Tag Antenna Design for Remote Healthcare Applications

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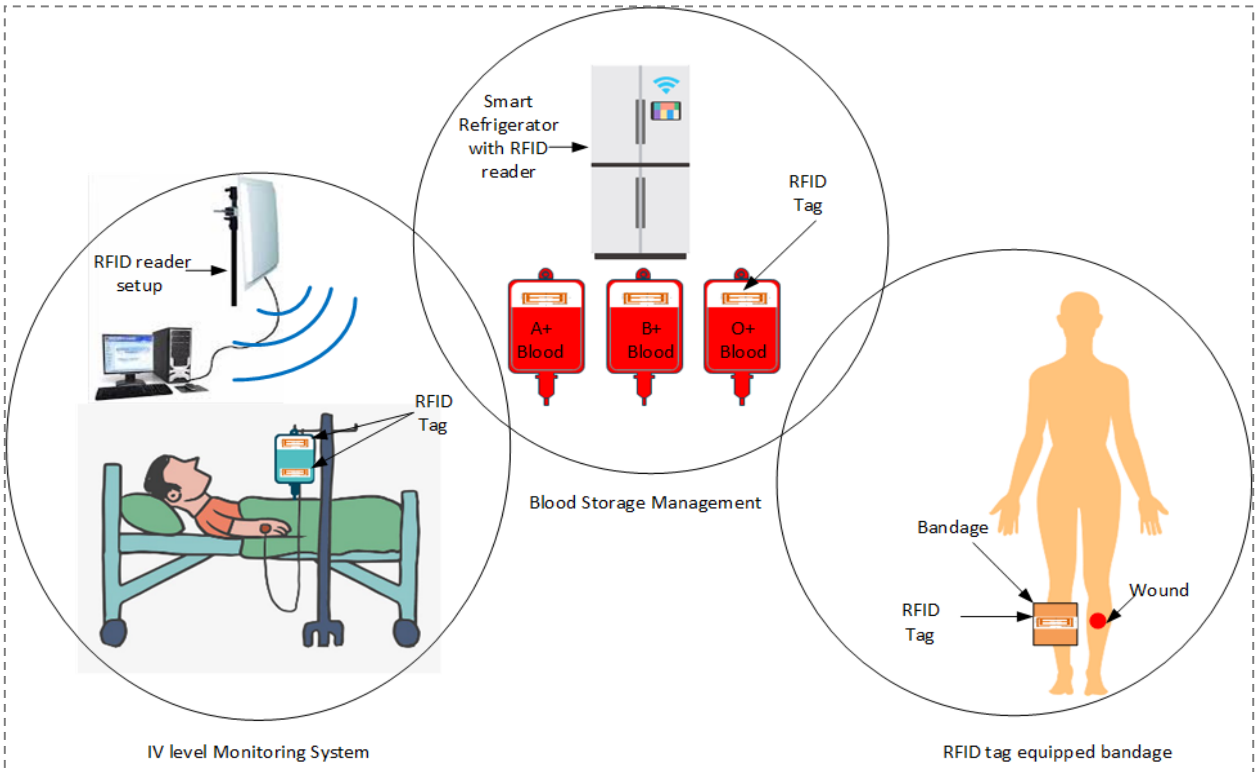

Schematic diagram for applications of the proposed RFID tag in remote healthcare

Take-Home Messages

- We exploit a low-cost and inkjet printed UHF RFID tag as a sensor by modifying the equivalent circuit of the antenna to mitigate the effects of water, blood, and the human body.
- The targeted biological and medical applications are intravenous (IV) level sensing, blood storage management and wound healing detection.
- The proposed RFID tag antenna features impedance match with Impinj R6 RFID from 890 MHz – 937 MHz and has a read range of 3 m, 2.5 m and 1.5 m on the surface of a water bottle, IV solution and blood bag, respectively.
- As compared with traditional designs, this tag antenna provides 26 % more read range with relatively small size 40 × 14 mm and has a specialty of water proximity sensing, leading to a compact and low-cost solution which is ideal for mass production.
- These features make this tag ideal for healthcare application in hospitals, which can add better facilitation for patient monitoring and also reduces the cost.

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Abstract. This paper presents a low-cost, inkjet printed radio frequency identification (RFID) tag antenna for remote health care applications. The electrically small tag consists of nested-slot configuration and parallel strips. The tag antenna is exploited as a sensor by modifying its equivalent circuit to mitigate the effects of water, blood sample phantom, and the human body. As a result, the proposed RFID tag antenna with compact dimensions of 40 × 14 mm, features a conjugate match with Impinj R6 RFID chip ranging from 890 MHz – 937 MHz. Moreover, this tag has a read range of 3 m, 2.5 m and 1.5 m on the water bottle, intravenous (IV) solution and blood bag, respectively. However, the read range of RFID tag on an empty water bottle or IV solution bag is 0.5 m. By comparing the read range of tag on empty and solution filled IV bags, the proposed tag was used as a water proximity sensor. Experimental testing of the tag is performed for sensing the level of the IV solution. Also, this tag is tested by mounting on liquid mixture (a mixture of salt and sugar is used as a phantom to mimic the blood) filled plastic bags, which leads to a low-cost solution for blood storage management. Experimental results show a good agreement of proposed tag towards its use in healthcare applications, which leads to better healthcare facilitation regarding cost, time and care.

***Keywords* — Equivalent circuit, Impedance matching, healthcare applications, IV level sensing, radio-frequency identification (RFID).**

I. Introduction

RFID and Internet of Things (IoT) are becoming more and more prevalent both in academia and industry. The ultra-high frequency (UHF) passive RFID technology is emerging in many new applications such as supply chain management, healthcare solutions, inventory management, localization, and tracking. Some of these applications require the tagging of surfaces (such as water, metal, the human body, and other high permittivity materials) that severely impair the performance of UHF tag in terms of impedance mismatch and gain reduction. On the other hand, the sensitivity of the UHF tag can be exploited for sensing applications [1]–[7]. Recently, the use of UHF RFID tags in healthcare applications has led to better facilitation, cost reduction, tracking and monitoring of patients [8]–[14]. A knitted wearable RFID tag was used as a strain sensor for respiration monitoring [15]. Moreover, an RFID based smart blood storage systems implemented in [16], which was capable of localizing individual blood bag. However, the RFID tag used for blood bag tagging was microstrip antenna having dimensions 50 × 50× 5 mm^3, which leads to a costly and bulky solution. A passive RFID tag based anemia detection sensor has been proposed in [17]. Whereas, the passive tag integrated with an additional sensor, which causes a further decrease in the detection range of the tag. In [18], an RFID system has been developed for the detection of IV needles. Although the low-cost tag used in this experiment embedded between the surgical tap, however, it has a large size with a small read range. Another passive tag (with 7 cm length) used for inventory management of IV solution and other drugs in [8]. However, this tag can't be readable, when directly pasted in the middle of the IV solution bag or bottle. A microstrip RFID tag proposed for high permittivity perishable goods and the human body [3]. However, the larger dimensions of this tag make it costly for mass production. In [19], a microstrip type RFID tag was proposed for moisture level sensing of soil. However, the proposed solution is costly with large dimensions. Moreover, another solution designed for the IV solution also consists of a microstrip type tag with relatively large dimensions [20].

Due to the shortage of nursing and medical staff, the care and monitoring of each patient's dose are very challenging. The level of IV drug solution is usually checked through periodic visual monitoring by nurse or patient. The essential alert regarding the empty level of IV solution is communicated by some attendant or patient using the emergency call button. This whole process of visual monitoring takes a lot of time and resources with some risk and errors. Therefore, in this paper, a low-cost, printed RFID tag antenna for healthcare applications has

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been proposed. Two different healthcare applications considered in this contribution, 1) IV solution level monitoring 2) blood storage management. The effects of high relative permittivity and conductivity of water, blood, and the human body are studied. The structure of tag is modified using equivalent circuit analysis; the modification is not huge for three applications, even a single tag can be fabricated and then remedied by adding small strips manually. Table I illustrates the comparison of the proposed RFID tag with the state of the art. The novelty of the proposed design is compared in terms of its size, cost, and water sensing capability. Moreover, the proposed tag can be printed directly on the IV solution bag or water bottle surfaces. The proposed tag provides the following features as compared with literature [19] - [23]: 1) low-cost (suitable for mass production), 2) a good impedance match with Impinj R6 RFID chip ranging from 860 MHz to 937 MHz, 3) relatively compact dimensions of 40 × 14 mm, and 4) water proximity sensing.

Section II describes the equivalent circuit analysis and optimization of the nested-slot and proposed RFID tag antenna. The measured results are compared with the simulation in Section III. Experimental testing of tag for IV level-sensing and blood phantom beg are presented in section IV, followed by conclusion in section V.

References	[This work]	[19]	[20]	[21]	[22]	[23]
Tag Size (mm2)	40 × 14	115×40	120 ×15	86 × 23	87.8× 57.9	96×26
Thickness (mm)	0.05	0.5	0.8	0.05	0.05	1.5
Substrate Type	Ink-jet printed Label-type Paper	Micro-strip	Micro-strip	Label-type	Label-type	3D Label-type
Fabrication Cost	Low	High	High	Low	Low	High
-10 dB Bandwidth	890 -937 MHz	850 -880 MHz	NA	860-920 MHz	NA	NA
Water Sensing	Yes	Yes	Yes	No	No	No
Read Range (Water Bottle),m	3.5, 2 (IV solution)	7.5 m (80 mL soil and water filled pot)	2.3 (IV solution)	2.2	2.5	0.36

* NA stands for Not Available

II. Concept and Design

A. Nested-slot Configuration

The nested-slot configuration (as shown in Fig. 1(a)) provides an excellent imaginary impedance on high permittivity materials [24] - [25]. The non-resonant behavior of slot forces it to offer inductive reactance both in free space and above high permittivity materials. The proposed tag was designed and optimized based on two aspects: 1) cost: label-type, compact tag is chosen for low-cost requirement due to mass production, 2) performance: to keep the good performance of tag on water bottle surface, the size especially the width of tag is kept small, because increasing width of tag poses an adverse effect on the performance of tag. The increase in width causes an increase in tag area under the influence of water, and hence more losses, which introduces a shift in impedance. The dimensions of and nested-slots are optimized using CST Microwave studio. Furthermore, as discussed in [26], the liquid causes an increase in loss resistance of the label-type tag. To investigate it further, the nested-slot structure translated to the equivalent circuit by applying the electric wall concept [2], [27]–[29]. Based on the symmetry of nested-slots, its equivalent circuit is shown in Fig. 1 (b).

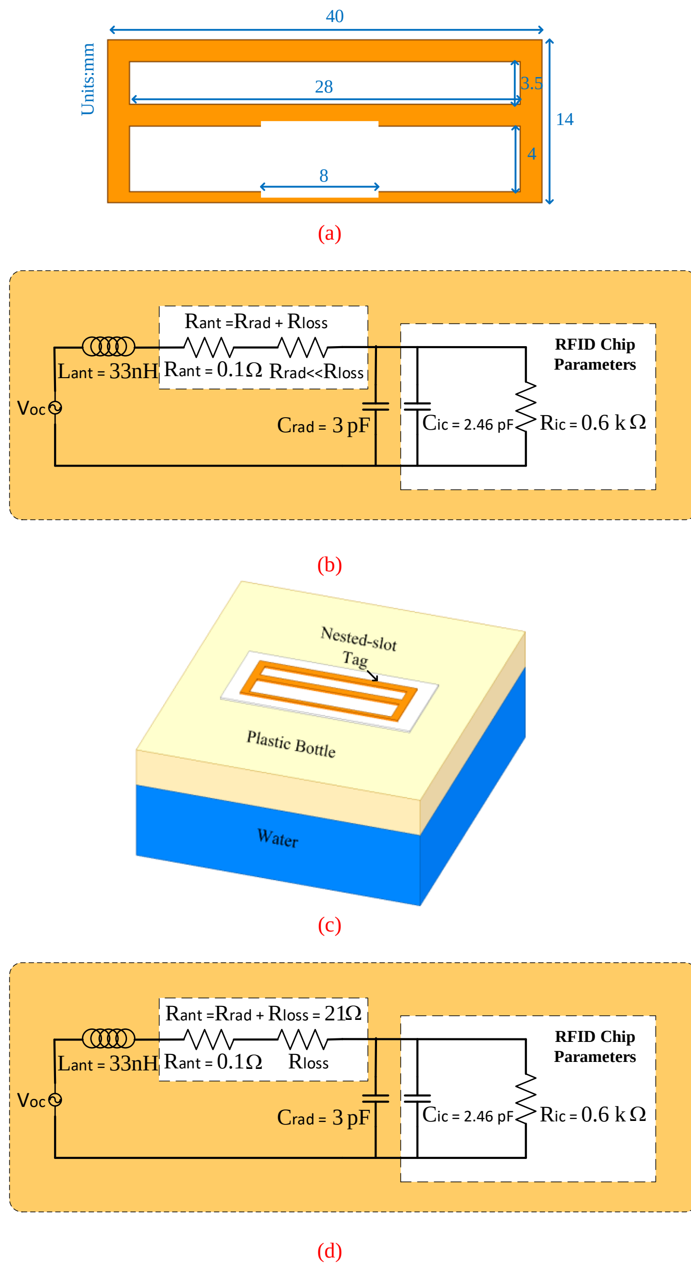
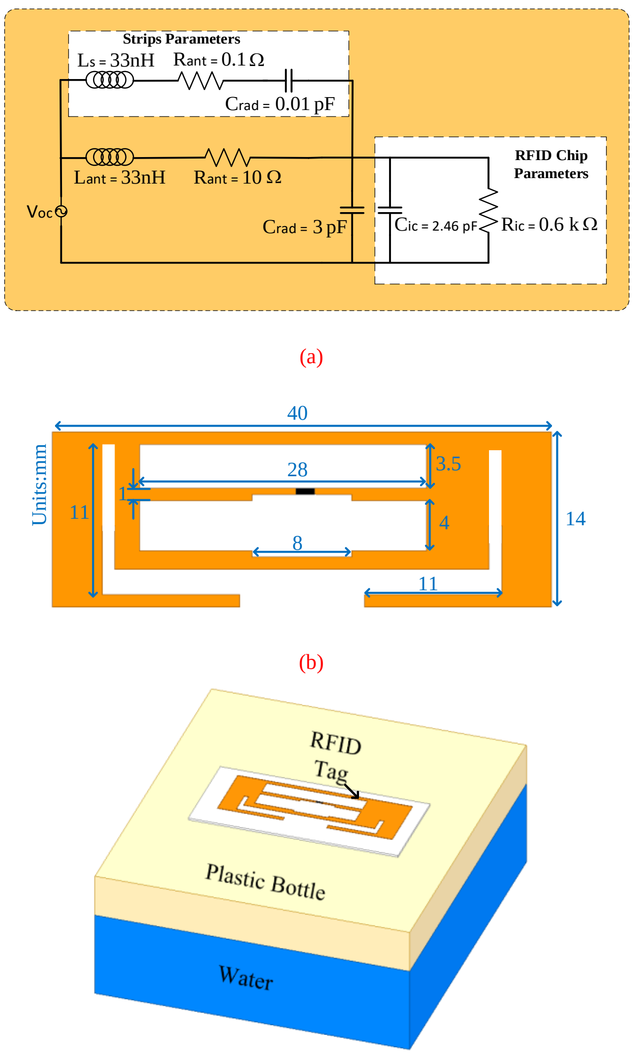


Fig. 1. (a) Nested-slot configuration used initially for tag design (b) Equivalent circuit of Nested-slot tag in the air (the values are approximated for free space) (c) Simulation setup for placement of the nested-slot based tag on water bottles (d) Equivalent circuit of Nested-slot tag on water bottles.

The estimated approximate value of antenna inductance using the electric wall concept [2] is L_{ant} =33 nH. The antenna resistance is the sum of loss and radiation resistance ($R_{ant}=R_{rad} + R_{loss}$). The radiation resistance is very small (ranging from 0.1Ω to 2Ω) in free space, which is equivalent to the resistance of the small loop. In free space, the loss resistance is usually very small as compared to radiation resistance. The antenna capacitance is due to the paper substrate and the part of the tag other than slots. The C_{ic}=1.23 pF and R_{ic}=1.2 kΩ are equivalent circuit parameters of R6 RFID chip. According to the electric wall concept, the value of chip capacitance should be multiplied by 2, while the chip resistance should be divided by 2. Furthermore, by analyzing the full wave simulated results obtained from CST, the equivalent circuit is simulated using ADS software, and optimized values are achieved by fine-tuning in ADS and curve fitting in Matlab, respectively.



(a)

(b)

(c)

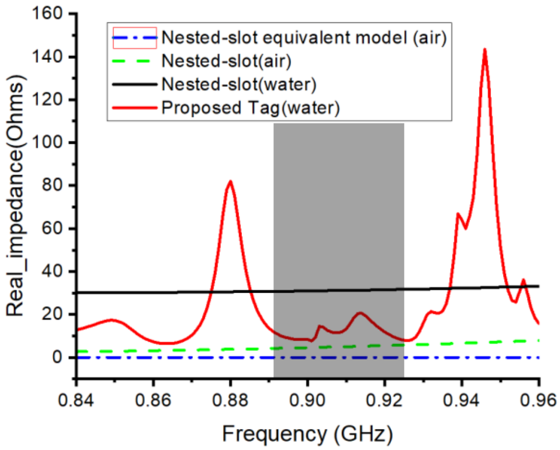
Fig. 2. (a) Equivalent circuit of proposed RFID tag on water bottles (b) proposed RFID tag antenna to mitigate water effects (c) Simulation model of placement of the proposed tag on water bottles.

To explore the effects of water on nested-slot structure, it was placed on a water bottle surface as shown in Fig. 1(c). After translating the effects of water into the equivalent circuit, it is revealed that its real impedance is increased ranging from 11 to 27Ω on the water surface as compared with real impedance in free space. This increase in real impedance is due to due to high relative permittivity and conductivity of water. Moreover, the increase in imaginary impedance is negligible. The increment in real impedance is favorable for impedance match with RFID chip. However, this increase in impedance is more as required for our RFID chip. This value can be reduced by shorting the length of nested-slots at the expense of a decrease in the value of the imaginary impedance value. However, to get better control over real impedance without affecting the imaginary part, parallel strips are added to the nested-slots tag configuration.

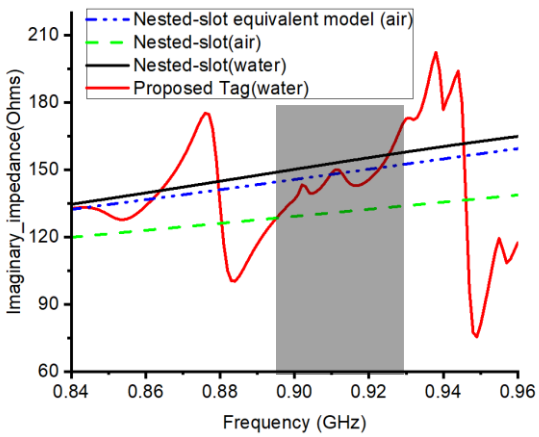
B. *Effect of parallel strip*

Furthermore, a degree of freedom to control the real impedance without affecting other parameters is achieved by adding an RLC circuit in parallel with existing antenna structure as shown in equivalent circuit model of Fig. 2 (a). After converting this equivalent circuit into the physical structure of the antenna, the proposed tag is shown in Fig. 2(b). The parallel RLC circuit can be view as parallel strips or a short dipole added with nested-slot structure. These parallel strips fulfill two main purposes 1) provide freedom in real impedance match 2) increases the value of gain on the water bottle surface (ε_r =78 and σ =0.05 S/m) [30], whereas these parameters for tap water at 20° C listed in [31] as follow (ε_r =79.2 and σ = 0.267 S/m at 1 GHz). To prove it further, the equivalent circuit based tag is simulated using CST by placing it on a water plastic water bottle. The dimensions of the simulation model of water bottle are 200 × 64 × 64 mm^3.

Figs. 3(a) and 3(b), show the real and imaginary impedance plot of nested-slot (CST), its equivalent circuit (ADS), and proposed tag (CST). The real impedance for nested–slot configuration and the equivalent circuit is very small in free space. However, the real impedance increases up to 30 ohms, when the nested-slot configuration mounted on the water surface. Additionally, the real impedance of proposed tag (with nested-slot and parallel strips as shown in Fig. 2(b)) on the water bottle is ranging from 13 Ω to 19 Ω (for US RFID band 902 MHz – 928 MHz), which is matched well with the real impedance of chip. On the other hand, imaginary impedance for nested-slot and its equivalent circuit is almost similar ranging from 125 Ω to 145Ω in the US RFID band, when it was placed in free space. Moreover, there is a slight change in the imaginary impedance of nested-slot on the water surface as compared with imaginary impedance in the air. The imaginary impedance of the proposed tag is varying in a different way; however, it is providing a good impedance match ranging from 130 Ω to 150 Ω in the US RFID band.



(a)



(b)

Fig. 3. (a) Real impedance plot for different configuration of the tag (b) Imaginary impedance plot for different configuration of the tag.

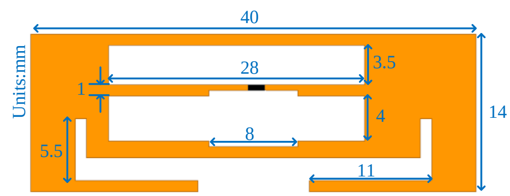
C. Optimization for IV solution, Blood tagging, and Human Body

The proposed tag needs some further optimized as it is to be used to sense IV solution, which has more conductivity as compared to water (0.001 to 0.05 S/m). For simulation purpose, the relative permittivity is taken as 78 for both water and IV solution. While, the conductivity of water and IV solution is taken as 0.05 and 0.59 S/m, respectively [30-31]. The primary effect of conductivity is a reduction of gain, while there is a little bit shift in the frequency band of operation. To mitigate this shift, the tag structure is modified a little bit, as shown in Fig. 4 (a). This revised version of tag is used for IV solution level sensing, blood bag tagging and human skin wound curing detection. The simulation model for tag mounting on the IV solution and human arm is shown in Figs. 4(b) and 4(c), respectively. The dimensions of the IV plastic bag are 200 × 200 × 1 mm^3. All components are modeled in simulation for more precise results. The human body is simulated using a 4-layered model with parameters described in [32]. Furthermore, the simulated gain of the proposed tag on water, IV solution, blood, and the human body (a four-layer model) is shown in Fig. 5. The gain of tag antenna on the water bottle is more as compared to other materials, which is due to less conductivity of water as compared with IV solution. Additionally, the skin depth value for water and human tissue is very less at 900 MHz due to their high relative permittivity and lossy nature [2], which is also a major reason for gain reduction. For the human body model, apart from conductivity, there are some other loss factors included; therefore, the value of gain for the human body is the least as compared with the other materials.

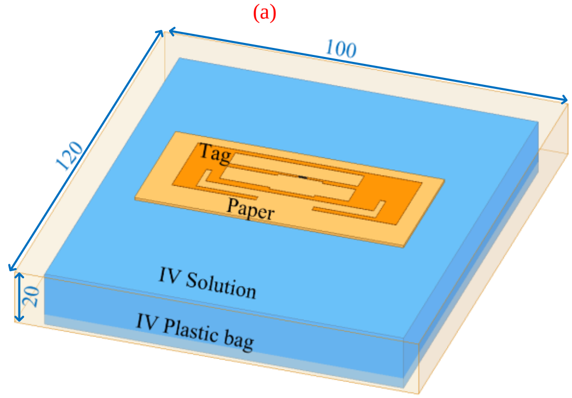
III. Measurements

A. Impedance measurement setup

The inlay without chip was employed for impedance measurement. The impedance measurement is carried out using a vector network analyzer by following the procedure described in [33].



(a)



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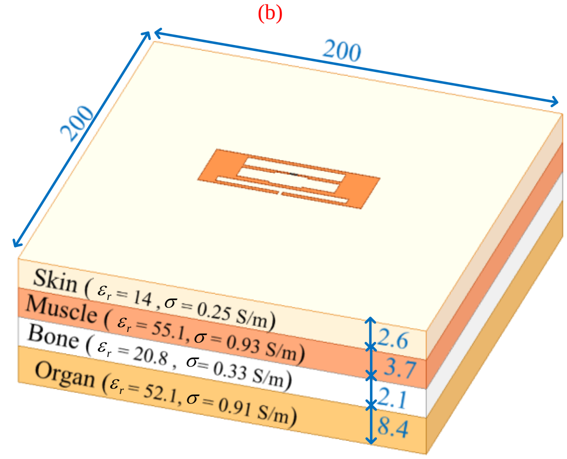


(c)

Fig. 4. (a) Modified tag for IV level sensing and blood tagging (b) simulation model for IV solution bag with tag antenna (c) Simulation model of the human body using for wound cure sensing.

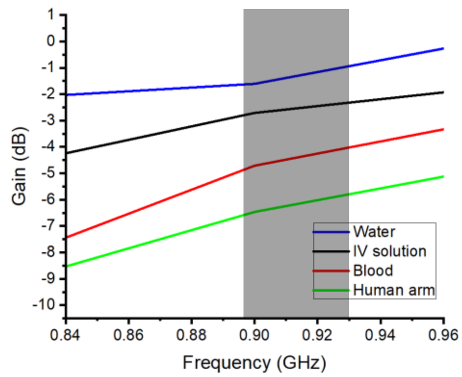
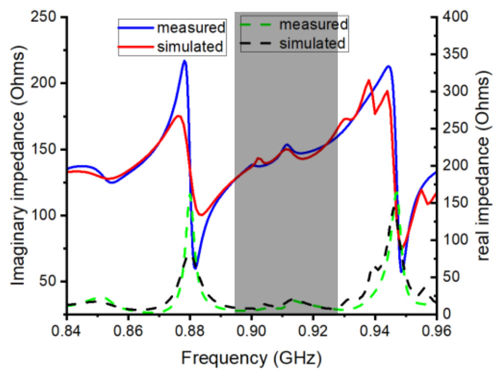
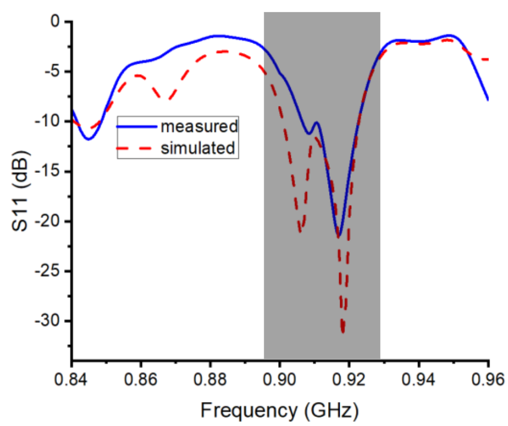


Fig. 5. Simulated modified tag antenna gain on different materials.



(a)



(b)

Fig. 6. (a) Measured impedance plot of proposed tag antenna (b) Measured and simulated return loss of proposed tag.

The measured real and imaginary impedance of the proposed tag is shown in Fig. 6 (a). The measured reflection coefficient (as shown in Fig. 6 (b)) is estimated using the formula given in [33]. Although, the measured results agree well as compared with simulation results. Whereas, the measured real impedance is less as compared with simulation. Since, we measured the impedance of inlay without soldering the measurement probe, since it is very difficult to solder probe in this case for such inlays.

So, there are a lot of discrepancies associated with this measuring method approach. Therefore, the measured return loss is less and a slight reduction in bandwidth, which may be due to measurement discrepancies, or difference in relative permittivity or conductivity of water from simulated value. Moreover, we have measured the performance of proposed tag in terms of read range using a more precise approach using Tagformance pro setup.

B. Read range measurement setup

Fig. 7 shows the fabricated prototype of nested-slot and proposed RFID tag printed on 50 μm paper substrate using conductive ink (15 μm Silver with σ = 12.5 x 10^6 S/m) by an ink-jet printer. A Fujifilm Dimatix DMP-2831 inkjet printer with 10 pL volume cartridge was used to print this tag on a paper substrate. Moreover, silver nanoparticle paste from Harima NPS series was used was used as an ink for tag printing propose. The tag was fabricated with 4 layered printing approach and sintering was done at 200° C for 30 minutes. The fabricated tag is mounted on an IV solution bag, containing 0.9 % sodium chloride injection solution as illustrated in Figs. 8(a) and 8(b). The read range is measured using the Tagformance setup as shown in Fig. 9. This setup provides a more accurate measure of read range. It estimates the read range with a smaller value of EIRP (equivalent isotropic radiated power) at a fixed distance, provided by foam spacer, then calculate the maximum theoretical read range using formula given in [34].

Fig. 10 shows the measured read range of the proposed RFID tag on different scenarios. The read range of the tag is maximum for water bottle (3 m) because the tag has more gain on water bottle due to less conductivity of water as compared with other materials. Moreover, this tag has a read range of 2.5 m and 1.5 m for IV solution bag and a blood phantom bag, respectively. However, the read range of tag for empty water bottle or IV solution bag is less than 0.5 m, due to impedance mismatch between RFID chip and tag. Although, the gain of tag in case of the empty bag is more as compared with the liquid filled case. Since the proposed tag was optimized to provide a match in case of IV solution, that's why there is an impedance mismatch in case of an empty bag causing less read range. Therefore, by comparing the read range of tag for an empty and filled solution case, it can be used as an IV solution level sensor.

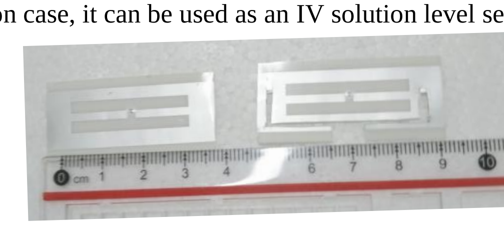


Fig. 7. A fabricated prototype of a nested-slot and proposed tag

(a) (b)

Fig. 8. (a) 0.9% sodium chloride injection solution (b) IV solution bag with fabricated tag.

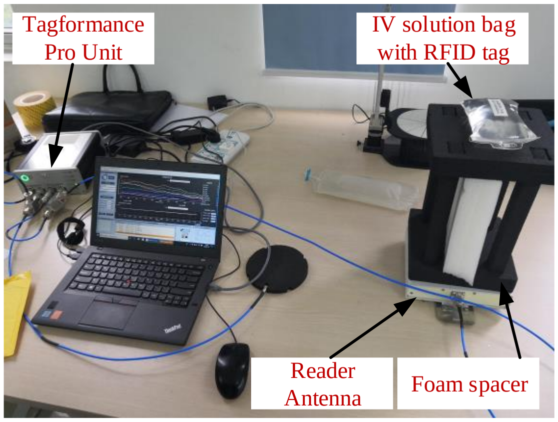


Fig. 9. Tagformance based read range measuring setup

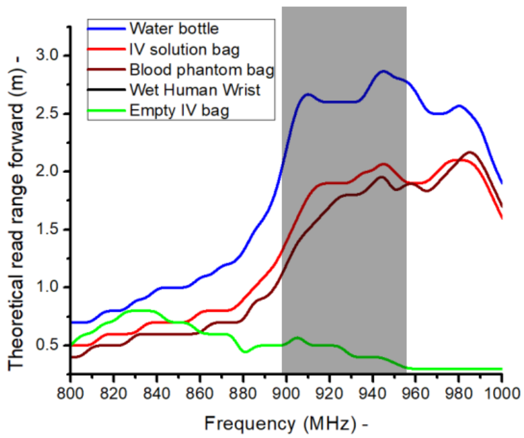


Fig. 10. Theoretical measured read range of proposed tag on different material using Tagformance setup.

IV. Experimental Testing

A. IV solution Level Sensing

The proposed tag is tested in a hospital ward room for IV level sensing as shown in Fig. 11. The tag is tested for both IV plastic bag and an IV plastic bottle. The fabricated tag mounted at the start and end of the plastic bottle. The 4 W EIRP reader setup with 8 dBi antenna was placed 1.5 m apart from IV tagged bag. Before the start of IV fluid injection, the reader can able to read both tags pasted at the top and bottom of IV fluid bag (as shown in Fig.8 (b)). After some time, the IV fluid has crossed the tag pasting level. At this point, the reader is not able to read tag pasted at the top of the bag, which can generate an alert for a successful start of IV injection into the patient body. When the level of fluid is below the tag are attached at the bottom, the reader again unable to read this tag, and hence can generate an alert for a nurse or other medical staff to stop the IV injection. Therefore, the proposed tag is suitable for IV level sensing for the hospital to improve healthcare facilitation. Furthermore, this tag can be used to monitoring the curing of the wound, by sensing the time for pouring more medicine on the dry wrist or by judging the dryness of wound.

B. Blood storage management

The bags containing a mixture of salt and sugar (as a substitute for a blood sample) are placed inside a refrigerator as shown in Fig. 12. The reader antenna placed at the bottom. The distance between the reader antenna and a shelf containing blood bags is 0.75 m. This experiment can be further extended to by placing tagged blood bags containing different blood group samples. A microstrip tag system for blood storage management was presented in [16]. However, a similar system with much lower cost can be realized by using a proposed RFID tag. The RFID tag based low-cost blood storage systems can be realized using the proposed tag to mitigate identification errors both at the blood bank and hospital side. Additionally, a cross-verification can be enabled using information stored in RFID tags such as blood group, collection date, expiry date, etc. Moreover, the reader can also use more EIRP due to the closed environment for a more accurate reading of the blood sample. This study will pave the way for better blood storage management and helps to reduce the risk of life by enabling safe blood transfusion.

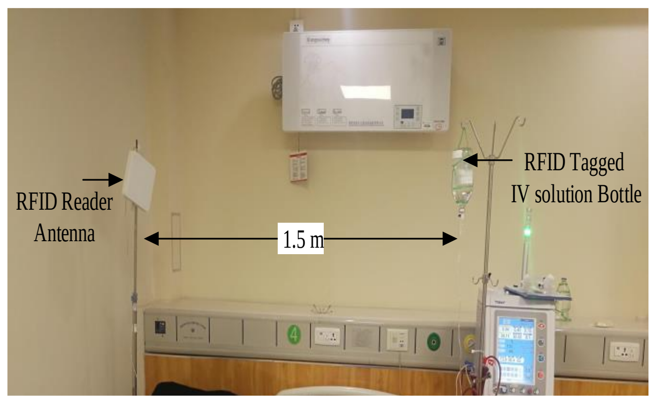


Fig. 11. Experimental setup for IV level sensing in a hospital's empty wardroom.

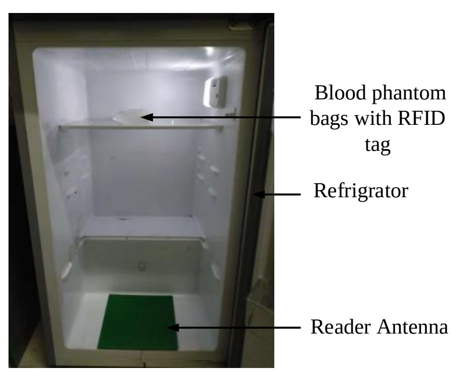


Fig. 12. Experimental setup for blood storage management.

V. Conclusion

In this paper, a low-cost printed RFID tag antenna has been presented for healthcare applications. The proposed tag consists of nested slots embedded with the parallel strip. The effects of water are mitigated using equivalent circuit analysis, and the results are translated to modify the tag structure. Moreover, the tag has read range of 3 m, 2.5 m, and 1.5 m on a water bottle, IV fluid bag, and blood bag, respectively. However, the read range of RFID tag on an empty water bottle or IV solution bag is 0.5 m. By comparing the read range of tag on empty and solution filled IV bags, this tag poses a unique feature of water proximity sensing. A fabricated prototype of the tag was tested for IV level sensing and blood bag tagging. Experimental results show a good agreement with simulation results. Furthermore, the IV level sensing experiment successfully conducted in the hospital ward room. For blood storage management, the tagged blood phantom bags are successfully read. These features recommend this tag for healthcare application in hospitals, which can add more care to patient monitoring and also reduces the cost.

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