Four-Channel NFC System for Electrochemical Sensing of Fluids

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***Abstract*—Electrochemical analysis systems are increasingly important for applications like Point-of-Care diagnostics and Lab-on-Package sensing. Herein, we propose a system composed of four passive NFC (Near Field Communication) microchips capable of performing open circuit potentiometry through interactions with commercial smartphones. The multi-chip NFC system can be used to quantify four chemical quantities within a unique liquid sample thanks to a microfluidic circuit which feeds four ad-hoc screen-printed electrodes. In this contribution, preliminary calibration on four analytes is reported. The four target quantities considered in this paper are sodium, potassium, calcium, and pH. The sensing matrix will be human blood and fluids derived from food spoilage Thanks to further implementation with microfluidic channels currently under development, the NFC chemical analyses can facilitate domestic monitoring of patients and rapid, on-site test of pieces of food to check food quality and prevent foodborne illnesses.**

Keywords—Antenna systems; Near-Field Communication; Point-of-Care; Screen printed electrodes.

I. Introduction

Electrochemical analysis systems are becoming more and more relevant for several uses such as, for example, Points-of-Care (PoCs) diagnostics [1], where they can effectively synergize with medical RFID sensors [2], or Lab-on-Package sensing [3] for the food industry. Recently, Near Field Communication (NFC) devices for rapid on-site chemical analyses have been proposed and developed [4], including innovative designs in epidermal and flexible forms [5]. Indeed, the use of NFC for chemical analyses is convenient in terms of costs and compatibility with commercial-off-the-shelves (COTS) smartphones that wirelessly provide the required energy to the NFC potentiostat. Despite these advancements, a significant limitation remains: the ability to quantify only a single chemical species at a time. This constraint is a substantial barrier, especially in complex applications where multiple analytes need to be measured simultaneously. Examples of such applications include oncology therapy, where

Fig. 1. Concept of the completed four-channel NFC system used for a PoC. The smartphone retrieves and stores medical data and metadata via NFC.

information on alterations in electrolyte disorders can provide invaluable feedback to physicians; in this case, the electrolytes serum levels to be monitored usually include sodium (Na), potassium (K), calcium (Ca) [6], and pH [7]. Sensing through NFC and personal smartphones would greatly enhance the individual cure for such patients by enabling telemedicine systems and storing all the patient’s medical data and metadata (Fig. 1).

To address the single-measurand limitation, a multi-chip NFC system for electrochemical sensing is proposed. Each chip is connected to a spiral antenna and interacts with the microfluidic through its own sensing electrodes; therefore, four NFC queries are required to retrieve all the data. This system is conceived to perform chemical analyses on four species from a single liquid sample, thanks to the further implementation with a paper-based microfluidic circuit. Indeed, in order to minimize measurement uncertainty, required time, and, eventually, patient pain due to taking multiple specimens, the electrochemical analysis should be performed by a unique liquid sample. Microfluidic channels can, hence, be designed to carry sufficient liquid to the sensing electrodes in the timeframe required to perform sensing and prevent liquid alteration. In this regard, it is crucial to deliver the correct quantity of liquid in a relatively short span of time. The use of four separate NFC boards allows for avoiding resorting to microcontrollers and switches that would slow down the overall reading of the board and could also introduce noise during measurements. Early results on this multi-chip NFC system, mainly focused on the communication performance of the boards, were presented in [8]. This paper, instead, reports the preliminary calibration of the sensing layer of the board to

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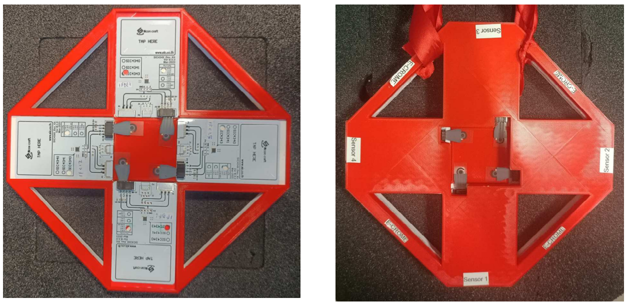


(a) (b)

Fig. 2. One manufactured system prototype. NFC boards in the (a) open and (b) closed 3D-printed case.

detect the four concentrations relevant for oncology applications mentioned above. The calibration process involves experimentation with known concentrations of analytes in standard solutions, and accounts for both the effects of the ad-hoc sensing electrodes and the transducing NFC microchips on the sensed signal.

II. Four-Channel NFC System

A. System Layout and Assembly

The multi-chip NFC system for electrochemical sensing was designed to ensure optimal performance in terms of read area, communication quality, and ease of use [8]. The NFC boards performing potentiometric chemical sensing are FlexSense boards (by SiliconCraft Technologies) integrating the microchip SIC 4343 (by SiliconCraft Technologies). The FlexSense boards are passive and energized by the interrogating smartphone during reading thanks to the NFC magnetic coupling. Interferences between the boards should be avoided when using the system, and the time required to retrieve a sensing data from a board is of about 15 seconds.

The final platform layout has been selected considering the future integration with a paper-based microfluidic circuit simultaneously feeding the four electrodes with liquid taken from a single specimen. In detail, a protection case for keeping in place the NFC boards and carrying the system as a whole was designed in CST Microwave Studio 2023 [9] and prototyped using colored PLA (polylactide) [10] and a RAISE3D E2 3D-printer [11]. The case is composed by a lower and an upper part closed by velcro straps and has a central opening which allows for substitute the single-use screen-printed electrodes [Fig. 2(a,b)]. The potentiometric sensors for sodium, potassium, calcium and pH detection are ad-hoc modified screen-printed electrodes. The sensing materials on the screen-printed electrodes were selected in agreement with previous works [12, 13], namely, the counter electrode and the working electrode are screen printed in graphite-based ink (Electrodag 421) whereas the pseudo-reference electrode exploits Ag/AgCl ink (Electrodag 477 SS; Fig. 3). The overall system can be carried wherever it has to be used and enables PoC or on-site food multi-analyte sensing.

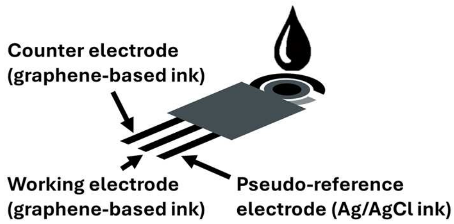


Fig. 3. Scheme of the potentiometric sensing electrodes.

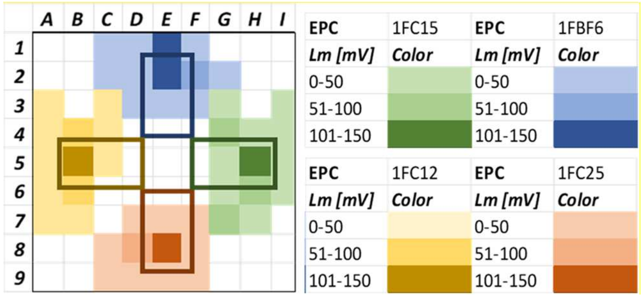


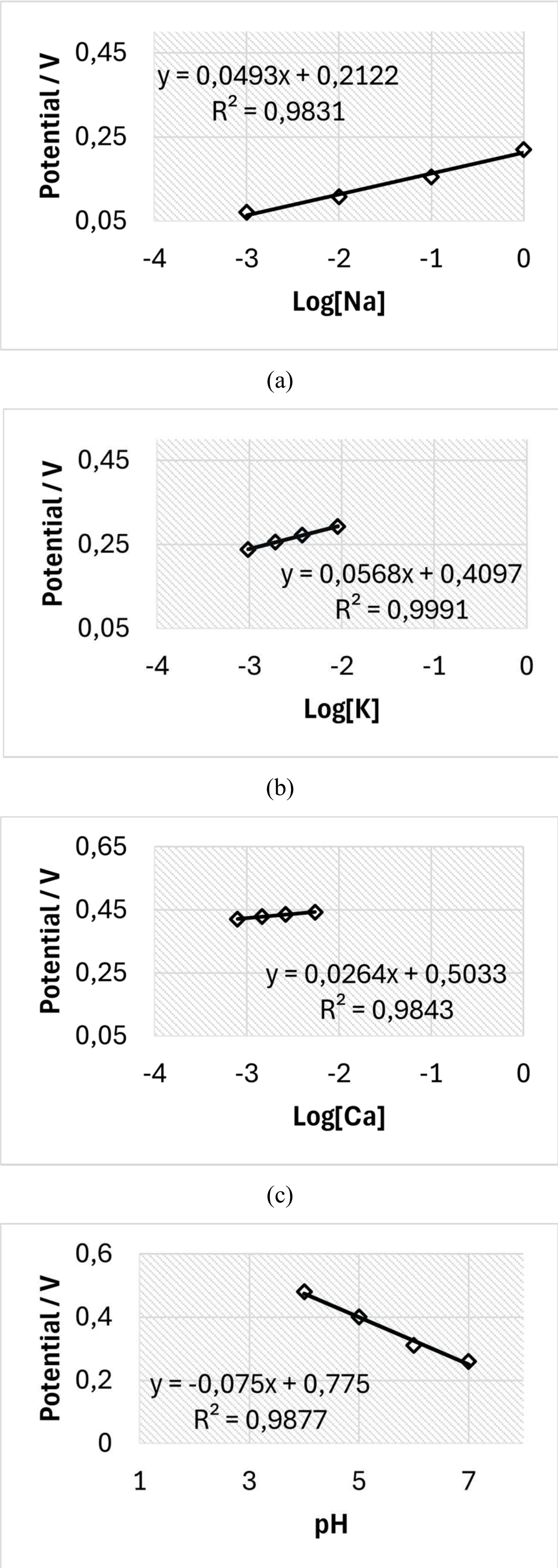
Fig. 4. Measured coverage map of the four-channel NFC system.

B. Communication Performance

The experimental setup for the quantification of the communication performance involved the use of the Tagformance Pro system by Voyantic, which includes the C60 interrogation antenna composed of four loops with a diameter of 60 mm. This setup was used to evaluate the NFC read area of each board. A grid with graph paper was employed to precisely measure the read areas, and the HF (High Frequency) functionality of the Tagformance Pro system was utilized to assess the strength of the NFC communication. Fig. 4 illustrates the coverage map for the system layout, showing a similar read area for each single NFC board and an absence of superposition areas (namely, areas wherein more than one board respond) that could cause measurement errors. The strength of the interrogator-responder magnetic coupling is quantified by the (passive) Load Modulation (Lm), viz., the variation of amplitude to the antenna voltage in the interrogator caused by the impedance switching in the responder [14]. By placing an interrogating smartphone directly on the 3D-printed case, it is possible to scan the four NFC microchip and retrieve the data on all the analytes in about one minute.

III. Calibration with Four Analytes

To perform the calibration, each single board receives as the input one drop of standard solution having only the target analyte at a known concentration. Then, the voltage registered by the board is recorded for 10 seconds, to monitor the temporal stability of the response; each voltage-concentration point is obtained as the average value of the 10-seconds-long track. The procedure is repeated for at least 4 different concentrations of each analyte. After having the calibration points of interest, a regression line for each analyte is drawn to derive the calibration curve of the sensor. It is worth highlighting that this procedure characterizes simultaneously the influences of the electrodes and the arranged NFC boards; hence, the



(a)

(b)

(c)

(d)

Fig. 5. Calibration curves of the multi-channel NFC system on the four analytes of interest: (a) sodium, (b) potassium, (c) calcium, and (d) pH.

TABLE I. REGRESSION LINES FROM THE EXPERIMENTAL CALIBRATION OF THE SYSTEM

Analyte	A	b	R^2
Sodium (Na^+); Fig. 5(a)	0.049 ± 0.002	0.212 ± 0.004	0.983
Potassium (K^+); Fig. 5(b)	0.057 ± 0.001	0.410 ± 0.002	0.999
Calcium (Ca^{2+}); Fig. 5(c)	0.026 ± 0.001	0.503 ± 0.001	0.984
pH; Fig. 5(d)	-0.075 ± 0.003	0.775 ± 0.006	0.988

calibration is system dependent. The regression curve expression is hereafter reported with the classical variables' notation $y = ax + b$ where y is the output in voltages, x is the target analyte's concentration, and (a, b) are the experimentally derived regression variables. The goodness of the fit is evaluated by the R^2 value.

Measurements were conducted in laboratory by dropping 80 µL of distilled water solution containing different concentrations of the target analyte onto the proper ad-hoc modified electrode. In detail, Na^+ was detected in the range 10^{-3}-1 M, K^+ in the range 10^{-3}-10^{-2} M, Ca^{2+} in the range 1-10 mM, and pH in the range 4-7. Fig. 5 reports the four calibration curves of the multi-chip NFC system, and Table I confronts the corresponding numerical values. The uncertainty on the regression line values is always extremely low thanks to the remarkably stable response of the electrodes. The system was able to detect all the concentrations of interest showing a linear response without any distortion so to allow precise quantification over the full range. Overall, the experimental calibration confirms the suitability of the system for sensing the analytes, and this same described procedure could be repeated for other analytes by developing new sensing electrodes and changing the standard solutions utilized.

IV. CONCLUSION AND ONGOING WORK

In this contribution, we presented a multi-chip NFC system for measuring four concentrations through open circuit potentiometry and reported the preliminary calibration of the system itself. The target concentrations are vital for oncology treatments and are sodium, potassium, calcium, and pH. Given proper sensing electrodes, the same calibration procedure can be employed to sense different chemical measurands for other applications, for instance, off-packaging sensing for the food industry.

Currently, we are testing the system in clinical settings involving actual patients to initially deploy the system for PoC purposes. We are also testing microfluidic circuits based on filter paper to feed the four boards with a single drop of liquid simultaneously. Additional results will be disclosed at the conference.

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