

Multi-frequency sensor for remote measurement of breath and heartbeat

M. Jelen and E. M. Biebl

Fachgebiet Höchstfrequenztechnik, Technische Universität München, Germany

Abstract. Remote measurement of breath and heartbeat is desirable in many situations. It avoids the discomfort resulting from electrodes applied on the skin for long-term patients or during sports activities. Also, surveillance of high security areas or finding survivors of disasters are interesting applications. Common methods identify the movement of heart and thorax by using the range resolution provided by UWB pulse radar systems. In this paper a low-cost approach is presented, that is based on detection of movement by means of Doppler radar sensors. Combining three sensors working in the ISM bands at 433 MHz, 2.4 GHz and 24 GHz, the presence of persons was reliably detected and the frequency of breath and heartbeat was measured.

1 Introduction

Heartbeat and respiration are a common attribute of all humans. They have a characteristic form and frequency which, in case of the heartbeat, can't be affected voluntarily.

In technical systems (e.g. in cars) there is often the need to detect the presence of a human. This task can be fulfilled by a wide variety of sensors, such as mechanical switches (e.g. in the seat) or ultrasonic sensors.

Also the frequencies of pulse and respiration are often measured. One obvious field of application is the medical sector, but numerous other applications (e.g. sport/fitness) can be thought of. Currently the measurements are performed by sensors which are in contact with the person being observed. This may be a serious disadvantage in situations where measurements must be taken over a long period of time (e.g. long term patients in hospital) or where physical contact is not possible.

An approach of detecting humans by means of radar, mainly for security applications, is described in Greneker

(1997). Bimpas et al. (2003) covers the use of a radar system for the detection of persons trapped in building ruins after an earthquake.

This article describes a multi-frequency-sensor approach for both the reliable detection of persons and the measurement of heartbeat and respiration rate.

2 Physiological and technical basics

The human heart is approximately the size of a fist. It is located off-center in the thorax, two-third in the left part, one third in the right. In resting state it beats about 70 times per minute. With physical effort the activity can increase up to 200 bpm. The heart is covered by several layers, the most important are skin, fat and bone. The thickness of these layers varies from person to person.

A movement detection of the heart by means of radar implies the transmission of electromagnetic waves into the human body as well as reflections at a border. To estimate the amount of reflected energy it is necessary to know the dielectric properties of the different body tissues. A rather complete list can be found in <http://niremf.ifac.cnr.it/tissprop/>. For the calculation the well-known equations

$$R[dB] = 10 \log \left(\frac{|Z_{F2}| - |Z_{F1}|}{|Z_{F1}| + |Z_{F2}|} \right)^2 \quad (1)$$

and

$$T[dB] = 10 \log \left(\frac{2 |Z_{F2}|}{|Z_{F1}| + |Z_{F2}|} \right)^2 \frac{|Z_{F2}|}{|Z_{F1}|} \quad (2)$$

can be used. Z_F can be calculated from μ_r and ϵ_r using the following equation:

$$Z_F = \sqrt{\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r}} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} = Z_0 \sqrt{\frac{\mu_r (1 - j \tan \delta_\mu)}{\epsilon_r (1 - j \tan \delta_\epsilon)}} \quad (3)$$

Correspondence to: E. M. Biebl (biebl@tum.de)

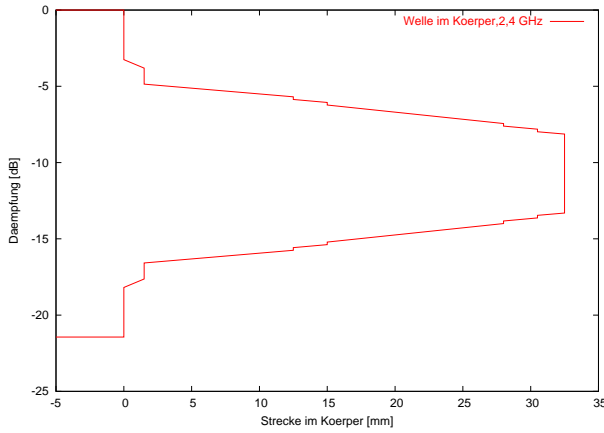


Fig. 1. Propagation of a wave at 440 MHz through the thorax and back.

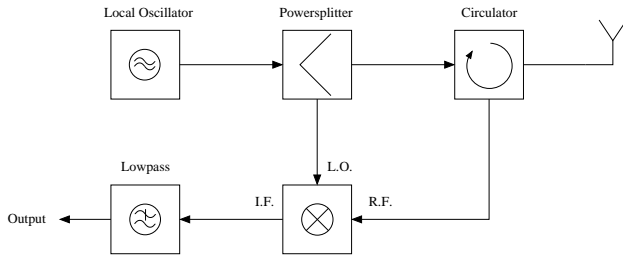


Fig. 2. Simple block diagram of a cw-doppler-radar.

Figure 1 shows an estimation of a wave at 430 MHz being propagated through the body towards the heart and being reflected back on the border fat/heart. The graph shows that a reflected wave is attenuated by approximately 22 dB. The reflection coefficient air-skin is about 2.38 dB at this frequency. Because the surface of the skin is also much larger than the surface of the heart, the difference between the two reflected signals will be at least 30 dB. Those values are very similar for 2.4 GHz.

The reflection coefficient at the border air/skin at 24 GHz is about -3.2 dB. In good approximation all power which is transmitted into the body can be considered as lost, so that no reflections from the heart can be measured at this frequency.

Two radar principles could be used for this task: ultra-wide-band(UWB)-radar and cw-doppler-radar.

The first one uses short pulses which are reflected at a target. The distance resolution that can be achieved is inverse proportional to the length of the pulses. As the movement of the heart is in the sub-cm-region, very short pulses (and therefore a very high bandwidth) would be needed. Despite from frequency regulation issues this would lead to a sophisticated broad-band design, not suitable for a low-cost approach. Staderini covers the use of such a system in medical applications in detail.

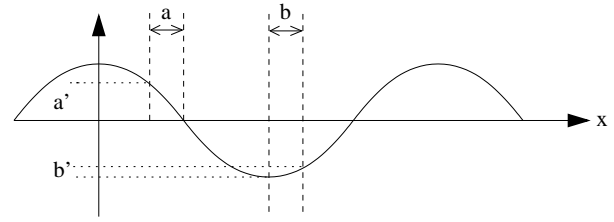


Fig. 3. Influence of phase on mixer output voltage.

The second one is much simpler to design. Figure 2 shows a simple block diagram of a doppler-radar circuit. Contrary to the pulseradar, the signal is sent continuously and unmodulated. Therefore only a small bandwidth is occupied. The information is contained in amplitude, frequency and phase of the received signal. The signal of the local oscillator is divided in two parts: One part is radiated via the antenna, the second part feeds the LO-port of the receiving mixer. The received signal feeds the IF-port of the mixer. If the frequency of the transmitted signal is ω_{TX} , and the frequency of the received signal is ω_{RX} , and φ_{TX} and φ_{RX} are the corresponding phases, the following signal can be observed at the IF-port of the mixer:

$$IF = A_1 \cos[(\omega_{TX} - \omega_{RX})t - (\varphi_{TX} - \varphi_{RX})] + A_2 \cos[(\omega_{TX} + \omega_{RX})t - (\varphi_{TX} - \varphi_{RX})] + \dots \quad (4)$$

A_1 und A_2 are constants depending on the mixer. If the frequency of the sent and received signals are equal, the equation simplifies to the following:

$$V_{Out} = A_1 \cos(\Delta\varphi) \quad (5)$$

A dc voltage depending on the phase can be observed at the output of the mixer. If the object which reflects the wave moves around a fixed position (as it is the case with the beating heart) the amplitude of this voltage changes. But the amplitude depends also on the absolute position of the target. This is illustrated in Fig. 3. A phase variation due to a movement within 'a' causes the voltage change of 'a'. A phase variation about (the same absolut) amount 'b' on another absolut position causes a much smaller change of 'b'. Because the amplitude of the heartbeat is much smaller than the used wavelengths, this effect is significant for the detection of heartbeats.

To overcome this problem of 'blind spots', the approach shown here uses three sensors at three different frequencies. In almost all cases at least one sensor will be able to achieve a meaningful measurement result.

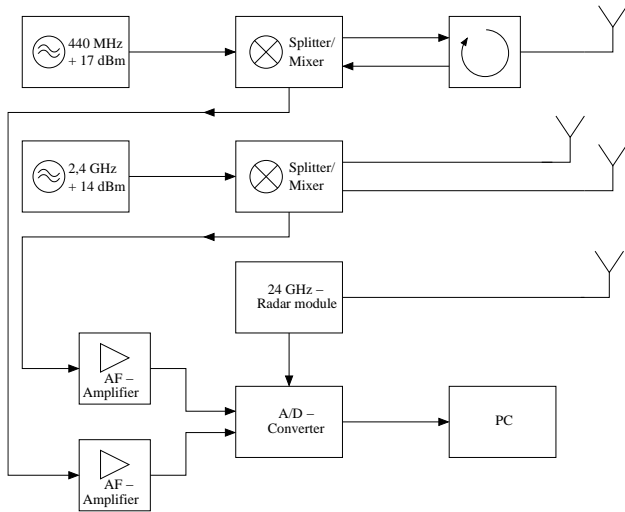


Fig. 4. Block diagram of the system used for the presented measurements.

Table 1. Used frequencies in the ISM range.

Wavelength	Frequency range	Output Power
70 cm	433,05 - 434,79 MHz	0 dBm
12,5 cm	2,4 - 2,5 GHz	0 dBm
1,25 cm	24 - 24,25 GHz	0 dBm

3 Measurement setup

Measurements were performed at three different frequency ranges. To make commercial applications possible, all chosen frequencies are located within the ISM (Industrial, Scientific, Medicine) bands. Table 1 gives an overview over the used frequencies and output powers.

Figure 4 shows a block diagram of the system used for the measurements. For 440 MHz, a circulator was available, thus a system according to Fig. 2 could be set up. The RF was supplied by a commercial signal generator. The maximum available output power was +17 dBm. Because a resistive power splitter was used to split the transmit and reference signal and due to the losses in the circulator, approximately +10 dBm (10 mW) were available at the antenna.

For 2.4 GHz no circulator was available, so two separate antennas were used for both the transmit and the receive path. Both antennas were realised as patch antennas etched on a low-loss substrate. To keep losses low, the power splitter and mixer were also included on the same substrate. Figure 5 shows the system. The power was also generated by a laboratory generator, and also about +10 dBm were fed into the transmit antenna.

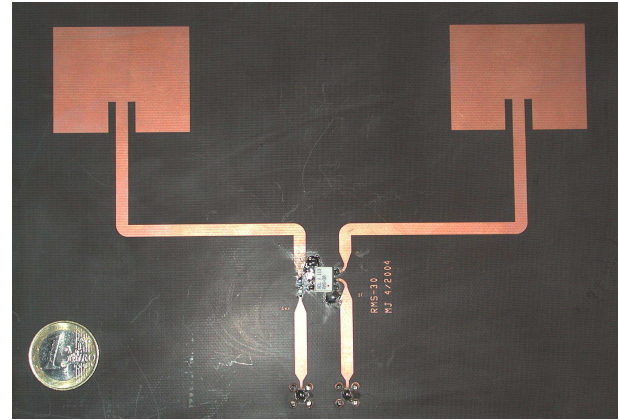


Fig. 5. The sensor used for 2.4 GHz.

The 24 GHz measurements were performed using a commercially available doppler radar module with a horn antenna with about 20 dBi antenna gain. The output of this module was ac-coupled, so the response to very slow movements (e.g. breath movement) was strongly attenuated or couldn't be detected at all. This can be seen in the measurement results.

All outputs were fed into a professional 16 bit A/D converter card connected to a notebook. The captured data was processed using MATLAB. First, the dc-offset was removed from the signal by calculating the mean value and subtracting it from all samples. Then the captured time domain data was windowed by a hanning-window to reduce the leakage-effect and converted to the frequency domain using the fast-fourier-transformation (FFT). There the signal was band-pass-filtered with a passband from 0.2 Hz to 5 Hz. For the time domain representation the filtered signal was transformed back into the time domain.

The achievable frequency resolution Δf is direct proportional to the length of the captured sequence N :

$$\Delta f = \frac{f_s}{N} \quad (6)$$

With a constant sample rate this can be converted into the recording time t_s :

$$\Delta f = \frac{1}{t_s} \quad (7)$$

If a resolution of 0.1 Hz is needed, the capture time must be at least 10 s.

4 Measurement results

For the actual measurements a sample rate $f_s = 8$ kHz was used. For the first measurement a person was seated on a chair and asked to sit quiet without moving and hold the

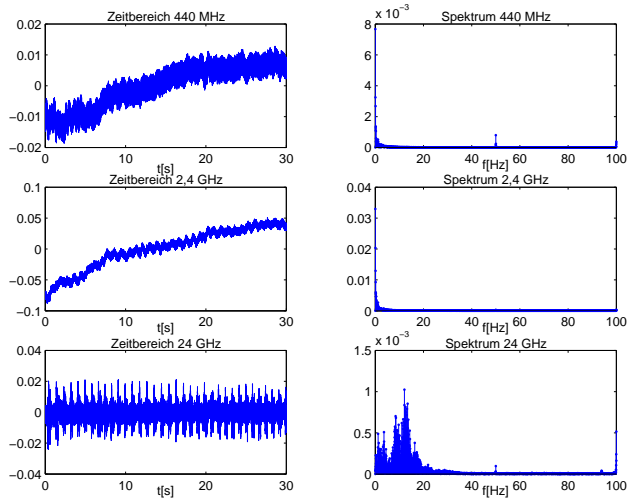


Fig. 6. Raw time- and frequency domain data.

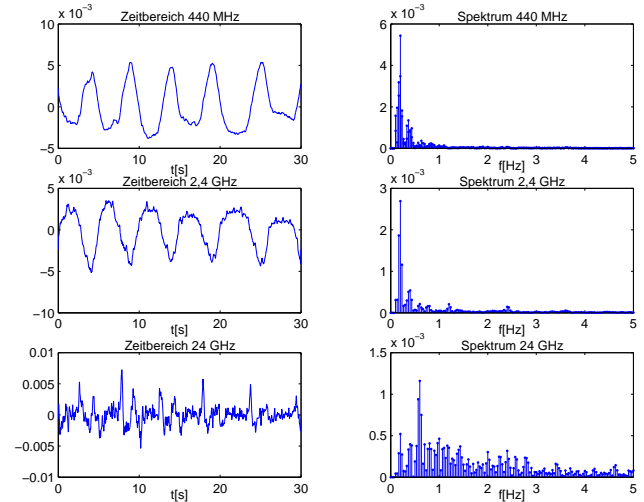


Fig. 8. Breath and heartbeat captured from a distance of 2 m.

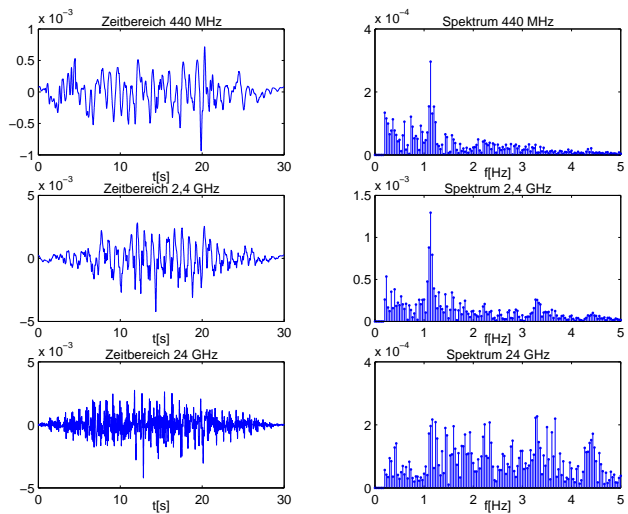


Fig. 7. Filtered time- and frequency domain data.

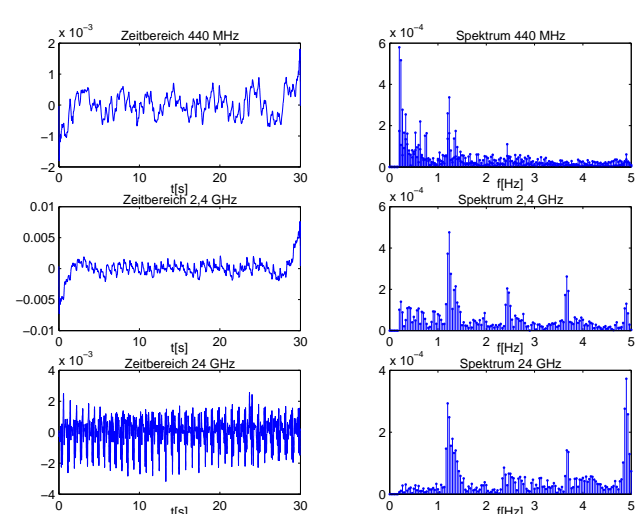


Fig. 9. Heartbeat captured from a distance of 2 m.

breath for 30 s. The data from all three sensors were taken parallel. Figure 6 shows the raw time- and frequency domain data as captured from the sensors, Fig. 7 shows the same data after digital filtering.

As one can see in Fig. 6 the spectral components are limited to very low frequencies. Therefore the maximum frequency range in Fig. 7 was reduced to 5 Hz. The frequency resolution with a measurement time of 30 s is 1/30 Hz. A peak is visible at 1.2 Hz. This equals a heart rate of 72 bpm which was confirmed by a parallel ‘classical’ measurement.

For the second measurement the person was again seated in the chair about 2 m from the sensors and asked to sit quiet, this time breathing. Figure 8 shows the results. The breath movement is clearly visible in the graphs resulting from the

measurements at 440 MHz and 2.4 GHz. As mentioned before, these low frequencies were cut by the hardware in the 24 GHz sensor. The spectrum has a peak at about 0.26 Hz, which equals a breath frequency of about 15.6 per minute. This was in fact the breath frequency of the test person.

After the measurement the person was asked to stop breathing so that only the heartbeat could be detected. Figure 9 shows the result. Here a peak in the spectrum is visible at all three measurement frequencies at 1.3 Hz. As a reference, the heart rate of the test person was measured with a pulse watch which showed 79 beats per minute. This equals 1.317 Hz.

Comparing the peak powers of breath and heartbeat with

Table 2. Increase of maximum compared to reference measurement.

Increase			
Measurement distance	440 MHz	2,4 GHz	24 GHz
Distance 1 m	> 35 dB	> 35 dB	> 35 dB
Distance 3 m	22,5 dB	23,5 dB	> 40 dB
Distance 3 m + door	16,5 dB	31,1 dB	–
Distance 8 m	21 dB	14 dB	30 dB
Distance 12 m	2,5 dB	15,5 dB	16,9 dB

the equation

$$V = 20 \log \frac{\text{peak}_{\text{respiration}}}{\text{peak}_{\text{heartbeat}}} \quad (8)$$

a difference of about 16 dB for 2.4 GHz and 20 dB for 440 MHz is found. Assuming that all returning power is reflected at the border air/skin at the breath measurement, these values are close to those predicted before. This may be a hint that actually reflections at the heart were measured.

If only the information is needed whether a person is present within the observed range, a threshold in the power spectrum could be defined. This was tested for different constellations. In all cases the persons were successfully detected if they were in the line of sight of the antennas. Even through obstacles, such as a closed wooden door, reliable recognition of the presence of persons could be achieved. Table 2 gives an overview over the increase of the low-frequency-spectrum compared to a reference measurement in an empty room.

5 Conclusions

CW-doppler-radar sensors at three different frequencies were successfully used to detect the presence of persons and to measure heartbeat and respiration rate over a distance of several meters. This was achieved with a low-cost hardware setup which could be easily implemented, for example, in the interior of a car. As expected, 440 MHz and 2.4 GHz show very similar properties for this application, whereas 24 GHz can only detect body movements due to its very small penetration depth.

The system still has some potential for improvements, for example the sensitivity of the radar sensors could be increased and therefore the output power could be decreased even further. Also only very basic DSP techniques were used for this measurements. A combination of the output from different sensors in combination with more sophisticated DSP algorithms could help to eliminate unwanted responses and overcome the disadvantage of the dependence from the absolute position.

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