Feasibility of Remote Vital Signs Sensing with a mm-Wave CW Reflectometer

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***Abstract*— 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. A demonstrator of RF vital signs sensing was designed and prototyped based on a continuous wave reflectometer involving a Software Defined Radio platform. The sensor operates at 110 GHz. The feasibility of remote respiration and heart rate (HR) monitoring was investigated. The breathing pattern was found to affect significantly the reliability of the HR estimation. The potential of remote VS sensing at distances up to 10 m was theoretically explored.**

Keywords—RF sensing; antenna; mm-wave, reflectometer

I. INTRODUCTION

Contactless, remote sensing of vital signs (VS) paves the path towards unobtrusive, easy-to-use and continuous health monitoring at home, work and hospital environments. The wide application space includes VS self-monitoring for healthier lifestyle, monitoring of persons with sensitive skin (e.g. newborns, burn victims, elderly people), safety (e.g. car drivers, pilots), as well as multi-person monitoring in assisted living environments. RF allows for the remote sensing of VS, through clothes and under any lighting conditions. Moreover, it enables the VS measurement at longer range and with potentially lower power consumption compared to other solutions, e.g. vision.

Two main technologies exist today for the monitoring of VS: electrocardiography (ECG) and photoplethysmography (PPG). ECG is the reference procedure (i.e., reference for quality, high reliability) for monitoring the heart rate (HR) and heart rate variability (HRV). ECG requires direct contact to the body and measures the bio-potential generated by electrical signals produced by heart activity. Applications include in-hospital and medical monitoring of the heart. PPG is an optical method that uses visual or infrared light to detect the variation of blood volume during heart activity. PPG measures both HR and breathe rate (BR). Unlike ECG, PPG sensors may be in contact with the skin or contactless (1cm-2cm). In either case, the quality is not as high as in the case of the ECG. The main advantage is low cost. Line-of-sight operation is required and the sensor does not operate through clothing or where lighting conditions result in interference. Potential applications include webcam based solutions and bedside monitoring (e.g. during sleep).

RF sensing offers the potential for remote, contactless monitoring at long distance (e.g. up to ~10m) which can enable its use in smart sensing environment applications (e.g. smart homes, assisted living). RF signals can pass through clothing with little loss and are suited to operation under any lighting conditions. Many studies have been published in the field of RF-based VS monitoring including different radar setups and operation at various frequency bands. 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. Finally an FMCW radar is proposed in [5] at 5.8 GHz where only BR is considered. Similarly, a fully integrated CMOS Doppler radar at 60 GHz is proposed in [6] where HR is estimated only when the subject is not breathing. None of these systems are available on the market today. On the market side, Withings [7] offers an RF VS sensing system that can sense BR at ~ 1m, but does not support HR. Further, while the 57-66 GHz ISM band offers a large bandwidth (9 GHz) for radar, it may become very crowded and the resulting interference may degrade the performance of the VS sensing. This band may also not be available after 2024 [8].

Our ultimate target is a miniature mm-wave sensor system which could potentially be integrated in a mobile device [9]. The target application is remote VS sensing in assisted-living and smart environments and, to this aim, distances up to 10 meters were considered. As a first step, in order to investigate the operational principles of VS monitoring, a CW reflectometer operating at 110 GHz was prototyped and developed. The use of the millimeter wave (mm-wave) frequency band offers increased displacement resolution, as well as good skin reflectance. The principles of RF-based VS monitoring were investigated, as well as the feasibility of VS measurement at distances up to 10 meters.

The paper is organized as follows: Chapter 2 describes the measurement setup, Chapter 3 presents the principles of RF-based VS monitoring, Chapter 4 discusses the methodology and Chapter 5 elaborates on the results and discussion. Chapter 6, summarizes the study conclusions and next steps.

II. VS SENSING RF MEASUREMENT SETUP

In order to investigate and demonstrate the principles of remote VS sensing, a continuous wave reflectometer was designed and prototyped, using a Software Defined Radio (SDR) platform. The SDR platform provides flexibility in the development of versatile RF sensing platforms with operation at various frequencies. Moreover, it allows for the development of dedicated software for the baseband and higher level signal processing based on the application requirements. One of the most advanced and suitable SDR platforms is the USRP X310, which is part of the system architecture shown in Fig. 1 and 2.

The demonstrator system comprises a transmitter (Tx) and a receiver (Rx) operating at 110 GHz, as shown in Fig. 1. The Tx is based on the mm-wave Radiometer Physics TX110-10 module operating at 75-110 GHz (with possible extension up to 122GHz). The mm-wave modules up-convert the carrier frequency coming from the frequency generator board. In order to obtain the correct input carrier frequency for the Tx module a x2 frequency multiplier and active amplifier are placed after the frequency generator board. At the Rx side, an identical frequency generator board is used as a Local Oscillator (LO). The Rx and LO signals are mixed in the harmonic mixer and the intermediate frequency (IF) signal passes from a low noise amplifier and subsequently is received at the USRP.

In addition to standard horn antennas, low-cost 3D printed Tx/Rx mm-wave antennas were developed, for the VS measurement setup [10].

The IF signal is digitized at 200 MHz at the USRP and transmitted to a PC using a 10G Ethernet cable for further processing. The SDR platform provides the software tools (GNU radio) for the development of RF digital signal processing and higher level algorithms for the signal treatment and the extraction of the VS.

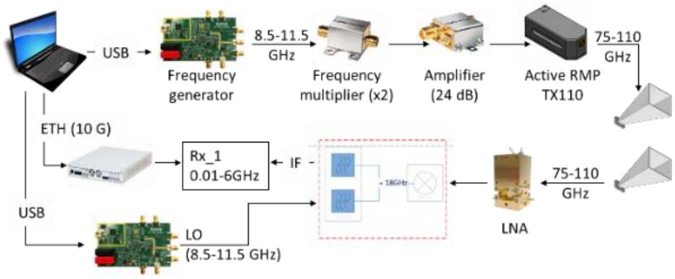

Fig. 1: The VSM system detail block diagram.

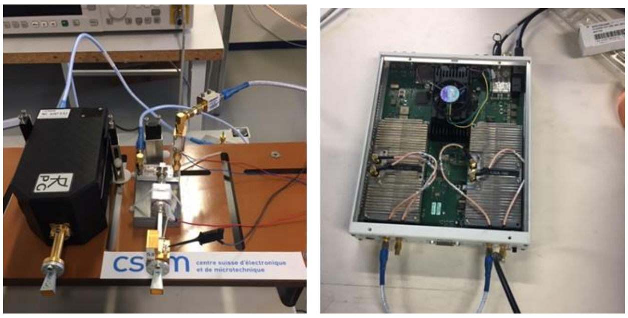

Fig. 2: Over view of the VSM system, RF-front-end (a) and SDR based platform (USRP X310) (b).

Specifications of the equipment used are provided in **Error! Reference source not found.** 1.

TABLE I. MEASUREMENT SETUP SPECIFICATIONS

Boards parameters		
	Tx board	
Frequency	9.2	GHz
Power @ 9.2	6.5	dBm
Power @ 18.5	2	dBm
Power @ 110.4	-9	dBm
	LO board	
Frequency	10	GHz
Power @ 10	6.5	dBm
	IF signal	
Frequency	3	kHz
Antenna Gain	16 / 38	dBi
Antenna_1 HPBW	24 / 3	degree
Distance to the target	0.2 – 10	m
Frequency	110	GHz
EIRP	20	dBm

III. VS MEASUREMENT PRINCIPLES

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. Fig. 3 illustrates the measurement principle of the VS sensor. A human is sitting in front of the radar at distance R. The overall distance between its torso and the radar can be expressed as:

$$R_t = R + r_{vs} \sin(\omega_{vs} t) \tag{1}$$

where r_{vs} is the body displacement due to respiration or heart beating and ω_{vs} is the respective VS frequency. A CW signal is transmitted from the radar as:

$$x_{TX} = A_{TX} \sin(\omega_c t + \varphi(t)) \tag{2}$$

where A_{TX} , ω_c and φ are the amplitude, carrier frequency and phase respectively.

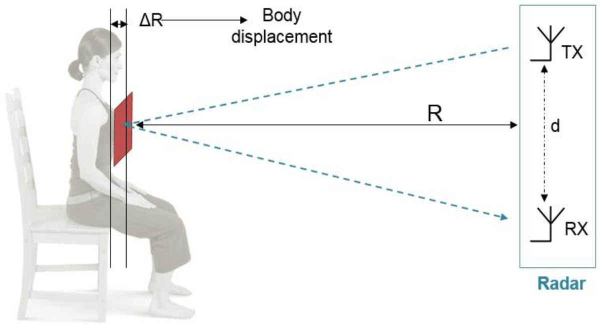

Fig. 3: Measurement principle of VS with the radar-based sensor

The signal is reflected off the human body and radiated back to the receiver with a delay τ proportional to the distance R between the person and the radar as:

$$x_{TX}(t)= A_{RX}(t)\cdot sin[\omega_c(t - \tau)+ \varphi_{RX}(t)+ \varphi(t - \tau)] \quad (3)$$

where both its amplitude (power) A_{RX} and phase φ_{RX} are modulated due to the body VS vibration as:

$$A_{RX}(t)= A_{RXdc} + A_{vs}sin(\omega_{vs}t) \quad (4a)$$
$$\varphi_{RX}(t)= \varphi_{RXdc} + \varphi_{vs}sin(\omega_{vs}t) \quad (4b)$$

and $\varphi(t - \tau)$ is the residual phase which can be neglected. The DC component of the power (A_{RXdc}) and phase (φ_{RXdc}) depends on the absolute distance R between the person and the radar, while the oscillating component is induced by the body motion during respiration and heart beating. In Eq. 4, A_{vs} and φ_{vs} correspond to the amplitude of the power and phase oscillation respectively while the frequency ω_{vs} is the corresponding BR and HR which we aim to recover. In this study, we investigate how the power and phase of the Rx signal are modulated by the body displacement, as well as methods for the estimation of the VS frequency.

IV. METHODS

The first step in the operational principles analysis was to investigate the conditions under which the modulated part of the power and phase can be detected. Subsequently, signal processing algorithms were developed for the extraction of the HR and BR.

A. *Link budget analysis*

A Link Budget (LB) analysis was performed in order to describe the effect of body displacement on the power and phase modulation of the Rx signal.

The well know radar equation describes the signal propagation from the transmitter to the target and back to the receiver and calculates the power P_r of the Rx signal as:

$$P_r=(P_t\cdot G_t\cdot G_r\cdot \lambda^2/((4\pi)^3\cdot R)^4)\cdot \sigma \quad (5)$$

where G_t and G_r are the Tx and Rx antenna gains, P_t is the transmitted power, λ the wavelength and σ the radar cross section. Using (1) and (5), the power variation occurring from the body displacement can be calculated over different distances R. The maximum operation distance for a given setup can be estimated.

Phase presents a linear relation to distance as:

$$\varphi(t)= 4\pi R/ \lambda \quad (6)$$

Substituting (1) to (6) we have:

$$\varphi_{RX}(t)= 4\pi R/ \lambda+(4\pi r_{vs} /\lambda) sin(\omega_{vs}t) \quad (7)$$

which corresponds to the DC and AC components of the phase (Eq. 4b). From (7), we can see that the modulated part of the phase is independent of the distance R and only depends on the body displacement r_{vs}.

B. *Signal processing for VS estimation*

The process of estimating the VS from the Rx signal involves two steps: i) Baseband signal processing and ii) High level signal processing for VS estimation. The two steps are discussed below.

<u>Baseband signal processing</u>

As previously stated, the USRP provides a software tool for the DSP of the Rx signals. After reception, the IF signal is first IQ modulated in the digital domain and down-converted. Next, the amplitude and phase of the signal are extracted. The phase is first unwrapped and subsequently the signals are provided to the high level processing block for the estimation of the BR and HR.

<u>High-level signal processing</u>

First the signals are bandpass filtered at cut-off frequencies 0.1 and 3 Hz. The filtered signals include both the BR and HR information. Estimation of the BR is straightforward using a Fourier Transform. However, this is not the case for the HR estimation. As discussed, the body displacement due to respiration is more than one order of magnitude higher than due to HR. Given that respiration is not purely sinusoidal, harmonics are generated, some of which may overlap in the frequency domain with the cardiac signal. Thus, a main challenge towards reliable HR estimation lays in its separation from the BR harmonics. In this study, four algorithmic approaches were investigated for the estimation of HR including Wavelet decomposition, Dynamic Time Wrapping, Principle Component Analysis and Dynamic Harmonic Notching.

V. RESULTS AND DISCUSSION

In this Section, the results of the LB analysis and VS estimation are presented.

A. *Link budget analysis*

Based on the LB analysis discussed in Section IV, the detectability of the Rx signal as well as the possibility to detect the Rx power and phase modulation were explored. In all cases, the parameters of (5) were set according to the specifications of our measurement setup (Table 1). Respiration amplitude was considered as 1 cm and HR amplitude as 0.6 mm.

i. Expected Rx power from a human target over distance

Using (5), the expected Rx power over distance *R* for a human target sitting in front of the radar was calculated. The results are depicted in Fig. 4. It can be seen that at a distance of 10 m, the power of the Rx signal is expected to be -85 dBm.

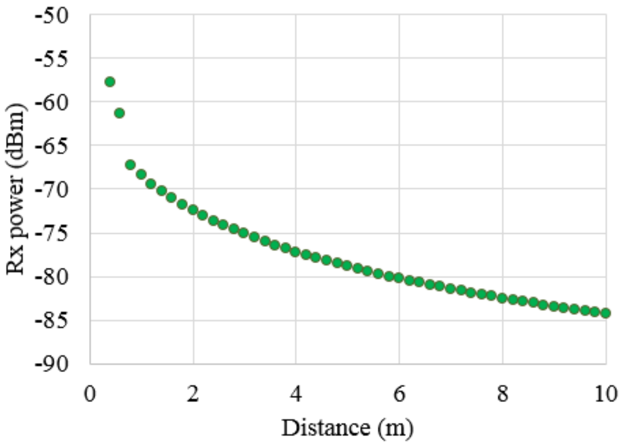

Fig. 4: Expected Rx power over distance for human target sitting in front of the radar

ii. Expected Rx power modulation from human target due to BR and HR body displacement over distance

Using (5) and (1), the expected Rx power amplitude over distance due to HR and BR for a human target sitting in front of the radar was calculated. Fig. 5 illustrates the results for the two VS. As expected, the power amplitude due to HR is lower than for respiration because the corresponding body motion is smaller. At a distance of 10 m, the Rx power amplitude for the case of HR was calculated as -120 dBm.

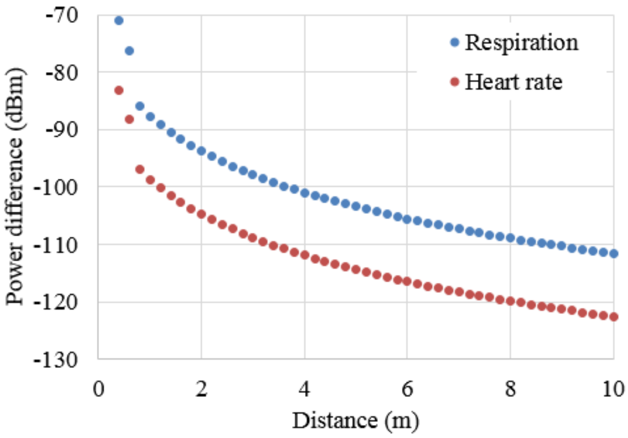

Fig. 5: Expected Rx power difference over distance for human target sitting in front of the radar due to HR and BR

Given to-date receiver capabilities which can provide a Noise Factor in the order of 10 dB, both the Rx signal and its modulated power amplitude can be detected at a distance of 10 m. However, in the presence of interference and clutter, which were not considered in this analysis, the power modulation may provide very low SNR at long distances, insufficient for VS extraction.

iii. Expected phase variation from human target due to BR and HR body displacement

Using (7), the expected phase modulation amplitude was estimated for the case of BR and HR. As previously discussed, the phase variation does not depend on the distance of the human to the radar. The results are illustrated in Fig. 6. It should be noted that for the case of respiration the depicted phase is unwrapped.

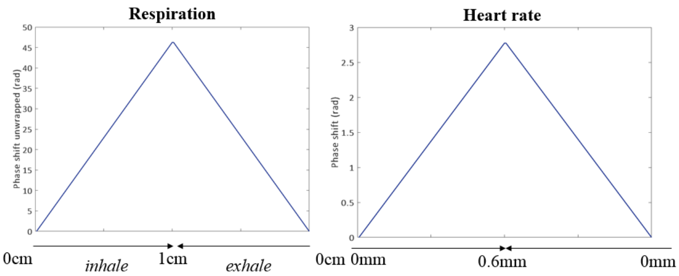

Fig. 6: Phase variation during respiration and heart beating

As shown in Fig. 6, the maximum phase difference for a displacement of 1 cm (respiration) is 45 rad (unwrapped) while for 0.6 mm (heart beating) is 2.7 rad. Both signals are very strong and can be easily detected in the presence of standard phase noise levels. As a result, we observe that phase provides very high SNR and can be, thus, more appropriate for the detection of both VS.

Due to its considerably higher SNR, only the phase signal was exploited for the VS estimation. Although the power signal can provide additional information, we cannot trust its usability in a real life scenario and was, thus, neglected, in this study.

B. System calibration

Prior to VS monitoring, measurements were performed on a benchmark setup which comprises a metallic plate oscillating at 1-3 Hz with an amplitude of 0.6 mm. The purpose of the benchmark setup was to calibrate and tune the system before proceeding to measurements with humans. Fig. 7 illustrates the phase modulation of the Rx signal due to the plate oscillating at 1.3 Hz and at distance of 1 meter from the setup. It can be seen that the periodicity of the phase corresponds to the plate oscillation frequency and, moreover, that the phase amplitude (approximately 3 rad peak-to-peak) corresponds to the plate amplitude of 0.6 mm. The benchmark measurements prove that very small displacements, in the order of the HR body displacement, are feasible to be detected with our measurement setup.

C. VS estimation

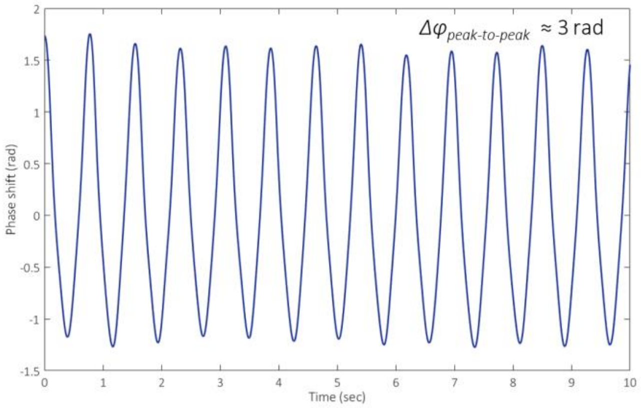

Fig. 7: Expected Rx power difference over distance for human target sitting in front of the radar due to HR and BR

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.

The Dynamic Harmonic Notching algorithm provided the best performance among the four candidate approaches and was the one used in our final solution. The effect of the respiration pattern on the reliability of HR estimation was further explored. It is expected that slow and uniform (close to sinusoidal) respiration will induce less harmonics and at lower frequencies, below the HR frequency band. Fig. 8 illustrates the HR estimation results for one adult and the two breathing patterns. It can be seen that for the case of slow, uniform respiration, the results are much more reliable, which clearly demonstrates the effect of the breathing pattern on the HR estimation.

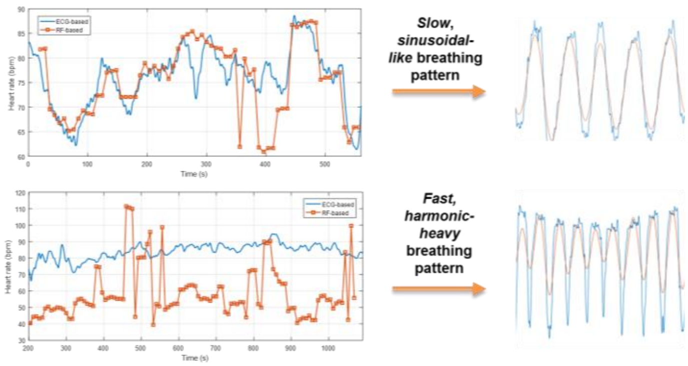

Fig. 8: ECG-based (blue) and RF-based (orange) HR estimation during sinusoidal (top) and fast, harmonic-heavy (bottom) respiration

VI. CONCLUSIONS

An RF sensing demonstrator was developed for the monitoring of VS. The system comprises a CW reflectometer operating at 110 GHz and is based on a SDR platform. 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. The feasibility of VS measurement at distances up to 10 m with the developed system specifications was explored and confirmed theoretically.

Future steps include the development of a microwave sensor prototype system based on a mm-wave (e.g. 122.25-123 GHz ISM band), micro-machined platform [9]. The miniature platform will be used for the development of a frequency modulated continuous wave (FMCW) radar for tracking and VS monitoring. Moreover, machine learning methods will be investigated for HR-BR separation, motion compensation and reliable VS estimation.

VII. ACKNOWLEDGMENT

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