A Low Power 24 GHz Radar System for Occupancy Monitoring

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***Abstract*— This paper presents a low power 24 GHz Doppler radar system for presence detection and occupancy monitoring. It is based on a minimalistic hardware approach and is able to wirelessly sense human respiratory signals so that even non-moving persons can be detected. By intermittently measuring, the average power consumption could be significantly reduced down to e.g. 0.2 mW for 20 measurements per second. Experiments verify that, due to the short wavelength, the single channel receiver limitations can be neglected when only a detection of human respiratory but no evaluation of the breathing frequency is necessary.**

***Index Terms*— Doppler radar, occupancy sensor, low-power**

I. Introduction

The growing population on our planet and the high standard of living leads to an energy consumption that is not sustainable for a long time. Therefore, smart solutions have to be found that allow conserving energy while keeping the high standard of living. For instance, in office buildings or on public roads and places a lot of money can be saved by smart lighting systems [1]. Also hotels can profit from an automated lighting and heating system that checks whether guests are in their room or in a certain area and switch off devices that are not in use. Medical patient care systems [2] could reduce their required power consumption for indoor localization by switching of the beacons that are not needed when no human is in the room.

For all these applications occupancy sensors are needed that detect the presence of humans. Various sensors are on the market that detect movements, e.g., passive infrared or ultra-sonic techniques are commonly used [3]. However, these sensors cannot detect stationary or almost not moving objects and exhibit high false alarm rates [1]. Thus, in [3] a Doppler radar sensor is proposed that can detect cardiopulmonary motions of humans, i.e. heartbeat and respiration rate. Key factors for the massive use of these sensors in smart energy saving systems are small size, low false rate and marginal energy consumption.

In this paper, a 24 GHz monostatic Doppler radar occupancy sensor is presented that detects the human respiration with an average energy consumption of only 0.2 mW. This also enables the use as an autonomous wireless sensor, bringing about more comfort and flexibility for the user.

II. System concept

The proposed radar system is a monostatic single-channel Doppler radar with a minimalistic hardware approach to minimize the power consumption. By intermittently transmitting, the power consumption can be significantly reduced while still being able to sense human cardiopulmonary motions [4]. In this paper the current approaches [3]–[5] will be further enhanced pushing the power consumption of the complete radar system in the submilliwatt range, while simultaneously increasing the transmit frequency to 24 GHz so that a single channel receiver design is sufficient.

The system concept is depicted in Fig. 1. The transmit signal, a 24 GHz continuous wave (CW), is generated by a commercial of the shelf voltage controlled oscillator (VCO). This signal is fed to port 3 of a hybrid coupler where it is splitted into two equal parts. The first portion is transmitted to the target using an antenna array at port 1, while the second portion is fed to the PIN-diode at port 4. Dependent on the bias current through the diode, the signal is attenuated and partly reflected, leading to the reference signal S_{ref} with the amplitude A_{ref}. The receive signal S_{rx} back-scattered by the target is fed again through the hybrid coupler and is finally superimposed with the reference signal leading to the interference signal S_{I} at port 2:

$$S_{\mathrm{I}} = \frac{1}{2}A_{\mathrm{ref}}\cos(\omega t + \varphi_{\mathrm{ref}}) + \frac{1}{2}A_{\mathrm{rx}}\cos(\omega t + \varphi_{\mathrm{rx}}) \qquad (1)$$

After passing a low-noise amplifier (LNA) a power detector is utilized for direct conversion to baseband. The baseband voltage is further amplified and low-pass filtered by an operational amplifier (op-amp) before being sampled and digitized by the analog-to-digital converter (ADC) of the micro-controller. Besides the digitalization, the micro-controller is also responsible for the power control of the whole system and can completely disconnect the VCO, LNA and baseband op-amp from the supply voltage through three independent P-MOS transistors.

It has been shown that single channel CW receivers exhibit several limitations for sensing periodic motions, like respiration or heartbeat signals [6]. The phase relationship between the local oscillator and the received signal has

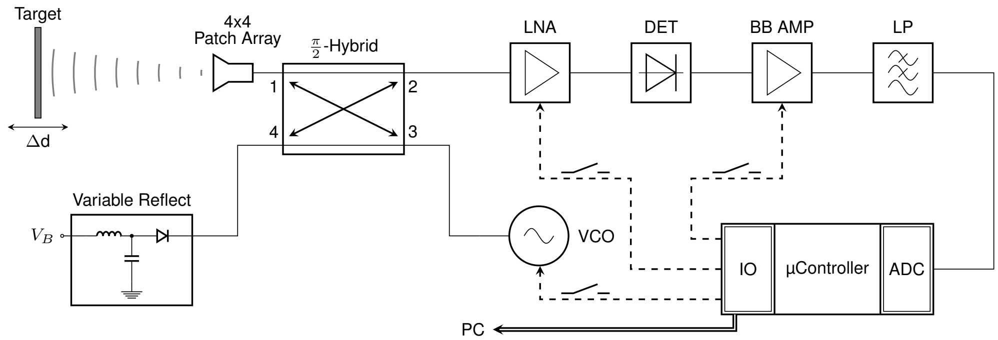

Fig. 1. System concept of the proposed low-power radar system.

significant influence on the demodulation sensitivity, resulting in so-called null-points and optimum points that are separated by $\lambda/8$ of the transmit frequency [6]. However, if only a detection of human respiration is required for occupancy monitoring and no accurate breath rate analysis is necessary, a single channel receiver can be sufficient if the transmit frequency is high enough. For a 24 GHz wave (λ = 12.5 mm) the optimum and null points are only separated by 1.56 mm. With a typical vertical chest displacement of 5 mm to 20 mm [5] for human respiration it is sure that the maximum sensitivity of the radar sensor is at least reached once within each breath.

III. Hardware Realization

A hardware prototype has been developed and is depicted in Fig. 2. The radio frequency (RF) circuitry with hybrid coupler, LNA, power detector [7] as well as PIN-diode has been realized on a 0.254 mm Rogers RO4350 high frequency substrate. It is interconnected to the 4x4 patch array antenna with 14 dBi gain, as well as to the commercial VCO through 2.92 mm connectors. An MSP-EXP430G2 LaunchPad was used as micro-controller platform, featuring an integrated 10-bit ADC. It is mounted on the baseband board (single-layer FR4) that provides the P-MOS transistors for power control as well as the baseband op-amps and filtering.

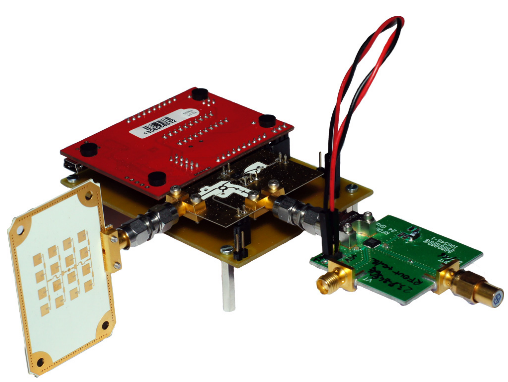

Fig. 2. Photo of the developed radar system prototype.

IV. Experimental Results

In the experimental setup the required measurement time for each pulse was analyzed and reduced as far as possible to allow the system to stay in power down mode most of the time. The baseband voltage, the supply voltage of the VCO and the conversion time required by the ADC have been acquired by a digital storage oscilloscope and the signals of a single measurement pulse are depicted in Fig. 3. It can be seen that after turning on the system the transient response of the VCO, LNA and baseband amplifier chain requires about 50 µs to reach a steady state and then the micro-controller requires additional 10 µs to aquire a sample. Thus, an overall measurement can be performed in less then 60 µs with the current hardware prototype.

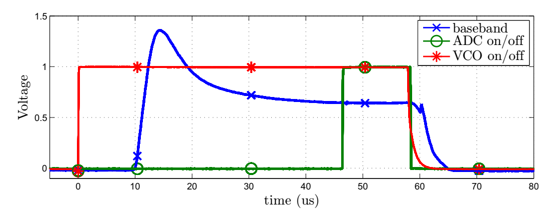

Fig. 3. Measured baseband voltage and active timing signals of the VCO and ADC.

A. Emulation of human respiration by a linear stage

To get a reproducible and deterministic scenario a small metallic plate (120 mm x 80 mm) was mounted on a linear stage that was programmed to move with a sinusoidal motion to emulate the human respiration like proposed in [5]. The motion amplitude was chosen to 5 mm peak-to-peak with an oscillation frequency of 0.2 Hz to represent the human respiration which is in general around 0.1 Hz - 0.3 Hz with a typical vertical chest displacement of 5 mm to 20 mm [5]. The radar system was placed in the distance d = 2 m from the target and programmed to 20 measurements per second, leading to an average power consumption of 200 µW. Two subsequent measurements were performed with (a) the target being in the optimum

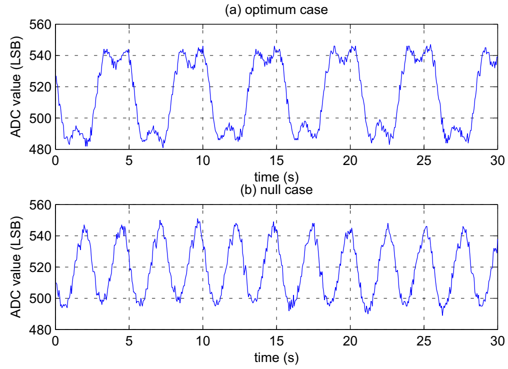

Fig. 4. Raw ADC measurement results without any further processing for a mechanical target movement with Δd = 5 mm peak-peak and an oscillation frequency of 0.2 Hz, in the distance d = 2 m for (a) the optimum case (b) the null case.

case and (b) the target being in the null case of the radar's sensitivity. The raw ADC data acquired by the microcontroller for a 30 s measurement interval is depicted in Fig. 4. As expected [6], the measured frequency in the null case is twice the original moving, but still a sinusoidal motion can be clearly detected indicating that there a human is present.

B. Repeatability in an empty room

The repeatability of the system was evaluated in an empty room, also for a 30 s measurement interval, leading to 600 independent measurements. A histogram of the results is shown in Fig. 5. The distribution follows an Gaussian shape with a mean of μ = 542.4 LSB and a standard-deviation of σ = 1.92 LSB. So dependent on the required sensitivity of the sensor and the number of acceptable false positive alarms the detection threshold can be set to e.g. 4 σ = 8 LSB, so that for an empty room more than 99.99 % of all measurements are within the bound.

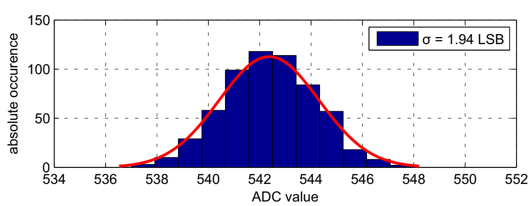

Fig. 5. Repeatability of the measurements in an empty room. In total 600 measurements were performed within 30 seconds.

C. Power consumption

The power consumption of the radar system for different operation modes was evaluated with a precision DC power analyzer (N6705B from Agilent Technologies). The results are summarized in Table I. The bias current of the PIN-diode (around 160 µA) is currently externally supplied and not counted to the radar's power consumption as the diode

TABLE I
MEASURED POWER CONSUMPTION FOR DIFFERENT OPERATION MODES

operation mode	average power consumption
10 measurements / s	0.1 mW
20 measurements / s	0.2 mW
50 measurements / s	0.52 mW
CW	137.5 mW

could also be replaced by an accordingly matched resistor. As the system is shut off most of the time there is an almost linear relation between number of measurements per second and average power consumption. In comparison to CW mode, requiring an average of 137 mW, the power could be significantly reduced down to 200 µW for 20 measurements per second.

V. Conclusion

A low-power monostatic 24 GHz Doppler radar system for presence detection and occupancy monitoring has been presented. A reduced hardware approach with only one single receiver channel leads to a simple and low-cost solution. Measurements verified that the system is capable to detect human respiration, overcoming one of the major drawbacks of currently available occupancy sensors: failure to detect stationary people. By intermittently measuring, the system's power consumption could be greatly reduced by a factor of more than 600 now requiring 0.2 mW for 20 measurements per second compared to original 137 mW in CW mode.

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