PRINTED WIRELESS DEVICES FOR LOW-COST, CONNECTED SENSORS FOR POINT-OF-CARE APPLICATIONS

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ABSTRACT

Resource-limited settings require point-of-care (POC) diagnostic solutions that can be rapidly manufactured at a low cost. These solutions require efficient ways to communicate data, and are therefore ideally suited to the internet of things (IoT). We present wireless devices towards the realization of connected, automated and low-cost sensing solutions, with focus on POC disease diagnostics for South African clinics as an initial example. Specifically, ultra-high frequency (UHF) radio frequency identification (RFID) and near-field communication (NFC) device implementations are presented, utilizing the printability of antennas on to low-cost, flexible substrates as a foundation on which to develop low-cost, connected sensors.

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1. INTRODUCTION

The evolution of the internet of things (IoT) has resulted in a drive to include intelligence in and connectivity between devices and systems [1]. In parallel, healthcare has seen a shift towards low-cost and automated point-of-care (POC) disease diagnostic solutions, particularly in resource-limited countries [2]. Data connectivity of such devices has become increasingly important to enable patient and result tracking and record-keeping [3,4]. Radio frequency identification (RFID) techniques provide a potential solution for POC data connectivity, by providing a wireless - and thus contamination-free - connectivity solution, where both ultra-high frequency (UHF) RFID and near-field (NFC) techniques can be implemented and have been investigated.

RFID has a number of advantages over existing identification techniques such as barcodes, including longer reading ranges, faster data transfer, and multiple, simultaneous tag reading. Passive RFID tags draw energy from the electromagnetic field radiating from the reader when the tags are within the reader range, a favourable implementation that does not require a battery or external power source, thus lowering the cost of the device. RFID has been used in many applications, including logistics, pharmaceuticals and healthcare, to name a few [5]. A thorough review of passive RFID sensors and systems, including current state-of-the-art, has been published [6].In addition, paper is considered to be one of the best organic substrates for UHF and microwave applications [7], making it ideally suited for the implementation of RFID technologies. As such, printing of antennas for wireless applications has been explored [8], and is being expanded on to include sensing capabilities for RFID technology [5].
Additionally, the field of printed electronics has seen rapid growth in recent years, enabling various functional modules ranging from components such as resistors and capacitors, to processing and wireless communication systems, to be implemented on flexible substrates [9]. This can be achieved using established, accessible, low-cost printing techniques such as screen printing, which lends itself to scale-up and mass manufacturability of printed devices. The evolution of printed electronics, in combination with paper-based microfluidics for low-cost disease diagnostics [10] has driven research towards integrated disease diagnostic solutions [11] that comprise these technologies in various functional printed modules. The focus of this work was to explore potential printable wireless sensing and communication mechanisms towards achieving the goal of integrated, low-cost POC diagnostics, while being suited to resource-limited clinics, such as those commonly found across South Africa.

Studies conducted at clinics in Gauteng, South Africa, showed the limitations of current clinic workflows, and the potential for RFID solutions to address the various challenges [12]. Recent developments in RFID technology enable sensing capabilities to be integrated as part of the RFID solution, making this technology ideally suited to clinic settings where automated read-out and communication of a test result is required. This work explores these aspects towards the long-term goal of a fully integrated POC diagnostic solution. Different RFID categories are suited to different POC diagnostic applications. NFC can make use of a mobile phone as a reader and thus is well suited to home-based use or personal healthcare applications. UHF RFID typically uses external reader devices and can achieve longer read-ranges using simple antenna designs, making it well suited to testing in clinics or hospitals, where the reader can be a permanent fixture. The printability of both NFC and UHF RFID tag antennas on to flexible, paper-based substrates has been investigated using both inkjet printing and screen printing techniques, with assembly of the tag integrated circuit (IC) to the printed antenna implemented in each case. Inkjet printing allows for finer resolution and features to be achieved but is better suited to low volume prototyping. Screen printing can be used for both prototyping in low volumes, making it ideal for research and development phases, but can also be scaled up to larger processes such as roll-to-roll printing.

Functional tags were illustrated by demonstrating wireless communication of information stored on the ICs to a mobile phone or a personal computer (PC). This information could include the type of test, serial number, manufacture date and expiry date for POC tests.

Integration of sensing capabilities with RFID solutions can also be explored for POC applications. The SL900A UHF RFID IC (ams, Austria) allows for a number of different sensors – including resistive, capacitive and optical - to be connected and the measured values to be wirelessly communicated. This provides a compact platform on which to develop sensors with automated, wireless communication of the results to an external device or cloud. Previous work using a similar approach illustrated temperature readout and fluidic detection [13]. Colour detection for lateral flow test read-out is currently being explored and could make use of the RF field to power a small light-emitting diode (LED) to realize a passive, low cost device.

2. METHODOLOGY

NFC and UHF RFID tags and circuitry were designed using computer-aided design (CAD) software. The tag antenna designs were based on the AS3955 NFC IC development kit (AS3955-WL_DK_ST, ams, Austria) and SL900A UHF RFID IC development kit (SL900A-DK-STQFN16, ams, Austria) for the NFC and RFID tags, respectively.

Figure 1 shows the tag designs used for printing of NFC and UHF RFID tags, with footprints and descriptions of the different components shown. One of the three basic reference NFC tag antenna designs that form part of the AS3955 NFC IC development kit was used for this work, namely the 23 mm x 38 mm coiled design (Figure 1). The NFC IC package size is 3 mm x 3 mm x 0.9 mm. Dimensions of the contact pads are 0.4 mm x 0.25 mm with a spacing of 0.25 mm between the pads. An insulating bridge was designed (yellow strip in Figure 1) to enable a connection to be made from the outer antenna coil to the NFC IC over the antenna loop.

The basic reference design for a dipole antenna for the SL900A UHF RFID IC development kit was used for this work, and is contained within a 110 mm x 35 mm area (Figure 1). The SL900A IC package size is 5 mm x 5 mm x 0.9 mm. Dimensions of the contact pads are 0.4 mm x 0.355 mm with a spacing of 0.8 mm between the contact pads.

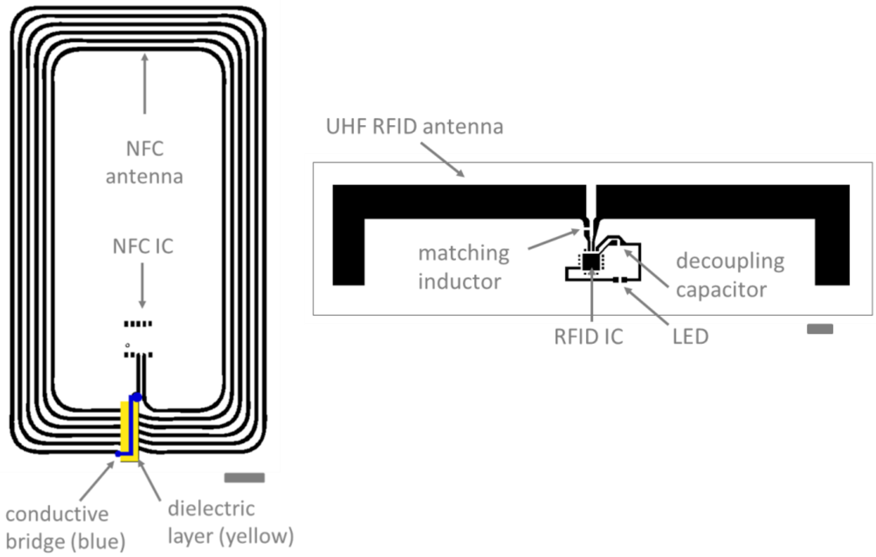

Figure 1: NFC tag design and components for AS3955 NFC IC (left) and UHF RFID tag design and components for SL900A UHF RFID IC (right). Scale bar = 3 mm in each case.

Both NFC and UHF RFID tag designs were inkjet printed on to photo paper (NB-RC-3GR120, Mitsubishi Paper Mills Ltd, Germany) using a Dimatix DMP 2831 materials printer (Fujifilm, Japan) and conductive silver ink (NPS-JL silver nanopaste, Harima Chemicals, Japan).

After printing, the devices were assembled by mounting the NFC and UHF RFID ICs and other surface mount device (SMD) components using superglue and a two-part silver loaded epoxy (RS Pro Silver Epoxy Conductive Adhesive, RS Components, South Africa) for creating connections to the printed tracks. Additional components used were a strip of insulating kapton adhesive tape to create a bridge, a 39 nH SMD matching inductor, a 2.2 µF SMD decoupling capacitor, to extend the read range, and a green SMD light emitting diode (LED), all from RS components, South Africa. After assembly, the epoxy was left to cure at room temperature for 24 hours for optimal conductivity to be achieved.

Manual screen printing of tags was also performed for the UHF RFID tags to illustrate printability on to different flexible, low-cost substrates. Screens were manufactured by Chemosol (Pty) Ltd, Johannesburg, South Africa. Screen printing was carried out using an LPKF Protoprint S stencil printer (CadShop, South Africa) with modifications made to enable screens to be manually mounted in to the frame of the printer. A synthetic mesh of 71 threads/cm (71/180-55 PW, SEFAR PET 1500) was used for the screen for this work, and was manufactured by Chemosol. A silver screen printable ink (AG-800, Applied Ink Solutions, USA) was used for screen printing with a rubber squeegee (70-75 Blue Apolan, Chemosol, South Africa) on to different substrates. Once printed, the ink was cured in an oven at 90 °C for 15 minutes.

3. RESULTS

NFC and UHF RFID tag designs as shown in Figure 1 were manufactured, assembled and tested to illustrate the functionality for wireless communication of data stored on the tags, as demonstrated in Figures 2 and 3. NFC has very short read ranges, up to only a few centimetres depending on the system parameters, and for the manufactured prototype in Figure 2, the mobile phone needed to be in very close proximity to the tag (almost contacting) to allow for detection of the tag.

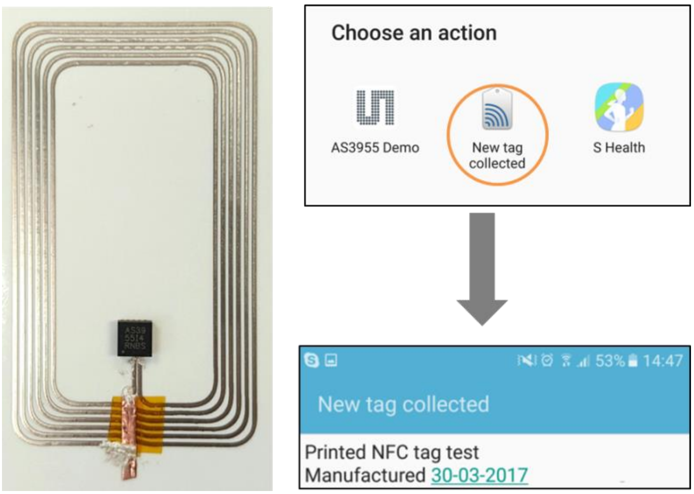

Figure 2: Printed and assembled NFC tag and resulting functionality of manufactured and assembled tag tested using a Samsung Galaxy S6 smart phone as a reader (NFC-enabled mode). The phone detects a new tag when in range of the reader (phone handset), and displays text information that was stored on the tag prior to scanning the tag. Other data formats can be written to the tag, including website links.

For the UHF RFID tag antenna design, read ranges of up to 2 metres would be expected in ideal conditions and in battery-assisted mode, with over a metre for passive mode (without a battery) having been reported in previous literature [14,15]. Read ranges of approximately 400 mm have been achievable using the inkjet printed tag antenna design with the SL900A IC (Figure 3) in passive mode, and more than 800 mm in active mode. The optimal read range specifications assume that there is perfect matching between tag and antenna, but as a result of the thin printed layers achieved with inkjet printing, there is a mismatch between the impedances of the antenna and the RFID chip, as well as poor antenna gain. In addition, the flexible substrate and consequent bending of the antenna could also hinder the read range achievable. A number of factors that are known to affect antenna performance are highlighted later during the discussion.

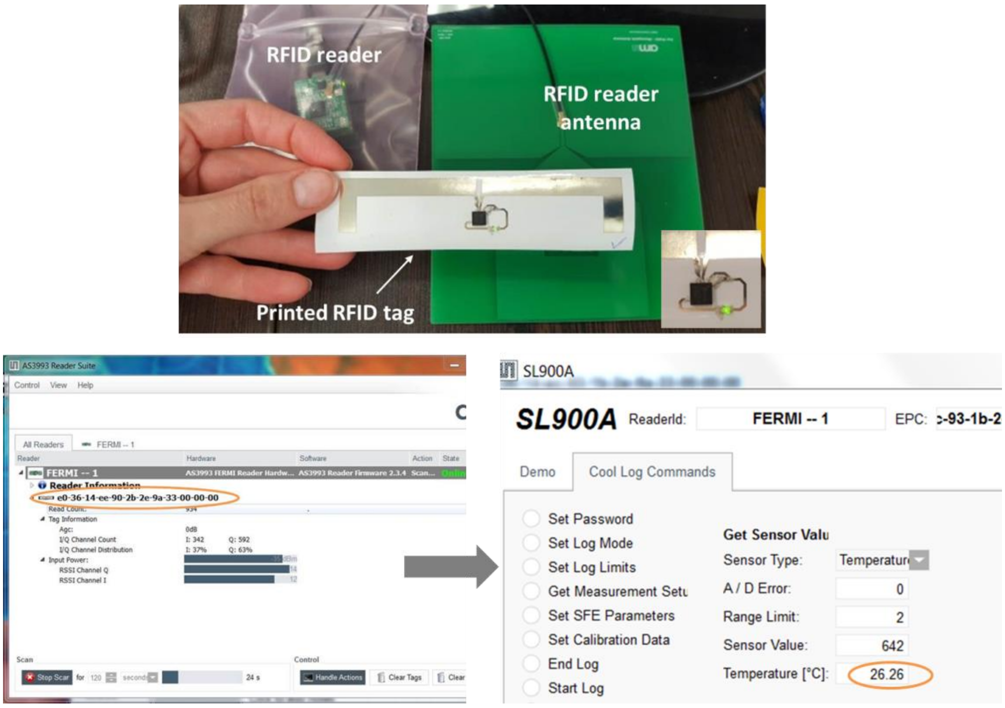

Figure 3: Printed and assembled UHF RFID tag and resulting functionality of manufactured tag tested using an AS3993 reader and antenna. When the tag is in range of the reader antenna, the green LED on the tag is illuminated using the RF field. The sensing capabilities of the SL900A IC enable the instantaneous read out of temperature using the development kit software.

With initial functionality being shown successfully, printing of different UHF RFID tag designs for use with the SL900A UHF RFID IC were also investigated. These tag designs obviated the need for an additional matching inductor, as required for the SL900A dipole antenna reference design. Figure 4 shows an example of a tag antenna design based on the AD-224 from Avery Dennison, which was inkjet printed. The SL900A IC was assembled on to the printed tag antenna, and successful scanning and read-out of temperature from the tag using the AS3993 development kit was demonstrated, although the read ranges of 100 mm – 200 mm were shorter than with the dipole antenna design.

Figure 4: Example of inkjet printed UHF RFID tag design based on AD-224 tag from Avery Dennison with SL900A IC assembled for readout of temperature and other sensor values.

Screen printing of SL900A tag antennas using the dipole antenna reference design was also performed to investigate the feasibility of implementing the tag antennas on to different low-cost, flexible substrates. Additional printed tracks were included on this design to allow for a coin cell battery to be included to extend the read range and power any additional components required for sensing applications. Initial results show that the tags can be successfully printed, assembled and detected by the the AS3993-QF_DK_R FERMI development kit reader for screen printing on to substrates such as standard printing paper, cardboard packaging, adhesive vinyl and poly(methyl methacrylate) (PMMA) with average read ranges of 300 mm achieved in passive mode.

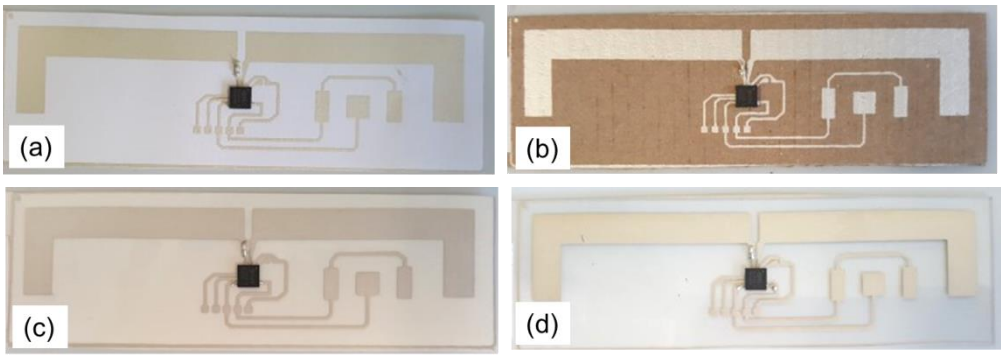

Figure 5. Examples of screen printed tags on to different low-cost, flexible substrates: a) standard printing paper, b) cardboard packaging, c) transparent adhesive vinyl and d) transparent PMMA. SL900A reference dipole antenna design was used with an SL900A IC and 39 nH matching inductor assembled.

4. DISCUSSION

The results illustrate the feasibility of implementing low-cost, flexible and wireless devices using printing techniques. Both NFC and UHF RFID technologies have been showcased, enabling different read-out platforms to be utilized, i.e. a mobile phone or a separate antenna and reader module, each applicable to different settings for POC testing. The SL900A RFID IC provides a neat, integrated package for implementing connected sensors – a variety of which are in the process of being explored specifically for POC diagnostic applications. In addition to temperature readout, sensors can be connected to the SL900A for readout of quantitative values from POC diagnostic tests.

Read ranges of between 400 and 800 mm were achieved for passive and active UHF RFID tags, respectively. These results are sufficient for the intended clinic applications. Manual assembly of the tags caused variations in the read ranges achieved. A number of other factors are commonly known to affect the read range, including: the antenna gain, antenna polarization, output power, reader sensitivity, transponder (SL900A chip) antenna type, and operating mode of the SL900A (battery assisted or passive). In addition, shorter read ranges can result if the transponder is handled with bare hands, if there are objects between reader and transponder antenna and can vary from room to room because of reflections of the RF signal. For the stated 2 m range in the data sheet for the Fermi reader development kit as used in this study, specifications of the reader and antenna are not provided, making it difficult to use this as a comparison. In addition, other literature making use of the SL900A IC and development kit have optimized the tag antenna designs for impedance matching according to the substrate to achieve read ranges of between 800 mm and 1.1 m in passive mode [14,15]. These are generally implemented on optimal substrates and each has different antenna and reader settings, which can affect the read range. The approach of this work was to print and assemble the tag as is to test the feasibility of printing and implementing the tag without optimization.

The initial functional results obtained for the UHF RFID tags provide sufficient read ranges for the intended applications for POC testing, as these are large enough to prevent contact of the sample with the reader, thus preventing potential contamination. Read range improvements could also be made through printing of multiple layers for the tags to improve the performance. Assembly techniques using automated pick and place equipment would also improve the reliability and repeatability of the assembled tag antennas.

The scale-up of these devices for mass production has also been considered. Both inkjet and screen printing techniques can be adapted to larger volume prototype production runs, and screen printing can be performed using roll-to-roll processing for mass production of the printed devices. Full production of standard RFID tags typically cost under EUR 0.15 per tag, and with the additional cost of the SL900A chip sensing capabilities, a cost of under EUR 3 per sensing antenna tag would be expected.

The low costs of existing RFID tags assist in achieving the long-term goal of low-cost POC diagnostic solutions. The tags implemented will be similar in cost to existing tags, and will provide an overall improved solution on current systems and workflows employed in clinics. The low-cost perspective focusses on the automation of the read-out and wireless communication of results from rapid POC diagnostics, which would ultimately reduce the cost of performing the diagnostic test as clinic workflows would be optimized, and trained staff and/or laboratory facilities would not be required. This work only focusses on a component of this long-term goal with full cost comparisons not possible.

Current cost projections for scaled up printed electronics facilities vary depending on the complexity of the device being manufactured. Some examples taken from Piila et al. [16] are mentioned to provide perspective on this. For purely printed layers, costs in the order of EUR 0.3 per 5 cm x 5 cm multi-layered printed device could be expected, and includes materials, facilities and personnel costs. Cost structures for hybrid flexible electronics are more difficult to predict, where IC assembly times, including bonding times and line capacity, also affect the costing.

Exploring all-printed components, as well as components without packaging could reduce the cost significantly. Costing projections will need to be investigated in more detail, and this will become feasible as the field of printed electronics and paper-based diagnostics continues to grow.

The cost savings of having a printed read-out and communication module for tests at the POC could potentially be large compared to the cost of sending a sample to a laboratory for analysis. A full blood count typically costs ZAR 120, while Gene-Xpert – a POC TB test – costs approximately ZAR 150 per test cartridge, with Government subsidies, and with additional peripheral equipment required. The proposed solutions that utilize the components presented in this work would cost R 50 per device or less. This read-out and communication module could be re-used multiple times with disposable rapid test strips, for example, further reducing the cost per test.

5. CONCLUSION

The successful design, manufacture and testing of both NFC and UHF RFID tags – the latter on to various substrates – has been showcased. Initial results show the feasibility of printing RFID tags on to different, low-cost substrates, which could be compatible with paper-based diagnostic tests – a field that has also seen rapid development in recent years [17].

Mounting of existing IC components, for example the SL900A RFID sensing chip, to paper-based devices is a challenge that is in the process of being addressed using alignment techniques and different adhesive materials. Small connection tracks and spacings often need to be implemented, and alignment and repeatability of circuit assembly for hybrid printed electronics is crucial. Further investigation in to the functionality and performance of the printed antennas will need to be carried out for different paper substrates, as well as different conductive inks, where copper ink could be a potential low-cost solution.

The solutions presented can be used for tracking and identification of diagnostic tests, and for sensing capabilities to provide automated, integrated, and connected sensing solutions using few components in a low-cost form factor. Additional work will explore the printability of additional components such as inductors, and the feasibility of using die format ICs to provide more flexible, thin device solutions. Future implementations could also include paper-based microfluidics integrated with the printed sensing RFID tag.

One of the biggest challenges to overcome for point-of-care testing in South Africa lies in the transportation of samples and results between clinics, hospitals and laboratories [4]. This work begins to address this challenge by investigating the read out and communication of results from paper-based diagnostic devices towards low power, low cost, automated printed solutions for point-of-care diagnosis in resource-limited settings. The devices presented have great potential for the development of low-cost, smart and connected POC diagnostics for resource-limited settings, and could greatly benefit rural clinics in South Africa.

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