J Med Syst (2012) 36:3733–3739
DOI 10.1007/s10916-012-9846-y

ORIGINAL PAPER

Monitoring, Control and Diagnostics using RFID Infrastructure

Anton Pleteršek · Miha Sok · Janez Trontelj

Received: 23 December 2011 / Accepted: 12 March 2012 / Published online: 22 March 2012

Abstract This work demonstrates the developed application for disinfection control by the sensing of chemical agents. The objective was to develop an *Automatic Disinfectant Tracker* (ADT) that would verify the disinfection of the hands of nurses, doctors, staff, patients, and visitors in hospitals within a required time frame. We have successfully investigated the development of hand disinfection control mechanisms and demonstrated two approaches, both based on the wireless *Ultra-High-Frequency-based Radio-Frequency Identification* (UHF-RFID) technology. The 100 % efficacy of detecting propanol and ethanol concentration was achieved by using the *static disinfectant control* (SDC-ADT) method. The time domain response provides an accurate determination of their performance in practice simply by measuring the applied disinfectant concentration and the duration of application. The present paper resulted from the measurements of a capacitive chemical sensor fabricated in the *Laboratory for Microelectronics*, (LMFE) and on measurements, based on a commercially available resistive type of sensor. A *graphic user interface* (IDS-GUI) is designed to successfully set the logger parameters and display the results.

Keywords Wireless sensors network · Ethanol sensor · Data loggers · RFID tag · Smart label · Disinfection control

Introduction

The active substance in most hand disinfectants is in the largest part ethanol (*ethyl alcohol*), CH_3CH_2OH, so our application focuses on detecting ethanol vapours in the air [1]. A typical use of hand disinfectant is a dose of 3.4 ml of fluid from the original dispenser, followed by 30 s of hand scrubbing (surgical 1,5 min), until the user's hands are completely dry. In this process, all of the disinfectant evaporates, and the resulting gas can be detected by chemical sensors. The preferable choices for low power applications – like wireless sensing – are capacitive sensors.

In this work we are proposing the control of rubbing hands by monitoring and tracking the healthcare workers, and consequently introducing a new infection-control technology. The proposed hand hygiene control in non-clinical environment, like kindergartens, is highly recommended.

The most important idea behind the proposed disinfection control is to be able to monitor the quality of hand rub use by a clean and therefore a contact-less method that offers simple and non-expensive measures. This is why we are advocating the Radio Frequency Identification (RFID) infrastructure to be used for the application of the disinfectant, a wireless technology which is already practiced in hospitals [2–5].

Nowadays RFID is used to automatically identify people and objects. Highly selectively sensitive, fast response and fast recovery chemical sensors connected in a wireless

A. Pleteršek
IDS d.o.o.,
Tehnoloski Park 21,
Ljubljana 1000, Slovenia

M. Sok
Clinical Hospital, UKC,
Ljubljana, Slovenia
e-mail: miha.sok@mf.uni-lj.si

A. Pleteršek (✉) · J. Trontelj
Faculty of Electrical Engineering, UL,
Trzaska 25,
1000, Ljubljana, Slovenia
e-mail: anton.pletersek@fe.uni-lj.si

A. Pleteršek
e-mail: anton.pletersek@ids.si

J. Trontelj
e-mail: janez.trontelj1@guest.arnes.si

network of sensors based on RFID technology seem to be the future solution [6]. For proof-of-concept we obtained two different ethanol sensors from different manufacturers and tested their performance using the IDS's RFID technology. The IDS-SL900A single-chip RFID data-logger is a *Smart Active Label* (SAL) with the transponder *integrated circuit* (IC) that combines a temperature sensor and can automatically both track and record the temperature as well as readings from an external sensor. The device has a *Real Time Clock* (RTC) and can be configured to notify users automatically in case of an event. It operates in semi-passive (battery-assisted) or fully passive modes in ambient temperature range from −40 ° to 125 °C, transmits at 860–960 MHz, and has an 8 k-byte EEPROM memory to store the level of alcohol concentration with a time stamp of hand rubbing and the external sensor interface that provides a flexible way of adding additional sensors to the system and supports up to 2 external sensors.

This paper is organized to include the following topics: the impact of hand disinfection on hospital-acquired infection is discussed in the first section, while materials for ethanol sensors are given in the second section which is followed by an application analysis, the principle of operation, and the results of measurements. Finally, the discussion and the strategic recommendations are presented.

Hand disinfection and its impact on hospital-acquired infections

It has been well known for a long time that hand hygiene prevents cross-infection in hospitals. Hand disinfection is therefore mandatory for medical staff in hospitals and clinics, especially when entering certain areas where all external pathogens need to be eliminated. It was found that fever and cough symptoms are significantly reduced when alcohol-based hand disinfectants are used by the employees [7]. In Europe, ethanol is a common active agent in hand rub formulations and is, nowadays, also recommended in guidelines for hand hygiene published by Centres for Disease Control and Prevention and by the World Health Organization [8]. Although, at the same concentration, ethanol is less efficacious than isopropanol, which, in turn, is less efficacious than n-propanol, it is the preferred alcohol for hand antisepsis in many countries [8, 9].

Alcohol sensors and materials used for production of sensors

Chemical sensors can be roughly divided into three major groups according to their sensing material; *metal-oxide-semiconductor* (MOS) sensors, polymer-based sensors and optical sensors. Based on their detection mechanisms, they can be further divided into sub-groups.

Commercially most widely available sensors are MOSs based on tin dioxide (SnO_2) films. Metal oxide semiconductor chemical sensors are in their essence resistive sensors. At high temperatures, oxygen is adsorbed onto the SnO_2 crystal surface, which creates a potential barrier, thus impeding the electron flow in the sensor. In the presence of reducing gasses, i.e. the target gasses of the sensor, oxygen surface density decreases, thus lowering the potential barrier. This effect reduces the sensors' resistance. MOS sensors respond to a number of different gasses but their response can be tailored by using different doping agent or different concentrations of dopants in the sensing film or by using different working temperatures.

Their advantages are low sensitivity to humidity and easy availability on the market. Their great disadvantage, however, is their extensive power use, due to the need of elevated temperatures for proper operation.

Polymer-based sensors on the other hand are based on the adsorption of target molecules into the polymer film. This effect results in the changing of dielectric constant ε, swelling of the polymer film or changing of the film's mass. The aforementioned changes are the basis of operation of polymer-based capacitive, resistive and microbalance sensors [10]. The capacitive sensors rely either on the swelling of the polymer-film or on the change in the dielectric constant of the film due to the addition of molecules with different dielectric properties [11].

Some articles about fabricating capacitive sensors have been found. They report fabrication of micro-machined humidity capacitive sensors implemented by two types of polymer films SU8 and PEUT [12]. The change in capacitance with absorption of analyte is related to three different processes: adsorption on the polymer surface (the given rise of a new thin layer on the top of the polymer), adsorption into the polymer phase (changing the dielectric constant of the polymer), and swelling of the polymer [13]. These three steps define the relation between the sensor's response, its reversibility, and its geometrical parameters.

Polymer-based sensors are promising due to reduced power consumption, and have therefore been the focus of much attention. Challenges in their design and fabrication relate to their higher sensitivity to ambient humidity, selecting the most suitable polymers, and the need for additional micromachining steps in their fabrication [13, 14].

Methods - application analysis and operation principle

The basic question that presents itself is how to control hand disinfection nowadays [16]. To be able to answer it, we have to pose three more questions. The first one is how to prevent infections by securing efficient hand disinfection through an automatic, easy-to-use and environmentally friendly disinfection process [17]. The second is concerned with monitoring the quality of hand disinfection or with measuring disinfection agents that do not consume too much power, while the last question deals with the search for data loggers. We are currently much closer to finding a successful answer to the first and third question, while we are still working toward meeting the requirements for answering the second question [6, 19]. Much more work will be required to find a low-power and selective chemical agent sensor that would be compatible with the existing wireless sensing technologies.

With respect to hand hygiene, we have developed an *Automatic Disinfectant Tracker* (ADT) that controls hand disinfection of health care workers (HCWs), patients, and visitors in hospitals within a required time frame. Conclusions in the present paper are the results of the disinfection control with ethanol 70 % that was tested at a 1 min application and was used with 20 randomly allotted volunteers. The main developed part of the RFID based ADT was a smart active label (SAL) with sensors functionality capable of measure and logging the time of application, its duration, environmental temperature and ethanol concentration. SAL was built-up using a capacitive sensor experimentally fabricated in the LMFE Laboratory for Microelectronics (Figs. 1 and 3), and on a commercially available metal oxide-based sensor (TGS-2620), mounted with a fan into a circular pipe (Figs. 2 and 5) [18]. Both types of demonstrators are described in details.

All evaluated methods were executed by using an RFID infrastructure, either as DC or AC measurement, and using limits and the interrupt functionality to save memory and power [19].

Applications description

There are two different basic detection mechanisms we have developed and successfully demonstrated. Both are based on chemical vapour detection.

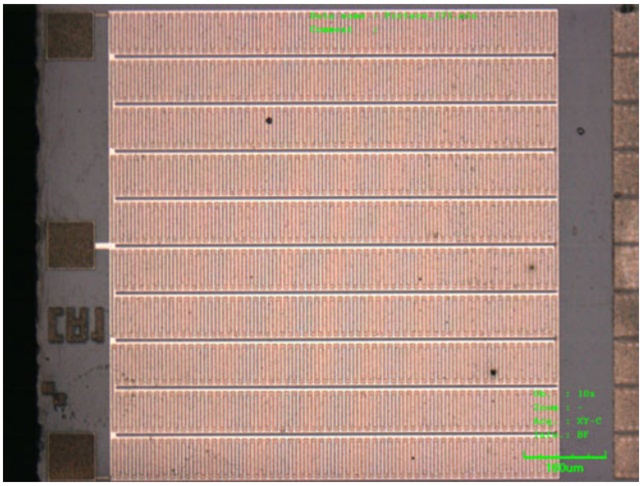


Fig. 1 Low power LMFE capacitive – polymer sensor die, processed on silicon as a surface micromachining MEMS. Die size is 1 mm^2

Fig. 2 Picture shows the TGS-2620. Electrical current of 50 mA is required for proper operation

Differential dynamic method (DDM)

The first developed disinfection measuring method is structured on a staff-individual tag-sensor, build-up of the SL900A integrated circuit, a printed battery and the low-power capacitive ethanol sensor, all in form of a badge-label (Fig. 3). This method is based on the assumption that the capacitor sensor is sufficiently sensitive to a selective chemical vapour in a disinfectant. As all chemical vapour sensors are highly sensitive to humidity, two methods have been investigated. Both are supported by SL900A's features. First, using a capacitive sensor that is sensitive to chemical vapour only, or second, the use of two sensors combined into a differential architecture, where both are equally sensitive to humidity, but only one is highly sensitive to ethanol (Fig. 4). This control mechanism has been named the differential-dynamic method (DDM). The nearby reader then detects the presence of an individual (who is disinfecting his hands - ID), the period of hand scrubbing, time

Fig. 3 Differential-dynamic disinfection mechanism, (DDM), with staff-personal sensor-tag, where the individual tagging of the ethanol level, temperature, and time stamp is executed [15, 19]. The reader, based on the IDS-902DRM interrogator chip, then provides traceability and tracks the staff's movement

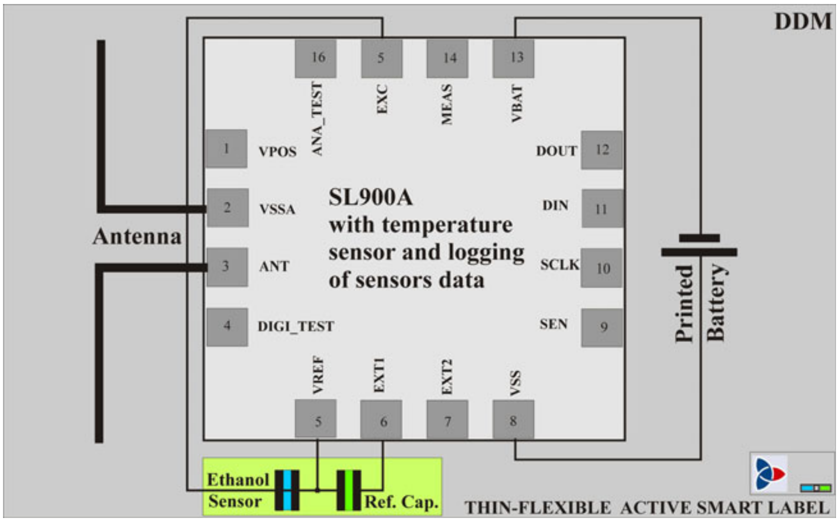


Fig. 4 Detailed schematic of the DDM active smart label. The same method can be used with any other low power chemical sensor

stamp, the temperature and the concentration of the applied ethanol (Fig. 3, and measurement in Fig. 7). The present DDM method is suitable for use only with a low power consumption disinfectant detector i.e. a capacitive type device which guaranties a long life of the printed battery that supplies the tag during the data logging. The use of the data logger feature in the tag is not mandatory if the reader controls the staff in real time. In this case the tag is supplied from the electromagnetic waves and can operate in a fully passive mode while the reader gets information simultaneously and the printed battery is no longer needed in the tag. This principle requires readers to be placed everywhere the disinfectants are. Therefore, an affordable and effective solution is the use of active labels with the data logging feature where the information is read-out where it is needed. The badge-label including the printed battery has a size and thickness of the credit card, and a battery life of over 2 years.

Static disinfection control (SDC)

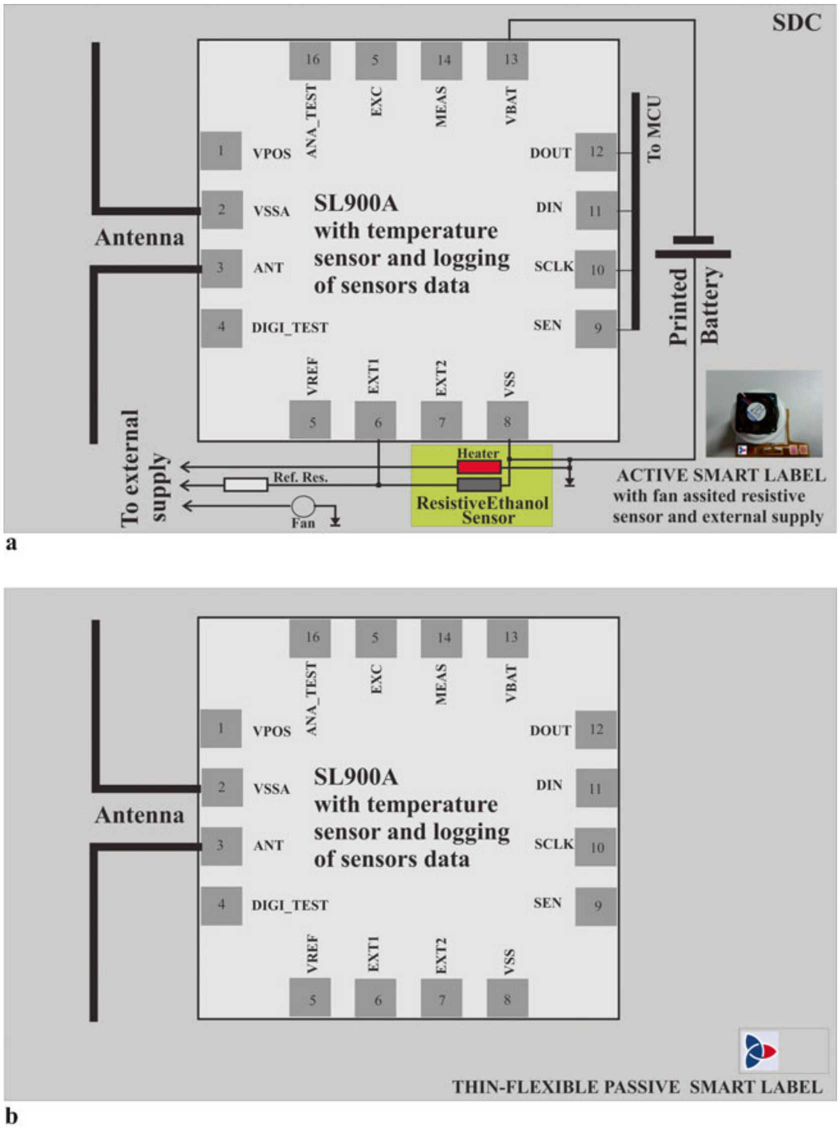
SDC method is suitable for the so-called ‘static applications (Fig. 5), where commercially available but power-hungry sensors, such as resistive sensors, are used. The TGS-2620 detector has been investigated in this method. These applications are based on SAL-tags carried by individual staff members. They only provide the *identification number* (ID) and optionally track the temperature and provide a time stamp (schematic shown in Fig. 6b), while the disinfectant tag-sensor is mounted on the static SAL-tag close to the exit or entrance door, or even close to the disinfectant place where power mains are available (schematic shown in Fig. 6a).

When the reader detects the *ethanol* from a tag-sensor which exceeds the certain level, it updates the nearby personal SAL-tag with the disinfection information. In the case when the tag-sensor is mounted near the exit door, individuals have to position their hand in close proximity to the tag-sensor (2–10 cm) for it to recognize the disinfected hand. In this case the required disinfecting time period is not controlled. The tag-sensor’s information is cleared after it has been successfully recorded (for instance, when exiting the patient’s room or surgery room).

The described application mechanism has been named Static Disinfection Control, or SDC. It was found that the very high sensitivity and proper operation can be achieved

Fig. 5 Static Disinfection Control (SDC). The TGS-2620 detector was used as a sensitive resistive sensor

Fig. 6 Schematic of the **a** fan assisted stationary active smart label and **b** personal passive smart label. The application is shown in Fig. 5



by mounting a micro fan in a tube with a tag-sensor to assure the proper air-vapour flow and fast response.

The SDC-based disinfection control is shown in Figs. 5 and 6. The commercially available high sensitivity chemical sensor can be powered externally and individually, apart from the smart-label. Both tags are under the nearby reader control. The SL900A also supports wired communication to MCU directly as shown in Fig. 6a.

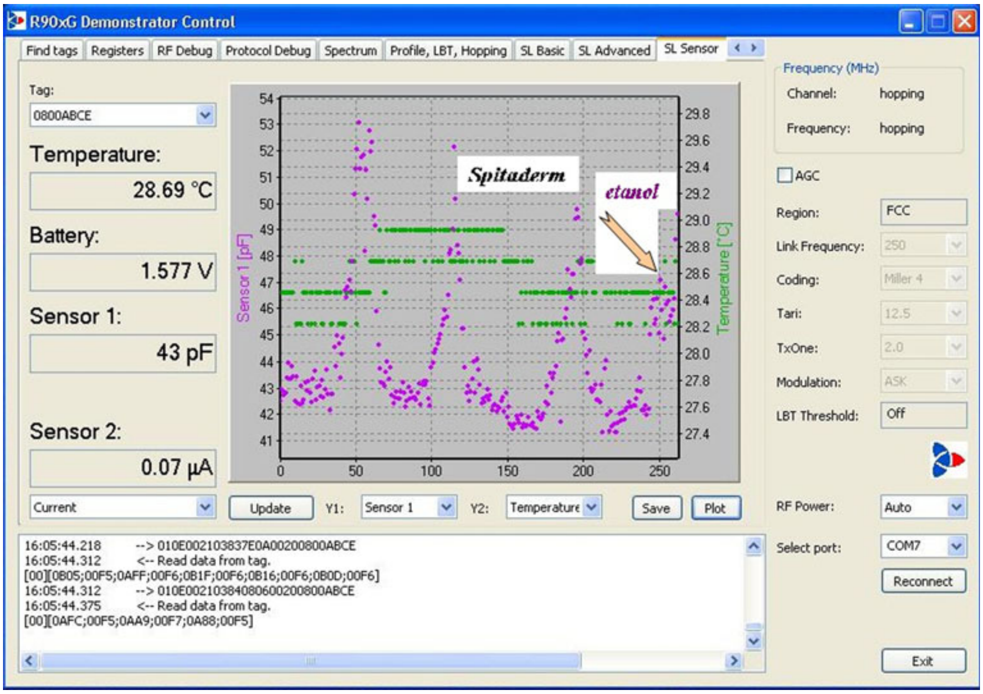
When the SDC method is used, a personal smart label can be used as a fully passive label (Fig. 5, left). This is important information, meaning that the cost of such product can be drastically reduced.

Measurement results

Measurements using the graphic user interface, GUI, are shown in Figs. 7 and 8. The GUI that was used for displaying the acquired data over a time period of 250 s shows the following information (Fig. 7): the current temperature acquired from the active SAL is 28.69 °C, the battery level is 1.577 V, and a current value of the sensor capacitance is 43 pF (application shown in Fig. 3). The sensor capacitance versus the applied disinfectant and temperature, both over time, are presented graphically. The duration of hand rubbing is also seen (samples are taken every second). This is an important control measure for meeting the criteria of EN standards.

Fast sensor response and a fast recovery are evident as well as the extended minimal sensitivity when disinfecting time is approaching the end of the 30 s period (ethanol vapour has already disappeared).

As a contrast, the resistive detector has a much more uniformed response (Fig. 8). In this case, the GUI shows the following information: the current temperature acquired from the passive SAL (application presented in Fig. 5) of



Tag: 0800ABCE
Temperature: 28.69 °C
Battery: 1.577 V
Sensor 1: 43 pF
Sensor 2: 0.07 µA
Current
Y1: Sensor 1
Y2: Temperature

Frequency (MHz)
Channel: hopping
Frequency: hopping
☐ AGC
Region: FCC
Link Frequency: 250
Coding: Miller 4
Tari: 12.5
TxOne: 2.0
Modulation: ASK
LBT Threshold: Off
RF Power: Auto
Select port: COM7

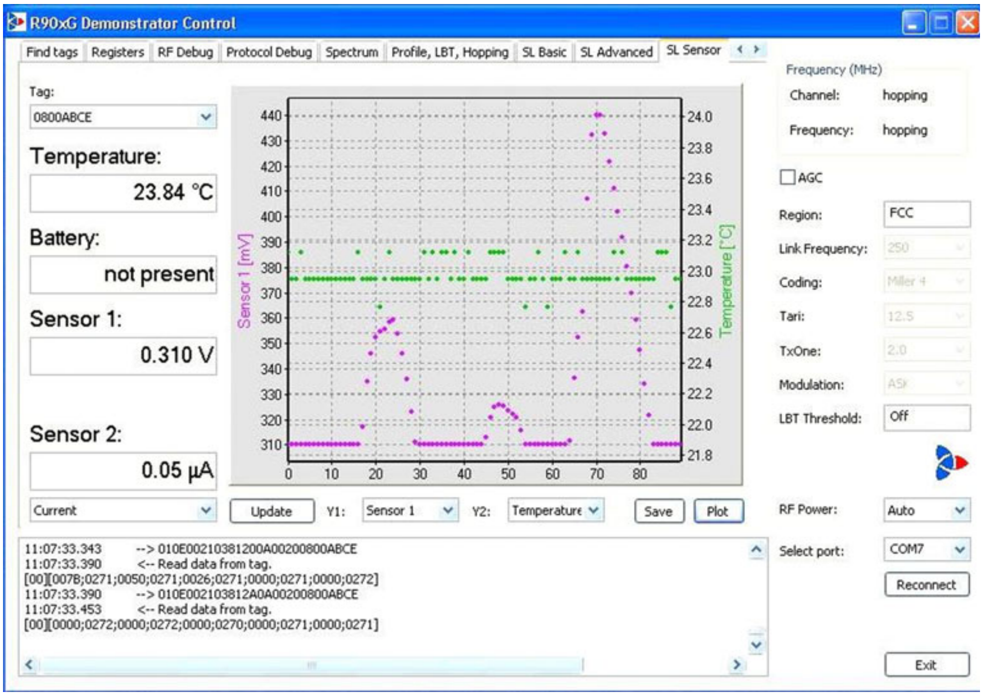
```
16:05:44.218        --> 010E002103837E0A00200800ABCE
16:05:44.312        <-- Read data from tag.
[00][0B05;00F5;0AFF;00F6;0B1F;00F6;0B16;00F6;0B0D;00F6]
16:05:44.312        --> 010E00210384080600200800ABCE
16:05:44.375        <-- Read data from tag.
[00][0AFC;00F5;0AA9;00F7;0A88;00F5]
```

Fig. 7 Hand disinfection using IDS's data logger and LMFE ethanol sensors - SU8/PEUT based polymer material (DC measurement of capacitance - left scale and bottom curve, DDC method, as shown in Figs. 3 and 4). The upper curve is temperature – right scale. Spitaderm (propanol) and 70% ethanol were used. On the horizontal scale the event number is given, the logging interval is set to one second

23.84 °C, the battery is not present, and the current value of the resistive sensor output voltage of 0.31 V.

As the reader is connected via USB connector to the computer, the data is compiled individually and statistically in a secure, real-time online database for easy and accurate reporting, and tracks the hygiene level of hospital staff. The proposed systems monitor the quality of hand rub use and may give automated and visual feedback to the healthcare staff as is shown in the demonstrator GUIs in Figs. 7 and 8.

Over 50 h of trials, 20 opportunities for hand hygiene were documented, all by hand rubbing with alcohol-based antiseptic and detected by ADT. We did not take to much care about compliance with the hand hygiene protocol, as it was recorded by ADT. As a dose of applied disinfectant and a distance to SAL detectors was always nearly the same, the 100 % efficiency was recorded simply by presetting the ethanol vapour level to be detected at each trial.



Tag: 0800ABCE
Temperature: 23.84 °C
Battery: not present
Sensor 1: 0.310 V
Sensor 2: 0.05 µA
Current
Y1: Sensor 1
Y2: Temperature

Frequency (MHz)
Channel: hopping
Frequency: hopping
☐ AGC
Region: FCC
Link Frequency: 250
Coding: Miller 4
Tari: 12.5
TxOne: 2.0
Modulation: ASK
LBT Threshold: Off
RF Power: Auto
Select port: COM7

```
11:07:33.343        --> 010E00210381200A00200800ABCE
11:07:33.390        <-- Read data from tag.
[00][007B;0271;0050;0271;0026;0271;0000;0271;0000;0272]
11:07:33.390        --> 010E002103812A0A00200800ABCE
11:07:33.453        <-- Read data from tag.
[00][0000;0272;0000;0272;0000;0270;0000;0271;0000;0271]
```

Fig. 8 Hand disinfection using IDS's data logger and TGS-2620 in SDC method, as shown in Figs. 5 and 6. Spitaderm (propanol) and 70 % ethanol were used. A large response and a fast recovery can be seen. Samples are taken every 3 s

Discussion and strategic recommendations

The basic message of the classic RFID tracking provides information on “who or what is where,” but it does not provide information about what is happening to them. Recently, we have shown that tracking the use of smart labels offers much more. We have successfully demonstrated the remotely detected disinfecting procedure of the individual staff and acquired data for further controls and staff tracking. It is important to note that the SAL we used offers read/write protection using 3 password sets.

The proposed control methods are highly universal and remain the same when any other substance in the disinfectant needs to be detected. The most important insight is that the continuous development of new chemical sensors is necessary. An important conclusion can also be drawn from the economical aspect i.e. only robust, and low cost solutions will be accepted for use in the hospital environment.

We believe that prevention of hospital infections by intervention and training are not sufficient. Introducing staff control by means of tracking and control measures is an important and promising step.

Next is the technical issue. Designing a battery-assisted, integrated system is a great challenge, mainly because such systems have to operate down to a 1 V supply with a battery, usually of the printed type, which must have a long life-time.

Future R&D should be concerned with the development of energy converters using readily available sources like sunlight, chemical energy, vibrations, movement, temperature change, EM waves, wood moisture, etc. Using these types of energy harvesting, a voltage up to 0.6 V and a current of up to a couple of microamperes are possible by the direct mounting of a converter to the tag. Higher voltage can be produced by connecting the basic cells into a serial circuit. The great challenge is therefore designing a low voltage and very low power transponders, as well as very efficient energy storage devices. The harvested and converted energy will supply SAL tags with data logging feature in the future.

Further research work on sensors should also be directed towards the solutions that are highly compatible with standard CMOS technology.

Acknowledgment The authors express their thanks to colleagues at IDS in Ljubljana for their RFID technology contributions to the projects and to staff members of the Laboratory for Microelectronics (LMFE) in the Faculty of Electrical Engineering in Ljubljana, for the production of capacitive sensors. We thank Katja Polh for her help with the experiments.

Funding sources This work has been supported in part by the University medical centre (UKC) Ljubljana, by LMFE, University of Ljubljana and by IDS d.o.o.

Conflict of interest statement We declare that there is no conflict of interest with any organization regarding the material discussed in this work.

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