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Sensing of Life Activities at the Human-Microwave Frontier

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ABSTRACT Modern microwave radar technologies and systems are taking important roles in healthcare, security, and human–machine interface by remote sensing of human life activities. This paper first reviews the developments in the past decade on the sensing front-end, transponder tag, and leveraging of other wireless infrastructure such as Wi-Fi. Based on the state-of-the-art engineering technologies, several emerging applications will then be studied, including continuous authentication, behavior recognition, human-aware localization, occupancy sensing, blood pressure monitoring, and sleep medicine. As radio frequency spectrum becomes a scarce resource, the allocation and spectrum sharing of life activity sensing bandwidth with other wireless infrastructures will be discussed. Several future research directions will be laid out to solve challenges for ubiquitous deployment of these sensing technologies at the human–microwave frontier.

INDEX TERMS Continuous-wave, energy, healthcare, human sensing, identification, life activities, localization, radar, security, sensing.

I. INTRODUCTION

The past decade has witnessed tremendous progresses in microwave theory and techniques for biological studies, medical applications, and interaction with humans. From very low frequency (kHz) to sub-millimeter wave (THz), a variety of instrumentation, device fabrication, theoretical modeling, and clinical/pre-clinical studies have achieved success based on novel methods utilizing microwaves. As new technical challenges are identified for emerging applications, more researchers have joined the task force to develop advanced solutions so that science and engineering advancements can benefit the wellbeing of humans.

Among many prominent research and development (R&D) sub-areas at this human-microwave frontier, using microwave signals to wirelessly sense life activities has attracted growing interests from researchers and practitioners in radar systems, signal processing, circuit and system integration, as well as healthcare sectors. In 2013, the authors reviewed the achievements in Doppler radar for remote detection of heartbeat and respiration of human subjects, including front-end architectures, baseband signal processing methods, system-level integrations, and validations in pre-clinical environment [1]. Since then, researchers have pushed the technologies further with technologies such as embedded DSP with support vector machines (SVM) [2], stepped-frequency continuous-wave radar [3], ultra-wideband frequency-modulated continuous-wave (FMCW) [4], channel imbalance compensation [5], digital post-distortion [6], six-port [7], adaptive beam-steering [8], and various deep learning algorithms [9]. The contributors are not only from academia, but also from industrial research labs [10], [11]. The applications have been extended to many other areas such as Internet of Things (IoT), occupancy sensing, security authentication, and wireless human-machine interaction.

This paper reviews some of the progresses made since 2013 with frequency-conversion based continuous-wave (CW) radar architectures. Due to page limit and research area of the authors, the paper does not cover impulse-radio ultra-wideband (IR-UWB) [12] and injection-locked detection architectures [13], although they also have unique advantages for sensing of life activities. The rest of the paper will start from new front-end technologies. It will then discuss emerging applications at the human-microwave frontier, including security authentication, behavior/gesture recognition, occupancy sensing, blood pressure monitoring, and sleep medicine. The use of microwave frequency bands and need of spectrum sharing will be discussed in Section IV. After that, the challenges for ubiquitous deployment and future research directions will be presented in Section V, followed by a conclusion and brief discussion of future outlook.

II. MICROWAVE TECHNOLOGY FOR REMOTE SENSING OF LIFE ACTIVITIES

A. TRANSCEIVER ARCHITECTURES FOR DETECTORS

Compact life activity sensing radar started with the well-known homodyne architecture that offers range correlation for effective cancellation of the oscillator phase noise [14]. However, direct down-conversion to dc and the subsequent baseband amplification circuit will introduce high flicker noise around the signal of interest, which has significant content around dc. To tackle the problem, coherent low-intermediate-frequency (IF) systems were adopted [15]. A comprehensive analysis showed that this architecture has the range correlation benefits of the homodyne system, while minimizing the baseband flicker noise [16]. Measurements on a mechanical target demonstrated effective signal-to-noise ratio improvement. Measurements on a human subject about 3 m away demonstrated low-IF heart rate detection with a root-mean-square error of less than 0.8 beats/min, whereas a reference direct conversion system failed in that case [16].

A variation of the low-IF architecture is the pulse Doppler radar [17]. In the transmitter, a CW RF signal is multiplied with an ON/OFF pulse signal with a pulse repetition frequency (PRF) of 100 Hz. The receiver down-converts the target reflected signal using the original CW signal. Therefore, the receiver output spectrum is shifted from dc to an IF that is equal to the PRF. This single-channel pulse Doppler low-IF radar architecture overcomes limitations of conventional quadrature receiver, including complexity and quadrature channel imbalance. A low-IF demodulation method was also developed in [17] based on digital filters and complex signal multiplication to retrieve the physiological information. Successful detection of different mechanical motion patterns was demonstrated.

Driven by the need of higher sensitivity, the first 100-GHz Doppler radar transceiver with double-sideband low-IF architecture for mechanical vibration and vital sign detection was developed in 65-nm CMOS process [18], [19], as shown in Fig. 1. The whole radar chip transceiver consumes 262 mW with a size of 0.9 mm × 2.0 mm. The transceiver was driven by a push–push frequency doubler with a 50-GHz

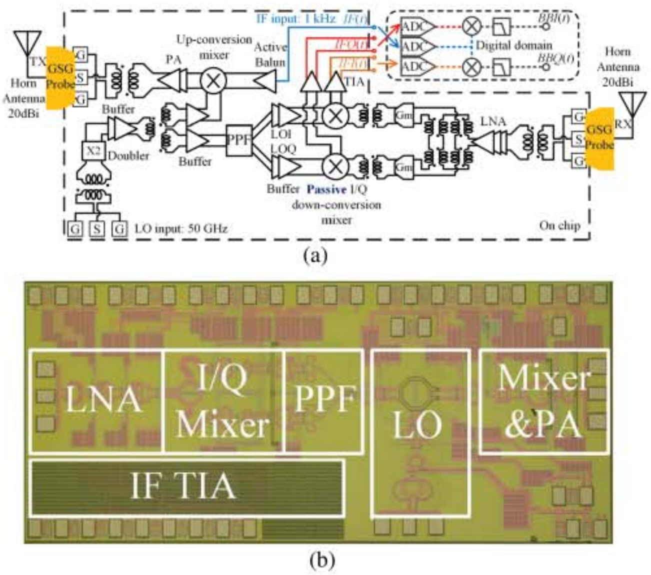


FIGURE 1. Block diagram and chip microphotograph of the first 100-GHz Doppler radar transceiver with double-sideband low-IF architecture. From [18].

external source. The chip could transmit 4-dBm power over 93–105 GHz with a 40-mV 1-kHz IF carrier. It achieved good *I*/*Q* performance of < 1° phase mismatch and <1 dB amplitude mismatch over 95–104 GHz. Benefiting from the short wavelength at 103 GHz, a probe-station-based test setup was able to successfully detect 1-μm mechanical vibration from 1.5 m, a human vital-sign signal from 2 m, and a small bullfrog's hybrid respiratory motion from 0.6 m.

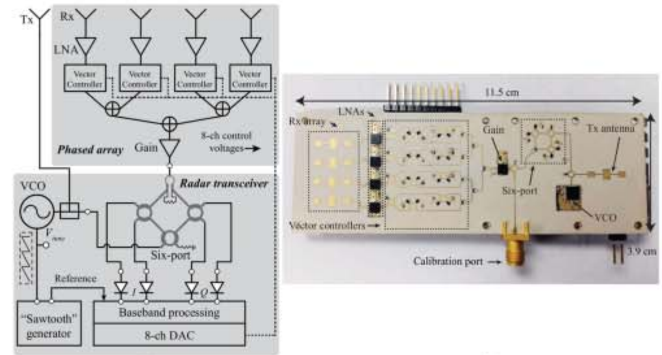
Conventional synchronous demodulation low-IF method typically consumes a large amount of ADC resources because of the elevated signal speed. To address this issue, a new envelope detection method to reduce the ADC sampling rate from 20 kHz to 20 Hz in a double-sideband low-IF continuous-wave Doppler radar was reported [20], [21]. Hardware implementation of carrier compensation and envelope detectors were key to recover and extract the envelopes in the IF domain. Experiments showed that, when the IF carrier frequency is higher than 1 kHz, the signal-to-noise ratio of this method would be comparable to that of a conventional synchronous demodulation.

Since transmitter (TX) signal is usually many orders of magnitude stronger than (RX) signal, it is important to minimize TX-to-RX leakage, to avoid saturating the RX and interfering correct detection due to TX noise or modulation. One way to reduce the leakage is to use separate antennas. However, this does not eliminate the leakage due to antenna coupling and echo from the static clutter, and leads to higher cost and bulky size. Single antenna system with quadrature hybrid, directional coupler or circulator, can achieve isolation in the order of 20–30 dB, but the performance is ultimately limited by specifications of the devices such as impedance matching. In [22], a TX leakage cancellation method based on antenna image impedance, i.e., the passive network synthesized to replicate the antenna impedance in the band of interest, was proposed. The concept was verified for a patch antenna array operating in the Ku band, where the achieved isolation is measured to be better than 35 dB in the 17–17.4 GHz range.

Since the first demonstration of fully integrated chip-scale vital sign radar in [14], [23], most of the chip-scale CW vital sign radars only integrated various analog front-end architectures without the ADC. To address this deficiency, [24] reported a 5.8 GHz radar receiver that integrates variable gain amplifiers and A/D converters on a single chip for non-contact vital sign detection. The system-on-chip was realized in a TSMC CMOS 0.18 μm process. To keep the baseband output signal in the optimal dynamic range, a clutter cancellation mechanism was also implemented in the system. Experimental results demonstrated successful detection of respiration and heartbeats of human subjects with an overall power consumption of 55 mW.

Although its detection principle has been established for years, the six-port interferometer has recently gained new attention as an alternative RF front-end structure for the radar detector. Its basic concept, applications in human sensing, as well as comparison with other front-end architectures were reviewed in [7], [25]. Since six-port detectors are based on planar passive microwave structures and RF diodes, they are attractive as low-cost board-level products for applications that feature a short development cycle. On the other hand, it was shown that special attention should be paid to impairment effects and non-ideal behavior, as well as compensation and linearization. In this inaugural special issue, another review article will cover six-port and its industrial applications.

Conventional radar-based localization solutions rely on a large RF bandwidth to achieve desirable range resolution, which is equally deployed to everything in the antenna field of view. This leads to heavy burdens to the limited spectrum resource and the on-board power supply. At the human-microwave frontier, a more efficient way to distribute spectrum and energy resources is adaptive delivery of resource to users. The unique human behavior that is distinct from natural/manufactured objects in the surrounding makes multi-mode sensing a valuable approach to efficiently allocate spectrum, power, and computational resource in a dynamic fashion. For example, the Doppler/interferometry mode is ideal to track the vital signs information of a single human subject at a fixed location. When the location of a subject needs to be known, a modulated waveform should be transmitted: an FSK probing signal can be used in a clear environment with limited clutters for its simple operation and small RF bandwidth requirement [26], while FMCW signals can be used for its range resolution in a cluttered environment. When multiple objects are present, the high range resolution FMCW mode is preferable to resolve the locations of different objects. Based on this concept, prototype multi-mode radar was first developed with the help of a benchtop RF signal generator [27]. Moreover, because the range correlation effect generally applies to the aforementioned modulation schemes, simple analog waveform synthesizers can be designed to control free-running VCOs in the radar front-end for mode switching [28].



(a) (b)

FIGURE 2. Block diagram (a) and RF front-end (b) of the *K*-band RF beamforming FMCW radar reported in [29].

Antenna is a key component not only because it has a strong influence on the angular resolution, but also because they largely affect the device size and weight for portable applications. Higher carrier frequency is desirable to reduce the physical size and more elements, either physically implemented or digitally synthesized, are beneficial for angular resolution. In recent years, analog and digital beamforming has been used to enable biomedical radar to scan a target area and dynamically track subjects in real time. A *K*-band portable FMCW radar with RF beamforming, as shown in Fig. 2, uses an array of RF vector controllers to continuously steer its beam within $\pm 45^\circ$ on the H-plane [29]. Each vector controller is capable of simultaneously controlling the phase and the amplitude of the array element around 24 GHz. In [30], a *K*-band multiple-input and multiple-output (MIMO) radar featured 3-D imaging capability to obtain the range, azimuth angle, and zenith angle of a target. A planar array was synthesized with 2-D digital beamforming based on a small number of transmitter and receiver (T/R) channels. Furthermore, a nonuniformly spaced array configuration effectively reduced the number of T/R channels without sacrificing the beamwidth and sidelobe level. The concept can be extended to a 16-TX channels and 16-RX channels design as shown in Fig. 3.

B. MICROWAVE TECHNOLOGIES FOR TAGS

Although advanced antenna arrays have been improving the angular resolution for radar transceivers, compared with other sensing technologies such as radio-frequency identification (RFID) and lidar, compact radar sensors have limited capability to differentiate target from clutters in a complex indoor environment. To overcome these deficiencies, nonlinear radars were developed to detect targets that carry a tag with nonlinear response to impinging electromagnetic waves [31], [32], based on the electronic characteristics present in components such as diodes and transistors. Since naturally occurring things are mostly linear in behavior with few exceptions such

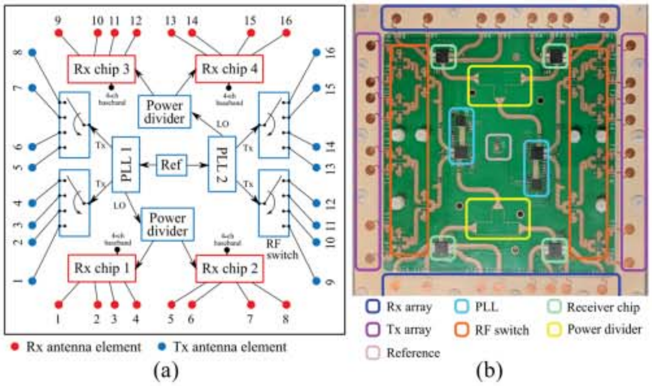


FIGURE 3. Block diagram (a) and RF front-end (b) of a *K*-band MIMO digital beamforming radar with non-uniformly spaced array and 3-D imaging capability.

as the rusty bolt effect [33], they can be distinguished from nonlinear tags. In nonlinear radars, fundamental tone(s) is sent towards a nonlinear tag, which in return reflects nonlinear tones along with the fundamental tone(s). The radar receiver extracts the nonlinear response to distinguish between targets and clutter.

Commonly used nonlinear radars work on the detection of harmonics of the transmitted tone(s) and have found important applications for decades. For instance, the RECCO system initially developed in 1980 are now standard equipment with many ski resorts, mountain rescue teams, and parks worldwide. The system consists of a reflector integrated into clothing and a detector used by professional rescue teams. If the signal sent by the detector hits a reflector, which integrates a foil antenna and a diode, it will bounce back with its frequency doubled. As a result, the second-harmonic detector can tell the direction of the reflector tag.

Despite great success achieved, the harmonic-based nonlinear detection also leads to some major challenges for modern applications that demands for ultra-small feature size, low-cost, and high spectrum efficiency. For example, the tag returns a frequency that is at least twice as high as the detector's transmit frequency, thus occupying different frequency bands and leading to radio spectrum licensing burdens. According to the free space path loss model, the higher path loss of the harmonic tones reduces either the detection range or the energy efficiency. In addition, the inherent requirement of dual-band transceiver design for the harmonic tag increases the hardware size and cost.

An attracting alternative is to explore the intermodulation response of a nonlinear tag, if more than one tone could be transmitted simultaneously from the detector. Since the 3rd-order intermodulation can be located within the same band as two transmitted tones, some challenges of harmonic radar could be resolved. For instance, the intermodulation response can lie in the same band as the fundamental tones, avoiding the extra 6 dB path loss of the 2nd-order harmonic. Unlike harmonic tags that require dual-band design, intermodulation tags can use a single-band design for both the antenna and converters. Recently, an intermodulation radar receiver and a nonlinear tag was reported in [34]. A dedicated coherent signal generation scheme was developed to select the 3rd-order tone at the receiver. Various experiments were performed to demonstrate the clutter rejection capability in mechanical motion and vital signs detection.

Furthermore, an intermodulation sensing in frequency shift keying (FSK) mode was developed for localization of human subjects based on life activities [35]. Another feature of this nonlinear detection setup was that the heartbeat signal component received more gain than the respiration signal, so that the sidelobes and harmonics of respiration do not interfere with heartbeat signal. This enhanced the heartbeat signal quality for easy track of cardiac activities. Experiments performed in nonlinear FSK mode demonstrated high accuracy in target motion detection and localization.

Besides enhancing the signal from the desired target, electronic tags also take important role as a reference for removal of undesired motion of the radar detector itself. In [36], a low-IF RF tag device was studied for motion artifact compensation in measuring vital signs using a mobile Doppler radar. The AC and DC coupling effects in low-IF tag assisted Doppler radar system was analyzed by investigating the coupling requirements of the amplifiers for signal conditioning of the received RF signal. With the help of the RF tag placed near the human subject in a lateral position and exposed to the moving transceiver, adaptive filtering can be performed to remove unwanted motion artifact from the radar baseband output. More works on motion artifact removal will be discussed in Section V.

C. SYSTEMS LEVERAGING WI-FI TECHNOLOGIES

The past decade has witnessed great progress in Wi-Fi based sensing, including vital signs monitoring [37], [38], gesture recognition [39], [40], through-the-wall imaging [41], [42], and localization [43]. The fundamental mechanism is that human subjects and physiological motions can be sensed by analyzing their impacts on the signals emitted from Wi-Fi devices. Gesture codes composed of forward and backward steps were successfully decoded through a wall in [39] with a customized MIMO device based on three USRPs. A contactless exercise monitoring system leveraged the Doppler displacement information extracted from the Wi-Fi channel state information (CSI) signal for bodyweight exercise type classification and repetition counting [40]. Leveraging the high sensitivity of injection-locking mechanism, a quadrature injection-locked radar used ambient wireless signals for gesture sensing [44]. Instead of requiring a cooperative source, the radar receiver captures Wi-Fi signals from a far IEEE 802.llb/g/n access point to identify several gestures.

Advances in Wi-Fi technologies for through-the-wall imaging have also been reported, such as flash effect elimination based motion tracking [39], finer-grain information based entire human figure imaging [45], and cross-modality supervision based three-dimensional mesh model extraction [41]. Nevertheless, these works adopted customized RF transceivers instead of commodity Wi-Fi devices. A passive bistatic Wi-Fi radar was designed to work with existing Wi-Fi access point in [42]. However, a reference receiver was required to be placed in the same room as the transmitter and with a clock synchronization between them. As for indoor localization, device localization was realized by performing synthetic aperture radar (SAR) processing using off-the-shelf Wi-Fi cards and motion sensors equipped in mobile devices [43].

Many Wi-Fi related vital signs sensing approaches require either conventional antenna arrays, wideband frontend, customized RF transceivers, or additional sensors. To truly leverage the existing Wi-Fi infrastructure, researchers have exploited information retrieved from off-the-shelf Wi-Fi devices, including CSI [46]–[50], Fresnel zone model [51], [52], and Cross ambiguity function (CAF) [38], [53]. Fundamentally, Wi-Fi systems can be regarded as bistatic radar systems, in which the transmitter and receiver do not share a signal source, and thus lack coherency. While lack of coherency limits sensitivity, it is partially compensated by the synchronization mechanism of the Wi-Fi protocol. Wi-Fi method holds promise for continuous human monitoring in environments with existing Wi-Fi infrastructure without the need for additional hardware. However further research and development may be needed for robust operation under varying wireless channel characteristics.

III. APPLICATIONS AT THE HUMAN-MICROWAVE FRONTIER

New applications are being pursued at the human-microwave frontier, ranging from security, smart living, future of work, to healthcare. Based on the authors' experience in this field, several typical applications are discussed in this section.

A. IDENTIFICATION AND AUTHENTICATION FOR NON-CONTACT SECURITY

Physiological Doppler radar is an emerging approach for continuous and unobtrusive identity authentication, which can reduce the vulnerability of traditional one-pass validation authentication systems. It is attractive as it requires neither contact nor line-of-sight and does not raise privacy concerns associated with video imaging. A Cardiac Scan system was studied in [54] based on geometric and non-volitional features of the cardiac motion. A DC-coupled continuous-wave radar was used to detect cardiac motion, which is an automatic heart deformation caused by self-excitement of the cardiac muscle, unique to each user, and difficult to counterfeit. Fiducial-based invariant identity descriptors of cardiac motion were extracted after the radar signal demodulation. A pilot study with 78 subjects in controlled environment evaluated the accuracy, authentication time, permanence, and vulnerability.

On the other hand, respiratory activities provide another means for identity authentication [55]–[57], as shown in

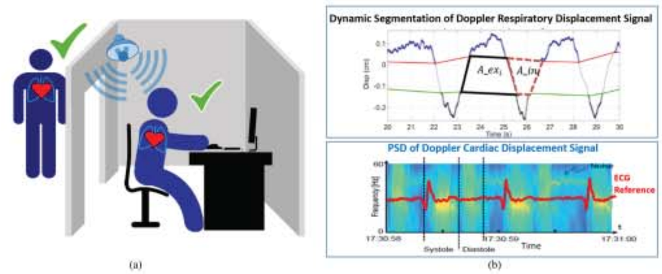


FIGURE 4. Radar authentication concept (a) and examples of respiratory dynamics pattern classifier and cardiac signal power spectral density (PSD) used for subject recognition (b). Modified based on [59].

Fig. 4. In [58], the feasibility of extracting identifying features from radar respiratory traces was tested for sedentary subject conditions and just after activities such as walking upstairs. Respiratory breathing dynamics related features extracted from radar captured signals include breathing rate, spectral entropy, breathing depth, inhale/exhale area ratio, mean and standard deviation of the peaks. Variations in feature parameters after physiological activities were assessed. Experiments demonstrated the uniqueness of residual heart volume after expiration for recognizing each subject even after short exertions. A Support Vector Machine (SVM) with a radial basis function kernel achieved high identification success rate for both sedentary-only conditions and a combined mixture of conditions (i.e., sedentary and after short exertion).

A review of radar-based identity authentication systems can be found in [59]. It evaluates the applicability of different research efforts and identifies aspects of future research required to address remaining challenges for practical deployment. It is expected that the advancement of machine learning and artificial intelligence will enable radar-based continuous authentication to serve a wide range of valuable functions in society [60].

B. BEHAVIOR/GESTURE RECOGNITION FOR SMART LIVING AND FUTURE OF WORK

Radar signatures such as micro-Doppler has been studied for human activity classification [61]. In the past decade, radar-based hand gesture recognition became attractive for wireless human-machine interfaces. Aided with advanced semiconductor technology and high computational power of mobile devices, industry is pushing for the use of such an interface for devices such as smart phones [10] and computers [62].

In [63], hand gesture recognition using a convolutional neural network was applied to radar echo *I*/*Q* plot trajectories. The radar echo trajectories were converted to low-resolution images for training and evaluation. Experiments demonstrated accurate recognition of six types of hand gestures for ten participants. In [62], a dual-channel Doppler radar aided with symmetric subcarrier modulation, bandpass sampling, arcsine demodulation, and a motion imaging algorithm was developed

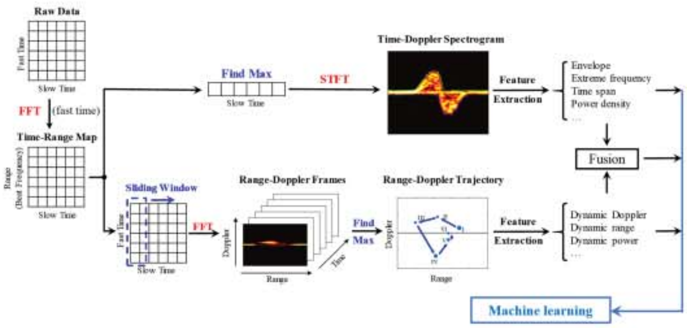


FIGURE 5. Flow chart of various feature extraction and fusion for classification of FMCW radar signals in inattentive driving behavior detection. Modified based on [67].

to reconstruct the hand and finger motions in a 2-D plane. A challenge is gesture recognition in the presence of random body movements. To tackle this issue, [64] adopted a single-input multiple-output frontend and a blind motion separation algorithm. Assisted by an additional receiving channel, Doppler signals caused by different motions can be separated by extending an algorithm originally developed for voice separation. Taking advantage of FMCW radar's range resolution, a range-gating technique can be adopted to extract gesture of interest and suppress interferences at other distances [65]. For signal processing, methods such as a barcode-based approach was also proposed [66], which classifies gestures based on barcodes generated from time-domain zero-crossing characteristics of the quadrature demodulated signal.

The hardware and signal classification methods can be applied to other fields such as human gait detection, behavioral identification, and anomaly detection. For example, 5.8-GHz and 24-GHz FMCW radar devices have been tested for inattentive driving behavior detection [67]. Based on the flow chart of Fig. 5, features of seven typical driving behaviors that result in reduced attentiveness were extracted from time-Doppler, range-Doppler, and radar cross-section (RCS). The influences of radar center frequency, individual diversity, and radar view angle are also investigated. With the help of an artificial neural network, another study demonstrated remote identification of a potential active shooter with a concealed rifle/shotgun based on radar micro-Doppler and range-Doppler signatures [68].

C. HUMAN LOCALIZATION AND OCCUPANCY SENSING

Occupancy information and user location have significant impact on building automation and energy management. Properly deployed occupancy sensors can effectively save energy used for lighting and heating, ventilation, air conditioning (HVAC) systems. However, major drawbacks of mainstream passive infrared (PIR) and ultrasonic sensors include high rates of false alarms and failure to detect stationary human subjects. Radar sensors can detect the presence of stationary human subjects with high sensitivity. Aided with Doppler processing, direction-of-arrival detection, and spatial beamforming, they can track humans even in through-the-wall scenarios [69]–[71]. CW Doppler radar monitoring systems can estimate occupant count based on the received signal strength (RSS) indicator, which is directly related to radar cross section [72]. Based on different time domain root mean square (RMS) values, the effects of motion on the noise floor of a room can be leveraged as a measure to discern an occupied room vs. an unoccupied one [73]. To track the locations of human subjects, FMCW radar can be leveraged for range detection while MIMO and beamforming can be used to obtain angular information [30].

An overview of occupancy sensor technology illustrated that the detection of human cardiopulmonary motion with CW radar could provide a promising approach to overcome the problems of false negatives and dead spots in conventional sensors [74]. Furthermore, true presence can be detected by discerning motions associated with vital signs activities from nonhuman motion that could otherwise trigger false positives. For commercial success of radar occupancy sensors, low-power and low-cost will be a focus of future R&D efforts.

D. BLOOD/PULSE PRESSURE MONITORING

Measuring the beat-to-beat blood pressure is valuable for cardiovascular diseases prevention. Unfortunately, traditional sphygmomanometry with a cuff is unable to measure the beat-to-beat blood pressure and extract the variability. Microwave radar has the potential to continuously measure pulse wave and blood pressure because of its sensitivity to small cardiac movements [75], [76]. A beat-to-beat blood pressure measurement method was proposed based on pulse transit time (PTT), which is the time of a pulse wave traveling between two arterial cites [77]. However, the system needs simultaneous measurement of electrical bioimpedance, electrocardiogram, and CW radar, which is not suitable for long-term monitoring. A similar approach was reported based on PTT determined from a radar for non-contact detection of heart beat and a piezoelectric finger pulse sensor [78]. To overcome the limitation of requiring multiple sensors, completely non-contact beat-to-beat blood pressure measurement was demonstrated using a single low-IF Doppler radar [79]. Upon acquiring the tiny displacement on body surface induced by the central aortic artery, the carotid-femoral PTT (cf-PTT) was extracted from the central aortic pulse wave [80]. This enables the measurement of both beat-to-beat systolic and diastolic blood pressures.

The above microwave radar-based approaches usually require remote line-of-sight alignment to the chest area by an off-body reader. An alternative microwave sensing approach was near-field coherent sensing, which can retrieve the heart sound through layers of clothing using ultrahigh frequency (UHF) band (300MHz – 3 GHz) signals [81]. This enables multi-point near-field assessment of motion and pressure at different parts of the heart [82]. Furthermore, the Hilbert-Huang frequency-time transform can be used to derive the

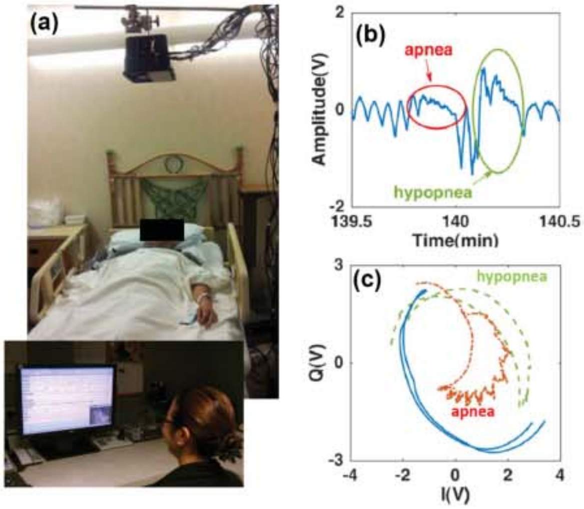


FIGURE 6. Photograph from sleep apnea detection clinical study (a) and corresponding examples of radar amplitude-time signatures for apnea and hypopnea events measured at 2.4 GHz (b) and I-Q trace signatures measured at 24 GHz. Modified based on [85].

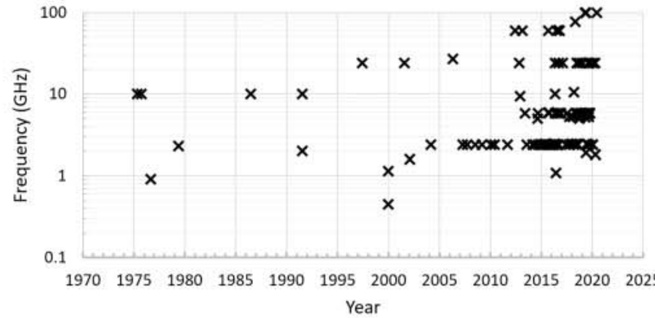


FIGURE 7. Frequencies of references cited in this article vs. their publication date.

central blood pressure from the vascular vibration characteristics as continuous transients.

E. SLEEP MEDICINE RESEARCH

Sleep quality is an important health indicator. The "gold standard" for sleep monitoring is polysomnography (PSG), which is available in specialized labs and confines the subject's activities with complex electrodes. Existing in-home sleep monitoring devices either fail to provide adequate information or are obtrusive to use. Radar sleep monitoring has the potential to guarantee natural conditions during sleep. A radar-based system with a sleep status recognition framework was tested for recognition of the sleep status, including on-bed movement, bed exit, and breathing section [83].

Sleep stage estimation is crucial to the evaluation of sleep quality and is a proven biometric in diagnosing cardiovascular diseases. A CW radar was used in [84] to measure sleep-related signals, including respiration, heartbeat, and body movement. Body movement index, respiration per minute (RPM), variance of RPM, amplitude difference accumulation (ADA) of respiration and heartbeat, rapid eye movement parameter, sample entropy, heartbeat per minute (HPM), variance of HPM, and time feature have been extracted and fed into machine learning classifiers. Eleven all-night polysomnography recordings from 13 healthy examinees were used to validate the system's ability to detect sleep stage.

Another system was studied in [85] for wireless sleep apnea detection, as shown in Fig. 6. It consists of two radar front-ends at 2.45 GHz and 24 GHz, respectively, to achieve both high sensitivity and high resolution. An algorithm was designed to perform real-time actigraphy and sleep apnea detection in two steps – first excluding unwanted body motion, then detection of apnea by the power of signal. The system was validated with clinical PSG in a sleep study facility on ten consented volunteers with known obstructive sleep apnea. Data obtained from both the radar monitoring and clinical PSG systems were rated by a sleep technician and show an excellent agreement in the detected apnea and hypopnea events. The apnea-hypopnea events were distinguished with an overall sensitivity of 86%, the specificity of 91% and accuracy of 92%.

For comprehensive reviews of microwave sensing of sleep interested readers are referred to [86] and [87].

IV. PLANNING OF MICROWAVE FREQUENCIES

Following the first demonstration of life-sign detection using 10-GHz microwave signals in 1975 [88], [89], researchers have been using different frequencies from UHF to mm-wave. In the beginning, particularly in academic research environment, the choice of frequency often depends on the available equipment and components, but it could also be driven by applications. In the first 25 years (1975–2000), 10 GHz (X-band) was more frequently used than other frequencies [88]–[96], but for searching life signs under concrete or bricks, lower frequency bands (UHF, L- and S-bands) which can penetrate deeper would be better choices [97]. Partly because of FCC regulations, ISM bands defined by FCC Part 18 naturally became the choices for this research field even though the transmission power could be low enough to meet FCC Part 15 requirements to operate as unlicensed devices at permitted bands other than ISM bands. Another main reason that ISM bands became popularly used is because of vastly available components with low cost in modern wireless era. Fig. 7 plots the frequencies of references cited in this article vs. their publication date. It can be seen that 2.4 GHz, 5.8 GHz, and 24 GHz ISM bands became popular choices in the recent decade (2010-2020). In addition, enabled by the same device technologies driving 5G wireless communications and automobile radar, compact integrated radar sensor chips operating in mm-wave bands such as 60 GHz [7], [10], [98], 77 GHz [65], and even above 100 GHz [18], [19] were developed for sensing life activities. As wireless systems and networks continue rapid growth, spectrum sharing and co-existence among wireless systems become an important issue and researchers working on life activity radar sensors also need to pay attention to future development of spectrum allocations.

A. FREQUENCY RANGES FOR DIFFERENT APPLICATIONS

If not limited by availability of components and technologies, the main driving factor of selecting carrier frequency is the sensitivity needed for the intended application. On the one hand, higher frequencies are desirable for higher sensitivity, smaller device size, and potentially larger available bandwidth. On the other hand, as the carrier frequency increases, the nonlinear effect to the radar detected spectrum will be more pronounced and harmonics of respiration signal component may interfere with heartbeat detection [99]. To address this issue, special care should be taken and techniques such as those can cancel respiration harmonics [100]–[102] should be used for vital signs radar sensors operating at frequencies in millimeter-wave region. While mm-wave frequencies might not be suitable for human vital sign sensing because the short wavelength is too sensitive to relatively large displacements, mm-wave vital sign radar sensors can easily detect vital signs of small animals [103], [104] or detect fine features of hand gestures [10]. Some radar sensor systems also used multiple frequencies to enhance the performance (e.g., [85]). As multiple carrier frequencies are used for sensing, similar to solving multiple unknows with multiple equations, additional information can be extracted to improve sensing performance.

B. SPECTRUM SHARING AND SPECTRUM REGULATION

Biomedical radar sensors enable new applications that promise significant societal and economic benefits. But at the same time, many mission-critical government and civilian wireless services including emergency response, navigation, radio astronomy observatories, geoscience remote sensing, and weather radar systems need to operate in quiet EM environments without interference from other wireless systems. While a low-power CW radar used for vital sign sensing is very narrow band and might not cause harmful interference to other systems, in certain scenarios requiring high range resolutions (e.g., sensing multiple human subjects) or multiple frequency bands, the demands on the spectrum may threaten the operations of existing technologies that offer critical service to society. Innovation in spectrum use and management may provide a means to ensure that the spectrum resources are utilized in a manner that benefits all applications, both current and emergent, including those operating at higher frequencies, such as mm-wave and THz.

As more wireless systems and devices are deployed and the wireless spectrums become more congested, spectrum sharing and management become inevitable, and this will eventually affect all wireless devices transmitting RF signals. While FCC and relevant government agencies might release or share more spectrums, the demand of wireless spectrum will continue, and more research is needed to ensure harmonious co-existence of various wireless systems. US National Science Foundation (NSF), for example, started a new program Spectrum and Wireless Innovation enabled by Future Technologies (SWIFT) [105] under the NSF Spectrum Innovation Initiative [106] to support research addressing challenges of effective spectrum utilization and spectrum sharing among various wireless systems. In this program, radars for motion sensing is mentioned along with other emerging applications such as 5G wireless. While researchers working on life-activity sensing radar may explore various frequency bands, certain bands may require a license to operate and researchers should check spectrum management organizations before experiments.

Significant advances in detection theory, networking, and protocol are needed to allow effective coordination and maximum utilization of the spectrum. New approaches could be considered within an AI framework to ensure effective spectrum sharing and coordination. Especially, leveraging existing infrastructure for passive uses, such as sensing of human behaviors and physiological signals from ambient wireless signals/devices as discussed in Section II-C, is a promising direction being pursued by many researchers. Using Wi-Fi or other signals from existing wireless systems for life-activity sensing avoids the need of spectrum sharing, however, the operating frequency and performance could be limited by the wireless standards' frequency bands.

V. CHALLENGES FOR UBIQUITOUS DEPLOYMENT AND FUTURE RESEARCH DIRECTIONS

Although many advancements have been made, there remains several key challenges to be resolved for ubiquitous deployment of microwave human sensing.

A. MOTION SEPARATION AND CLASSIFICATION IN DYNAMIC ENVIRONMENT

Random motions of both the human subject and the radar platform are one of the biggest challenges toward reliable extraction of physiological signals. Noise induced by random motions may not only corrupt the desired physiological signal, but also saturate the sensing front-end. Therefore, researchers have been developing innovative methods to separate undesired motions.

A high-dynamic-range radar can be aided with algorithms such as matched filters to retrieve signals concealed by body motion noise [107]. The characteristic of the frequency spectrum of the vital sign signal under body motion can be leveraged. In [108], the direction of body motion is extracted along with the new position of the respiration peaks in the frequency spectrum and respiration rate was calculated. When no prior knowledge of the body motion waveform is available, a low-IF SIMO system employed a two-step blind motion separation to sequentially tackles signal separation and nonlinear demodulation [109]. Experiments were able to separate combinations of triangular, sinusoidal, and random motions when the velocities or initial phases of such motions are different.

Unmanned aerial vehicle platforms are ideal for remote sensing in military, humanitarian, and post-disaster search and rescue operations. However, the vibration and motion of the platform need to be addressed. In [110], respiration signal was recovered by measuring the platform motion with a secondary radar and removing the motion induced phase modulation from the primary radar signal that contains both the desired vital signs signal and the platform motion. A 26-dB improvement in signal-to-motion interference ratio was measured on an airborne quadcopter. In [111], the vital signs signal fidelity was improved using RSS indicator and Direction of Arrival (DOA) to compensate for the platform motion via a closed loop control system that modulates the UAV electronic speed controller. In addition, an optical tracking system [112] or an RF tag [113] can be used to achieve adaptive platform motion noise cancellation.

Instead of compensating for platform motion, SAR leverages platform motion to sample the target at different locations and synthesize an image. The portable size of modern radar sensors makes it ideal to be mounted on small UAVs and robots. This is especially useful as the radar can also differentiate humans from clutters based on physiological signal patterns. For example, a precise phase-based human target 2-D SAR imaging and recognition system based on vital sign tracking was demonstrated [114]. It first relies on FMCW phase detection to extract the vital signs of multiple human targets, then applies a SAR algorithm to obtain the 2-D imaging of the scene and labels human targets.

Despite the progresses made, more innovative solutions, likely with the help of AI techniques, are desirable to enhance the robustness of radar sensors, especially in the presence of large-scale random motions.

B. CROWD DETECTION AND SIGNAL-OF-INTEREST EXTRACTION

Effectively extract signal-of-interest from a multi-user or crowded environment has been challenging. Many reported systems have so far been constrained on subject separation based on radar range resolution and antenna beamwidth. Recent works tried to overcome such a limit. An SNR-based intelligent decision algorithm integrated two different approaches to isolate respiratory signatures of two subjects within the radar beamwidth [115]: Independent Component Analysis with the JADE algorithm (ICA-JADE) [116] and DOA [117], as shown in Fig. 8. They also estimated angular location with phase-comparison monopulse and extracted respiratory information with an integrated beam switching mechanism.

Continued efforts are expected on both physical layer and baseband signal processing, to detect signals from more human subjects. In the meantime, it is worthwhile to investigate integration of the system and algorithm in portable devices with reasonable size, speed, and power consumption.

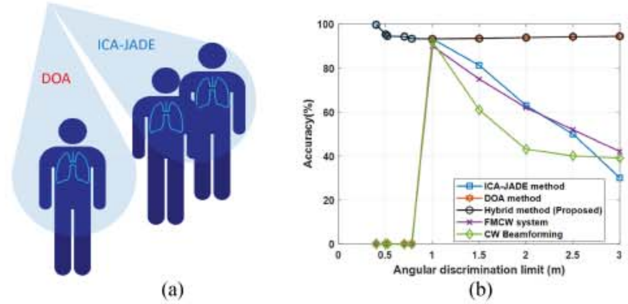


FIGURE 8. Concept for hybrid-based separation of subjects (a) and performance illustrating the proposed method maintained separation accuracy above 93% for separations both less than and greater than 1 m (b). Modified based on [117].

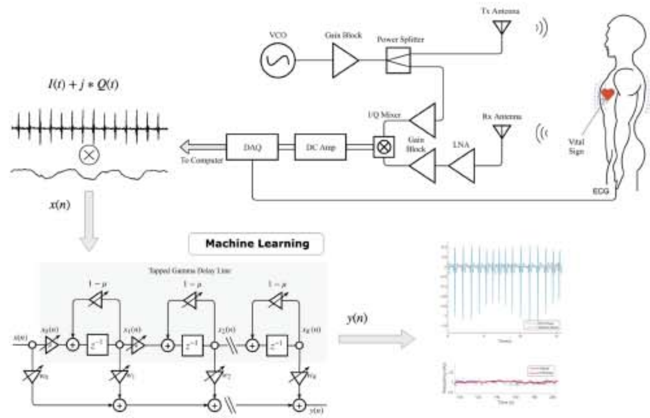


FIGURE 9. Signal processing chain for time series heartbeat reconstruction with the help of a supervised machine learning algorithm in [118].

C. INTERACTION OF MICROWAVE TECHNOLOGY AND ARTIFICIAL INTELLIGENCE

Recent years have witnessed rapid progress of integrating AI and advanced signal processing techniques to expand the capabilities of microwave radar systems. To overcome the nonlinearities and harmonics that pollute the radar detected spectrum, a supervised machine learning algorithm, the gamma filter, was used to model the time series heartbeat signal under the influence of respiration and respiration harmonics, which enables extraction of heartbeat from respiration in real time [118]. Its signal processing chain for time series heartbeat reconstruction is shown in Fig. 9. In a multi-domain fusion approach, a dynamic range-Doppler trajectory method for FMCW radar was developed to extract range, Doppler, RCS, and dispersion features as inputs to a machine learning classifier for continuous human motions recognition [119]. To achieve both fast detection and high accuracy, a time-window-variation technique [120] and a wavelet-transform-based data-length-variation technique [121] were developed.

It is expected that more advanced AI techniques with targeting specific application scenarios will be investigated. For example, for radar-based anomaly detection (e.g., fall detection, cardiac failure detection), few-shot learning could be valuable in handling such extreme situations, where the number of instances belonging to a minority class is very limited. In many biomedical radar applications such as smart living and elderly care, the number of anomaly events is significantly smaller than that of non-anomaly events, some anomaly event may hardly occur during the training stage, while the system must be responsive to multiple emergency. Therefore, multi-anomaly detection algorithms, including imbalanced learning, rare anomaly detection, and unseen anomaly detection, could be important areas of research and development.

VI. CONCLUSION AND FUTURE OUTLOOK

It is evident that microwave sensing of life activities is bringing profound benefits to modern society. Its broad impacts range from healthcare, energy efficiency to military and defense. The authors wish this review could not only serve as a resource for both researchers and practitioners to understand the state-of-the-art, but also attract experts in various areas to collaborate and devote their expertise to solve the potential challenges and push forward the technology for promising applications.

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