# DESIGN AND EVALUATION OF SEAMLESS HAND HYGIENE MONITORING SYSTEM

**Omar Badreddin[1], Ryan Simmons[1], Waylon Dixon[1], Ricardo Castillo[2], Michael Albanese[1], Duke Ayers[1], and Ian Humphrey[1]**

Northern Arizona University, Department of Electrical Engineering and Computer Science[1]
Northern Arizona Healthcare, Flagstaff Medical Centre[2]

## ABSTRACT

In-hospital infections pose a great risk for patients' health; extend patients' stay at hospitals, and increase per patient costs significantly. It is well recognized that better compliance to hand hygiene can significantly reduce such infections. Current monitoring approaches are difficult to deploy, and bring about significant level of overhead to clinicians. Therefore, many hospitals today still rely on direct observations, surveys, and dispenser usage measurements to assess sanitization compliance. We have developed a seamless monitoring technique that utilizes smart phones instead of additional dedicated devices. The key novelty of this approach is its compatibility with any existing hospital dispenser, and that it does not involve any overhead to participating clinicians. In addition, this approach enables the monitoring of missed-opportunities, where a clinician fails to utilize a sanitizer at key steps along a care delivery process. This paper presents the approach, and presents an experimental evaluation of the technology in the lab and at a large urban hospital.

***Index Terms***— Healthcare, Hygiene, Infections, Monitoring.

## 1. INTRODUCTION

In-Hospital infections are a well-recognized and persisting challenge [1]. The problem occurs when a patient contracts an infection where healthcare service is delivered. A recent analysis from Zimlichman et al. estimated that five most common in-hospital infections cost the U.S. hospitals more than $9.7 billion in 2009 [3]. According to a 2011 survey conducted by the Centers for Disease Control and Prevention (CDC), roughly 1 out of every 25 patients in U.S. hospitals contracts an in-hospital infection [4]. Furthermore, about 75,000 of these patients passed away while staying at the hospital where the infection occurred [4].

In-hospital infections represent a major challenge for modern healthcare systems from a safety and financial aspects as well. Many hospitals today rely on direct manual observations and sanitizer consumption to estimate the level of compliance to hand sanitization by the hospital staff. On the other hand, current automated monitoring systems require hospital staff to carry an additional RFID device [11] to communicate with the hand sanitizer to monitor compliance. Such approaches help hospitals measure and improve compliance levels. However, these approaches suffer from key limitations. 1) Manual direct observations are time consuming. Staff behaviour may change during the sparse monitoring sessions. 2) Approaches that involve an RFID tag present a significant overhead to clinicians. In addition to having to purchase and manage a potentially large number of RFIDs, such devices require daily charging and are linked to each specific staff member. More importantly, such devices can be in conflict with disinfection processes at many hospital units [12]. 3) Hand sanitization monitoring approaches fall short in reporting missed opportunities of sanitization along key moments in care delivery process. For example, a monitoring system should report on sanitization before and after care providers' encounter with patients. Because current approaches monitors sanitization incidents only, they fail short in monitoring incidents where a care provider enters an examination room, and to report whether sanitization actually occurred during such incidents.

This paper contributes a novel prototype system that relies on smart phones and Bluetooth signal to monitor hand sanitization compliance. The key novelty in this approach is its reliance on staff cell phones for effecting the monitoring of sanitization practices, and its seamless integration with any existing hand sanitizer stands. Second, this approach is able to monitor care delivery activity as it relates to hand sanitization. Initial deployment suggests that the prototype functions reliably in the face of complex hospital sittings and procedures.

This work builds on our previous study that investigates the use of wearable and mobile technologies to improve performance and compliance in care delivery processes [14][15]. The previous work focuses on indoor-localization using Bluetooth signal, and investigates the indoor localization activities in modern wearables and portable devices.

The rest of the paper is organized as follows. We present related work in the next section. In section 3 we present the design and architecture of the prototype. In section 4 we present an evaluation of the prototype. Limitations and threats to validity are discussed in section 5, followed by a conclusion in section 6.

## 2. RELATED WORK

A number of studies have proposed a hand sanitization monitoring system, aiming at monitoring and/or improving compliance. One such system, proposed by Fisher et al., utilizes ultrasonic transmitters installed in patient areas and receiver tags carried by hospital staff members [5]. In addition to simply monitoring hand hygiene activities, this system will also send an audio alert to remind staff when they have missed a hand hygiene opportunity. This system underestimated hand hygiene compliance by only 5.2% compared to trained manual auditors, and the audible reminders increased compliance by 6.8% when compared to a control group.

A similar approach, proposed by Levchenko, Boscart, and Fernie, utilizes electronic controllers to monitor patient areas and traditional hand hygiene stations [6]. These controllers use infrared emitters to communicate with wireless electronic monitors worn by the staff. These monitors are able to collect their own compliance data, and vibrate to prompt staff to perform a hand hygiene action. This system also includes a wearable sanitizing gel dispenser, which communicates with the monitor, making hand hygiene compliance even more convenient. This method was found to increase hand hygiene by 1.5 fold, despite some dispensers in test areas not yet equipped with controllers.

Boudjema et al. applied MediHandTrace®, a patented setup which combines RFID technology and sensors on hand hygiene stations, to observe compliance with seven distinct steps of the hand hygiene process [7]. The system's recorded results were tested against video recordings of the rooms in which it was installed. Though there were some troubles with false negatives when dealing with certain steps of the process, mostly due to bed and antenna placement issues which were eventually rectified, the results were generally positive. Specifically, steps 3-5 of the process (disinfection before being near a patient, contacting a patient, and disinfection before leaving the room, respectively), which the study focused on, resulted in 99% accuracy, 95% sensitivity, and 100% specificity. The system has the capability to keep compliance records on a wide range of factors (type of patient, amount of staff in the room, time of day, etc.). Therefore, the system will be used not only as a way to audit medical staff, but to investigate which situations and scenarios result in particularly low compliance.

The system described by Baslyman et al., which utilizes a real-time location system, infrared beacons, an application server and performance reporting software, improves on the level of recognizing hand hygiene opportunities [8]. When there are multiple healthcare providers in the room, it can identify situations of insufficient hand hygiene actions, and though it cannot identify who exactly did not take action, it will send reminders to everyone in the room. Also, beacons positioned over beds make it possible to tell if medical staff performed hand hygiene while switching between two patients in the same room. Baslyman et al. attempted two methods for collecting information: a time-based approach, where it was assumed that hand hygiene was not performed if the healthcare provider did not spend at least 15 seconds in the hand washing zone during a hand hygiene opportunity, and an activation-based approach, where dispensers can let the system know when it has been pressed. The later has demonstrated better accuracy.

A recent study from Pineles et al. attempted to quantify the accuracy of a simple RFID system in a live hospital setting compared to a controlled situation produced strictly for observation purposes [9]. After studying a variety of RFID systems, they selected *nGage* [9]. They implemented the system at two hospitals, first testing it in a simulated environment along a set path, and with users wearing their badges in different locations and standing in different areas while using the dispensers. Then, the system was tested by healthcare providers working actual 12-hour shifts who were told exactly how to wear the badge and to otherwise not alter their typical work behavior in any way. The results for the simulation were very good, with the *nGage* system recording 88.5% hand hygiene accuracy and 100% room entry and room exit detection. The simulation also found that wearing the badge on the upper lapel and facing the front of the dispenser gave the best results, whereas standing perpendicular to the dispenser and wearing the badge on the opposite side of the body returned the worst results. However, when the badges were put into clinical use, the numbers plummeted, to 52.4% hand hygiene accuracy, 54.3% room entry detection, and 49.5% room exit detection.

## 3. SEAMLESS HAND SANITIZATION MONITORING SYSTEM ARCHITECTURE

The key novelty in the proposed system is that it utilizes smart phones held by staff members to monitor hand sanitization. The advantage is that staff members are not required to carry an additional beacon or a device. More importantly, this approach utilizes the storage and processing power available in modern smart phones to improve the accuracy of monitoring. The system architecture is driven by the following key constraints:

1. The system must integrate with the existing hand sanitizers at the hospital.
2. The system must require no wirings or physical fixtures.
3. The participating staff must not be required to carry any additional devices or badges.
4. Dashboards must be available in near-real-time and reports should be generated on the fly, at irregular intervals.
5. The system must support advanced monitoring of missed opportunities of hand sanitization in key incidents along the care delivery process.

The first constraint means that the system cannot use the activation-based approach as described by Baslyman et al [8]. The second constraint means that monitoring devices must be battery-powered, and must rely on wireless signal for data communication.

The system is designed to work with employee badges and/or with the smart phone carried by the hospital staff. Figure 1 illustrates an overview of the system architecture. We utilize a *Raspberry Pi* device [2] that we place inside any existing hand sanitizer stand, or below a bathroom sink. The *Raspberry Pi* is battery-powered and can communicate through Bluetooth with the staff smart phone or through NFC with the staff badge. The *Raspberry Pi* sends the encounter information to the Application Server Rules Engine. This engine is responsible for deducing whether hand sanitization has in fact took place. This is achieved by calculating the signal strength and the duration of the encounter. If the encounter is successful, the data is sent to the Database system. The collected data is used to generate real time dashboard of compliance levels as well as generating periodic reports.

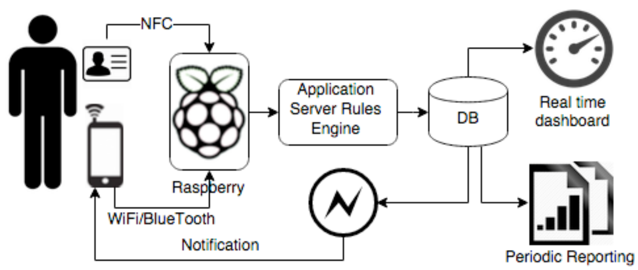


**Figure 1**: Overview of the Prototype Architecture

The Rules Engine is responsible for identifying whether the encounter is successful or not. This is important so as to distinguish between an event where the staff member has passed by the sanitizer, or had actually used the sanitizer.

The Rules Engine collects the duration, the signal strength, and the phone MAC address or the badge ID (Figure 2). The rules engine provides one of three results. 1) Success: the staff member has in fact used the sanitizer. 2) Missed opportunity: the staff member has not used a sanitizer for a specified period of time and was in close proximity to a sanitizer. 3) No evidence: the encounter is not successful and the staff member did not in fact use the sanitizer.

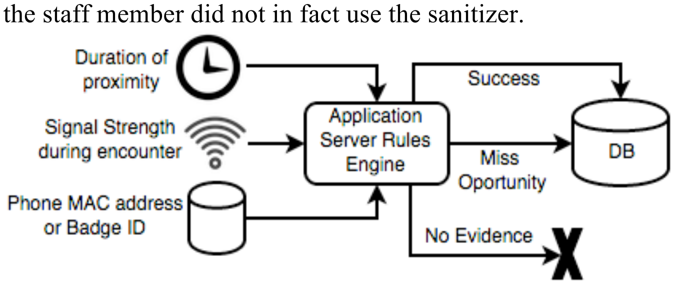


**Figure 2:** Rules engine functionality and operation [14]

## 4. SYSTEM TESTING AND EVALUATION

We have tested the system in a controlled environment to calibrate signal strength and the Rules Engine. In the lab, we continued calibration until the system was successful in identifying at least 9 out of 10 successful encounters, and 9 out of 10 of unsuccessful encounters. This was achieved by asking participants to walk up to the sanitizer stand and either pass by it or use it. Participants and the system response were monitored.

We then deployed the system in a hospital-like environment. The system deployment is depicted in Figure 3 below. The objective of the deployment is two folds. 1) To validate the effectiveness of the system functionality in a complex hospital environment, especially where there are multiple hand sanitizers in close proximity, and when hospital staff can move in unpredictable patterns. 2) We wanted to collect staff perception of the technology and its effectiveness.

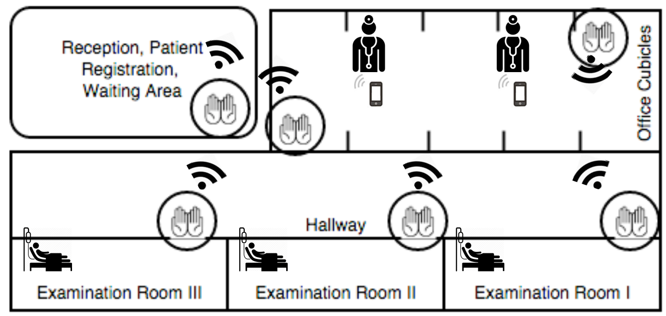


**Figure 3:** Layout of smart hand sanitizers [14]

As shown in the figure, we deployed six hand sanitizers, two in the physician cubicle office space, one in the patient reception area, and three in front of the examination rooms. The *Raspberry Pi* was installed inside the sanitizer, and was not visible from the outside. Staff members were not able to visually identify the instrumented sanitizers.

The deployment was partial, in the sense that not all sanitizers had *Raspberry Pi* installed inside of them. However, the area selected for deployment was self-contained; all hand sanitizers in this region were monitored.

### 4.1. Healthcare staff perception

We have deployed the system in the hospital clinic that has typically 3 physicians during a given shift, each has 2 to 3 examination rooms, as well as 4 nurses and 3 administrators. In addition, we worked with the infection prevention team in selecting the deployment environment, as well as the setup of the deployment. In this section, we report staff perception, excluding that of the infection prevention team.

The staff was briefed about the technology, and the purpose of the technology. The researcher gave a 20-minute presentation of the system design and what data is collected, and what reports are generated. A mobile app was installed on the staff members' phone to enable Bluetooth communication with the instrumented sanitizers.

The key disadvantage of this approach, according to the clinic staff, is the fact that staff must carry their phone with them. Staff members at the hospital are not allowed to use their phone during working hours, and therefore, they tend to leave the phone on their desk or at home. On the other hand, using the badge is problematic since the badge must come very close to the hand sanitizer for the system to capture the encounter.

Privacy was not a concern to most members; we made it clear that no personally identifiable data will be retained. The staff has also become accustomed to be monitored by members of the infection prevention team for hand sanitization compliance.

### 4.2. Observation results

During the study duration of 4 weeks, we have observed the system over 8-hour duration spread randomly over the 4 weeks. During the observation sessions, we manually recorded which participant utilized which sanitizer. We then compared this to the system results. We found that the system was able to correctly identify 62.4% (253/405) of positive hand sanitization incidents. In addition, false positives were about 102 incidents over the observation period. The false positive occurred when a participant was standing in front of the sanitizer (81%) or passing slowly (7%) without utilizing the sanitizer.

Even though the deployment results is significantly lower than the lab results, what is interesting about the data is whether we can identify trends of sanitizer utilization over an extended period of time. The trend will be meaningful especially that we can assume that the error rate will remain to a large extend constant.

One issue that emerged after the deployment is the fact that that different phone manufacturers have different Bluetooth signal sensitivity. Our lab calibration was performed using a specific phone manufacturer, which happened not indicative of the phone prevailing at the hospital. We believe that calibration of the Bluetooth signal strength for a variety of phones may increase the accuracy of the system.

## 5. LIMITATIONS AND THREATS TO VALIDITY

We deployed the system in a separate hospital clinic. The clinic serves a small number of patients daily, and has relatively narrow hallways and small rooms. There is an external validity threat that such a technology may exhibit different levels of accuracy for different hallway and room sizes.

The staff perception is inevitably influenced by their initial exposure to the technology and its potential. In addition, the study duration was short (four weeks). It is possible that the staff perception of the technology changes as the system remains in deployment for a longer period of time. Perception regarding carrying their phone is also influenced by the hospital guidelines that discourage the staff from carrying their phone during working hours.

We note that the accuracy results for the clinic deployment are significantly lower than lab deployment. We observe that clinicians tended to spend more time in hallways, as they are aware of the smart hand sanitizers. This may have negatively impact the results.

Different phones manufacturers have different Bluetooth sensitivity. We calibrated the system to work well with a particular model that we had handy at the lab. It is possible that a per-phone calibration may have given different results.

## 6. CONCLUSIONS AND FUTURE WORK

In-hospital infection is a persistent problem in the majority of healthcare institutions. The World Health Organization's "Guidelines on Hand Hygiene in Health Care" includes 20 studies on the link between improved hand hygiene and in-hospital infections, 80% of which showed a significant reduction in infections based on improved hand sanitation [10]. Current monitoring techniques are either manual, or bring about significant overhead to clinicians. Such approaches required RFID devices to be carried by the staff members at all time.

This work explores a monitoring system that utilizes mobile phones to monitor sanitization practices. The key novelty in this approach is that it adds little to no overhead to hospital staff members. The accuracy levels of the system were much higher in the lab sittings (90%) than the clinical deployment (62%).

We are going to perform a second deployment, and we plan to provide the data for hospital staff and try to uncover compliance patters. In addition, we are designing a prototype that utilizes the same system to collect micro-measurements on staff work patterns. In particular, we will use the system to study physician movements inside hospital boundaries to find ways to improve work productivity, such as studying whether adding additional examination rooms may reduce patient wait time.

### 5.1 Monitoring of Sanitization Missed Opportunities

The ultimate goal of hand sanitization monitoring systems is to reduce in-hospital acquired infections. Towards that goal, it becomes essential to monitor sanitization along key care delivery incidents and in timely fashion. For example, when a care provider walks into or out of a room where a new patient has been admitted, the system must be able to recognize such situation, and monitor sanitization in those incidents.

This goal requires more data collection, including:

1) Data on incidents when new patients are admitted into an examination room.
2) Data on when a physician is walking into or out of a room.
3) Data on when a patient is discharged from a room.

Our next iteration of this work includes designing a system that collects such data to report on missed hand sanitization opportunities.

## REFERENCES


[1] Calfee, David P. "Crisis in hospital-acquired, healthcare-associated infections."*Annual review of medicine* 63 (2012): 359-371.

[2] Upton, Eben, and Gareth Halfacree. Raspberry Pi user guide.John Wiley & Sons, 2014.

[3] Zimlichman, Eyal, et al. "Health care-associated infections: a meta-analysis of costs and financial impact on the US health care system." *JAMA internal medicine* 173.22 (2013): 2039-2046.

[4] "Data and Statistics | HAI." *CDC*. Centers for Disease Control and Prevention, 12 Jan. 2015. Web. 6 Feb. 2015.

[5] Fisher, DA, et al. "Automated measures of hand hygiene compliance among healthcare workers using ultrasound: validation and a randomized controlled trial." *Infection*

*Control and Hospital Epidemiology* 34.9 (2014): 919-928.

[6] Levchenko, A.I., V.M. Boscart, and G.R. Fernie. "Hand hygiene monitoring and real-time prompting system." *2012 IEEE International Systems Conference (SysCon)* IEEE CS (2012): 1-5.

[7] Boudjema, S., et al. "MediHandTrace®: a tool for measuring and understanding hand hygiene adherence." *Clinical Microbiology and Infection* 20.1 (2014): 22-28.

[8] Baslyman, Malak, et al. "Towards an RTLS-based Hand Hygiene Notification System." *Procedia Computer Science* 37 (2014): 261-265.

[9] Pineles, Lisa L., et al. "Accuracy of a radiofrequency identification (RFID) badge system to monitor hand hygiene behavior during routine clinical activities." *American journal of infection control* 42.2 (2014): 144-147.

[10] World Health Organization. *WHO guidelines on hand hygiene in health care: first global patient safety challenge. Clean care is safer care.* World Health Organization, 2009.

[11] Katz, James E., and Ronald E. Rice. "Public views of mobile medical devices and services: A US national survey of consumer sentiments towards RFID healthcare technology." International journal of medical informatics 78.2 (2009): 104-114.

[12] Nguyen, Hap, and Bich-Dao Thi Nguyen. "RFID-based medical equipment sterilization systems and disinfectant dispensers including methods relating thereto." U.S. Patent Application 11/983,053.

[13] Barsocchi, Paolo, et al. "A novel approach to indoor RSSI localization by automatic calibration of the wireless propagation model." Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th. IEEE, 2009.

[14] Omar Badreddin, Ricardo Castillo, Lysanne Lessard and Michael Albanese. "Towards Improved Performance and Compliance in Healthcare using Wearables and Bluetooth Technologies". Proceedings of the 2015 Conference of the Center for Advanced Studies on Collaborative Research. IBM Corp., 2015.

[15] Omar Badreddin, Ricardo Castillo. "Patient Flow Management: Combining Analytical and Observational Data to Uncover Flow Patterns". Proceedings of the International Conference on Health Informatics, Lisbon, Portugal, 12-15 January, 2015.