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Contactless Vital Signs Sensing: a survey, preliminary results and challenges

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Abstract

Contactless, remote monitoring of vital signs (VS) is an emerging technology with a vast number of possible uses from hospital care to the automotive industry and assisting living environments. Radio-frequency (RF) sensing enables the remote and unobtrusive measurement of VS without the need to wear any special device or clothing and under any lighting conditions. In the present paper, the feasibility of remote respiration, heart rate (HR) and stress detection monitoring was investigated. In this paper, an overview of short-range radar technologies is presented. The results of measurements made using a continuous wave reflectometer based on Commercial-off-the-Shelf (COTS) components and laboratory equipment are presented and challenges for achieving a reliable, contactless RF vital signs sensing system are discussed.

1 Introduction

Contactless, remote sensing of vital signs (VS) paves the way towards unobtrusive, easy-to-use and continuous health monitoring of vital signs and stress at home, work and hospital environments. RF sensing enables the contactless, remote measurement of VS at distances up to ~10m and with potentially lower power consumption than vision based systems, without the need to wear any special device or clothing, and under any lighting conditions. It is also suitable for use with persons that have sensitive skin (e.g. babies, elderly and burn victims) and the simultaneous monitoring of multiple persons. Millimeter wave (mmW) frequencies in particular are suited to the detection of the small, mm scale variations in distance; essential for extraction of heart rate (HR) and breath rate (BR). The mmW band is also suited to the realization of future miniature devices.

At CSEM, our objective is the development of a miniature mm-wave sensor system which could potentially be integrated in a bed side or portable device. As a first step, in order to investigate the operational principles of VS monitoring, a continuous wave reflectometer based on COTS components and laboratory equipment was designed and developed. The developed measurement setup operates at 75-110 GHz in case of remote respiration, HR and stress and 325-500 GHz for the remote stress study only. The principles of RF-based VS monitoring were investigated, as well as the feasibility of VS measurement at distances up to 10 meters.

This paper is organized into five sections. Following the Introduction in Section 1, a survey of short-range radar techniques is presented and the relative pro's and con's are discussed in Section 2. In Section 3, the layout measurement setup and results are presented for a state-of-the-art test system and results are discussed. Concluding remarks are provided in Section 5.

2 Short-rage radar survey

Many studies have been published in the field of RF-based VS monitoring including different radar setups and operation at various frequency bands. Sensing may be accomplished either via: 1) a single device (transmitter / receiver pair) or 2) reflection of the radiated signal from one or more transmitter devices to a receiver device. In the first case, the angle of incidence is nominally 90 degrees (point the transmitter at the target). In the second case, it may vary, with the minimum reflectance occurring at 45 degrees and the maximum at 90 degrees (we consider 45 degrees / minimum reflectance). The detection of the sensor signal may be done by measuring the amplitude & phase in the case of the reflectometer or a FM detector (i.e., in the case of the IMEC UWB FMCW radar). An FMCW radar offers potentially better performance, especially in the future where multiple targets and mobility are concerned. Non-coherent energy / intensity detection is also possible for simple reflectance (e.g. stress sensing).

In [1] a continuous wave (CW) radar operating at 34 GHz was proposed for HR and BR measurement for persons lying, sitting and walking at distances up to 2 m. In [2] a CW radar at 94 GHz is proposed for HR and BR monitoring at distances up to 9 m. [3] and [4] propose an ultra-wideband (UWB) impulse radar at 1.4-4.5 GHz and a frequency modulated continuous wave (FMCW) radar at 60 GHz respectively for the monitoring of both BR and HR. In the case of both the 8 GHz band and the mm-wave bands, losses through clothing are quite low. Finally, the potential stress detection based on changes in the Galvanic Skin Response (GSR) is proposed [5]. It has also been shown that the GSR is correlated with the reflection coefficient of the skin and that it is possible to asses it via changes in the skin's reflectance at frequencies in the mm-wave / sub-THz band (e.g. 75-170 GHz), since the skin reflectance is relatively good in these frequency bands.

Currently, these frequency bands are reachable with CMOS technology which is capable of operation up to about 500 GHz. This, coupled with the fact that mm-wave / sub-THz radiation is non-ionizing, opens the door for realization of miniature, low power, safe and low cost solutions for potential applications in the domains of health (e.g. contactless scanner for stress sensing) and security (e.g. remote lie detector).

Table 1: An overview of short-range radar solution

Company	Chip [mm]	Frequency (BW) [GHz]	Applications	Radar	Range [m]	Power [mW]	Resolution [cm]	Comments
Acconeer [16]	5.5x5.2	60	Contactless monitoring	IR-UWB	m's	mW's	---	FCCSP, coherent modulation
CSEM	---	60 (4), 122	Contactless signs monitoring	FMCW	≤10	---	---	COTS based, RoC in development, MIMO antenna, ML
EasyRadar [13]	40x40	122	Generic platform	FMCW	m's	---	---	MIMO, STMicro, Bosch and others
Fraunhofer [14]	---	240 (2)	Range measurements, µm precision	FMCW	m's	---	0.4	SiGe, MIMO (2x2)
GOOGLE [8, 9]	8x10	60	Gestures recognition	FMCW DSSS	m's	---	---	Uses Infineon technology
IMEC [10, 11]	1.2x1.2	79 (4), 140 (10)	Remote vital signs monitoring	IR-UWB	≤10	---	0.15@140	MIMO (1x4), ML. 28nm CMOS RoC
NXP [7]	35x35	77-81 (2)	Safety, Automotive	FMCW	≤300	2500	---	MIMO (2x3)
Silicon Radar [12]	3x3	24 (3), 60 (4), 122 (6)	Industrial (tank level, speed, etc), Distance sensor, Bio sensing	FMCW / CW	20-200	89@24 112@122	---	MIMO, range dependent on antenna
Staal [6]	7x7	60 (7)	Automotive, industry (e.g. distance, level), smart buildings (e.g. presence, lighting), drones (height)	FMCW	15	<1000	2.1	0.2mm accuracy, formerly OmniRadar
TI [15]	10.4 x 10.4	60 (4)	Automotive radar, contactless vital signs monitoring	FMCW	---	---	---	MIMO, TI RF CMOS, 161-Pin

Table 1 provides an overview of some of the short-range radar solutions available or in development (non-exhaustive) [6-11]. The automotive radar solutions [6, 7, 15] could in principle be used for contactless vital signs monitoring; however, they are typically over designed for such purpose (i.e., relatively high power, longer range than needed). The 77GHz frequency band [7] is also not intended for health and medical applications (reserved for automotive radar).

The 24GHz ISM band [12] is also crowded and the bandwidth available (3 GHz) means that it the resolution is less than that of e.g. 60 GHz ISM band with 4 GHz of bandwidth [6, 8, 9, 12, 15, 16].

The 140 GHz band, with 10GHz bandwidth, offers the highest potential resolution, however, this is not an ISM band and, at least at this time, itis reserved for telecom applications. 240 is today lightly used [14], but the technology remains difficult to reach with low cost CMOS technology.

This leaves us with the 60GHz and 122 GHz [12, 13] ISM bands. Potential solutions include both FMCW radar as well as IR-UWB radar [10, 11, 16]. At CSEM, we are developing a 60GHz Radar-on-Chip (RoC) and have also experimented with the 122GHz ISM band, as will be discussed in the sections that follow.

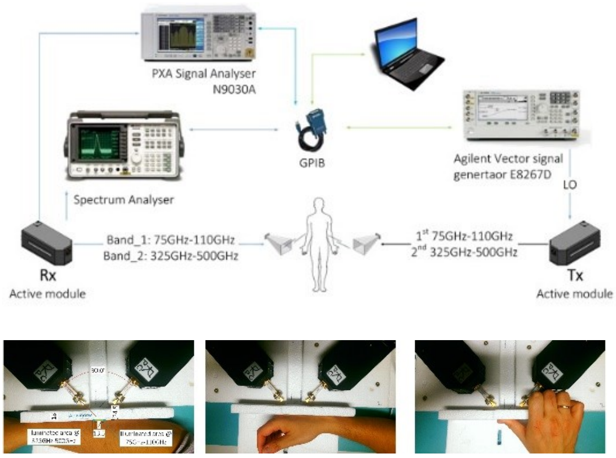
3 Test and measurements setup and results

An RF sensing demonstrator was developed for the monitoring of VS (Fig.1). The measurement setup (Fig.1b) is based on a continuous wave reflectometer implemented on a Software Defined Radio platform (SDR). The SDR platform provides flexibility in the development of versatile RF sensing platforms with operation at various frequencies. This setup is designed to study and demonstrate the principles of remote sensing of aircraft, namely respiration and heart rate.

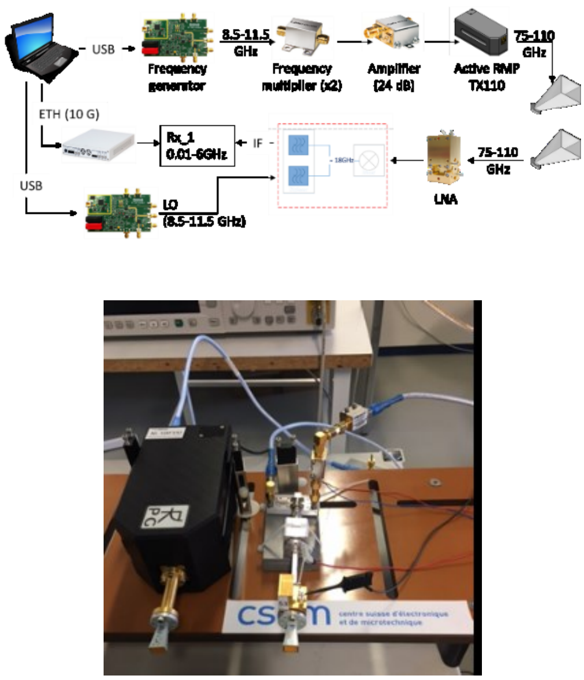
Vital signs monitoring

The human body vibrates due to the respiration and the heart beating. The displacement varies according to the body site and presents maximum amplitude at the torso.

The torso displacement is in the range of [0.1 0.2] cm for respiration and [0.6 1.2] mm for heart beating. The aim of the radar-based VS sensor is to detect this fine body movement provoked by the VS.



(a) stress test



(b) remote respiration, HR test

Figure 1: Measurement Setup: a) vital signs (respiration and heart rate) and b) stress test

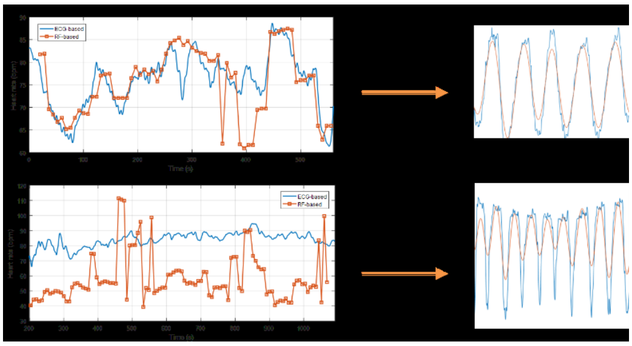


Figure 2: ECG-based (blue) and RF-based (orange) HR estimation during sinusoidal (top) and fast, harmonic-heavy (bottom) respiration.

Using our measurement setup, a series of measurements were performed with a human subject sitting in front of the VS sensor at a distance of 1 meter.

The subject was simultaneously monitored by an ECG device, which was used as an evaluation reference. Two scenarios were investigated were the subject was asked to breathe i) slowly and uniformly and ii) fast and irregularly. Three adult subjects were monitored in total. It can be seen (Fig.2) that for the case of slow, uniform respiration, the results are more reliable, which clearly demonstrates the effect of the breathing pattern on the HR estimation.

Physical and mental stress

The measurement setup is based on laboratory equipment as presented in Fig.1a. This setup is used for investigation of physical and mental stress through measurement of the skin reflectance in two frequency bands: 75-110 GHz (Band-I) and 325-500 GHz (Band-II).

The skin reflectance was measured during rest and after mental and physical stress [18]. Physical stress was provoked using a dynamometer under 15 N of force for 5 minutes. Provocation of mental stress was achieved with the use of the Stroop Test for 15 minutes. The measured reflected from the skin amplitude response is used during the study.

Further, in the context of the present contactless RF sensing study, the detection of physical and mental stress was also investigated. The test setup depicted in Figure 1 b) was used to evaluate stress based on changes in the skin reflectance in two frequency bands: 75-110 GHz (Band-I) and 325-500 GHz (Band-II). Three measurement conditions were considered: (1) Rest; (2) Mental stress: Stroop Test for 15 minutes and (3) Physical stress: Dynamometer under 15 N of force for 5 minutes. Stress measurements were always preceded by a rest period of at least 15 minutes. Three locations on the hand were considered for the purposes of the measurements (Fig. 3): arm, hand and finger.

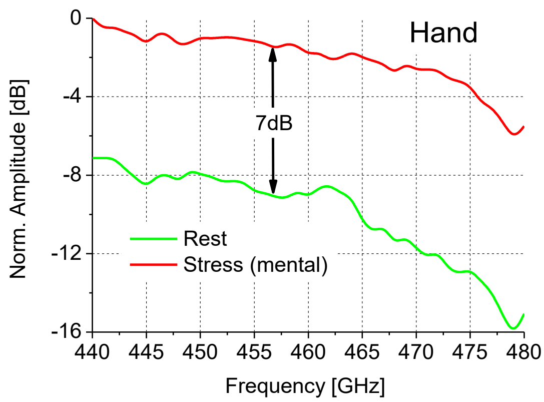


Figure 3: Mental stress based on measurement of the skin reflectance on a hand.

Figure 3 depicts the results of measurements performed between 440 GHz and 480 GHz in frequency band II. It can be seen that the shape of the measured amplitude (i.e., the shape of the spectrum) over this frequency range is effectively the same in the case of stress as it is in the case of the person at rest. However, there is a clear difference between the results at rest and under stress. The measured amplitude response is stronger in the case of stress than at rest (i.e., about 7 dB across the frequency range for measurements performed on a hand.

Challenges

The results demonstrate the potential for both vital signs monitoring, as well as stress. However, important challenges were identified, most notably, with respect to reliability. For example, in the case of vital signs monitoring, both HR and BR are observed as amplitude modulations, at similar frequencies (50-100 times per minutes), with HR being much lower in amplitude. This makes it difficult to reliably extract. The problem is compounded by interference and harmonics. Tests that have been performed (e.g., CSEM, Nature, IMEC) [17], were done with the person either holding their breath or control breathing. This is clearly not practical. To address such issues, the use of MIMO antennas and Machine Learning (ML) are considered (e.g. IMEC, Fraunhofer and CSEM). The case of stress is different. Signal strength and extraction of the signal is not the issue. Rather, normalization of the results (identifying a suitable baseline) poses a major challenge. Here again, it is believed that ML techniques may help.

4 Concluding remarks

A general RF sensing demonstrator was developed for the monitoring of VS. The system was comprised of a CW reflectometer operating at different mm-wave frequency bands. The results demonstrate the potential for contactless remote sensing of both vital signs and stress. The reliability of HR monitoring was investigated in the presence of slow and fast breathing patterns. Respiration was found to affect significantly the quality of the HR estimation.

Future steps include the development of a microwave sensor prototype system based on a mm-wave. The miniature platform will be used for the development of a frequency modulated continuous wave radar for tracking and VS monitoring. Moreover, machine learning methods will be investigated for HR-BR separation, motion compensation and reliable VS estimation. Such solutions will become of the BAN IoT solutions.

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