This full text paper was peer-reviewed at the direction of IEEE Instrumentation and Measurement Society prior to the acceptance and publication.

A smartphone-enhanced pill-dispenser providing patient identification and in-take recognition

C. Crema, A. Depari, A. Flammini, M. Lavarini, E. Sisinni, A. Vezzoli
Dept. of Information Engineering
University of Brescia
Brescia, Italy
{claudio.crema, alessandro.depari, alessandra.flammini, mirko.lavarini, emiliano.sisinni, angelo.vezzoli}@unibs.it

***Abstract*— The wider and wider availability of powerful, low-cost mobile devices (e.g., smartphones or tablets) is deeply changing healthcare, so that the mHealth term has been coined. The announcement of healthcare projects by market big players as Apple and Samsung confirms this trend. In particular, the opportunity to collect reliable patient data automatically allows to enhance patient/user self-management and helps in better delivering therapies. In this paper, authors propose an innovative architecture for a smart pill-dispenser enhanced by a smartdevice that furnishes the capability of automatically identifying the user, other than logging medicine in-take activities. A real-world prototype, based on an emulated pill-dispenser connected via an NFC link to different smartdevices, has been purposely realized. Experimental tests confirm the architecture feasibility. Low-cost requirements are satisfied and a user-friendly interface has been implemented.**

Keywords—eHealth; mHealth; self-management; smartdevice; Near Field Communication

I. INTRODUCTION

Healthcare has deeply changed in the recent past thanks to the continuous improving of electronic devices and the advent of affordable and ubiquitous communication technologies. Several terms have been created to address these changes, including the eHealth and the mHealth neologisms. The former term, used since nineties, identifies the use of information and communications technology (ICT) into healthcare products, services, and processes on one side and into organizational and governmental infrastructures on the other one. As reported in the European Commission's eHealth Action Plan 2012–2020, the adoption of "ICT applied to health and healthcare systems can increase their efficiency, improve quality of life, and unlock innovation in health markets" [1],[2]. The term mHealth, conversely, refers generally to the practice of medicine and healthcare supported by mobile devices, especially mobile phones, tablets, computers, and PDAs (personal digital assistants) [3]-[5]. The growing importance of mHealth is also confirmed by the announcement, on May 2014, of the "Simband" and the "HealthKit" projects by Samsung and Apple, respectively. The former is a smartwatch purposely designed for supporting health-related data acquisition and complemented by a Cloud platform called SAMI (Samsung Architecture for Multimodal Interactions); the latter is a development framework, within the iOS8, that allows apps providing health and fitness services to easily share their data. More in detail, an example application of mHealth is the real-time monitoring and logging of activity level or vital signs, and direct provision of care (the so called telemedicine). From the medical point of view, the adoption of mobile health tools allows clinicians, practitioners and researchers to automatically monitor the type, quantity, and quality of everyday activities of patients, thus potentially improving daily care and establishing cost-effective, evidence-based medical practices. Possible advantages include a reduced hospitalization time and better home-based rehabilitation. In addition, the availability of an immediate feedback for the patient, for example provided by inexpensive smartdevices (this term includes both smartphones and tablets), also allows for a better self-management of the daily care. In the past, for instance, the use of mHealth was suggested to facilitate the self-monitoring for weight loss, which is traditionally performed with paper diaries [6]. Clinical trials may benefit from mHealth as well, since remote data collection allows for cost reduction and avoids burden of travel, improves recruitment and retention, and permits to gather more reliable experimental data.

In this paper, a smart pill-dispenser is described. Authors mainly focus on the low-cost requirement, in order to overcome one of the limitations of currently available devices. In particular, the novelty of the proposed approach is the adoption of a smartdevice not only for providing a user-friendly human-machine interface, but also for the automatic identification of the patient (a feature particularly important for elderly). The developed solution embeds a supervising microcontroller and uses the short-range Near Field Communication (NFC) wireless link to exchange data with the smartdevice. In addition, the proposed instrument also monitors the user actions in order to infer in-take activity, performs timestamped-data logging and allows for remote data collection.

The paper is structured as follows. In the next section, the application scenario and related works are briefly resumed. In section III the proposed solution is better detailed and in section IV the real-world prototype is described and some experimental evaluations are reported, confirming its effectiveness. Finally, some conclusions are drawn.

This work was supported in part by EULO Grant D88C13000050005: "Smart ECG: uno strumento miniaturizzato ad elevate efficienza energetica per il monitoraggio a lunghissimo termine dell'elettrocardiogramma: aspetti tecnologici, clinici e scientifici" and by Smart Cities and Communities and Social Innovation Grant D84G14000220008: "Smart Aging".

978-1-4799-6477-2/15/$31.00 ©2015 IEEE

II. APPLICATION SCENARIOS AND RELATED WORKS

During treatments contemplating the daily usage of medicaments on a regular basis, it is important to strictly follow the given prescription. Failure to respect given dosage and timing could decrease effectiveness or invalidate the prescribed therapy, leading to risks for the health and in the worst cases to death. In [7], it is reported that about 21% of patients does not strictly follow prescriptions and about 6% is not able of identifying medicines. Moreover, a percentage of patients varying from 12% and 20% takes medicines prescribed for other patients. In general, it is estimated that about 50% of patients significantly alters the prescribed therapy. The lack of knowledge about medicament in-take procedure, the large quantity of different pills prescribed in some therapies and simple mistakes or inadvertency are the main reasons for the non-adherence to the prescribed pharmacological treatment. As expected, the more significant incidence of such dangerous behavior is related to the elderly population.

In the case of hospitalization, the patients are constantly monitored and medicaments are given by medical personnel, thus reducing, but not completely eliminating, the occurrence of the aforementioned situations, especially the misrecognition of the therapy recipient. On the other hand, in case of home-based therapy, the adherence to the prescribed treatment is a task demanded to the patients themselves or to their relatives/caregiver. Especially in these latter cases, the availability of automatic systems supporting and monitoring the patient behavior is therefore essential. Generally speaking, such systems inform or remind to the patient (or more generally, the system user) when and which medicament needs to be taken and interact with him/her to acknowledge the medicament in-take. In addition, a monitoring feature capable to track the in-take events by time permits the medic to be informed about the adherence of the prescribed treatment. It is important to underline that the last feature could contemplate a remote access to the in-take log (telemonitoring), thus allowing a faster and more effective reaction in case of significant deviation from the prescribed treatment.

Recently, different solutions of automated pill-boxes appeared on the market for these purposes. Generally speaking, such medication self-management systems implements the following features:

- Configuration of the medication scheduling on the automated pill-box, by specifying the events, i.e., what time a medicament must be taken and where it is stored among multiple compartments of the pill-box itself. This action should be performed by medical personnel or the users themselves at the beginning of the therapy.
- When each scheduled event occurs, the automated pill-box sends a notification to the user. Moreover, it provides an unequivocal indication related to the compartment storing the medicament to take.
- When the user opens a compartment door, an in-take feedback related to that compartment is automatically acquired by the automated pill-box. In this way the system is capable to identify if the correct medicine (or a wrong one) has been taken. Each action is timestamped to provide a time-related feedback, and thus the system can detect if a medicament has been taken at the scheduled time.
- The automated pill-box creates a monitoring log, which can be remotely examined by the medical personnel to verify the adherence with the prescribed therapy.

For instance, MedMinder™ proposes a set of automatic pill-dispensers for treatments on a weekly basis [8]. They host 28 compartments in which several pills can be simultaneously stored. Philips Medication Dispensing Service (MDS) is an automated pill-dispenser capable of managing up to 60 pre-filled dosage cups (20/25 pills per cup) [9]. Finally, MedReady Inc. proposes another 28-compartment pill dispenser, where a rotatory system combined with a single-hole cap is employed to make accessible to the user only one compartment per time [10]. All these commercial solutions are characterized by a high cost, around 300 $ to purchase the device or a rent and service subscription around 50 $ per month. The basic user interface could be not so intuitive for all patients, especially elderly ones. In addition, they do not provide any mechanism of patient identification, leading to possible misrecognition, especially when the device is shared by more that one patient in hospital/clinic or during an in-home therapy. Furthermore, the closed nature of such devices makes impossible the integration or requires high level interconnections with the numerous personal and wearable devices nowadays available for the monitoring of biological parameters of the user.

The aim of this work is to overcome such limitations providing a low-cost system based on a smartdevice, which also provides a more intuitive and easy-to-use user interface. Since it can be imagined that a smartphone or tablet is a personal device, a simple mechanism for patient identification is therefore obtained, thus allowing the pill-dispenser to be shared among several users. Moreover, being a smartdevice connected to the Internet, the device natively offers mobility, allowing innovative support or monitoring services to be realized. Finally, the proposed architecture is open and easy to be interconnected with other smartdevice-based healthcare systems (e.g., wearables nodes for biosignals acquisition [5]), thus improving the monitoring capability of patients following in-home recovery therapies.

III. THE PROPOSED APPROACH

As stated in the introduction, a new architecture for a smart pill-dispenser is evaluated in this work. As highlighted in the previous section, the novelty of the proposal is the capability of automatically identify the patient/user. In order to satisfy this requirement, a simple pill-box is enhanced with embedded logic and sensors and it is capable to wirelessly communicate with a smartdevice, which also represents the input/output port of the system. Since it can be reasonably assumed that each pill-dispenser user possesses its own smartdevice, the smartdevice itself represents the user identity. For this reason, the wireless link must be robust and secure; conversely a reduced range is allowed or even preferable. Consequently, the adopted standard solution is the NFC, further detailed hereinafter. Nevertheless, the adoption of a smartdevice easily allows for the exploitation of wireless local and body area networks as WiFi and Bluetooth; innovative cloud services can be implemented as well.

A. Smartdevices platforms

First of all, a comparative analysis has been performed in order to identify the smartdevice reference platform. Several market analyses confirm that the two most diffused operating systems (OS) for smartdevices are iOS and Android; e.g., see reporting data from Kantar WorldPanel [11] and resumed in TABLE II. . Another interesting characteristic, highlighted by the IDC Worldwide Mobile Phone Tracker report [12], is the increasing gap between iOS-based and Android-based device selling price; in particular, the average selling price of an iOS-device was more than twice as high as the average price of an Android-device in 2013.

TABLE I. SMARTDEVICE OSS MARKET SHARE.

USA	3rd Trimester 2014	EU5	3rd Trimester 2014
Android	48.4	Android	68.8
iOS	47.4	iOS	23.8
Windows	3.0	Windows	8.3
Other	1.2	Other	1.2

App development on these two platforms requires different approaches, programming languages, and has different methods of app publication. A brief overview of the platforms is given in the following.

The iOS platform is based on a proprietary model developed by Apple, which also furnishes the Xcode integrated development environment (IDE) complemented by a simulator for iOS-based devices (currently iPods touch, iPhones and iPads). The Objective C is the preferred programming language and the apps creation and deployment requires the availability of *keys* for that device and application, obtainable thanks to a service subscription with Apple. The iOS platform is derived from the OS X.

Android code is open source since 2008, when Google, which acquired Android Inc. in 2005, officially released the 1.1 version. Similarly to iOS, Android is based on a modular architecture organized in several layers offering different level of abstraction; as usual, the lower layers offer services to the higher ones (see Fig. 1). As reported on the Android developer site, Android architecture is designed as a specialized version of Linux for smartdevices. In particular, apps are generally executed within a virtual machine called the Dalvik Virtual Machine (DVM). User apps can be published in the Google Play Store only after a subscription and a fee payment, but creation, installation on actual Android-based devices, and test procedures do not need registration. The preferred language for developing apps is Java, by means of the Android SDK (software development kit), despite the use of C/C++ language is permitted by means of the Native Development Kit (NDK).

Android Studio, running under Windows, OSX and Linux, is the official IDE for Android application development; however, a plug-in to be used with Eclipse also exists. Authors chose to develop the proposed solution using the Android suite thanks to its open nature and the use of the diffused and portable Java language. In addition, the Android platform nowadays offers a wider set of communication interfaces natively supported, including the employed NFC technology, detailed later in the paper (interesting to notice, currently iOS only partially supports NFC).

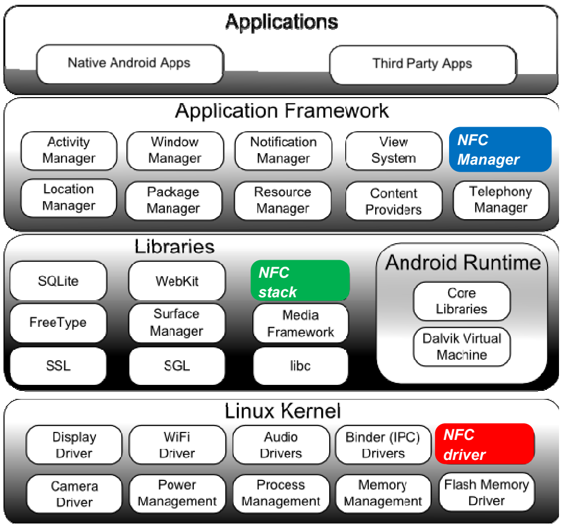

Fig. 1. Simplified Android architecture.

B. Smartphone communication interfaces

A simplified block diagram of a smartdevice is shown in Fig. 2. Roughly speaking, smartdevice's components can be grouped into four main areas. There is a section for handling interaction with the user, including the touch display and the microphone/speaker pair; the power supply unit managing the battery use; the processing unit, executing the firmware and software (including user apps) and the communication unit, which not only implements the radio for mobile call but also handles other (standard) wireless communication solutions. In particular, one of the main advantages of using an operating system is the availability of application programming interfaces (APIs) for handling hardware features of the smartdevice, no matter the actual manufacturer. In fact, libraries are provided furnishing a hardware abstraction layer which harmonizes the access to the underlying hardware. Depending on the OS release, Bluetooth (IEEE802.15.1), WiFi (IEEE802.11), and NFC are the most interesting connectivity solutions nowadays supported.

As previously stated, in this work authors decided to use NFC as the wireless link for connecting the smartdevice and the pill-dispenser. In particular, if a smartdevice supports NFC, the manufacturer provides the NFC driver which is running in the Linux kernel with super-user rights. The actual NFC stack (also provided by the hardware constructor), is implemented in the Android library layer. Finally, the NFC-related APIs are exposed to the user app in the Android Application Framework layer. Among all the NFC "flavors" supported by Android, the so called Reader/Writer modality is used, allowing the smartdevice to behave as a regular RFID (Radio Frequency Identification) tag reader.

Indeed, the NFC is based on the physical layer of widely diffused High Frequency RFID, operating at 13.56MHz. Transmitter and receiver are magnetically coupled (i.e., they behave as the primary and secondary side of a coreless transformer), allowing an operating range on the order of few centimeters. A variety of NFC standard stacks are defined, offering different modulation schema, bitrates and message formats. Among all of them, the NDEF format is used in this work, based on the ISO14443-4A specification [13]. In particular, a proprietary application level protocol has been purposely designed and encapsulated within NDEF messages.

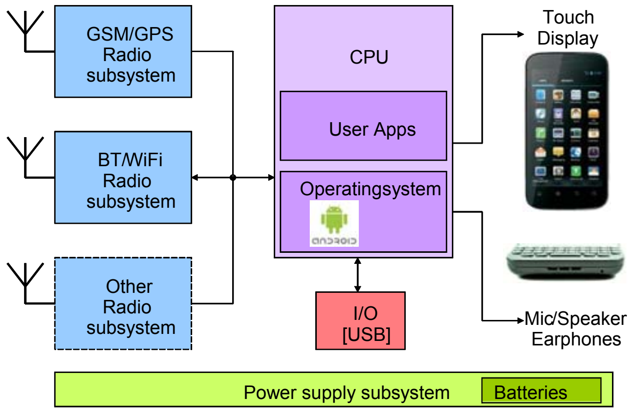

Fig. 2. Smartdevice anatomy.

An interesting opportunity of the NFC technology is the capability to power supply tags, allowing for a completely passive device.

IV. REAL-WORLD IMPLEMENTATION

The proposed smart pill-dispenser is composed of two parts: a instrumented pill-dispenser, which actually stores the medicaments and offers compartment indication and door compartment opening feedback, and a smartdevice, which provides user interface, communication features and manages the whole system. The two parts communicate each other by means of the aforementioned NFC link. As better described in the following, in this work the instrumented pill-dispenser has been emulated by a purposely-designed microcontroller-based system. In order to test interoperability, two smartdevices have been considered: a smartphone, Samsung S4 Mini (GT-I9195), running Android 4.2, and a tablet, ASUS Nexus 7 (2012), running Android 4.4. It must be noticed that the adoption of consumer-market communication standard solution and the use of microcontroller allows for an overall cost of the pill-dispenser engineered solution on the order of tens of USD.

A. The pill-dispenser "emulator".

The pill-dispenser is only emulated (as shown in Fig. 3), since the presence of physical compartments to store medicines is not significant to demonstrate the applicability of the proposed approach. A general-purpose microcontroller (μC) has been complemented by a single-chip NFC interface to realize the communication channel with the smartdevice. This NFC-enhanced μC behaves on the wireless link just like an NFC tag; it also manages the exchange of commands/responses encapsulated into NDEF messages, in order to realize pill-dispenser related logic. Moreover, it provides digital outputs used to drive three LEDs and digital inputs employed to read three push buttons; the former are used to virtually notify the user about the correct compartment containing the medicament to take, whereas the latter virtually represent the open/close state of each compartment door.

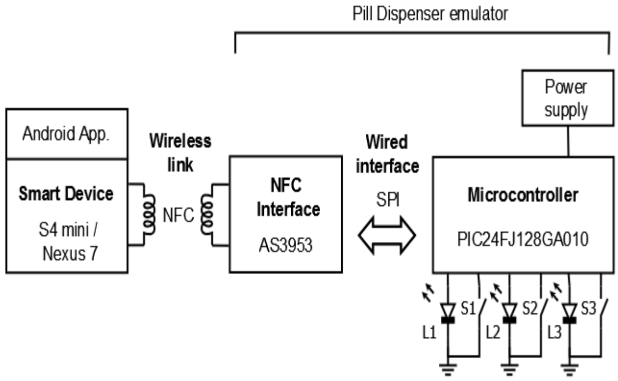

Fig. 3. System overview of the proposed smart pill-dispenser.

The NFC interface is obtained by means of low cost AS3953 by AMS. This device, belongs to the AMS NFiC family and offers an analog front-end with integrated ISO 14443A data framing and 4-wire SPI interface. The AS3953 supports ISO 14443A standard up to Level-4, so that an NFC forum compatible tag (Tag Type 4) can be built. This feature has allowed communication, in Reader/Writer mode, between the AS3953 and standard NFC-enabled smartdevices. The AS3953 has been passively powered from smartdevice magnetic field by means of an appropriate antenna coil tuned to 13.56 MHz (despite the μC is battery powered).

The Explorer 16 Development Board hosting a low-cost PIC24FJ128GA010 (by Microchip) has been chosen as system core. In Fig. 4 a flow chart describing μC firmware operation is proposed. After initialization, the μC waits for ISO 14443-4A frames coming from AS3953 SPI interface. The firmware manages frame exchange procedures necessary to provide remote reading/writing operations of an NDEF message, according to Tag Type 4 specifications [14]. Proprietary application level commands/responses are simply encapsulated into NDEF messages.

Every time the smartdevice interacts with the emulated pill-dispenser, it provides synchronization to the μC. Date and time are retrieved from a Real-Time Calendar implemented by μC HW-timer in order to timestamp occurring events. Eventually, the firmware fetches the application level commands from NDEF messages and processes them to realize the pill-dispenser logic, as illustrated in II.

B. The android app

An Android application has been realized in order to allow the user to configure the emulated pill-dispenser and to interact with it. The application comprises the following Android activities:

- **Main activity:** It is the application entry point. From here the user can launch other activities or trigger an application reset.
- **Configuration activity:** Within this activity the user can configure the pill-dispenser medicines scheduling, by linking proper medicines to each emulated compartment.
- **Communication activity:** In this activity communication between the smartdevice and the emulated pill-dispenser takes place.

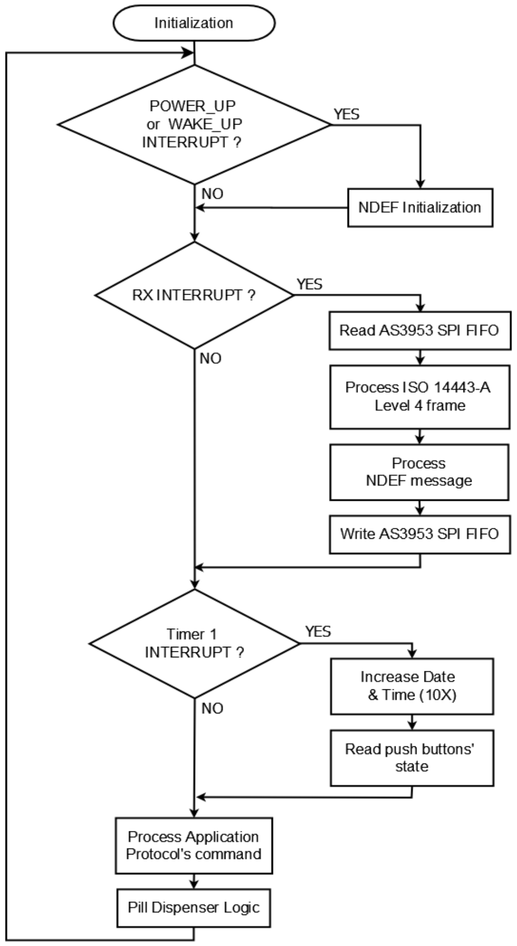

Fig. 4. µC firmware flow-chart.

As previously described, the communication on the NFC link is performed by writing/reading NDEF messages (over ISO 14443-4A) which encapsulate proprietary application level commands/responses. Due to demonstrative purposes, the events associated with the medicine in-take are manually triggered by the user. However, this is logically equivalent to receive pre-configured calendar-based alarms. These events are time-stamped in order to calculate the delay between the notification event and the user action on pill-dispenser side, which is assumed to be the actual medicine in-take.

When the smartdevice is approached to the emulated pill-dispenser, the application sends a synchronization command with local date and time information. Then, if an event occurs (either scheduled or manually triggered), the app sends a command to show the user, by means of the notification LEDs, which medicine should be taken (i.e., which compartment should be open). Afterwards, a readout polling cycle is started to fetch feedbacks related to user's actions on pill-dispenser side (i.e., the emulation of the compartment door opening by means of the pressed push button). Polling cycle completion is notified on the app with a ring and a vibration, therefore the user can check feedbacks state. Screenshots of the developed app are shown in Fig. 5.

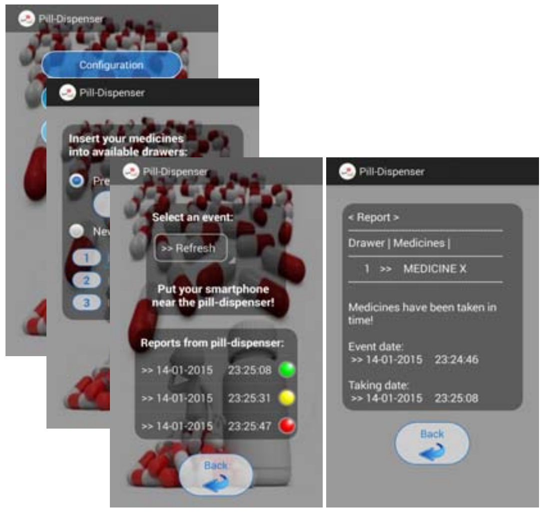

Fig. 5. Screenshots of the developed Android application.

C. Experimental validation

A test bench has been assembled to demonstrate the feasibility of the proposed approach and to evaluate overall system potentialities in terms of communication delays, as depicted in Fig. 6.

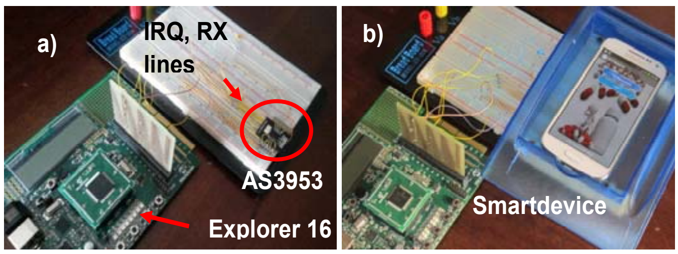

Fig. 6. Real-world prototype; a) NFC device highlighted; b) the whole system including the smartdevice.

Digital interrupt line (IRQ) coming from the AS3953 module and µC GPIO line (RX) have been chosen as measurement points. Measurements have been performed by means of a digital 4-channel oscilloscope (Agilent InfiniiVision MSO-X 3054-A). Using the considered smartdevices and the testbed shown in Fig. 6b) a useful range of few centimeters is achieved.

Latency measurement is intended for evaluating time elapsed between the passively energizing of AS3953 and the reception of an NDEF message by µC.

Results have been obtained according to the following steps:

- The smartdevice is approached and wirelessly powers the AS3953 module, which sends a power-up interrupt request to µC on IRQ line.
- The smartdevice sends an NDEF message to the AS3953 module and µC RX line is toggled when the reception of the message on µC is completed.
- The time elapsed between first interrupt request on IRQ line and the RX line toggling is measured.

Latency measurements performed for different data rates and for different devices are summarized in TABLE II. , referred to a population of 30 readouts.

TABLE II. LATENCY MEASUREMENTS.

	S4 mini		Nexus 7	
Latency	**848 kbps**	**212 kbps**	**848 kbps**	**212 kbps**
Mean [ms]	538.30	572.40	511.90	548.90
Std. Dev. [ms]	49.10	41.00	135.23	168.66

Jitter measurement is intended for evaluating system behavior on periodic message communication. Tests conditions are the following:

- The smartdevice executes a 1s-interval periodic task. Within this periodic task, the smartdevice sends an NDEF message to the AS3953 module.
- When each message reception on µC is completed, µC RX line is toggled.
- Half-period of resulting square wave on RX line is measured.

Jitter measurements performed for different CPU loads (i.e., when only the smart pill-dispenser app is active or when ten generic apps are simultaneously active) and for different devices are summarized in TABLE III. , once again referred to a population of 30 readouts.

TABLE III. JITTER MEASUREMENTS.

	S4 mini		Nexus 7	
Jitter	**One App**	**Ten Apps**	**One App**	**Ten Apps**
Mean [ms]	1002.10	1003.20	1000.50	1001.20
Std. Dev. [ms]	7.72	20.72	3.77	5.86

The µC firmware occupies less than 15 kB of µC code space and the Android app occupies about 1.5 MB of smartdevice internal memory.

V. CONCLUSIONS

In this work an innovative smart pill-dispenser is described. Following a today usual approach, a smartdevice has been used to implement a user-friendly, easy to use interface. A short range NFC link is used to connect a sensorized pill-dispenser with the smartdevice. The novelty of the proposal is the capability to automatically identify the user and to log the in-take activity, thus reducing oversights in following the therapy, especially at home. A real-world prototype has been realized, based on low-cost microcontroller. Experimental tests, carried on with a smartphone and a tablet, confirms the effectiveness of the proposed architecture.

The short range of the NFC standard allows for an intrinsically secure access but it also represents a strict limitation. Possible future work is a review process in order to include new low-power wireless technologies as the Bluetooth Smartready (also known as Bluetooth Low Energy).

REFERENCES

[1] Kovac, M., "E-Health Demystified: An E-Government Showcase" Computer , vol.47, no.10, pp.34,42, Oct. 2014.

[2] European Commission, eHealth Action Plan 2012–2020: Innovative Healthcare for the 21st Century, 12 June 2012; 42 COMPUTER COVER FEATURE; available online: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2012:0736:FIN:EN:PDF.

[3] R.S.H. Istepanian, E. Jovanov, Y.T. Zhang, "Guest Editorial, Introduction to the Special Section on M-Health: Beyond Seamless Mobility and Global Wireless Health-Care Connectivity," IEEE Transactions on Information Technology in Biomedicine, Dec. 2004, 8(4): 405 - 414.

[4] D. Raskovic, T. Martin, E. Jovanov, "Medical Monitoring Applications for Wearable Computing," The Computer Journal, July 2004, 47(4): 495-504.

[5] A. Depari, A. Flammini, E. Sisinni, A. Vezzoli, "A wearable smartphone-based system for electrocardiogram acquisition", 2014 IEEE International Symposium on Medical Measurements and Applications Proceedings (MeMeA), Lisbon, Portugal, June 11-12, 2014, pp. 54-59.

[6] L.E. Burke, M.A. Styn, S.M. Sereika, M.B. Conroy, L. Ye, K. Glanz, M. A. Sevick, L. J. Ewing, "Using mHealth technology to enhance self-monitoring for weight loss: a randomized trial", American Journal of Preventive Medicine, Vol.43, Issue 1, July 2012, Pages 20–26.

[7] A. I. Wertheimer e T. M. Santella. "Medication compliance research: still so far to go". J. Appl. Res. Clin. Exp. Ther. 3 (2003), pp. 254–261.

[8] http://www.medminder.com

[9] http://www.managemypills.com

[10] http://www.medreadyinc.com/

[11] Available on line: http://uk.kantar.com/media/876729/kantar_os_share_jan_2015_final.pdf

[12] Available on line: http://www.idc.com/getdoc.jsp?containerId=prUS24857114

[13] ISO/IEC 14443-4:2008, "Identification cards -- Contactless integrated circuit cards -- Proximity cards -- Part 4: Transmission protocol".

[14] NFC Forum Type 4 Tag Operation Specification 2.0 (November 2010), Available on line: http://members.nfc-forum.org/