Wireless Passive Monitoring of Electrocardiogram in Firefighters

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***Abstract*—Firefighters, although equipped with specialized protective garment, are in danger not only during but also after incidents. This calls for a dire need to monitor firefighters' survival signs such as body temperature and heart rate. Here, we develop a novel electrocardiogram (ECG) monitoring system consisting of non-contact electrode (NCE) bio-potential sensors and an inductive link for both wireless power transfer (WPT) and data communication. Various experiments were thoroughly conducted to characterize the efficiency of WPT and ECG signal quality in practical scenarios. Our method can also be implemented to obtain other physiological parameters, such as motions and body temperature, thus holding promise to promote safety of firefighters.**

***Index Terms*—Non-contact electrode (NCE), electrocardiogram (ECG), wireless power transfer, backscattering.**

I. Introduction

Cardiovascular-related issues contribute 45% of on-duty mortality in firefighters in the U.S. [1]. In a recent study, Farioli *et al.* reported that 1.1 million firefighters suffering from sudden cardiac death with underlying reasons of coronary heart diseases and/or left ventricular hypertrophy [2]. Furthermore, not only middle-aged firefighters have high risks of CVDs, but it also applied to younger individuals. Therefore, monitoring of vital signs such as body temperature, electrocardiogram (ECG) and blood pressure (BP) would be crucial to firefighters prior to, during and post incidents. Currently, firefighters' standard protective equipment costs over $8,000, yet still has no means for personal health monitoring.

Many assistant monitors for on-duty firefighters have been developed [3, 4]. Zieba *et al.* introduced an ECG monitor using textile electrodes and the ECG signal was comparable to that using conventional Ag/AgCl electrodes [3]. However, more experiments should be carried out to demonstrate its efficiency in real scenarios. Another study used a 12-lead ECG Holter to detect cardiac events among 28 firefighters [4]. This research was successful to track firefighters' heart activity prior to and post duty; however, it would not be applicable if a bulky ECG Holter was worn while they were on duty. Further, none of those systems stored data for post-incident analysis which is critical to study the performance and issues of firefighters.

We have developed a solution that is suitable for current and next-generation systems for firefighters [5]. The immediate purpose is to reduce risks firefighters facing now with an overall goal to enhance the performance of the rescue and disaster-relief teams. In our previous work, we deployed non-contact electrode (NCE) method to acquire ECG signals. The NCE ECG unit designed to be incorporated in the base-layer garment was developed on flexible polyimide and wireless communication was demonstrated using a commercial-off-the-shelf (COTS) Bluetooth Low Energy (BLE) module. The operating power was obtained by near-field inductive coupling via a pair of identical planar spiral antennas embedded in the base layer and the external unit, respectively (**Fig. 1**). In this paper, we demonstrate a fully-passive wireless ECG monitoring system so that the ECG signal would be backscattered to the external unit where communication means should be ready for continuous monitoring, analysis and data logging. This helps reduce the components in the base layer, thus improving the feasibility of the entire system. The efficiency of wireless power transfer and the NCE ECG signal quality were comprehensively characterized through various experiments, mimicking real-world scenarios.

II. Design And Implementation

The conceptual design of the entire system and the block diagram are illustrated in **Fig. 1.** The base layer comprises of NCE ECG acquisition, wireless power transfer (WPT) harvesting and simple-yet-novel backscattering communication. Specifically, the receiver coil (RX) and transmitter coil (TX) were fabricated with identical size and spiral planar topology as previously reported [5]. The TX was located on the fire entry suit and powered by the existing power source (i.e. battery). In the RX side, the ECG output will modulate the backscattered signals; thus, by extracting signal components at the TX, the ECG signal can be collected.

A. NCE ECG Acquisition

The NCE ECG acquisition used two NCEs configured as shown in **Fig. 2** to collect the ECG signal throughout the base layer in the firefighter's suit. It is then amplified by the instrumentation amplifier INA333 (*Texas Instruments*) which has a

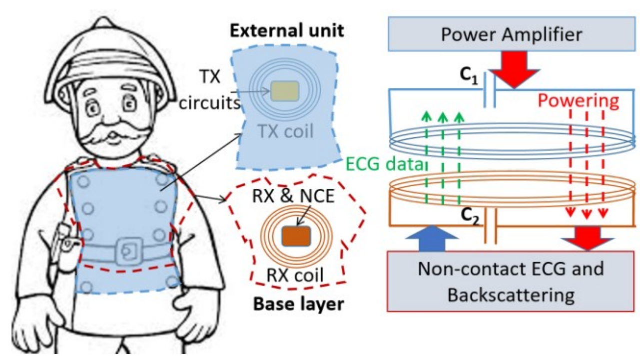

Fig. 1. Conceptual design and block diagram of the system.

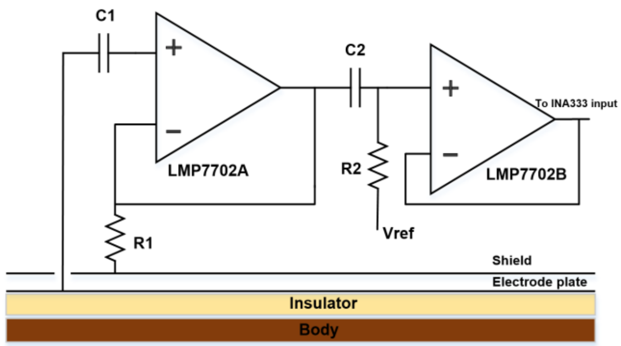

Fig. 2. Non-contact electrode schematic.

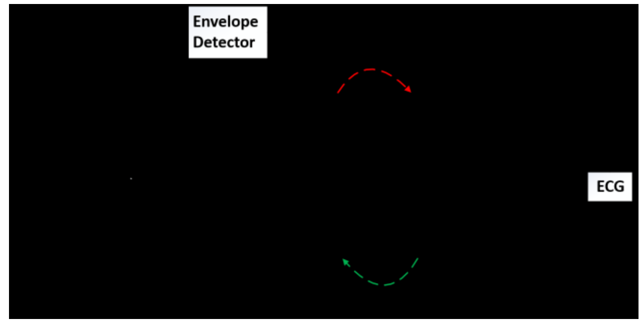

Fig. 3. Simplified schematics of the external unit and base layer for the sensor.

high common mode rejection ratio (CMRR>100 dB). Subsequently, a high-pass filter with 0.5 Hz cut-off frequency was established so that motion artifacts can be eliminated. To get rid of the power line interferences, a second order Sallen-Key low pass filter with 40 Hz cut-off frequency was implemented.

The use of NCE for ECG acquisition has been widely exploited recently owing to its advantages over the conventional approaches using wet/dry contact electrodes [6, 7]. While the wet electrodes can cause allergic reactions or skin irritation as well as discomfort due to adhesion on skin [6], the NCE can be considered as a perfect alternative one without signal degradation for long-term monitoring application and considerably appropriate for the firefighters on duty [8]. Further, the NCE measurement presents advantages as it is independent of skin conditions (hairy, oily, etc.), those significantly affect the performance of contact electrode methods. However, it has drawbacks, especially the susceptibility to motion [7]. In this application, the effect of motion artifact can be reduced owning to the integration of NCEs within the snugly-fitted base layer. In our design, the NCE circuit was combined by a proper shield and unity gain buffer as shown in **Fig. 2** [9]. The role of the buffer was emphasized because measuring the ECG signal without direct contact to the skin would result in extremely high input impedance. Therefore, a unity gain buffer (LMP7702 – *Texas Instruments*) would help reduce interferences from the ambient environment.

B. Wireless Powering and Communication

In our WPT system, two identical coils for TX and RX (L=7.68 μH) were used. The operating frequency was chosen at ~ 1 MHz to simplify component selection [10]. In the external unit (**Fig. 3)**, a class-E power amplifier was selected and the power MOSFET (Q1) was IRF530 (*Vishay Siliconix, Santa Clara, CA)* to minimize undesired system responses. Other parameters include Q_L = 6; P = 1 W; L_1 =24 μH; R=46.73 Ω; L_2=44.65 μH; C_1=625 pF; and C_2=773 pF. Furthermore, to compensate the forward voltage that drops in the diodes and optimize conduction to the load, a full wave rectifier with voltage doubler was designed as shown in **Fig. 3.** C_5 and C_6 *w*ere selected as 10 nF. The output of ECG acquisition was fed back for communication. Finally, an envelope detector circuit is used to extract the ECG signal that is rectified by diode D_1 at the TX.

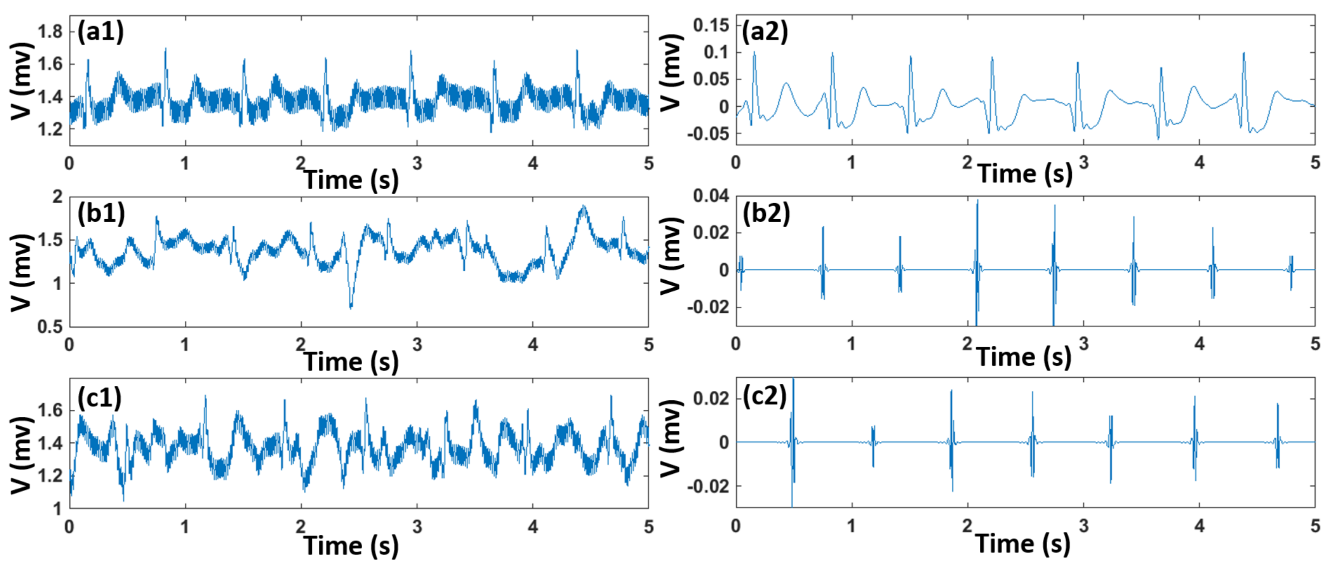

Fig. 4. The ECG signal obtained in various scenarios (**a1**) Stable posture, (**b1**) Leg movement and, (**c1**) Arm movement. (**a2**), (**b2**), (**c2**) Signals of those after wavelet de-noising.

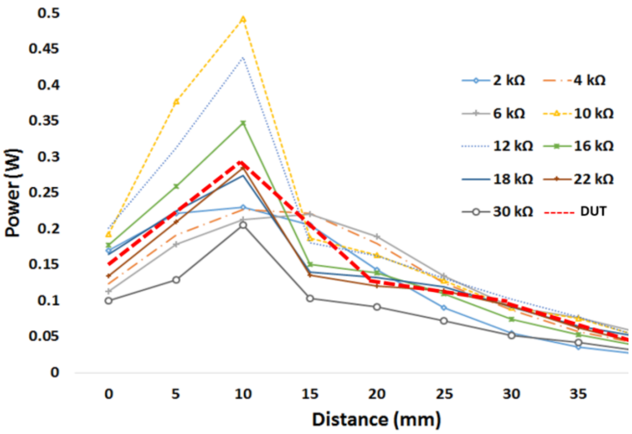

Fig. 5. Power delivered to the different loads versus distance.

III. Experiments, Results and Discussion

A. ECG Acquisition with NCE in Different Scenarios

Due to unexpected movements of the highly-acrobatic firefighters during fire incidents, the NCE ECG signal is investigated in various practical scenarios such as stable posture, leg and arm movement. **Fig. 4** shows ECG signals before and after de-nosing in those three afore-mentioned scenarios. Here, we adopted the wavelet de-noising technique which has been extensively employed in our group [11]. It is obvious that the ECG signal at stable posture (**Fig. 4 a2**) provides full-feature ECG after de-noising while the movement added noise components which made it hard to recognize P and T waves (**Fig. 4 b1 & c1**). However, R peaks could still be easily determined in all cases after de-noising (**Fig. 4 b2 & c2**), demonstrating heartrate was always successfully acquired.

B. *Wireless Power Transfer Characterization*

Fig. 5 shows the power obtained at RX with different loads from 2 kΩ to 30 kΩ. The distance between TX and RX was incremented by 5 mm and then the delivered power was calculated. The power reached the highest values at 10 mm for all different load resistors and the maximum power was found at 10 kΩ load. The power of device (NCE ECG acquisition) under test (DUT) curve (dot red trace) showed that the maximum power of 0.28 W is obtained at 10 mm. The WPT scheme can guarantee the device operation within 40 mm which is way above a nominal distance between the fire suit and the base layer (<20 mm).

IV. Conclusions

In conclusion, we have successfully demonstrated a wireless passive ECG system that could be used to continuously monitor the cardiac activity of firefighters during fire events. Various experiments were conducted, showing the ECG acquisition with NCE could obtain usable data for real-time monitoring as well as post-incident diagnoses. For future work, we will optimize the wireless power transfer efficiency as well as integrate other sensors such as body temperature, respiration rate, etc. into our system. We will also work with fire suit manufacturers, such as Blauer Manufacturing Co., Inc. to incorporate our systems for real-scenarios testing and validation.

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