Radar Remote Monitoring of Vital Signs

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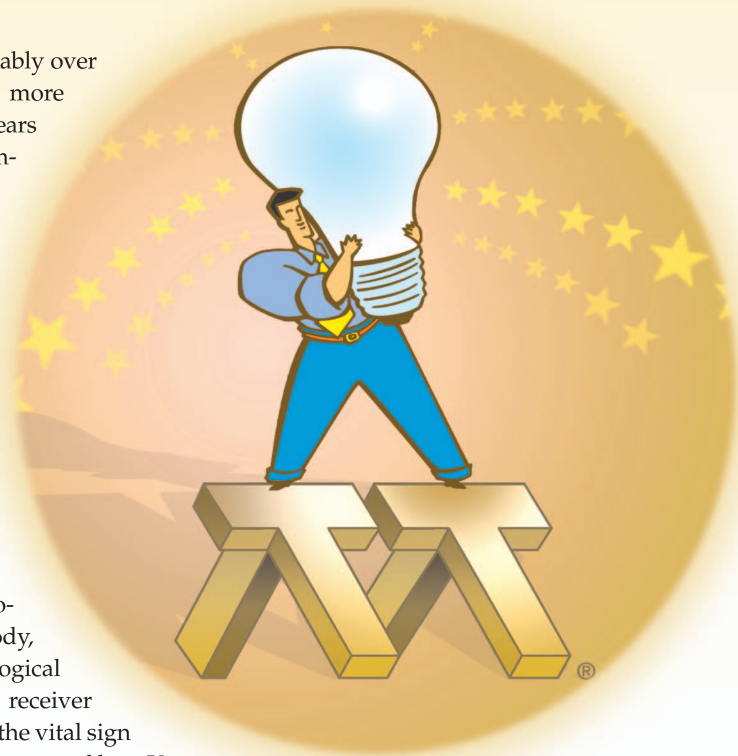

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Medical technology has improved remarkably over the past few generations, becoming more sophisticated and less invasive as the years progress. Until recently, however, completely noncontact health monitors have existed only in the realm of science fiction alongside flying cars and other promised technological marvels. Perhaps the best known example is the medical "tricorder," used to collect medical information in the popular science fiction television series *Star Trek*. Now, with microwave Doppler radar phase modulation, noncontact respiration and heartbeat monitoring offers an attractive alternative to commonly prescribed chest-strap monitors.

As an example of this technology, Figure 1 shows a system level block diagram of a Doppler radar using double-sideband transmission for vital sign detection from four sides of a human body. An unmodulated radio-frequency signal is transmitted toward the human body, where it is phase-modulated by the periodic physiological movement and reflected back to the receiver. The radar receiver captures the reflected signal and demodulates it to extract the vital sign signal components. Figure 2 compares a heartbeat record measured by a Ka-band radar with one measured by a fingertip sensor as the reference. As the figure shows, the noncontact detector is quite accurate.

There are several advantages to a noncontact measurement method: physically, it neither confines nor inhibits the subject and does not cause discomfort or skin irritation as electrodes and straps do. This is especially important over extended periods of time, making the detector ideal for long-term continuous monitoring. Also, reliability can be

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Digital Object Identifier 10.1109/MMM.2008.930675

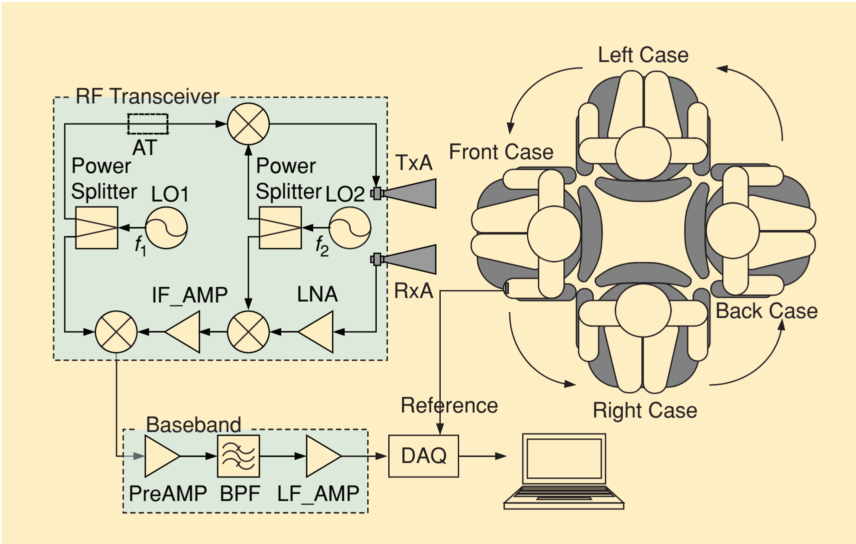

Figure 1. *Block diagram of a Doppler radar system using double-sideband transmission with the target in four different positions [1].*

in diagnosis and observation of sleep apnea and other respiratory ailments. Obstructive sleep apnea syndrome (OSAS) affects 4% of all adult males and has many symptoms, including hypertension, psychological distress, and cognitive impairment. Infant monitoring for respiratory or cardiac concerns is another potential market for this technology, since infants are much more sensitive to traditional contact monitoring methods. Noncontact infant heartbeat/respiration monitors may become as prevalent as traditional sound and video monitors, thus alleviating many parents' fear of sudden infant death syndrome (SIDS), the third leading cause of infant mortality. In short, a simplified portable instrument with noncontact physiological motion detection could improve the quality of life for many people.

increased since patients are unaware of the measurement and are therefore less likely to alter their respiration. Additionally, accuracy is enhanced due to the lack of surface-loading effects that have been shown to reduce the accuracy of some other measurement methods [2].

This technology will most likely have an impact on the growing home health care monitoring market. Among many possible home health care applications, an immediate market for this technology can be found

By measuring heartbeats, this technology can also be used to detect a person's presence, making it a good candidate for applications such as search-and-rescue for earthquake or fire victims, border patrol, and entrance security. It has also attracted the interest of organizations requiring high security, such as see-through-wall radar and airport security monitoring.

This article reviews recent work at introducing this technology in practical applications. It covers the following topics:

- history of advances in remote vital sign detection techniques
- design considerations at the board and chip levels
- a case study of an infant vital sign monitor
- a discussion of continuing work.

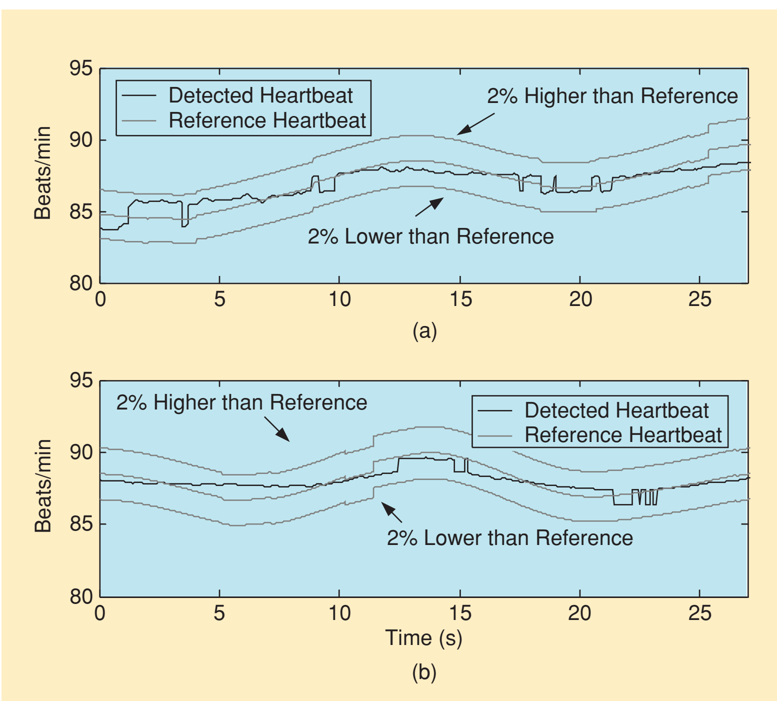

Figure 2. *Heart-rate comparison at 2-m distance measured from the front (top curve) and from the back (bottom curve) of a human body [1].*

History and Advances in Detection Techniques

When Doppler radar noncontact vital sign detection began to draw the interest of researchers [3], [4], the first emerging problem was the choice of radio frequency. In the 1980s, a microwave life-detection system, which operates at the X-band (10 GHz) for sensing the physiological status of soldiers lying on the ground of a battlefield, was reported [5], [6]. It turned out, though, that such an X-band microwave beam cannot penetrate earthquake rubble or collapsed building debris deep enough to locate buried human victims. For this reason, two other systems, one operating at 450 MHz and the other at 1150 MHz [7], [8], have been implemented. In a series of experiments [9], it was found that an electromagnetic (EM) wave of 1150 MHz can penetrate earthquake rubble (layers of reinforced-concrete slabs) with metallic wire mesh more easily than a 450 MHz wave. However, an EM wave of 450 MHz may penetrate deeper into rubble without metallic wire mesh than a 1150 MHz wave.

A key technology implemented in these efforts is a microprocessor-controlled clutter-cancellation system that creates an optimal signal to cancel the clutter from the rubble and the background [9]. In this technique, a phase shifter and an attenuator were digitally controlled by a microcontroller to provide a delayed version of the transmitted signal. The delayed version of the transmitted signal was combined with the received signal in a directional coupler. Additionally, a microwave power detector was used to monitor the dc level of the combined signal, serving as an indicator for the degree of the clutter cancellation. The microcontroller automatically adjusts the phase delay and attenuation to minimize the dc level in the combined signal. And an optimal setting for the clutter cancellation corresponds to the point where the dc level of combined signal was minimized.

Another potential problem for noncontact vital sign detection is the phase noise of the electronic circuit. Since the vital sign signal has a very low frequency (typically in the 1- to 2-Hz range, approximately) the large close-in phase noise of the signal generator may be hazardous and prevent the detection mechanism from working properly. Fortunately, the range-correlation effect [10] makes the detection possible. In the Doppler radar receiver, the same source is used for the transmitted signal and the local oscillator signal. Therefore, the phase noise of the received signal is correlated with that of the local oscillator, with the level of correlation dependent on the time delay between the two signals. When the two signals are mixed, the correlated portion of the phase noise effectively cancels, leaving a residual phase noise spectrum at baseband that is far below the phase noise spectrum at the radio frequency (RF). In the works of Droitcour et al. [11], phase-noise reduction due to range correlation was experimentally evaluated and the measured residual phase noise was within 5 dB of predicted values on average.

It was also shown in [11] that in a direct-conversion receiver, the phase relationship between the received signal and the local oscillator has a significant effect on the demodulation sensitivity. At some detection positions, the phase difference accumulated in the transmission path maximizes the desired signal, corresponding to the optimal detection point. At other detection positions, the phase difference minimizes the desired signal, corresponding to the null detection point. It additionally was shown in [11] that the null points can be avoided with a inphase and quadrature (I/Q) receiver. Other techniques such as double-sideband transmission [12], complex signal demodulation [13], and arctangent demodulation [14] have also been proposed to eliminate the null-detection point problem.

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By using the range correlation effect and properly selecting the carrier frequency, researchers have built Doppler radar vital-sign detection systems for several different applications. They found in experiments that other major problems with Doppler noncontact vital sign detection are the noise caused by motion artifacts and presence of multiple subjects. The multiple-input, multiple-output (MIMO) technique was then proposed to solve these problems. Another proposed approach is the single-input, multiple-output (SIMO) technique. In [15] and [16], the single and multiple antenna systems and SIMO/MIMO signal processing were explored to isolate desired radar return signals from multiple subjects. A generalized likelihood ratio test (GLRT), based on a model of the heartbeat, has been developed to show that this technique can be used to distinguish between the presence of two, one, or zero subjects, even with a single antenna. Furthermore, this technique was extended to detect up to $2N-1$ subjects by using N antennas. On the other hand, multiple transceivers have been used to cancel out the noise caused by motion artifacts such as random body movement [13]. The authors of [13] demonstrated that, on the basis of different movement patterns of physiological movement and random body movement, it is possible to cancel out noise caused by random body movement by using two transceivers detecting from two sides of the human body.

Having dealt with the problem of motion artifacts around the subject under test, researchers turned their attention to a problem on the radar side. Since the phase stability of the measurement system plays an important role in successful detection of life signs, small unwanted mechanical motions of the transmit antenna cause unrecoverable phase errors in the received signals. To overcome this issue, it was proposed [17] to use a bistatic radar with a sensor node receiver placed in the vicinity of the human subject. The sensor node consists of an antenna and a mixer, similar to the RF identification

(RFID) tag used in [18]. It receives both the direct signal from the transmitter local oscillator (LO) and the signal reflected from a human subject. Both signals are subject to the same "mechanical" phase noise. If these path lengths are similar, there will be a significant phase noise reduction due to the range correlation effect, making accurate detection of life signs possible.

A common observation of microwave Doppler radar under small-angle linear approximation is that shorter wavelengths produce higher detection sensitivity [11]. Therefore, a Ka-band double sideband bench-top radar was built and reported in [12]. The drawback of a Ka-band detector, however, is noticed in experiments [19]: when monitoring is done from the front of the body, the harmonic and intermodulation interferences to the heartbeat signal can prevent accurate detection at certain nonoptimum distances. For example, Figure 3 shows the normalized baseband spectrum detected by a Ka-band radar. The figure shows that the nonlinear Doppler phase modulation generates harmonics of the desired signal components. Rigorous spectral analysis of harmonic issues and system level optimization based on Ka-band radar is discussed in [1]. Harmonics can interfere with the desired heartbeat signal component and may affect detection accuracy, although careful selection of optimal carrier frequencies for different subjects can minimize this effect [20]. If used properly, though, harmonics can benefit certain new applications. By taking advantage of harmonics caused by the nonlinear phase modulation effect, a method accurately measures both the amplitude and the frequency of periodic vibration by analyzing the harmonic components generated in the received signal [21]. This method is not based on the measurement of absolute signal amplitude and reduces cost since it does not require signal strength calibration.

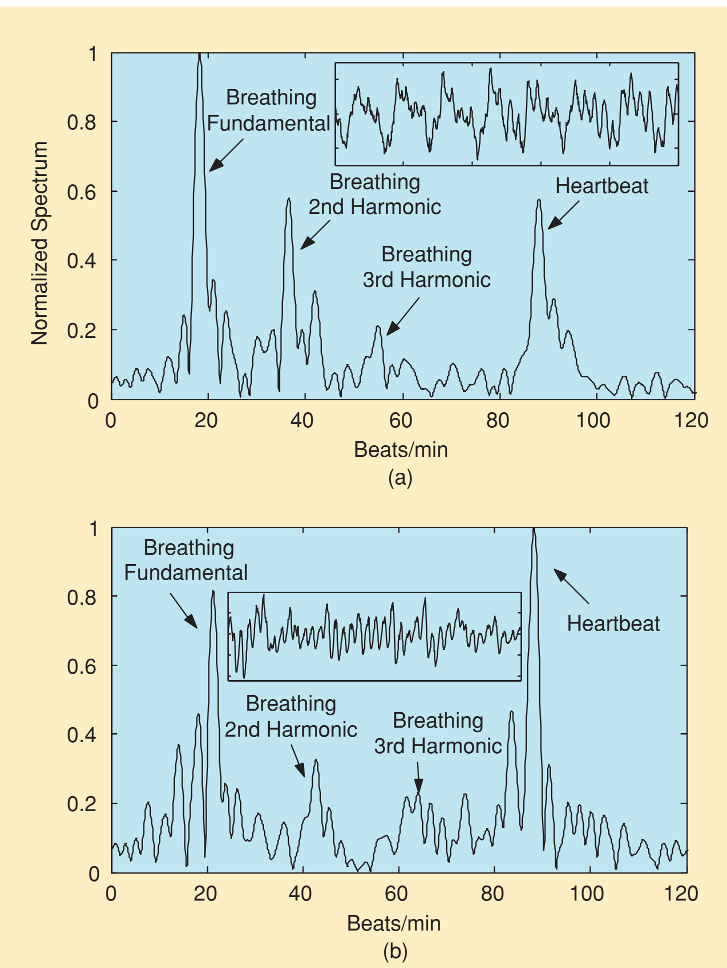

Figure 3. *Normalized spectrum detected by Ka-band radar at 2 m distance from the front (left) and from the back (right) of the human body. (Insets: corresponding real time signals, with time span of 27 seconds) [1].*

System Design

Board-Level Design

Perhaps the easiest way to build a noncontact vital sign detector is to use a commercially available motion sensor, although such devices are not optimized for the purpose of vital sign detection. Examples of this kind of motion sensor include the Microwave Solutions MDU1020 sensor, which was used for 10-GHz Doppler radar sensing of respiration and heart movement [22]. In this demonstration, the system consisted of the MDU1020 Doppler radar transceiver, an analog-to-digital converter, data acquisition software, and digital signal processing software for rate extraction. The demonstration showed that the radar function can be realized with a compact and inexpensive commercially available motion sensor detector and that the heart beat and respiration signals can be successfully detected.

Since various radio architectures have been reported for noncontact vital sign detection, it is worthwhile to compare the advantages and disadvantages of radio architectures. In [23], the direct-conversion nonquadrature, direct-conversion quadrature, and indirect-conversion architectures were used to build three radars working at 5.8 GHz. It was demonstrated that the direct-conversion nonquadrature architecture has the null-detection point problem, while the direct-conversion quadrature and the indirect-conversion architecture can avoid the null detection by using I/Q demodulation or frequency tuning. In the meantime, [23] proposed a ray-tracing technique to model and simulate the noncontact vital sign detection. This work also demonstrated that there are varying optimal carrier frequencies for different people with various physiological movement amplitudes. Therefore, radar with large tuning range of carrier frequency is desirable for everyday applications.

Because of this, part of the research focus has been moved on to system-level integration for everyday applications. While the Ka-band double-sideband transmission radar system is the most sensitive, systems with lower carrier frequencies have lower costs and fewer harmonics issues; this is a significant advantage when the requirement for sensitivity is not as high. Additionally, the direct-conversion quadrature transceiver architecture can employ complex signal demodulation [13] to perfectly solve the null-detection point problem in software, thus making it a competitive alternative to double-sideband transmission radar. The dc offset inherent in direct-conversion communication systems is not an issue for general purpose vital sign detection, since the frequency components of interest are not related to dc.

Because of these advantages, a portable 4–7-GHz direct conversion quadrature radar was designed and implemented [24]. Figure 4 shows a block diagram and photo of the radar, which integrates a quadrature transceiver, a two-stage baseband amplifier, and a power management circuit on a single 6.8 × 7.5-cm Rogers printed circuit board (RO4350B). In the transceiver part, four voltage controlled oscillators (VCOs) are used to completely cover the frequency range from 4.4 to 6.7 GHz. A dc to 8.0-GHz single-pole four-throw (SP4T) electronic switch is used to move between the four VCOs. To change the operation range (i.e., the distance between the radar and the subject to be monitored), a gain block is used to adjust the gain after the switch. The receiver chain contains a 3.5–7-GHz low noise amplifier (LNA), two stages of adjustable gain block, and the down-conversion mixer, which is a compact I/Q mixer utilizing two standard double balanced mixer cells and a 90 degree hybrid fabricated in a GaAs MESFET process. The radio frequency part of the receiver chain has an adjustable 30 dB of dynamic range.

The down-converted baseband quadrature signals are amplified by a two-channel two-stage amplifier, which is realized in a space-saving package with four unit-gain stable operational amplifiers. Two fixed-output voltage regulators (5 V and 3 V) are implemented and an adjustable output regulator with up to 11 V output voltage is used to tune the frequency of the VCOs. A switched-capacitor voltage converter is used to generate a −5-V logic supply. Either a 6–9-V wall plug or a 9-V battery can be used to power the radar.

By removing three of the on-board VCOs, simpler versions of the radar were fabricated and packaged for a baby monitor prototype and a vital sign detection robot prototype; both were built to demonstrate the immediate real-life applications of this technology.

Chip-Level Design

The first integrated chip for noncontact vital sign detection was developed at Bell Labs during 2000–2002. In the late 1990s, researchers at Bell Labs began working to integrate a Doppler radar sensing

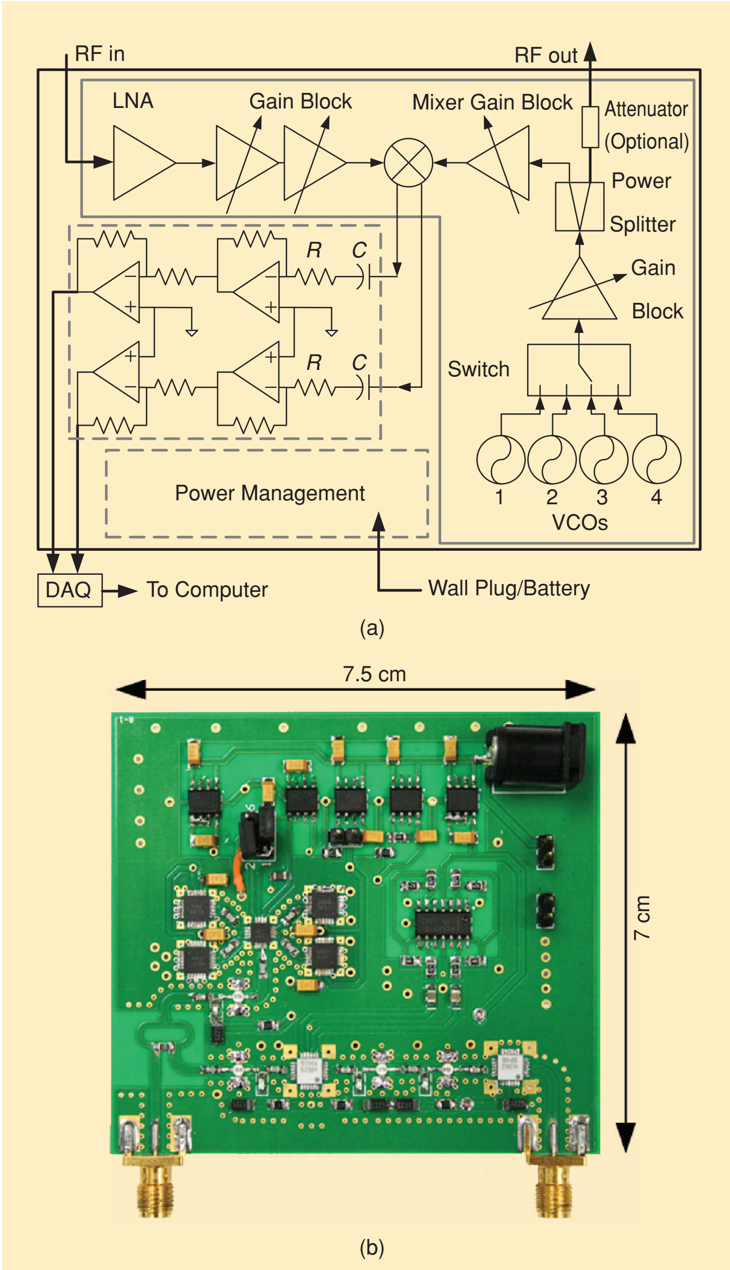

Figure 4. *Block diagram [24] (a) and photo (b) of the 4–7-GHz vital sign detector.*

function in cell phones and other portable wireless communications devices as a means to detect the user's heartbeat and respiration [25], [26]. Incorporating the bipolar complementary metal-oxide-semiconductor (BiCMOS) chip set developed for cellular base station RF transceiver front ends [27], an integrated physiological motion sensor radar module on a printed circuit board was developed and reported in 2001 [28]. The chip set includes a low-noise amplifier (LNA), a double-balanced resistive mixer, a voltage-controlled oscillator (VCO), and an active balun buffer amplifier. Although the chip set was optimized for low noise and high linearity for the purpose of shrinking a cellular network base station's RF front end, it was found suitable for building a physiological motion sensor radar. Fully integrated vital-sign detection sensor chips, implemented in 0.25-μm BiCMOS and complementary metal-oxide-semiconductor (CMOS) processes, were later developed and reported in 2002 [29]; this marked the first demonstration of the noncontact physiological motion sensor chip. The demonstration showed the feasibility of making these sensors in large quantity and low cost, and the potential of integrating them into portable electronic devices. A photograph of the sensor chip is shown in Figure 5 [30]. The chip was implemented in 0.25-μm CMOS process and had direct-conversion quadrature receiver architecture and operated at 2.4 GHz. The chip was packaged in a TQFP 48-pin package. The chip delivered 2 mW at RF output and dissipated 180 mW from a dc supply [30].

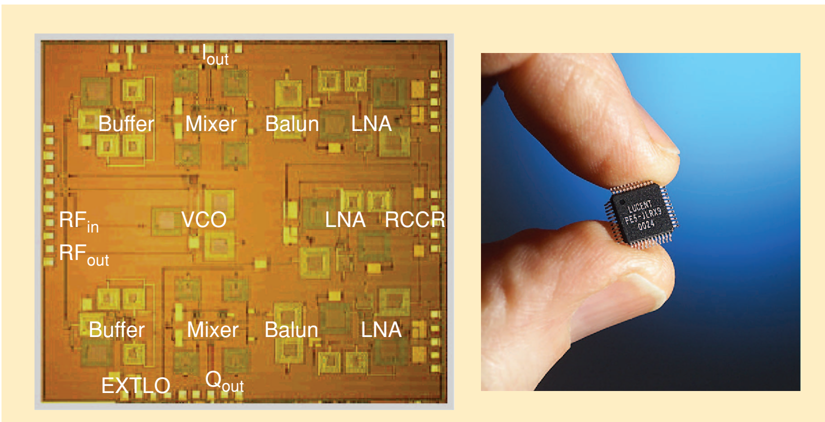

Figure 5. *The first noncontact physiological motion sensor chip using quadrature receiver architecture [30].*

Taking advantage of the same Doppler effect, an integrated 24-GHz intruder detection radar [31] has been developed to cover a fan-shaped ground area 90 degrees in azimuth and 0 to over 14 m in range, when mounted at a height of 5 m. The radar was implemented with three vertically switched beam antennas; each switched beam monitors a different range segment with a monopulse scheme designed to achieve the wide azimuth coverage. Experiments show that the radar integrated in monolithic microwave integrated circuits (MMICs) can successfully detect a human intruder with a position accuracy of 50 cm when moving at 1.4 m/s.

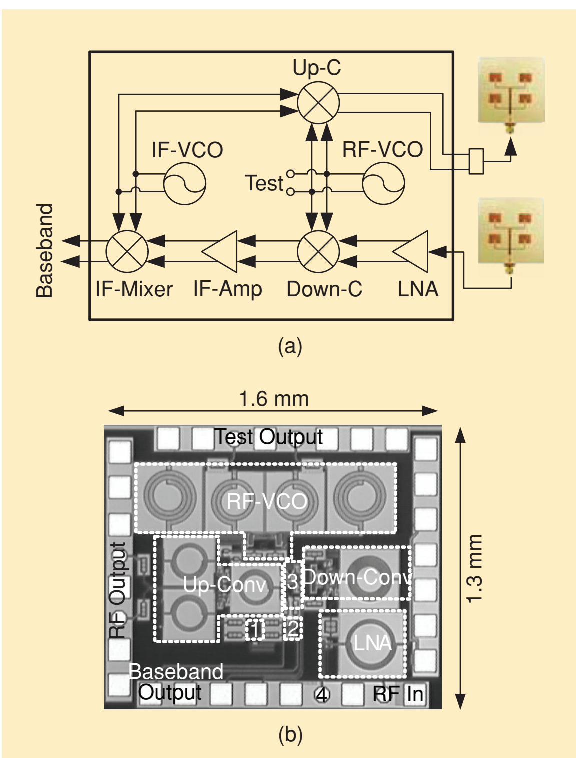

Figure 6. *Block diagram (a) and chip micrograph (b) of a 5-GHz radar transceiver designed and fabricated using UMC's 0.18-μm mixed-signal/RF process [32].*

Because the indirect-conversion radio architecture can avoid the null detection point by tuning the intermediate frequency, a 5-GHz double-sideband radar sensor was recently designed and fabricated by UMC's 0.18-μm mixed-mode/RF CMOS process [32]. A block diagram and chip micrograph of the resulting radar sensor chip are shown in Figure 6. The transmitter simply uses two VCOs as signal sources and a Gilbert double-balanced mixer as the up-converter (Up-C). The receiver chain has a low-noise amplifier (LNA), a Gilbert double-balanced mixer as the down-converter (Down-C), an intermediate frequency amplifier (IF-Amp), and a second stage passive mixer (IF-Mixer). Measurements show that this chip has a tuning range over 1 GHz [32]; the differential architecture also has the advantage of reducing LO leakage. The on-chip integrated 5-GHz radar was tested in a lab environment for vital sign detection of a human subject 1.75 m in height. Measurements were performed when the subject was seated at 0.5 m, 1 m, 1.5 m, and 2 m away from the radar, facing the antenna. As shown in Figure 7, both the respiration and heartbeat components were successfully detected in the baseband spectrum.

Application Case Study—Infant Vital Sign Monitor

Infant monitoring is a prime application for noncontact vital sign detection technology. The fear of sudden infant death syndrome (SIDS) and the prevalence of infant breathing problems have many parents searching for a way to monitor the health and well-being of their children, especially while sleeping unattended. Therefore, a noncontact monitor is expected to have a prime market in first-time parents with the income and the inclination to buy baby monitors that provide more than just sound or video. A noncontact heartbeat/respiration monitor would remotely watch over the health of the child and provide parents with peace of mind.

The remainder of this section outlines a prototype monitoring system designed for the purpose of baby monitoring. Figure 8 illustrates the receiver unit and the monitor unit in use. The monitor unit is designed to hang on the side of the infant's crib and detect the infant's breathing and heartbeat. It then communicates wirelessly with the receiver unit, allowing a parent to monitor the child remotely. Alarms sound and red lights flash on both units if the child's respiration and heartbeat are too weak.

System Architecture

The monitoring system consists of two main devices: a monitor unit, which is placed on the side of the infant's crib, and a receiver unit, which is carried by the parent. The monitor is divided into several subsections: radio-frequency circuitry to produce and receive the radio signals for vital sign detection, a microcontroller for signal processing, an XBee wireless communication chip for communication with the receiver, a power management circuit, and a simple user interface consisting of buttons, switches, LEDs, and a speaker.

Figure 9 shows a block diagram of the monitoring system's hardware. In the monitor unit, a 5.8-GHz single-tone unmodulated carrier signal is generated by a voltage controlled oscillator (VCO). It is amplified and transmitted via a microstrip antenna towards the infant. The reflected RF signal, which has been phase-modulated by the movement of the infant, is captured by a receiver antenna and amplified by a low-noise amplifier (LNA) and a two-stage variable gain preamplifier. The local oscillator signal and the received signal are then mixed together, amplified by a two-stage baseband amplifier, and sent through a

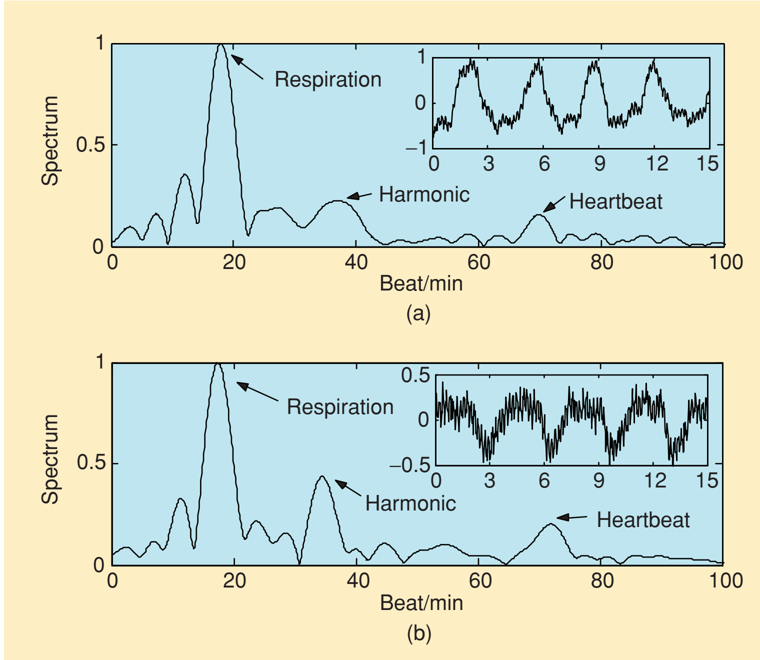

Figure 7. *Baseband spectrum detected by the on-chip integrated 5-GHz radar when the subject was 0.5 m away from the antenna (a) and 2 m away from the antenna (b). (Insets: detected baseband signal [volts] versus time [seconds].) [32].*

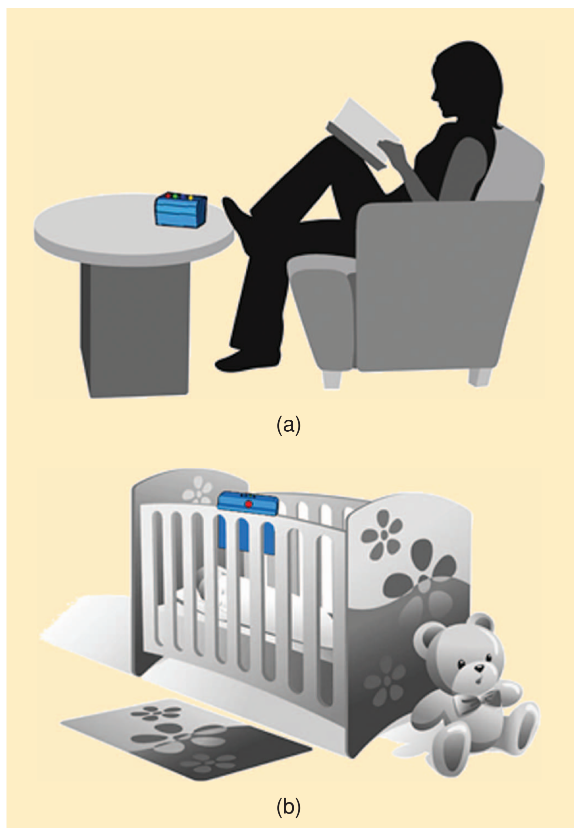

Figure 8. *Infant monitoring system with the receiver unit (a) and monitor unit (b) in operation.*

Since the monitor unit merely makes a determination whether heartbeat or respiration is present or not, signal processing is kept to a minimum and performed in the time domain for simplicity and speed.

low power microcontroller's A/D port for analysis. Voltage regulators and battery management microchips are integrated into the system to support wall-plug power supply, battery power supply, and battery recharge functions.

Since the monitor unit merely makes a determination whether heartbeat or respiration is present or not, signal processing is kept to a minimum and performed in the time domain for simplicity and speed. Since spectrum estimation methods such as fast Fourier transform (FFT) are not required, time-domain processing also reduces cost and power by eliminating the need for a sophisticated digital signal processing microprocessor. The dc offset, produced not only by electronic circuits but also by the down-conversion of signals reflected from stationary objects in the surrounding environment, is no longer negligible as in the case of frequency-domain signal processing. To address this issue, the time-domain signal processing supports automatic calibration to compensate for the dc offset of the system in different application environments.

Because the radar circuitry is implemented only on the monitor side, the receiver carried by the parent has a much lower power level for its power management circuit. Wireless communication with the monitor unit via XBee wireless transceivers keeps the receiver unit updated with the current alarm status. A vibrating motor was also added to the receiver to ensure that all possible methods of alerting the parent (light, sound, and movement) are utilized.

Features

The main features of the baby monitor prototype are design simplicity, range, reliability, and automatic calibration. The 5.8-GHz carrier frequency was chosen for two main reasons. First, this frequency has been successfully demonstrated for noncontact vital sign detection in [13], [23], and [32]. Second, this frequency is in the unlicensed industrial, scientific, and medical (ISM) bands, where low-cost commercial components are available. The power level at the transmitter output can be adjusted from −10 dBm to 8 dBm. The prototype system, using a low-cost, low-power microcontroller, was able to accurately detect respiration with a

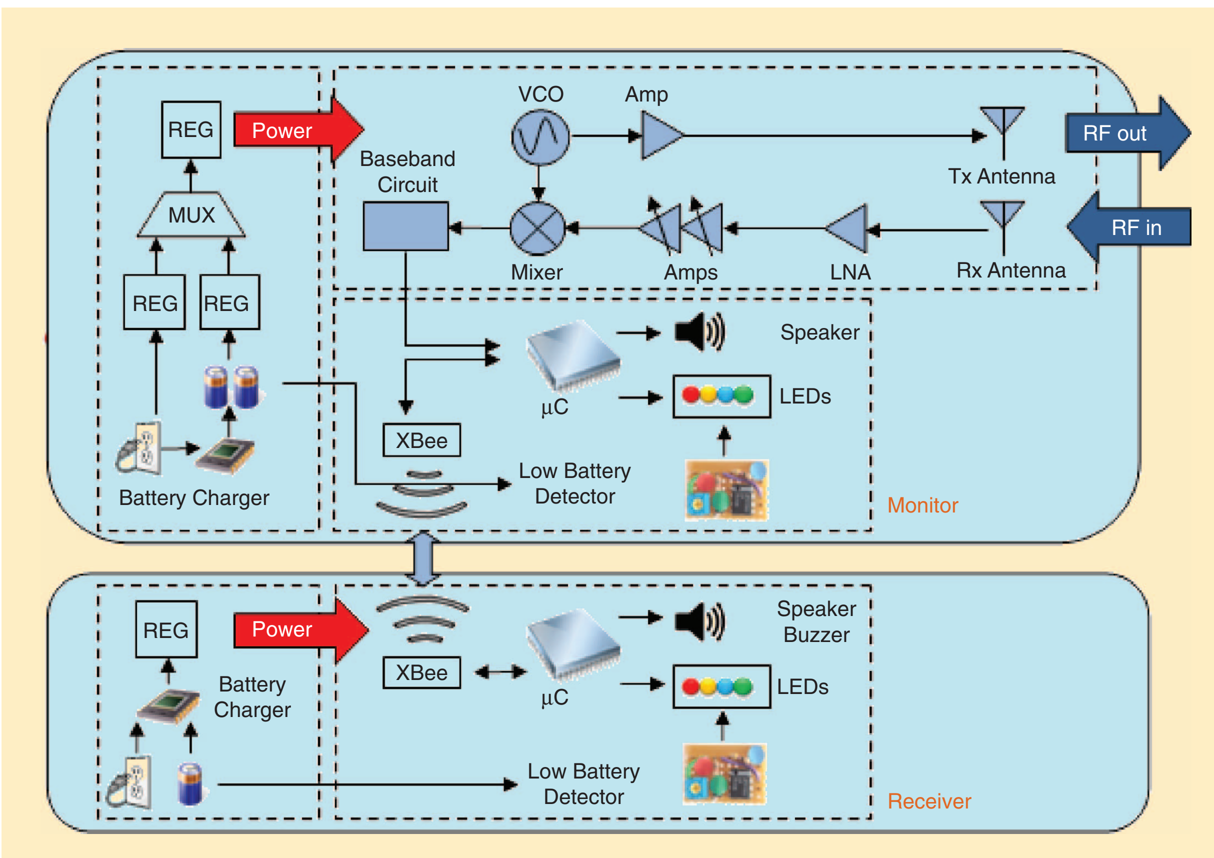

Figure 9. *Block diagram of the infant monitoring system hardware.*

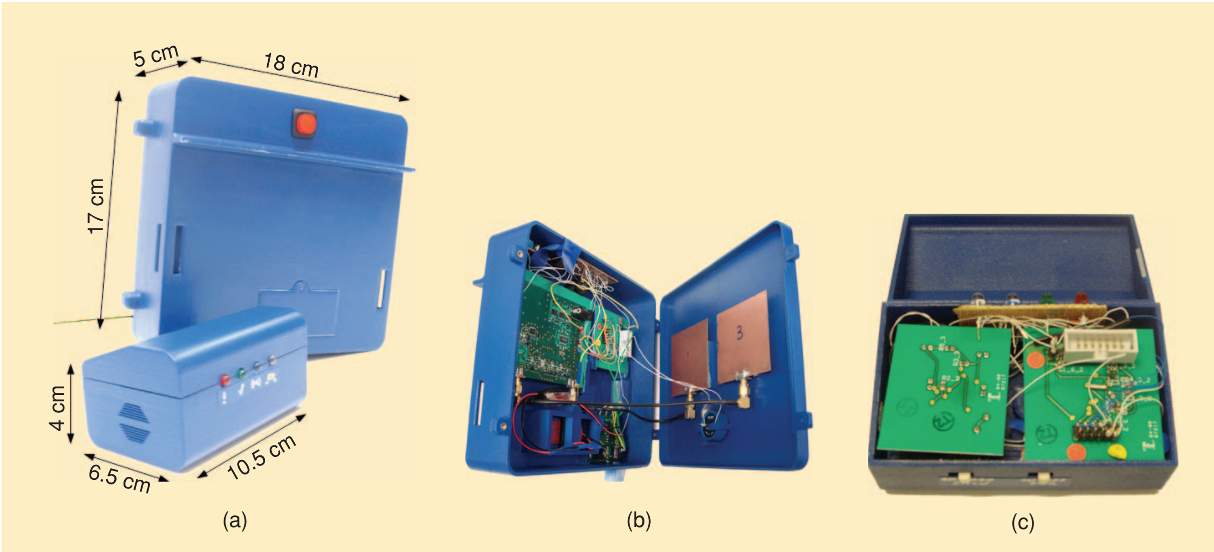

Figure 10. *(a) Exterior of the prototype system, (b) interior of the monitor unit, and (c) interior of the receiver unit. Not to scale.*

range of at least 1.15 m. This distance reaches to the furthest corner of a standard crib and allows for consistent monitoring regardless of the infant's position. Automatic calibration of the dc offset, performed on start-up, allows the system to maintain accuracy in a variety of environments.

To provide flexibility and ease of use, both the receiver and monitor units can be powered by batteries or plugged directly into wall power. The receiver unit can travel up to 50 meters away from the monitor while still being able to alert the parent. For operating range larger than 50 meters, the receiver needs to be connected to a laptop, which forwards the alarm to the parents' cell phones or PDAs.

The fabricated prototype is shown in Figure 10. The cost for mass production of the monitoring system is targeted to be under US$80 for the monitor and receiver pair; multiple receivers could be added to work with a single monitor. Limited by the packaging available, the prototype has a relatively large size (see Figure 10 for dimensions). With more refined packaging, the receiver could be reduced to the size of an ordinary cell phone. The size of the monitor could also be significantly reduced, with the limiting factor being the two 6×6-cm patch antennas.

Continuing Work

Because of its many promising daily life applications, Doppler radar remote vital sign detection technology has attracted a great deal of interest in recent years. Continuing efforts have been spent on this technology and much progress has been reported. Several unique challenges of noncontact vital sign detection, though, still require further attention.

One area of continuing investigation is the elimination of noise caused by random body movements and clutter. Since noncontact vital sign detection is based on sensing the small physiological movement in the millimeter or centimeter range, the presence of random body movement or environmental changes can interfere significantly with accurate detection. For example, when the radar was used for overnight monitoring of sleep apnea in a clinical environment, the detected vital sign signal was interrupted whenever the subject under test rolled over on the bed, causing a potential false alarm. Techniques such as multiple-input, multiple-output (MIMO) are being further optimized to eliminate the noise caused by random body movements and clutter.

Advanced signal processing methods are always topics of interest for noncontact vital sign detection. For Doppler radar vital sign detection, a spectral estimation algorithm is needed to accurately estimate the sinusoidal frequencies before identifying the heartbeat and respiration rates. The existing frequency estimation approaches used for vital sign detection are mainly based on fast Fourier transform [33]. In some cases it could not reliably separate the rich sinusoidal components because of the smearing and leakage problems, especially for the case of limited data samples. Recently, a parametric and cyclic optimization approach (referred to as the RELAX algorithm [34]) has captured the interests of researchers for its potential to mitigate these difficulties in Doppler radar vital sign detection.

In the meantime, effort is being spent on the complete system-level design for portable applications, such as earthquake and fire search and rescue. Each application has its own set of unique requirements for the technology. For example, applications in emergency situations such as search and rescue require a relatively large operating range (maximum distance at which the radar can successfully detect vital signs). To address this issue and provide an improved operating range, circuits with digital automatic gain control and improved dynamic range are under investigation.

From using fewer uncomfortable chest straps and electrodes to remotely monitoring an infant's breathing, or finding buried earthquake victims, the wide range of ways remote vital sign detection technology can be used to benefit people is astounding. Although the technology is still in the development phase, the nonintrusive approach, high accuracy, and attractive features of Doppler radar noncontact vital sign detection indicate that it will soon become a part of daily life for many people.

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