Smart radio-frequency identification tag for diaper moisture detection

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A passive smart tag is described that responds to dampness in diapers once a pre-defined threshold value is reached. A high-frequency (HF) system at 13.56 MHz is used as this allows operation through water or human tissues with less absorption that would occur for an ultra-HF signal. A circular spiral coil and swelling substrate facilitate a reaction to dampness that can be detected without contact to the diaper wearer. A prototype design is simulated and measured results are provided together with a demonstration of a tag integrated into a worn diaper.

1. Introduction: Average life expectancy worldwide in 2025 will reach 73 years [1], with the elderly population expected to rise faster than the general population [2]. Longevity related disabilities and diseases will put more pressure on healthcare. In this Letter, our aim is to design a cheap flexible sensor embedded in a diaper to reduce the workload of carers in nursing homes by logging and notifying staff of the urinating habits of elderly residents.

Wireless technologies are already contributing in many biomedical applications and there have been a number of recent studies reporting wireless diaper dampness detectors. In [3], a GSM network communication is used to a tele-monitor in the diaper comprising a processor and a humidity sensor, whereas [4] utilises Zigbee as the transmission system to a sensor including a signal converter, Zigbee module and power supply. A radio-frequency identification (RFID) system is proposed at ultra-high frequency (UHF) in [5] to help juveniles overcome nocturnal enuresis and for geriatrics with incontinence problems. A commercial UHF tag was placed in a diaper and was observed to decrease in function when it became surrounded by liquid and saturated superabsorbent gel. RFID systems are similar to barcoding, and can identify a tagged object. They however can carry more information and therefore are used in many logistics and asset tagging applications where wireless and non-line of sight identification is required [6]. RFID tags are also detectable when obscured by dirt, covered by polymer housing or even embedded with an object to be identified [7–9]. Moreover, external components and microelectromechanical system sensors can be added for additional functionality [10]. However, the RFID system performance can be influenced by materials such as metals and water in the environment in which the tag has been applied because the wireless transmission is degraded with a subsequent reduction in the tag read range [7, 9, 11].

Rather than using the UHF band discussed in [5], we propose a tag using high-frequency (HF) RFID, which transmits by induction between two coils and is widely used, often at 13.56 MHz, in short range applications such as NFC [12] and the MiFare system [13]. The use of magnetic coupling to communicate is advantageous in the presence of the human body which is highly capacitive and causes significant tuning problems in conventional antenna systems such as those at UHF. Experimental studies of HF tag performance have shown that close proximity to a metal plate increases the antenna resonance frequency above that in open space and weakens its field intensity [14]. It is also found that this effect strongly depends on the distance between the metal plate and the antenna, which severely affects the read range of the system. This strong dependency on the exact coil separation from a conducting plate will be exploited here in a smart RFID tag developed to be hidden inside a diaper. The tag activates when a dampness threshold is reached, allowing it to identify itself to an external read device. HF tag costs can be up to \$0.2 which compares with the \$2.2 unit price of a disposable diaper, and therefore integration of sensing tags should not represent a significant cost barrier. The tags required for this application do not require random access memory and therefore are at the lower cost end. The proposed system requires the reader to be placed near the tag and for the coils to be parallel. The patient would not need to be undressed in order to check a visual dampness indicator.

2. RFID tag coil resonance: Passive HF RFID systems at 13.56 MHz that have no internal power supply to energise and activate the low-powered CMOS tag transponder chip employ the near-field inductive coupling of the transponder tag with the reactive energy of the reader antenna. The tag antenna with inductive reactance large enough to match the tag IC capacitive reactance maximises the power collected by the tag antenna and transferred to the IC. Since the wavelength at HF is very large for practical RFID applications, highly inductive printed spiral coil antennas are used to transfer energy between tag and reader. The two coils in close proximity can be interpreted as a transformer in which a very weak coupling is formed between the two windings, and the efficiency of power transfer is proportional to the number of windings and the distance between the two [6].

The efficiency of the energy transfer from the reader to the tag depends on the precision of the parallel resonant loop antenna tuned to the system resonance frequency. The tag used in this paper is shown in Fig. 1*a*, whereas the circuit shown in Fig. 1*b* depicts the simplified equivalent circuit, where the resonance frequency f_0 and the equivalent resistance R_{eq} are given by

$$f_0 = \frac{1}{2\pi\sqrt{L_{ant} \cdot C_{ic}}} \tag{1}$$

and

$$R_{eq} = \frac{R_{ic} \cdot R_{ant}}{R_{ic} + R_{ant}} \tag{2}$$

where R_{ic} is the tag IC resistance, C_{ic} is the tuning capacitance of the chip, R_{ant} is the antenna coil parallel resistance and L_{ant} is the antenna coil inductance.

The tag read range is the primary tag performance indicator for the purposes of sensing and is directly related to the Q value of the inductance. A high Q antenna is preferred to provide higher sensitivity, providing the system has adequate bandwidth and manufacturability. A spiral coil is chosen to fit inside the diaper, where the

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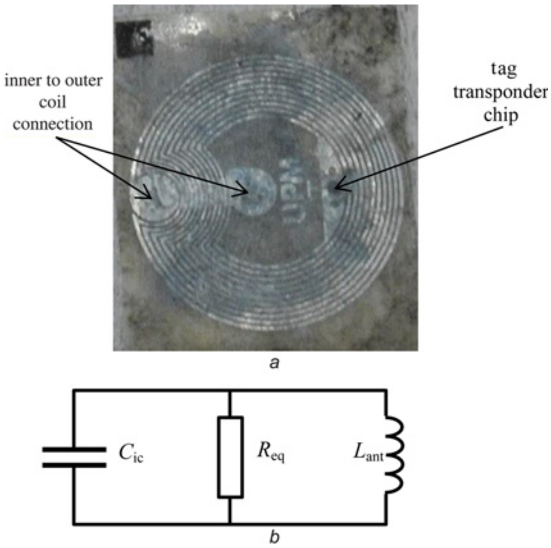

Figure 1 *HF RFID tag and equivalent circuit*
a HF RFID tag
b Equivalent circuit of HF RFID tag

coil size is a compromise between the tag size restriction of the application and the read range. Satisfying these constraints and knowing the capacitance of the RFID transponder chip allows the coil dimensions to be found that offer the appropriate inductance [15]

$$L_{\text{ant}} = \frac{A^2 N^2}{30A - 11D_{\text{i}}} \tag{3}$$

where coil area A is

$$A = \frac{D_{\text{i}} + N(w + s)}{2} \tag{4}$$

and D_{i} is the inner diameter in inches, N is the number of turns, s is the inter-winding gap in inches and w is the track width in inches. When the coil is placed in close proximity to a metal sheet, the eddy effect acts to reduce the effective coil inductance and the resonance frequency of the coil and chip is increased. As the metal sheet is moved away, the effective coil inductance increases, meaning that the tag resonance decreases. This is the basis of the sensing function of the tag.

3. Smart substrate principle of operation: The dampness sensing smart tag design consists of a perforated metal sheet slightly larger than the tag antenna. The conducting sheet and the tag are glued to a permeable paper layer and covered with a small amount of sodium polyacrylate powder [16], as shown in Fig. 2*a*. The permeable layer is formed from high strength tissue paper, which is folded over and sealed at the edges with water resistant glue with sufficient slack to allow the polyacrylate powder to expand on the absorption of liquid, Fig. 2*b*. In Fig. 2*c*, a sketch of the sealed tag schematic in the dry stage is shown, where the antenna is very close to the perforated metal plate and the thickness of the entire tag is <2 mm. At such close proximity to a conducting surface, the tag would not respond to a reader device and is in what we term as a ‘deactivated’ state.

If a sufficient quantity of water comes into contact with the smart tag, it will be absorbed by the sodium polyacrylate through the tissue paper lining. Sodium polyacrylate expands significantly as it absorbs liquid, and this causes the tag coil to separate from the perforated metal plate to a distance of about 10 mm as shown in Figs. 3*a* and *b*. The separation distance is directly related to the wetness of the diaper, and therefore once a threshold separation is reached, the tag will respond to reader interrogation.

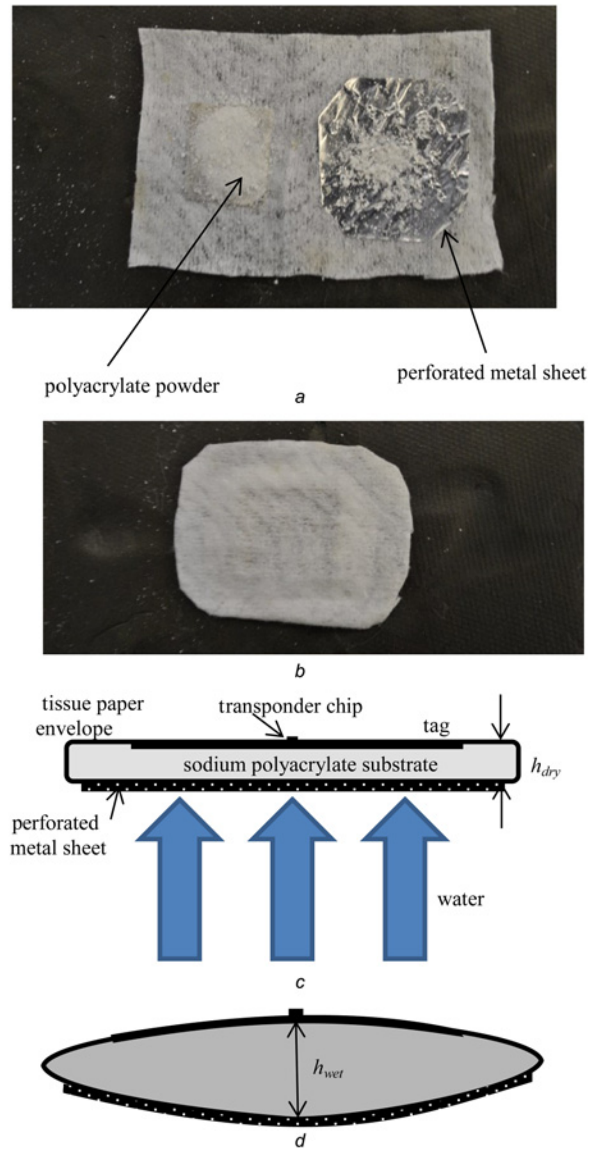

Figure 2 *Prototype tag in dry stage, sealed prototype tag, schematic of dry stage and schematic of wet stage*
a Prototype tag in dry stage, showing perforated metal plate, tag antenna and sprayed sodium polycarbonate
b Sealed prototype tag
c Schematic of dry stage
d Schematic of wet stage, showing swelling of sodium polycarbonate in presence of liquid

4. Simulated and measured performance: A circular coil, with the dimensions given in Table 1, was modelled in CST Microwave Studio® and simulated using the frequency solver. Fig. 4 depicts the simulated tag reactance where the tag antenna has been designed to resonate, and therefore be read at 13.56 MHz in the wet state. The broken line shows that because of the close proximity of the perforated metal sheet, the tag antenna is detuned in the dry stage and resonates at too high a frequency. In this situation, no read occurs. The solid lines in Fig. 4 illustrate how, as the smart tag absorbs liquid from the surrounding environment and the sodium polyacrylate expands, the induced capacitance reduces. This causes a parallel resonance to occur where the reactance has a zero crossing at 13.56 MHz for about 12 mm separation between the tag and the perforated metal sheet.

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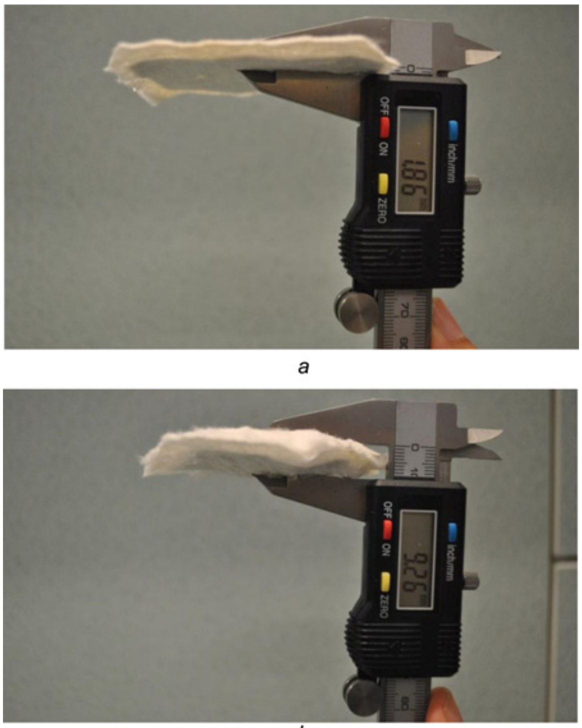


a

b

Figure 3 *Prototype tag in dry stage and after exposure to water*
a Prototype tag thickness in dry stage
b Swollen prototype tag after exposure to water

According to Fig. 3*b*, the swollen tag is ∼10 mm thick, which is sufficient to cause the tag to read.

The smart tag measurement was carried out using a desktop development reader [17], with output power of 500 mW and a commercial spiral tag. The maximum read range achievable for the development reader with its small (5.84 cm × 9.14 cm) integrated antenna is 12 cm when used with full size tag coils. Before assembling the smart tag, the reader was able to identify the spiral tag when placed directly on a dry tissue at 7 cm, and at 6.7 cm range on a saturated wet tissue. The observed read ranges are small compared with the maximum possible for the reader because the tag coil used in this demonstration is small. This indicates that the tissue wetness has little effect on the tag response.

When the tag was fitted to the smart substrate as shown in Figs. 2*a* and *b*, as intended, the reader failed to detect the tag even at close proximity to the reader. Once more than 7 ml of liquid was added to the smart substrate, it expanded as illustrated in Figs. 3*a* and *b*, and the tag response was recognised by the reader at up to 4.7 cm. This reduction in the detection range by about 40% indicates that the close proximity of the tag to the perforated metal plate in the smart substrate adversely affects the system efficiency, and in future work it is intended to investigate improvement in tag design to operate on a wet substrate and in close proximity to the perforated metal plate. The smart tag was fitted at the centre part of the diaper, as in normal operation most dampness is absorbed in this section. However, this tag position is not favoured to achieve maximum detection range, and further work is intended to investigate and design tags with wider detection angles, as well as optimising reader antenna design and positioning to achieve maximum detection range.

Table 1 Tag coil dimensions in millimetres

D_i	S	w	N	h_{dry}	h_{wet}
15	0.5	0.5	10	1.9	9.3

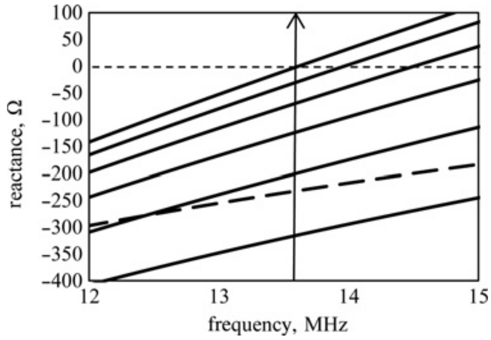
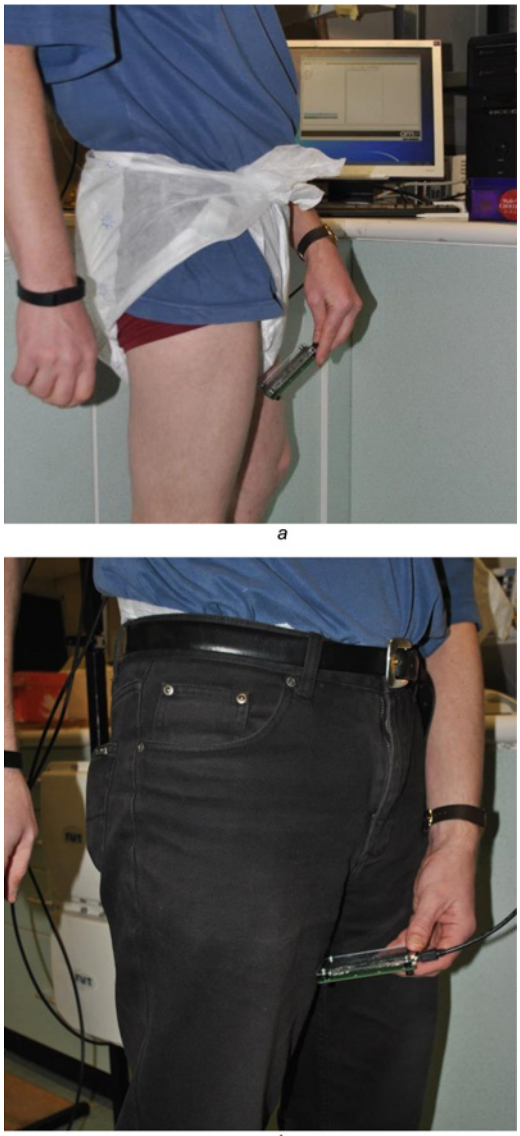


Figure 4 *Simulated smart tag reactance in dry state (broken line) and as tag absorbs water and expands in thickness from 2 to 12 mm (solid line)*
Direction of the arrow shows increase in tag thickness in 2 mm increments.



a

b

Figure 5 *Demonstration of diaper sensor HF read antenna position to obtain response*
a Without outer clothing
b With outer clothing

5. Demonstration: To demonstrate the system, the tag was mounted inside the outer lining of a large size adult disposable diaper. The dry tag was first observed not to read before it was

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worn. The diaper was then put on an adult and again the tag was observed not to read when the reader system was brought close. The diaper was then removed and 200 ml of water was poured into the absorbing lining. The nappy was then worn again. Within 3 min of the diaper being dampened, the tag was observed to read when the reader was brought into the proximity (several centimetres) of the sensor. The tag read when the diaper was both exposed, Fig. 5*a*, and worn under clothing, Fig. 5*b*.

6. Conclusion: The HF tag reported here could communicate with a reader coil built into furniture or bedding. The read ranges obtained could allow discretion in detecting dampness and, being contactless, can be used without disturbing a wearer while they are asleep. External antennas fixed to bed posts with higher power readers (1 W) connected to a network could increase detection range to close to 1 m, and notify carer station. Alternatively, the substrate could be used in association with an UHF tag design to facilitate read ranges in the order of metres and this would reduce the risk of false negative reads where the reader is not correctly aligned with the tag, or is too far away. Finally, as the tag became damp, a slight decrease in frequency and increase in activation power was observed associated with the permittivity and loss tangent of water within the substrate. These effects were secondary to those of the plate separation.

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8 References

[1] 50 Facts: Global health situation and trends 1955–2025. Available at http://www.who.int/whr/1998/media_centre/50facts/en/, accessed 19th December 2014

[2] Hooyman N., Kiyak H.: ‘Social gerontology: a multidisciplinary perspective’ (Allyn and Bacon, 2002, 6th edn.)

[3] Qin T., Li X., Wang Y., Liu Z.: ‘Design of GSM-based telemonitoring and alarm system for disposable diaper’. IEEE Int. Conf. on Green Computing and Communications and IEEE Internet of Things and IEEE Cyber, Physical and Social Computing, 2013, pp. 392–394, doi: 10.1109/GreenCom-iThings-CPSCom.2013.84

[4] Wu M.-Y., Huang W.-Y.: ‘Health care platform with safety monitoring for long-term care institutions’. Seventh Int. Conf. on Networked Computing and Advanced Information Management (NCM), 2011, pp. 313–317

[5] Nilsson H.-E., Siden J., Gulliksson M.: ‘An incontinence alarm solution utilizing RFID based sensor technology’. IEEE Int. Conf. on RFID-Technologies and Applications (RFID-TA), September 2011, pp. 359–363

[6] Finkenzeller K.: ‘RFID handbook: fundamentals and applications in contactless smart cards, radio frequency identification and near-field communication’ (Wiley, 2010, 3rd edn.)

[7] Qing X., Chen Z.N.: ‘Proximity effects of metallic environments on high frequency RFID reader antenna: study and applications’, *IEEE Trans. Antennas Propag.*, 2007, **55**, (11), pp. 3105–3111

[8] Want R.: ‘An introduction to RFID technology’, *IEEE Pervasive Comput.*, 2006, **5**, (1), pp. 25–33

[9] Dobkin D.M., Weigand S.M.: ‘Environmental effects on RFID, tag antennas’. Proc. IEEE Int. Microwave Symp., June 2005, pp. 135–138

[10] RFID Sensor Systems. Available at http://www.rfidsensorsystems.com/, accessed 19 December 2014

[11] D’hoe K., Van Nieuwenhuyse A., Ottoy G., De Strycker L., De Backer L., Goemaere J., Nauwelaers B.: ‘Influence of different types of metal plates on a high frequency RFID loop antenna: study and design’, *Adv. Electr. Comput. Eng.*, 2009, **9**, (2), pp. 3–8

[12] Near Field Communication. Available at http://www.nearfieldcommunication.org/, accessed 19 December 2004

[13] Mifare Smart Cards. Available at http://www.mifare.net/en/products/mifare-smartcard-ic-s/, accessed 19 December 2014

[14] Kuoa S.-K., Hsub J.-Y., Hungb Y.-H.: ‘A performance evaluation method for EMI sheet of metal mountable HF RFID tag, Measurement’, 2011, **44**, (5), pp. 946–953, doi:10.1016/j.measurement.2011.02.018

[15] Wheeler H.A.: ‘Simple inductance formulas for radio coils’, *Proc. Inst. Radio Eng.*, 1928, **16**, (10), pp. 1398–1400

[16] Sodium Polyacrylate, Superabsorbent Polymers. Available at http://www.depts.washington.edu/chemcrs/bulkdisk/chem142A_aut05/notes_Sodium-Polyacrylate.pdf, accessed 19 December 2014

[17] AS3910-HF RFID DEMO KIT. Available at https://www.ams.com/eng/Support/Demoboards/NFC-HF-RFID/NFC-HF-RFID-Reader-ICs/AS3911-Demo-Kit, accessed 19 December 2014