Fall Detection and Warning System for Nursing Homes based on Bluetooth Low Energy

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***Abstract*—Fall accidents are a frequent problem with the elderly and lead to severe injuries and/or could have a lethal ending. To prevent these potential deaths the nursing personnel visits the elderly on a regular basis. This has an enormous influence on the mental and physical capabilities of the nursing personnel. In combination with the ever-growing presence of Internet of Things (IoT) applications, this paper proposes a low-power wireless fall detection and warning system based on Bluetooth Low Energy (BLE). The aim of the system is to lower the workload of the nursing personnel and prevent elderly from dying from hypothermia. The system consists of a patient wearable (P) monitoring the movement of the elderly, a Detection Node (DN) scanning the room of the elderly to pinpoint the position of the fallen elderly, multiple Network Nodes (NNs) in the hallways sending the alert messages to the closest caretaker wearing a Caretaker Node (CN). This node visualizes all vital parameters, so the nursing personnel can help in the fastest way possible. A proof-of-concept is proposed in this paper, together with measurements and power analysis.**

***Index Terms*—Bluetooth Low Energy (BLE), fall detection, nursing, Internet of Things (IoT), Radio-frequency identification (RFID)**

I. Introduction

About $40\,\%$ of elderly people over 65 year old, pass away due to fall accidents [1], [2], [3]. To prevent these falls from happening, much effort is performed in personal training for the elderly [4]. These fall accidents have a large financial impact on the medical system [5] since the nursing personnel has to manually check if a fall occurred. The consequence of this action, is an extra physical and mental stress added to the baseline stress level of the nursing personnel.

In current literature, much research is performed in developing algorithms based on cameras [6], wearables [7], RF based [8] detection or a fusion of different data streams [9], [10]. Many of these algorithms are based on a type of Machine Learning (ML). A disadvantage of this system is the need for representative training data [11] which can be difficult to achieve. Most wearables proposed in literature are large and have the sole purpose to obtain data, but cannot be used in real life. Furthermore, it is a known fact that elderly people do not like the use of large or too complicated wearables [12], [13]. Next, the care taking personnel is never part of the proposed solutions, so no effort in lowering their stress levels is proposed.

To prevent the elderly from suffering serious injuries and trying to lower the stress level from the nursing personnel, a small unobtrusive fall detection and warning wearable was proposed in a previous publication [14]. Here, a proof-of-concept for a low-cost fall detection and warning system based on Bluetooth Low Energy (BLE) [15] is proposed. This system has to send the alert messages from the wearable to the closest nursing personnel in a fast and low-power way.

This paper is further structured as follows. First, the design of the system and the development of the different nodes is elaborated in section II. It is followed by the executed measurements in section III and by a small conclusion in section IV. In section V, some extra future features are summarized.

II. Design

A. Design requirements

Based on the advantages and disadvantages of the current system presented in literature, multiple design requirements were adopted:

1) A low-cost and low-power system
2) Easy to implement system
3) Compact and unobtrusive wearable for patient and care taker
4) Fast reception of an alert package at the care taker

B. System design

Taking the previously called design requirements into account, a system with four different types of nodes is proposed. The first node is the patient wearable P_1, which is depicted as a green dot in Fig. 1. This wearable contains an accelerometer to monitor the movements of the elderly and was developed in an earlier publication [14]. It utilizes a rule based algorithm based on the retrieved accelerometer data. The algorithm consists of two thresholds. First, the Signal Magnitude Vector (SMV) is calculated. When this value is higher than a predefined threshold of 2.5 g, the peak of the fall is found. Second, the orientation towards the gravitational vector before the peak and after the peak is calculated. When the difference between these two angles is larger than 45°, a fall occurred and the wearable will send an alert. This alert will be picked up by the Detection Node (DN), which is depicted as a red dot in Fig. 1. This node will not only forward the alert package, but will also include the necessary data (like room number and floor), so the nursing personnel can find the elderly efficiently. In this way, the system can detect other elderly who fall in a room different from theirs, and the nursing personnel does not go to the wrong room or floor. In subsection V, some extra features that could be added are summarized.

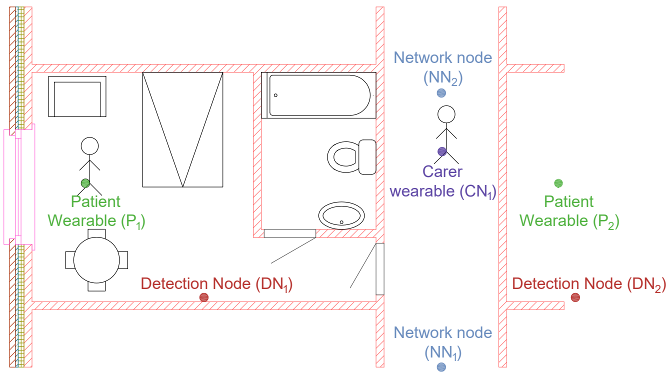


Fig. 1: Top view of a typical nursing room with a part of the hallway. The patient is wearing the wearable P_1 (green dot) and the Detection Node (DN) is placed in a central position of the room (red dot). Furthermore, the Network Nodes (NNs) (blue dot) are mounted on the ceiling of the hallway while the nursing personnel is wearing the Caretaker Node (CN) (purple dot).

The DN sends this updated alert package to the Network Nodes (NNs), which are depicted as blue dots in Fig. 1. For illustrative purpose, these nodes are drawn close to each other, in reality the distance is larger. These nodes have the sole purpose to look for the closest nursing personnel or forward it the surrounding NNs. When a Caretaker Node (CN), depicted as a purple dot in Fig. 1, is in proximity of a Network Node (NN), the alert will be picked up. The nurse will get an alert and see the important parameters like temperature, patient name, patient room, floor number, etc. To achieve this, a custom-made advertisement package is made and sent to the required nodes.

When an alert is handled, the nursing personnel pushes a button on the CN and the complete system knows the alert is handled. To handle multiple fall accidents at the same time, the NN is equipped with an alert stack function, so the first in first out (fifo) principal is used.

C. Communication steps

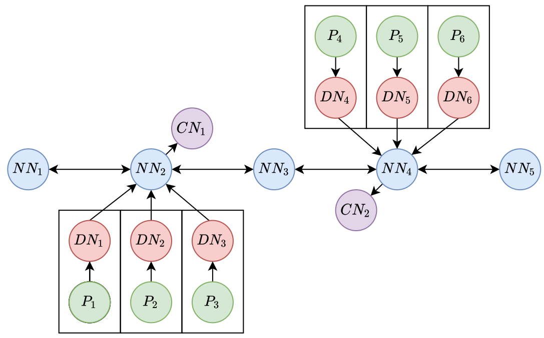


Fig. 2: Graphical representation of the different communication steps of the proposed system.

Fig. 2 gives a graphical representation of the communication steps that are taken when a fall is detected by one of the patient's wearable P_x. It triggers an alert and sends an alert package to the DN_x inside the room where the elderly fell. This node adds the necessary data to the alert package and sends it to the closest NN_x. This node sends the message to the other NNs when there is no CN is in the proximity. When the CN receives the alert message, the NNs marks this alert stack entity as *'Being Handled'*. When the nursing personnel helped the elderly, the handled button on the CN_x or DN_x is pushed. This sends a package to the closest NN_x and the alert stack entity is cleared. Next, the NN forwards the message to all other NNs where the same entity is cleared.

D. PCB Design

To test the proposed system, some hardware was designed. Since most of the nodes contain the same hardware and peripherals, only one PCB is designed. Fig. 3 displays the layout of the PCB for the designed nodes. The design relies on the EFR32MG13P632F512GM48-CR wireless System-on-Chip (SoC) from Silicon Laboratories (SiLabs) [16]. This multiprotocol SoC uses the BLE5.1 stack and contains an on-board 32-bit 38.4 MHz ARM [17] Cortex-M4 microcontroller (MCU) with DSP instruction set. This ARM Cortex-M4 is a modern general-purpose MCU and makes it ideal for employment in many low-power systems.

The complete module has an overall size of 30×30 mm. It contains two pushbuttons, four LEDs and the other peripherals, required by the SoC. Furthermore, a TAG-connect [18] connector is used to program the nodes via the Serial Wire Debug (SWD) protocol [19]. The Power Supply Unit (PSU) is a standard small battery of 3.3 V or can be switched to a standard lab PSU. Since this is a proof-of-concept, an SMA connector is added so multiple antennas could be tested. The

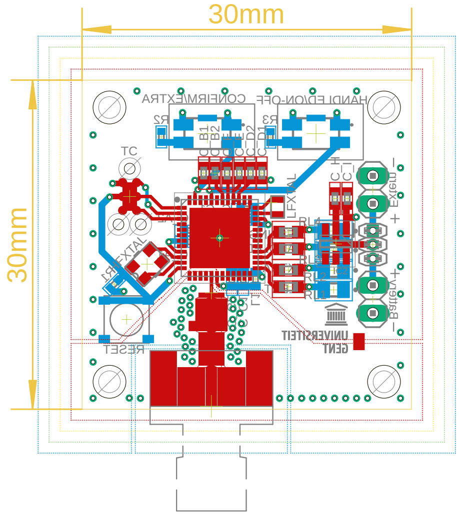
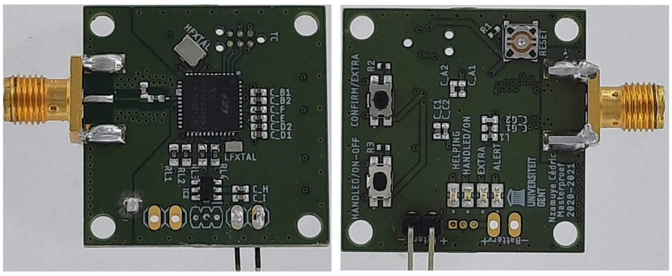


Fig. 3: Graphical representation of the developed CN Printed Circuit Board (PCB).



(a) Top (b) Bottom

Fig. 4: Picture of the developed PCB.

pushbuttons and LEDs have a specific purpose for each node. For the CN, the pushbutton have a "alert handled" or "require more help" function. For the NN they are not necessary and hence not soldered.

Fig. 5: The soldered PCB with the hinged dual-band Delta 7A from Siretta connected.

Fig. 5 illustrates the Delta 7A hinged mount WiFi/ISM antenna of Siretta is selected to perform the measurements proposed in subsection III. This is a dual-band $\lambda/4$ omnidirectional dipole antenna tuned at the 2.4 GHz and 5.8 GHz range, with a radiation efficiency of 63.6 % and 66.2 %, respectively. This antenna is vertically polarized with an almost omnidirectional radiation pattern at 2.45 GHz, which makes it an appropriate antenna for BLE. This cylindrical hinged mount antenna has an overall length of 108 mm and the bottom diameter is 9.3 mm. The integrated SMA connector, makes this an ideal and low-cost antenna to perform these measurements. In the future, the antenna will be co-optimized with the fall detection circuit for optimal performance.

III. Measurement & Discussion

To test this proof-of-concept, some measurements were performed.

A. Range Measurement

First, the range of the system is determined based on a series of Received Signal Strength Indicator (RSSI) measurements over different distances. One of the design requirements of this system (section II-A) is a low-cost and low-power solution. To meet this requirement, BLE is used as main communication protocol. This makes the system easily scalable and uses minimal power to transfer large amounts of data. Furthermore, the amount of NNs should be limited to keep the production and installation cost low.

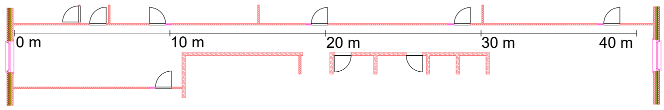


Fig. 6: Graphical representation of range measurement setup in the hallway at a Ghent University building.

To get a general idea of the range the system covers, RSSI measurements are performed. The first NN is placed on the left side of the hallway and is set to a fixed Tx level of 0 dBm. This node sends 2000 labelled advertisement packages. In this way, no other packages can be received and influence the measurements. The second NN is placed at a distance of 10 m, 20 m, 30 m and 40 m and continuously scans for advertisement packages. A graphical representation of the measurement setup is visible in Fig. 6. Afterwards, the RSSI values are used to calculate the Average Received Power (ARP) and the Package Receive Rate (PRR) based on equation 1 and 2, respectively.

$$ARP_{TX}\,[\text{dB}] = 10.\log_{10}\left(\frac{1}{m}.\sum_{n=1}^{m} 10^{\frac{RSSI_n\,[\text{dB}]}{10}}\right) \tag{1}$$

$$PRR_{TX}\,[\%] = \frac{m}{2000} \tag{2}$$
$$m = \text{number of received packets}$$

The results of the range measurements are visible in Fig. 7 and Fig. 8. Fig. 7 illustrates the calculated ARP of 2000 RSSI values received at the NN. An ARP of −48.61 dBm, −58.12 dBm, −60.04 dBm and −64.78 dBm at a distance of 10 m, 20 m, 30 m and 40 m result in a perfect communication possibility. Taking into account that the minimum Rx sensitivity level of the used MCU is −94.6 dBm. These result also illustrates that at a distance of 40 m, communication is still perfectly possible and could be extended even further.

Fig. 8 illustrates the calculated PRR of 2000 RSSI values received at the NN. This graph, just like the previous, illustrates reliable communication with an average PRR of ±90 %

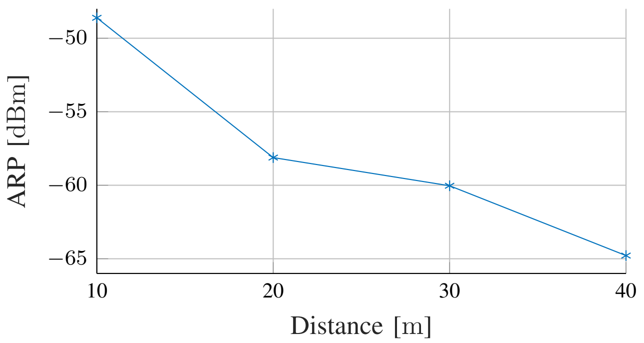


Fig. 7: Measured ARP at a distance of 10 m, 20 m, 30 m and 40 m from a NN sending 2000 advertisement packages at a Tx level of 0 dBm.

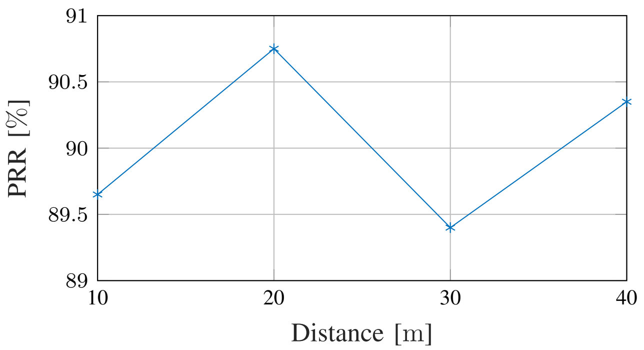


Fig. 8: Measured PRR at a distance of 10 m, 20 m, 30 m and 40 m from a NN sending 2000 advertisement packages at a Tx level of 0 dBm.

over all measured distances. Both graphs clearly illustrate that the hallway has a positive effect on the range and performance of the system. Furthermore, placing an NN every ±40 m in a hallway of a nursing home keeps the system low-cost. The low-power requirement is also achieved, since a Tx level of 0 dBm has minimal influence on the battery lifetime or power consumption.

B. Latency Measurement

Latency is the second important factor that is measured. Since the system has to send alert messages to the CN, it is important to know how long it takes to receive an alert. For this setup, the hallway from another Ghent University building is used, as can be seen in Fig. 9. The P and DN are placed at position *A*. The NN and CN are placed at a certain position, ranging from 22 m to 84 m (labelled from *B* to *I* in Fig. 9). The positions were chosen based on obstacles in the hallway that could hinder the communication signals. During these measurements, the time between registering a fall and receiving it on the CN is logged. The nodes transmit at a fixed Tx level of 0 dBm to keep the energy consumption as low as possible.

The latency between sending an alert on the wearable P and receiving this on a CN, passing a DN and one NN, resulted in an overall latency of ±3 s. Adding an extra NN to this chain has a serious influence on the extension of the range, but a limited influence on the latency. The overall latency is increased to ±3.5 s. This measurement provides the required proof for the fourth design requirement in section II.

IV. Conclusion

This paper proposes a proof-of-concept for a low-cost fall detection and warning system based on BLE for nursing homes. The proposed system consists of four nodes. The first node is worn on the patient and triggers an alert in case of a fall event. Inside each room, a DN is mounted that will scan the room for alert messages. In the hallway of the nursing home a network of NNs is deployed. On arrival of an alert package, these nodes scans for the closest CN and sends the alert. When no CN is in proximity, the alert is forwarded to the next NN.

This paper covers the high-level communication steps of the complete system, as well as the hardware that is developed. Some extra peripherals are added to these PCBs, so each node could be used in a real-life test. Furthermore, some measurements were performed. First, RSSI levels are measured to calculate the ARP and PRR. An ARP of −64.78 dBm and a PRR of ±90.5 % were measured at a distance of 40 m. This proves the low-cost and low-power property of the proposed proof-of-concept. Furthermore, the numbers prove that the system can cover more than 40 m. In the latency measurements, over a distance of 50 m the systems takes ±3 s with one NNs to transfer an alert from patient wearable to CN. When an NN is added, a distance of 84 m is achieved with a latency of ±3.5 s, proving the fourth design requirement of fast reception of an alert package at the care taker. In conclusion, based on the communication protocol of BLE and the performed measurements, all design requirements are fulfilled.

V. Future Work

In a next step, multiple modifications can be made for each node. The DN could be extended with Angle of Arrival (AoA). Since the MCU is utilizing BLE5.1, AoA is a good extension to the detection range. When a fall occurs, the wearable detects the fall, but the DN is able to pinpoint at with position the fall happened. This way, the nursing personnel can determine how dangerous the fall was. If an elderly person falls in the bathroom for instance, there is a greater risk of serious injuries.

The CN can be extended with a small LCD screen. The LCD screen makes it more convenient to read the data from the wearable and replaces the LEDs efficiently. Next, a vibration motor and buzzer can be added to make the receiving alert more noticeable for the nursing personnel wearing the CN. Of course, the power management is an important parameter in this design. In an addition, a wireless charging coil is a nice feature to charge the integrated battery.

Both nodes can be extended with Near-Field Communication (NFC) and/or Radio-frequency identification (RFID). When the nursing personnel enters a room, they can cancel

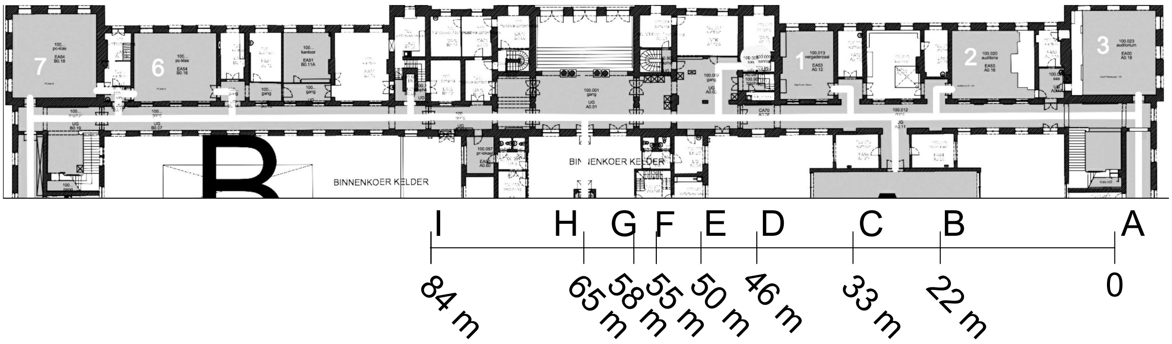


Fig. 9: Graphical representation of the latency measurements in the hallway at the Ghent University building.

or handle the alert by simply touching the NFC and/or RFID reader with their tag integrated in the CN. This small and inexpensive adaptation has a large influence on the ease of use. Furthermore, a suitable antenna topology is needed for both nodes since they are placed on the ceiling of the hallway or against the wall of the room. Therefore, a hemispherical radiation pattern is preferred.

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