INKJET-PRINTED UHF RFID TAG BASED SYSTEM FOR SALINITY AND SUGAR DETECTION

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ABSTRACT: *This paper presents an RFID system to detect the salinity and sugar contents of water. The proposed system is based on low-cost ink-jet printed passive ultra-high frequency (UHF) RFID tag. The tag is designed using slot match technique, which poses a good imaginary impedance match with RFID chip both in free space and after mounting on the water bottle. Moreover, the tag antenna is exploited as a sensor to detect salt and sugar contents of water by measuring the backscatter power from the tag in term of received signal strength indicator (RSSI). A Tagformance Pro setup form Voyantic is employed for measuring RSSI. Furthermore, an approximate relationship is derived between backscatter power and no. of grams of salt and sugar dissolved in water. This study paves a way to check the contents of drinks using portable devices, which is pivotal for healthcare applications in smart cities and the future Internet of things (IoT).*

Keywords: *Impedance match, RFID system; RFID sensor; Passive RFID tag; slot-match,*

1. INTRODUCTION

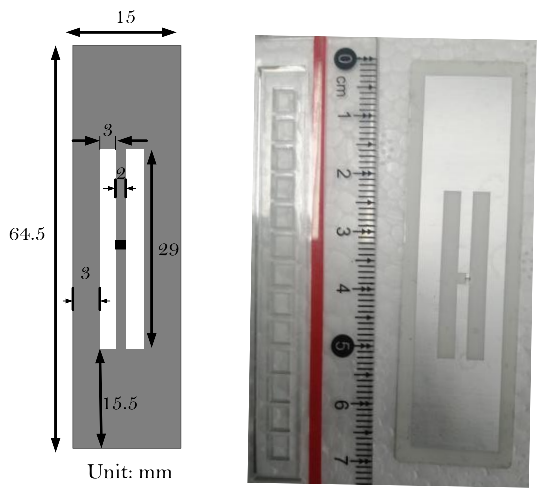
Radio frequency identification is opening new paradigms, especially in collaboration with the Internet of things(IoT). The passive UHF RFID tags are more promising in retail markets and inventory management due to their long read range and low-cost printable structure. However, the UHF tags are more sensitive towards its tagging surfaces and environments, which is considered to be a major drawback inherited with UHF tags. On the other hand, this sensitivity towards tagged surfaces makes UHF tags a battery-less and low-cost sensing device, which is pivotal for IoT applications [1-5]. As with the advancement of technologies people are becoming health conscious. Recently, a number of people are using their wearable devices and smartphone apps to record their diet and exercise habits to know how many calories gained or consumed. Similarly, in future people can sense the contents of their drinks in order to find how much calories they will gain by drinking. The salt and sugar are major contents of many drinks. Figure 1 shows the conceptual future water bottle with smart materials that can sense and display the contents of drinks. Therefore, in this paper, we propose an RFID system to sense the salt and sugar contents of water. The key behind the successful sensing of water contents is a low-cost printed RFID tag. Normally, the performance of UHF tags is seriously degraded near vicinity of water or high permittivity liquids. So, to mitigate water effects, the tag is designed using slot-match technique [6], which provides a high inductive reactance both in free space and on the surface of the water. Moreover, the dimensions of the tag are optimized to work properly after mounting on plastic bottles having pure water (without any manual addition of salt and sugar). Since the proposed tag was designed for pure water. Adding salt and sugar in water will affect the electrical properties of water such as conductivity and permittivity, and hence the performance of proposed tag will deviate from the optimal point (in case of pure water) in terms of gain reduction and impedance mismatch between the tag and

Figure 1 Conceptual Future water bottle with smart materials that can sense and display the contents of drinks [7]

RFID chip. So, the proposed can detect the change in water contents. The performance deviation of the tag (after mounting on water bottles having salt and sugar contents) can be detected by measuring the backscatter power from the tag. Consequently, the proposed tag is exploited as a sensor to detect salt and sugar contents of water by measuring the backscatter power using Voyantic Tagformance Pro setup. Furthermore, an approximate relationship is derived between backscatter power and no. of grams of salt and sugar solved in water.

2. CONCEPT AND DESIGN

The basic structure of the proposed RFID sensor tag is slot-match configuration [6], which provides a good inductive reactance on the surface of high permittivity dielectrics such as water. The tag is designed and optimized based on three main aspects: 1) electrical properties: electrically small with impedance match covering US RFID band (902 MHz - 928 MHz), 2) sensing features: Only provides a suitable read range and good impedance match with RFID chip on water bottle surface, 3) fabrication cost: low-cost and inkjet printed, which is suitable for large-scale usage. Figure 2 (a) shows dimensions of proposed tag antenna optimized using CST microwave studio. The fabricated prototype of tag printed on a paper substrate by an ink-jet printer using conductive ink (15 μm Silver with σ = 12.5x106 S/m) is shown in Figure 2 (b). The Impinj Monza R6 with impedance 16-140 j at 915 MHz (calculated by simulating equivalent circuit of the chip using ADS) is employed as an RFID chip. For simulation propose, the following parameters were used for water (permittivity=78 and conductivity=0.05 S/m [8]). Also, we employed the simulation model of a plastic water bottle (PET with permittivity =3.4) with dimensions 200x64x64 mm3. The performance of slot-match configuration is analyzed in free space and on water bottle surface in terms of impedance match with RFID chip.



(a) (b)

Figure 2 (a) Geometry and detailed dimensions of the proposed RFID sensor tag (b) Fabricated prototype of sensor RFID tag [Color figure can be viewed in the online issue, which is available at Wiley online library.com]

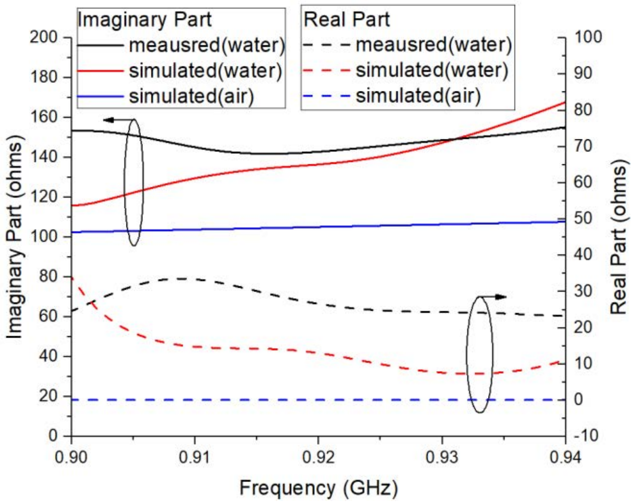


Figure 3 Measured and Simulated impedance plot of proposed RFID tag in free space and after mounting on water bottles

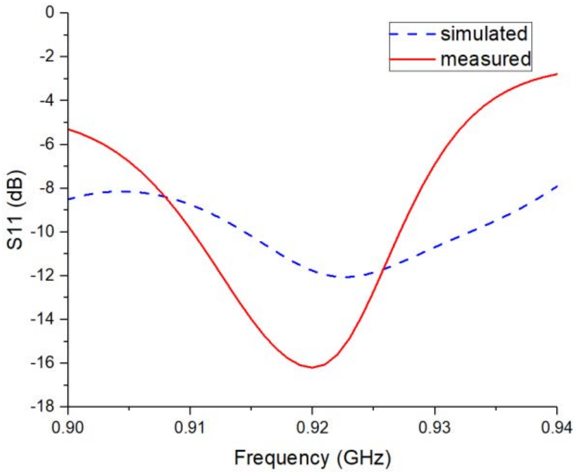


Figure 4 Measured and simulated return loss (S11) of the RFID tag antenna [Color figure can be viewed in the online issue, which is available at Wiley online library. com]

Figure 3 shows the simulated and measured impedance plot of the proposed tag in free space and after mounting on water bottles. It is clear (from Figure 3), the proposed tag configuration provides an imaginary impedance in US RFID band ranging from 100 to 110 ohms in free space. Similarly, it also poses an imaginary impedance ranging from 135 Ohms to 145 Ohms above water bottle surface, which is matched well with Impinj Monza R6 chip. On the other hand, the real impedance of tag in free space is very low limited to 0.01 to 0.05 Ohms. However, there is an increase in the real impedance of tag antenna as compared with real impedance in free space, which provide a base for sensing the water and water contents. The real impedance of tag 12 to 30 Ohms, which is due to the high dielectric loss of water. Furthermore, a tag inlay without RFID chip was deployed on the water bottle for impedance measurement purpose. The impedance of tag is measured by following the procedure specified in [9] using Agilent E8363B vector network analyzer. The measured results matched well with simulated results with a slight increase in the value of real impedance. The measured imaginary impedance is ranging from 138 ohms to 150 Ohms, while the measured real impedance is ranging from 20 to 30 Ohms, which may be due to the glue used to pasted the tag on the surface of the water bottle. Figure 4 shows the simulated and measured return loss (S11) of the proposed tag. The S11 is measured using formula listed in [9]. The simulated return loss shows a good match with RFID chip in US RFID band. However, there is a little bit decrease in the measured bandwidth of the proposed tag, which may be due to increased real impedance. Therefore, this tag provides a good impedance match on the water surface and poor impedance match in free space, which shows its capability to work as a sensor. In addition to this, the simulated gain and impedance of the proposed tag with a different conductivity value of water is shown in Figure 5 and 6, respectively. There is a decrease in the value of gain can be observed with increasing the conductivity of water. The change in conductivity of tag is more significant as compared to impedance. However, there is also a change in real and imaginary impedance of the tag. Overall, all these features of the proposed tag make it a suitable candidate to sense the contents of water.

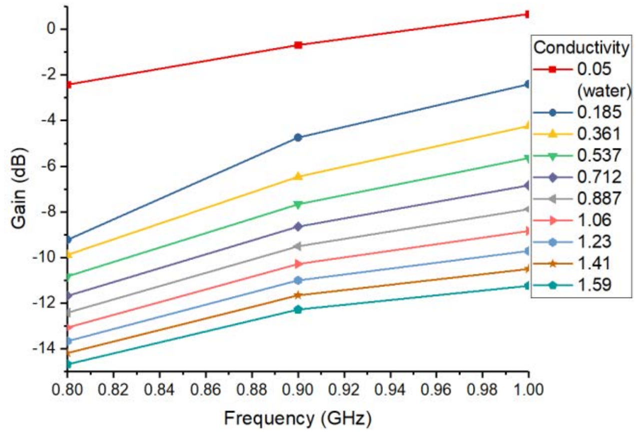
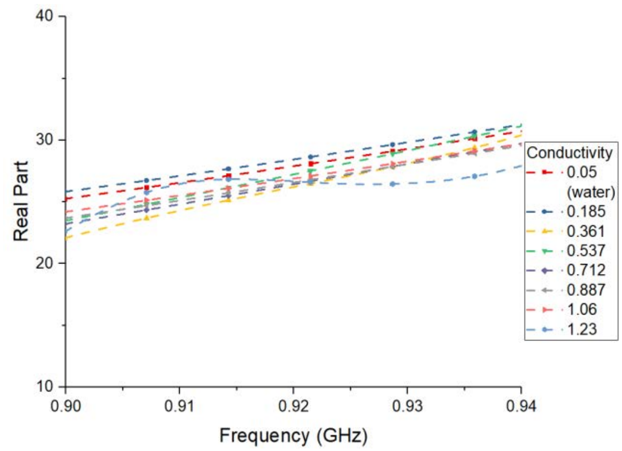
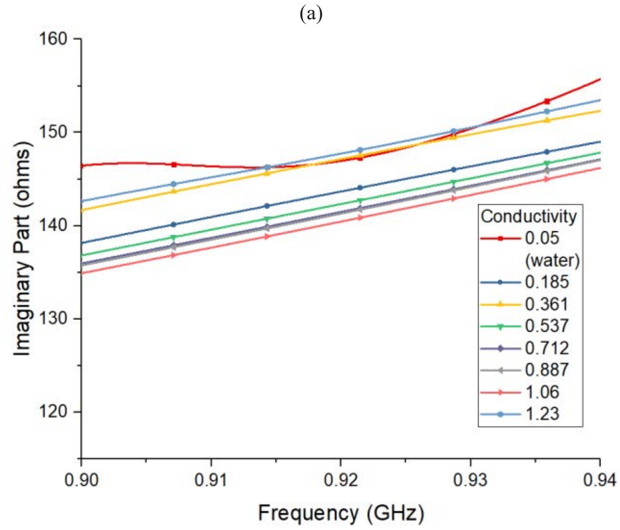


Figure 5 Simulated gain of tag antenna with different values of conductivity [Color figure can be viewed in the online issue, which is available at Wiley online library. com]



(a)



(b)

Figure 6 (a) simulated real impedance with different conductivity values of water (b) simulated imaginary impedance with different conductivity values of water [Color figure can be viewed in the online issue, which is available at Wiley online library. com]

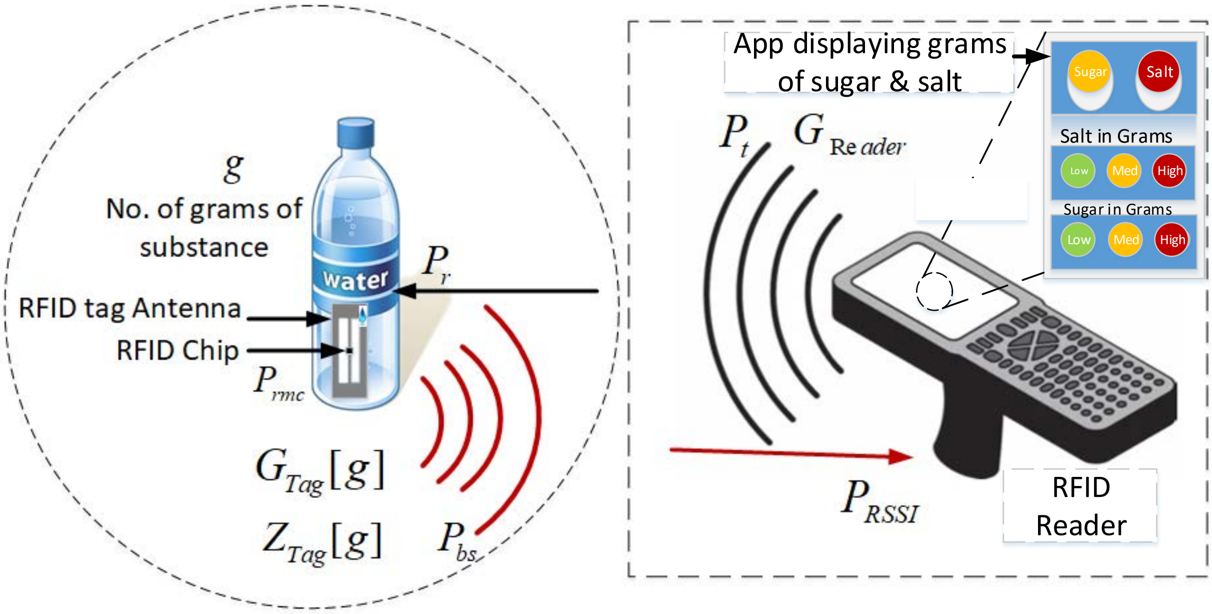


Figure 7 Sketch of sensing methodology employed to use the proposed tag as water content sensor [Color figure can be viewed in the online issue, which is available at Wiley online library.com]

3. SENSING METHODOLOGY

The reduction in gain and impedance mismatch due to changing the contents of water can be sensed by measuring backscatter power from RFID tag. Figure 7 shows the sensing methodology employed to use the proposed tag as a water content sensor. The reader setup is placed at a fixed distance 'd' from the tag is mounted on the plastic water bottle. The parameters of reader setup are known, such as input power P_t and reader antenna gain G_{Reader}.

Let 'g' denotes the no. of grams of substance (sugar or salt) dissolved in water, which has to be sensed. Where P_r, P_{rmc}, P_{bs} and P_{RSSI} are power received by tag, power input to RFID chip, backscatter power, and backscattered power measured by a reader in terms of RSSI, respectively.

Therefore, the equations expressed in [10] and [11] can be re-write in free space accordingly, to extract the sensing parameters.

The power received by tag antenna can be written as:

$$P_r = \frac{P_t G_{Reader}}{4\pi d^2} * \frac{\lambda^2}{4\pi} G_{Tag}[g]\eta_p \qquad (1)$$

Where $G_{Tag}[g]$ and $Z_{Tag}[g]$ are gain and the input impedance of tag with respect to substance contents g. Also, η_p is polarization mismatch between tag and reader antennas.

The power transferred to microchip can be expressed by

$$P_{rmc} = P_r * \tau[g] \qquad (2)$$

Where $\tau[g] = 1 - |\Gamma_m(g)|^2$ is the power transmission coefficient, $|\Gamma_m(g)|$ is reflection coefficient of tag, which measures impedance mismatch between RFID chip impedance $Z_{chip} = R_{chip} + jX_{chip}$ and antenna impedance $Z_{Tag}[g] = R_{Tag}[g] + jX_{Tag}[g]$.

The reflection coefficient and power transmission coefficient with respect to substance contents g can also be expressed in terms of antenna and chip impedance as follows:

$$|\Gamma_m(g)| = \frac{Z_{chip} - Z_{Tag}[g]}{Z_{chip} + Z_{Tag}[g]} \qquad (3)$$

$$\tau[g] = \frac{4R_{chip}R_{Tag}}{|Z_{chip} + Z_{Tag}|^2} \qquad (4)$$

Moreover, the power transferred to microchip can be written as:

$$P_{rmc} = \frac{P_t G_{Reader}}{4\pi d^2} * \frac{\lambda^2}{4\pi} G_{Tag}[g]\eta_p * \tau[g] \qquad (5)$$

The backscatter power from the tag is

$$P_{bs} = P_r \bullet G_{Tag}[g] \bullet |\Gamma_m(g)|^2$$

$$P_{bs} = \frac{P_t G_{Reader}}{4\pi d^2} * \frac{\lambda^2}{4\pi} G_{Tag}[g]\eta_p \bullet G_{Tag}[g] \bullet |\Gamma_m(g)|^2$$

$$P_{bs} = \frac{P_t G_{Reader}}{4\pi d^2} * rcs_T[g] \qquad (6)$$

Where $rcs_T[g]$ is RFID tag's radar cross section

$$rcs_T[g] = \frac{\lambda^2}{4\pi} G_{Tag}{}^2[g] \bullet |\Gamma_m(g)|^2 \qquad (7)$$

Similarly, the backscatter power from the tag can be measured by a reader in terms of RSSI:

$$P_{RSSI} = \frac{1}{4\pi d^2} * \frac{\lambda^2}{4\pi} G_{Reader} * P_{bs} \qquad (8)$$

$$P_{RSSI} = \frac{1}{4\pi d^2} * \frac{\lambda^2}{4\pi} G_{Reader} * \frac{P_t G_{Reader}}{4\pi d^2} * rcs_T[g]$$

$$P_{RSSI} = \frac{1}{4\pi}\left(\frac{\lambda}{4\pi d}\right)^2 P_t G^2{}_{Reader} rcs_T[g] \eta^2{}_p \qquad (9)$$

Hence, the content of substance dissolved in water of water can be sensed by measuring P_{RSSI}.

4. RESULTS AND DISCUSSION

The backscatter power from the tag is measured using Voyantic Tagformace Pro setup in a laboratory environment as shown in Figure 8. The tag is mounted on water bottles (as shown in Figure 9) and placed at 30 cm apart from reader antenna using a foam spacer (d=30 cm). This setup is usually employed to find theoretical read range of RFID tags by finding the threshold for reading the tag in each frequency. By applying (9), the system software finds the backscatter power of RFID tag in terms of RSSI. Firstly, the backscatter power is measured for the proposed tag after mounting with simple 500 ml plastic water bottle without adding any sugar or salt contents. Moreover, to detect the salinity and sugar contents of water, the backscatter power from the tag is measured after mounting the tags on the same water bottle by adding different concentrations of salt and sugar.

(1) Detecting salinity of the water

Adding more and salt in water cause an increase in the conductivity of water [12], with little bit change in permittivity of water. Therefore, with the increase in the salt contents dissolved in water mainly cause a reduction in gain of RFID tag as compared with a gain on simple water. Also, it will cause a mismatch between the impedance of tag and RFID chip. Figure 10 shows the backscatter power from tag measured using Voyantic setup for different concentration of salt (NaCl, kitchen salt was used in this experiment) dissolved in water. Overall, the change in water due to salt contents can be sensed by measuring the backscatter power. Moreover, it can be noticed the backscatter power continues to decrease with increasing salt contents of the water (as illustrated in Figure 10).

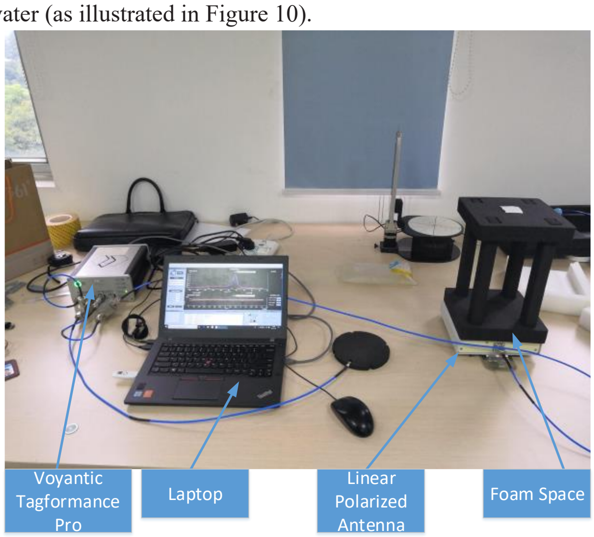


Figure 8 Voyantic Tagformance Pro Set for measuring RSSI [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Figure 9 Fabricated prototype of RFID sensor tag antenna pasted on water bottle [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

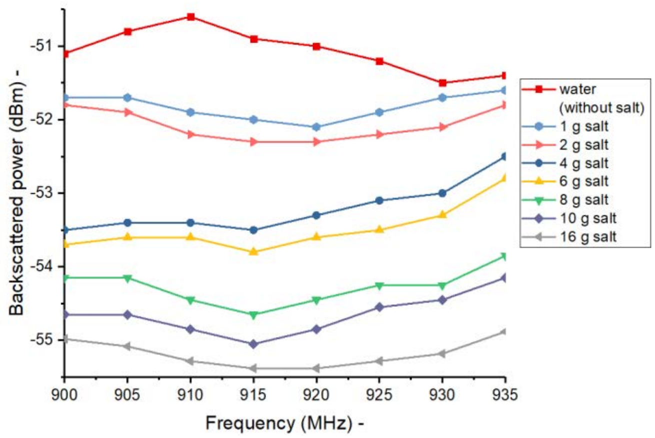


Figure 10 Measured backscatter power (RSSI) from RFID tag with different salt concentration dissolved in water [Color figure can be viewed in the online issue, which is available at Wiley online library.com]

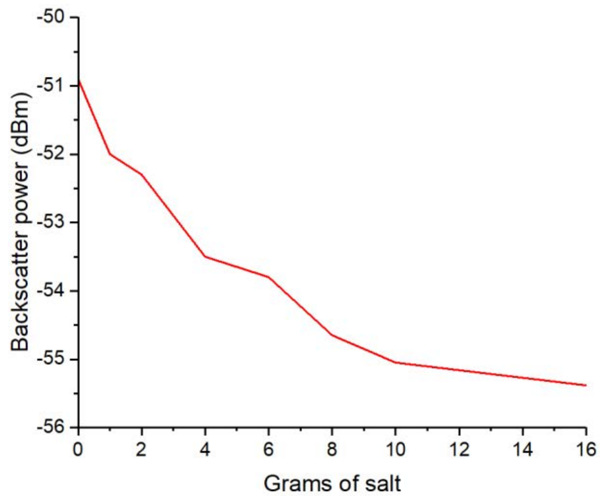


Figure 11 Response of backscatter power measured towards grams of salt dissolved in 500 ml water bottle at 915 MHz [Color figure can be viewed in the online issue, which is available at Wiley online library.com]

Figure 11 illustrates the response of backscatter power at 915 MHz in terms of the number of grams of salt dissolved in water. To analyze the tag's sensing capability, we derived an empirical relationship between backscatter power from tag and number of grams of salt dissolved in water, using MATLAB curve fitting technique.

The derived relationship can be described as follow:

$$g_{salt} = 0.000013P^4_{RSSI} - 0.00031P^3_{RSSI} + 0.049P^2_{RSSI} - 2.597P_{RSSI} - 51 \qquad (10)$$

Where P_{RSSI} is backscatter power in dBm and g_{salt} is the number of grams of salt dissolved in water.

(2) Detecting sugar contents of the water

As referred to [12], adding more and more sugar contents does not increase the conductivity of water rather, it will decrease the relative permittivity of water. Therefore, with the increase in the sugar contents dissolved in water also cause an impedance mismatch and gain reduction as compared with simple water. Figure 12 depicts the backscatter power from tag measured by Voyantic setup towards different concentration of sugar contents dissolved in 500 ml water bottle. Overall, the number of grams of sugar is sensed by measuring the backscatter power. Moreover, it can be observed the backscatter power continues to decrease with increasing sugar contents in water as illustrated in Figure 12. By comparing Figure 10 and 12, it can be witnessed that adding more sugar content into water cause little reduction in backscatter power of tag as compared with backscatter power measured in case of salt contents. Actually, the salt contents increase the conductivity of water, which mainly results in the gain reduction of RFID tag. Consequently, the gain reduction in the case of sugar is less as compared with the salt case.

Furthermore, Figure 13 illustrates the response of the backscatter power of proposed sensor tag in terms of the number of grams of sugar dissolved in water. we also tried to find an empirical relationship between backscatter power and number of grams of sugar dissolved in water as follow:

$$g_{sugar} = 0.0000051P^4_{RSSI} - 0.00094P^3_{RSSI} - 0.007P^2_{RSSI} - 2.55P_{RSSI} - 51 \tag{11}$$

Therefore, by using (10) and (11), the proposed tag can sense salt and sugar contents dissolved in water with approx. 82.82 % and 78.83% accuracy, respectively. This experiment can also be realized with RFID reader with RSSI measuring capability. This study paves a way for sensing the contents of drinks for healthcare in smart cities and the Internet of things (IoT) applications.

5. CONCLUSION

This paper proposes an RFID system for detecting salt and sugar contents of water. This system is based on a low-cost, inkjet printed RFID tag, which is mounted on water bottles to sense the contents of water. The proposed tag is designed using the slot-match technique, which provides a high imaginary impedance match both in free space and after mounting on the water bottle. Initially, the tag was optimized to operate with water-filled plastic bottles. Additionally, the proposed tag was exploited to sense the salt and sugar contents of water by measuring the backscatter power from the tag in terms of RSSI. A Voyantic Tagformance Pro set was employed for measuring RSSI. Furthermore, we derived an approximate relationship between backscatter power and no. of grams of salt and sugar dissolved in water. This study paves a way to check the contents of drinks using RFID enabled smartphones and other embedded portable devices, which is pivotal for healthcare in smart cities and the future Internet of things (IoT) applications.

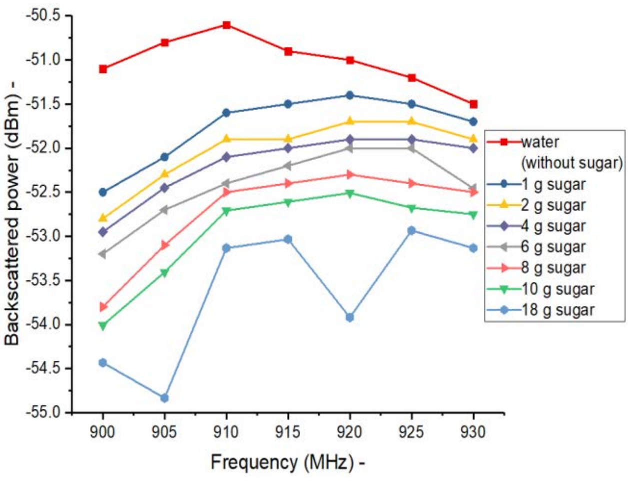


Figure 12 Measured backscatter power (RSSI) from RFID tag with different sugar concentration dissolved in water [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

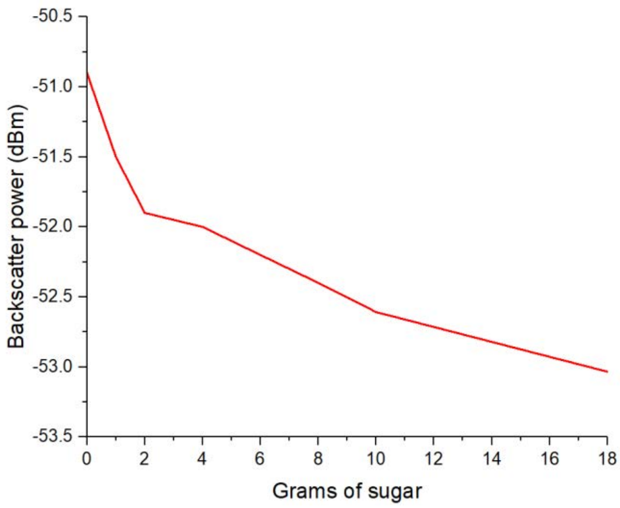


Figure 13 Response of backscatter power measured towards grams of salt dissolved in 500 ml water bottle at 915 MHz [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

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