# Dual-Mode Wireless Sensor Network for Real-time Contactless In-door Health Monitoring

*Marco Mercuri[1], Mohammad Rajabi[1], Peter Karsmakers[1], Ping Jack Soh[2], Bart Vanrumste[1], Paul Leroux[1], and Dominique Schreurs[1]*

[1]*Department of Electrical Engineering, KU Leuven, 3001 Leuven, Belgium*

[2]*School of Computer and Communication Engineering, Universiti Malaysia Perlis, 02600 Perlis, Malaysia*

**Abstract — Due to the ageing population, real-time and autonomous health monitoring is an emerging priority in ambient assisted living. In this work, a wireless sensor network is proposed for home environments by which the sensors are dual-mode radars, enabling concurrent remote localization of a person (i.e., without use of a tag) and fall detection. We elaborate on the network architecture, and in particular on the signaling as to enable real-time data processing (i.e., max. delay is 0.3 s) combined with radar-based wireless sensing. The approach is successfully demonstrated experimentally.**

**Index Terms — Contactless, fall detection, movement classification, radar remote sensing, real-time health monitoring, tagless positioning, trilateration, WSN, Zigbee communication.**

## I. Introduction

Radar techniques have been recently investigated for applications in healthcare, such as vital sign monitoring [1]-[3] and fall detection [4]-[6].

However a single radar sensor is insufficient for real situations. Depending on the position of a person in a room, his/her reflection as consequence of radar excitation may be obstructed by furniture. Moreover, in case of fall detection where it is fundamental to assess the changes in speed as experienced by a subject during normal movements or fall incidents, it is not possible to detect falls perpendicular to the line of sight (LoS) of the antenna [5], [6]. These problems can be overcome by means of a wireless radar sensor network (WRSN). In fact, by combining data from several sensors, a better estimate of the motion is obtained. Moreover, a single radar can detect absolute distance so by using multiple sensors it is possible to detect position. These effects combined allows tracking the person as well as detecting fall incidents in all directions. It should be specified that in [6] it was demonstrated that fixing a single radar sensor on the ceiling might overcome the Doppler effect limitation because most of the falls have an important vertical motion component. However, positioning multiple radar sensors to the ceiling presents a serious limitation for in-door positioning applications. In fact, as opposite to the case with the radar sensors fixed to the wall, the much smaller target's radar cross section (RCS) makes its reflection very weak, such that it is buried in the noise. Moreover, the target's position cannot be determined using an analytical trilateration procedure because the radar sensors and the subject do not lie on the same geometric plane [7].

Academic investigations on WRSN aiming at contactless vital sign monitoring have been reported in [8], [9]. In [9], the authors combined three M-sequence UWB (Ultra Wideband) radars to perform also tagless positioning. However such type of radar involves both a complex architecture and huge amount of data that cannot be transmitted through wireless communication links. An example of WRSN using an RFID tag for automatic guided vehicle for warehouses was proposed in [10]. To our knowledge, nothing was reported on WRSN for contactless fall detection, especially in combination with in-door positioning.

In this work, we present a dual-mode WRSN aiming at both these goals, namely contactless fall detection and in-door positioning in real-time. It should be noted that this approach is tagless, meaning without any use of radio frequency identification (RFID) tag attached to the person. As opposite to [4]-[6] where only one sensor was used, three sensors are now involved. This means dealing with all the challenges that the real-time modality imposes, considering also data originating at the same time from multiple sensors. It should be specified that in [4], [6] the system was proven to be accurate but not able to work in real-time. In [5], the system was extended to perform only real-time fall detection.

In Section II, the WRSN architecture is presented and detailed. Experimental results are shown in Section III.

## II. Wireless Radar Sensor Network Architecture

The dual-mode WRSN consists of multiple radar sensor nodes and a base station for real-time data processing (Fig. 1). In this work, we focus on covering one room, and assume that the network consists of three nodes, but the approach is scalable to a higher number of nodes and multiple rooms. The sensor node, consisting of a microcontroller, a Zigbee module, and a microwave radar sensing front-end, was already described by the authors in [4]. The waveform generated by the radar consists of a single tone in the industrial, scientific and medical (ISM) radio band at 5.8 GHz, which is used to detect the target's speed exploiting the Doppler effect, alternated with a stepped frequency continuous wave (SFCW)

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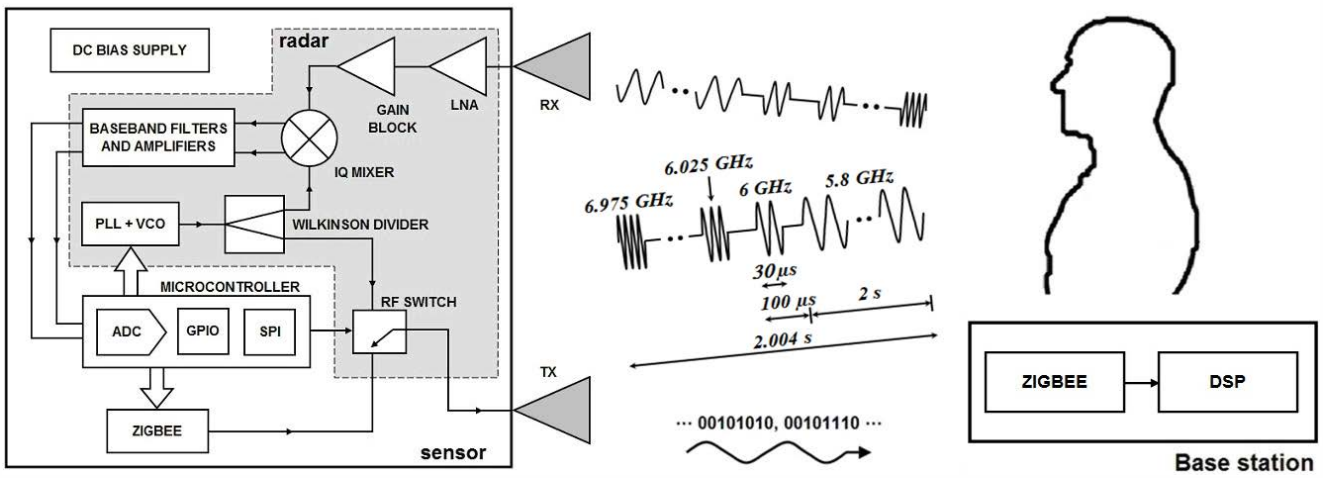



Fig. 1. Block diagram of the dual-mode WRSN. The system consists of three microwave radar sensors and a base station for real-time data processing. For simplicity's sake only one sensor is shown in the figure [4].

signal, operating in the UWB frequency band between 6 and 7 GHz, and which is used to detect the target's absolute distance (Fig. 1). The latter consists of 40 coherent CW pulses (called bursts) whose frequencies are increased from pulse to pulse by a fixed increment $\Delta f$ = 25 MHz, allowing an unambiguous radar detection range of 6 m with a smallest resolution of 15 cm. Each pulse is $\tau$ = 30 μs long, and the time interval between pulses is $T$ = 100 μs. In contrast to [4], the single tone lasts 2 s while the SFCW signal is 4 ms.

The procedure to synchronize the dual-mode WRSN is illustrated in Fig. 2. The most important condition to verify is that the radar sensor functionality would not interfere with the operation of the wireless communications module, and vice-versa. Moreover, it is fundamental that the sensors do not interfere each other. Therefore, time division multiplexing (TDM) technique has been adopted. This means that, for each sensor, the wireless communications and the radar sensing do not execute their function at the same time. Moreover, all the sensors transmit the data to the base station in different time intervals. In addition, to avoid interferences among radar waveforms, frequency division multiplexing (FDM) technique has also been exploited for the speed measurement. In fact, Sensors 1, 2, and 3 operate with the single tone at 5.775 GHz, 5.8 GHz, and 5.825 GHz, respectively. These frequency shifts are much higher than the receiver's bandwidth of 100 kHz. Moreover, these shifts produce negligible differences in the resulting Doppler frequencies, and consequently in the speed signals, implying that the same classification model, in order to differentiate between fall and normal movement, can be used for all the sensors. It should be specified that the Zigbee communication does not produce interference since it operates at 2.45 GHz. Moreover, the adopted TDM and FDM procedures ensure also that the bursts are transmitted in different time slots and they do not interfere with the single tones.

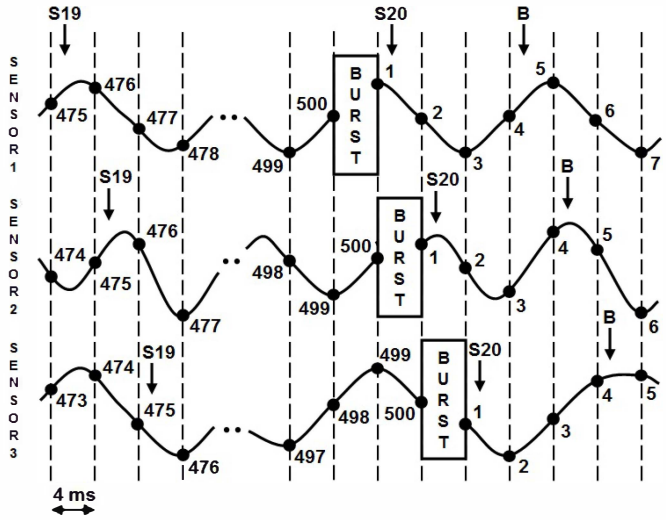



Fig. 2. WRSN synchronization procedure. The solid lines and BURSTs represent the baseband monitoring signals corresponding to the single tone and SFCW signals, which are transmitted to the base station at instants $S$ and $B$, respectively. The numbers indicate the $n$-th event during a full radar waveform, while the dots indicate the sampling rate instants.

In order to simplify the synchronization, a delay of 4 ms has been inserted among the sensors. However, due to the low human speeds, the target does not significantly change in movement over a time period of 4 ms such that it is possible to assume that the sensors virtually operate at the same time. After power on, the sensors wait until the base station sends a command to initiate operation. Since they are in the same room, one can assume that the command is received by all the sensors at the same instant. After that, Sensor 1 starts to operate instantly, while Sensor 2 and Sensor 3 start to operate after 4 ms and 8 ms, respectively. Each sensor acquires and digitizes the IQ baseband speed signals produced by the single

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tone with a sample time of 4 ms. Since each sensor integrates a 10-bit ADC, each IQ sample pair is mapped in three bytes which are inserted in frames of 76 bytes (i.e., 1 byte indicating the sensor's number and 25 IQ sample pairs) and then transmitted to the base station. This means that each sensor transmits the digitized speed signals each 100 ms. This operation is achieved in between speed sampling times. The base station therefore receives three Zigbee speed frames from the three sensors every 100 ms, which are separated temporally of 4 ms, and processes the signals coming from each sensor independently. Therefore, for each sensor, each incoming frame is concatenated with part of the previous signal to create a new complex signal window of 2 s with 95% of overlap, which is processed using the technique described by the authors in [5]. In this paper, a fall alarm is triggered when at least a single sensor detects a fall. A sensor detects a fall when the model discriminates three consecutive windows as fall related. Since the time to classify a signal window of 2 s is about 20 ms, the maximum time to detect a fall incident is about 320 ms, which demonstrates the real-time aspect. On the other hand, the IQ burst baseband signals are transmitted in single frames to the base station, where they are combined to be processed in real-time through the trilateration technique described in [7].

## III. Experimental Results

In order to validate the dual-mode WRSN, tests were conducted with two volunteers in a room of 5 x 5 $m^2$. The physical positions of the sensors are shown in Fig. 3.

Regarding fall detection operation, the subject was invited to position in the centre of the room, namely at x = 2.5 m and y = 2.5 m, and to mimic frontal falls trying to produce, with the LoS of the antenna of sensor 1, angles between 0 and 315 degrees with step of 45 degrees, as indicated in Fig. 3. For each body orientation, two falls have been mimicked by each volunteer, who was alone in the room during the speed measurements. Subjects 1 and 2 are 1.8 m, and 1.77 m tall, respectively, while their weights are respectively 77 kg, 70 kg, enabling the analysis of different fall speeds. Experimental results reported in Table I, where *D* means detected and *ND* not detected, show that the dual-mode WRSN was able to detect all the mimicked fall events. In fact, for each test, there was always at least one radar sensor able to detect the fall incident. This demonstrates that the use of the WRSN allows overcoming the limitations of a single-sensor approach.

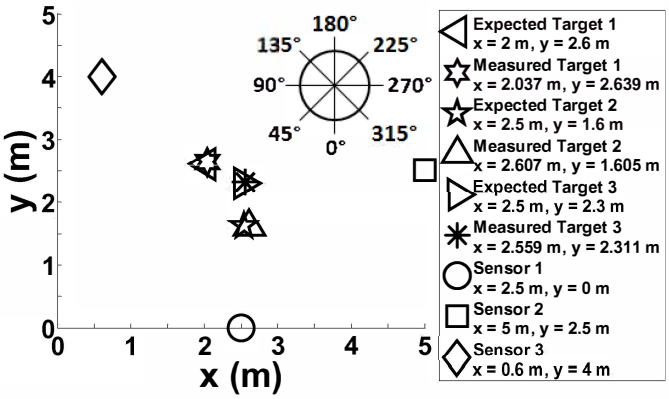



Fig. 3. Sensors physical positions and tagless positioning. The sensors are oriented such that the antennas' LOS are aligned with the centre of the room, i.e., x = 2.5 m and y = 2.5 m.

Figure 3 shows the results of the 2-D tagless positioning operations with the person in a standing position. The last condition ensures that the target's body part that produces the main reflection lies in the same plane as the radar sensors (i.e., z = 1 m), necessary for the 2-D geometry [7]. The expected positions in Fig. 3 indicate the target's position measured by a tape ruler. The measured positions are the results of the trilateration with the absolute distances between the targets and the radar sensors determined with the sensors. The algorithm used to determine the target's absolute distance and

TABLE I
Fall Detection Experimental Results

| Angle (°) | Subject 1 | | | | | | Subject 2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sensor 1 | | Sensor 2 | | Sensor 3 | | Sensor 1 | | Sensor 2 | | Sensor 3 | |
| | Test 1 | Test 2 | Test 1 | Test 2 | Test 1 | Test 2 | Test 1 | Test 2 | Test 1 | Test 2 | Test 1 | Test 2 |
| 0 | D | D | ND | ND | ND | ND | D | D | ND | ND | ND | ND |
| 45 | D | D | D | D | ND | ND | D | D | ND | ND | ND | ND |
| 90 | ND | ND | D | D | D | D | ND | ND | D | D | D | D |
| 135 | ND | ND | D | ND | D | D | ND | ND | ND | D | D | D |
| 180 | D | D | ND | ND | ND | ND | D | D | ND | ND | ND | D |
| 225 | ND | ND | D | D | ND | ND | ND | ND | D | D | ND | ND |
| 270 | ND | ND | D | D | ND | ND | ND | ND | D | D | D | D |
| 315 | ND | ND | D | D | D | D | ND | ND | D | D | ND | ND |

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to solve practical limitations, namely environmental reflections and radar fixed frequency shift, was described in [4]. It can be noted from the experimental results that the errors among the expected and measured positions are within the radar resolution of 15 cm.

The experimental validations have demonstrated that the target can be always correctly monitored if it is within the area of the room corresponding to the intersection of the antennas' beamwidths. In this work, the antenna beamwidths are approximately 60° in the azimuth plane.

If this condition is not satisfied, the target might not be correctly monitored. In fact, in case of positioning, when the target is situated at the edge of the beamwidth its reflection can become very weak, implying that the reflection is buried into the noise. In such case, the data processing may locate the subject in a wrong position. In case of fall detection, it can happen that one or more sensors cannot see the target while the other sensors are not able to detect the fall, due to Doppler effect limitation. In this case, the fall event will not be detected.

## IV. Conclusion

In this work, a dual-mode wireless radar sensor network aiming at in-door fall detection and tagless positioning has been proposed and detailed. Experimental results demonstrate the feasibility of detecting in real-time fall events over all orientations and in performing in door positioning, allowing to overcome a single-radar's limitations.

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