Overview of Recent Development on Wireless Sensing Circuits and Systems for Healthcare and Biomedical Applications

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***Abstract*—This paper provides a comprehensive overview of the recent advances in the field of wireless contactless sensing circuits and systems for healthcare and biomedical applications. In particular, special emphasis is made on wireless implantable devices, radar-based techniques to detect human motions, such as vital signs or gestures, wireless neural interfacing and prosthesis, and the characterization of biological materials by means of imaging approaches as well as the determination of their electrical properties. It is believed that this overview can serve as a starting point to the biomedical wireless-sensing topic and could encourage researchers and practitioners to continue works in the exciting area of wireless technologies with application to healthcare and biomedical contexts.**

***Index Terms*—Non-contact characterization, contactless, non-contact sensing, implantable devices, radiofrequency interaction, wireless neural interface.**

I. Introduction

BECAUSE of the rapid advancement of radio-frequency, infrared, and optical technologies, many wireless-sensing approaches have emerged and enabled novel biomedical applications, such as diagnosis of diseases, telemedicine, implantable medical devices, characterization of biological materials, wireless neural prostheses, and remote-human-motion classification. Some of these applications entered human daily life shortly after their invention, significantly improving the productivity and life quality in our society. With solutions ranging from sensor-on-chip to bench top implementations, the driving forces behind these revolutions are largely based on circuits and systems tools, micro and nanofabrication processes, semiconductor technologies, and embedded systems.

The rapid engineering and technical developments in wireless technologies and techniques have drawn enormous interests from researchers and professionals from private organizations, academic institutions, and industrial research centers working in the area of circuits and systems for non-contact wireless sensing and control related to healthcare and biomedical applications, such as those around veterinary, human subjects, and biological materials and tissues.

For example, one interesting application of wireless technologies to healthcare and biomedical scenarios is the non-contact powering of devices implantable in tissues and/or organs. These devices may be actuators that take some actions on the surrounding tissues (e.g., electrical stimulation, drug delivery, application of local heat, and so on) or sensors that test the surrounding environment and communicate the measurements to the outside. The wireless technologies employed to transfer power to implantable devices or to communicate data for telemetry or control purposes are manifold, ranging from ultrasonic to radio-frequency and millimeter-wave technologies. An example that is reviewed in this manuscript is the use of wireless technologies as support for neural interfacing and prosthesis. In particular, big efforts are currently dedicated to wireless technologies that can efficiently—and at a low cost—transfer raw neural data.

In relation to the application of radar systems to healthcare and biomedical scenarios, this manuscript reviews important works on the fundamental theory of continuous-wave (CW) biomedical radar systems, including phase-based coherent interferometry radars, frequency-modulated continuous-wave (FMCW) prototypes, and hybrid-mode remote-sensing systems. In addition, specific fields of investigation are reviewed, such as: i) those related to the non-contact wireless monitoring and/or detection of vital signs (e.g., respiration and heartbeats) for applications in hospitals, in life detection after avalanches or earthquakes, and in sleep monitoring for patients and babies; ii) research areas to localize humans in indoor and outdoor applications and two-dimensional (2D) environment mapping;

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iii) investigations around coherent radar schemes and architectures that enable the exploitation of range-Doppler maps for robust tracking of motions with mitigation of surrounding clutters (i.e., unwanted echoes); and iv) the monitoring and tracking of hands to classify different gestures for human-machine interaction and gaming. The survey of radar-based applications is centered on short-range RF/microwave radar sensing systems that feature cost-effectiveness and portability characteristics.

As an important tool for healthcare and biomedical applications, wireless technologies are also employed to characterize biological materials. The importance of this research subject rests in the fact that this diagnosis of biological tissues is going to be connected with the therapy. This paper reviews the two main approaches to biological materials characterization, i.e., imaging techniques and electrical properties measurement. In relation to the former, non-ionizing magnetic resonance imaging (MRI) based on detectable radio-frequency signals generated by atoms excited by strong magnetic fields and near infrared spectroscopy (NIRS) based on the electro-optical near infrared spectrum are to be emphasized. Regarding the latter, several solutions are approached for the determination of the electrical conductivity and the dielectric permittivity of the analyzed tissue. Variations in these parameters are important and can be used to determine the physiological and/or pathological state of the tissues.

This overview manuscript aims to probe into a few selected topics for the readers, rather than to discuss each related topic that would otherwise leave no room for details. The rest of the manuscript is organized as follows. Section II reviews the use of wireless technologies for the powering and communication of wireless implantable devices. The employment of RF/microwave radar systems and techniques to detect and monitor vital signs, to localize human motions indoors and outdoors, to track targets in the two-dimensional range-Doppler domain, to detect unfortunate falls, and to detect small gestures of hands are reviewed in Section III. An overview of methods for wireless neural interfacing and prosthesis is provided in Section IV. Imaging solutions and the determination of electrical properties for the characterization of biological materials are reviewed in detail in Section V. Finally, the main conclusions of this work are set up in Section VI.

II. Wireless Implantable Devices

Wireless technologies serve as a key component for data communication and energy transfer of many implantable biomedical devices. From ultrasonic to millimeter-wave, they cover a large spectrum and provide a variety of ways to link an implantable device with the external world.

A. Ultrasonic Data and Powering

Different wireless powering techniques are compared in Fig. 1 [1]. Ultrasonic can deliver high power with a smaller implant size than the inductive coupling devices [2]. Also, ultrasonic transducer can obtain a high power efficiency, and is immune to electromagnetic radiation from other devices [3]. A longer ultrasonic wavelength can penetrate to a deeper tissue, while a short wavelength can focus on the desired area. Moreover, data can be transmitted to the implanted medical device (IMD) via ultrasonic although its data rate is relatively low. An ultrasonic power transfer with a hybrid bi-directional data communication link as shown in Fig. 2 was presented in [1]. The downlink is a piezoelectric receiver (RX), and thus the low data rate control and clock signals can be transmitted to the IMD. The uplink can transmit ultra-wideband (UWB) pulses for an energy-efficient transmitter (TX) with ~Mbps data rate. Based on [1], ultrasonic is used for both downlink and uplink. To avoid the interference and harmonic problem between the downlink and uplink, 1 and 2.6 MHz are chosen for the carrier frequency, respectively [4]. Although its uplink data rate is much lower due to the limited bandwidth of the ultrasonic. The full-packaged IMD in [4] is 2.5× smaller than [1], and has a 2× deeper transmission range.

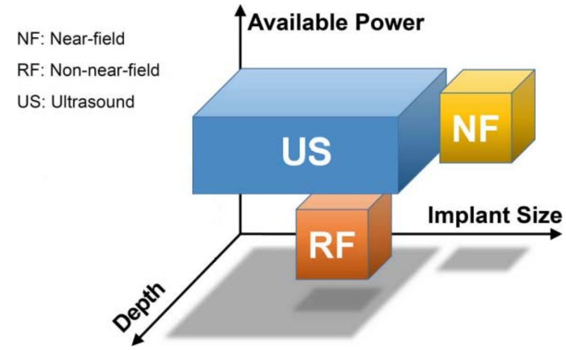

Fig. 1. Conceptual diagram comparing the different wireless powering techniques [1].

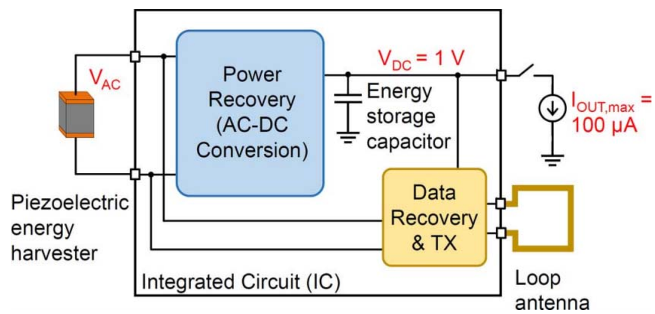

Fig. 2. Block diagram of an ultrasonic powering IMD [1].

B. Millimeter-Wave Data and Powering

Thanks to the advance of phase-array techniques, millimeter- wave powering has been demonstrated as a promising solution for tiny wireless sensor nodes. The conceptual tradeoff for electromagnetic power transfer between the harvesting efficiency and received power is shown in Fig. 3 [5]. Millimeter-wave energy harvesting can achieve a higher received power level by beamforming than that at lower frequencies with a similar-sized phased array [6]. However, it is challenging to achieve a high power recovery efficiency at millimeter-wave frequency. It is arguable whether the optimal frequency is at millimeter-wave or RF frequencies. A millimeter-wave tag operated at 46 GHz [7] with 2 dBm

TABLE I
PERFORMANCE SUMMARY AND COMPARISON FOR DIFFERENT POWERING METHODS

	Powering method	Range (cm)	Frequency (GHz)		Data Rate (bps)		Process
			Downlink	Uplink	Downlink	Uplink	
[1]	Ultrasonic	3 (animal tissue)	0.001	4	N/A	N/A	65nm CMOS
[4]	Ultrasonic	6 (animal tissue)	~0.001	~0.0026	25k	100k	65nm CMOS
[5]	mm-Wave	50	24	60	6.5M	12M	65nm CMOS
[6]	mm-Wave	Estimated 1.9	71	79	N/A	5-50k	65nm CMOS
[10]	RF-powered	N/A	0.902-0.928	2.405-2.475	5M	5M	90nm CMOS
[13]	RF-powered	N/A	1.86	1.74	2.5M	58M	40nm CMOS

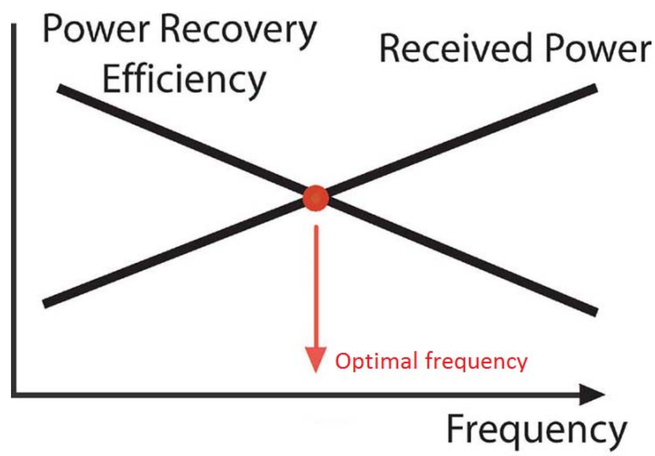

Fig. 3. Conceptual tradeoff between power recovery efficiency and available received power versus frequency [5].

input power only achieved 1.2% efficiency. Yet, [6] and [8] performed on-chip RF power harvesting at 71 and 62 GHz with 8% and 7% rectifier efficiencies, respectively. Reference [5] is a fully self-sufficient mm-wave radio that requires no pads or external components. The downlink and uplink exploit 24 and 60 GHz frequency to allow multiple-access communications. The standby power was 1.5 μW while delivering a 12-Mbps aggregate data rate across a 50-cm range. The chip size is only 3.7×1.2 mm^2, due to no required pads.

C. RF Powering

RF powering takes the advantages of mature integration and reliability of CMOS technologies. Low frequency can deliver more power with deeper penetrating ability in tissue, while the antenna size for sub-GHz power harvesting can be very large [9], [10]. The wireless transponder in [11] demonstrates a transmission efficiency as low as 330 fJ/bit, while the inner diameter of the off-chip transformer is 15 mm for the 535-MHz carrier frequency. Using low-gigahertz frequencies [12] can balance the receiving coil area at a reasonable deep penetration. A wireless transceiver for neural implants was presented in [13]. The RX and TX operate at separate carrier frequencies to allow the frequency full-duplex operation given that the duplexer offers over 50 dB band-to-band isolation. It can achieve a high data rate (2.5 and 58 Mbps for downlink and uplink, respectively) and thus a high energy efficiency for both uplink and downlink thanks to the wide signal bandwidth at low gigahertz frequencies. A fully integrated 2×2 60 GHz CMOS transceiver harvests energy at 2.45 GHz [14]. The output power and data rate can be reconfigured to suit different transmission ranges and applications. Table I summarizes and compares the key metrics of different powering methods from the prior art.

III. RADIOFREQUENCY NON-CONTACT HUMAN MONITORING

This section will be focused on RF circuits and systems for non-contact monitoring of human vital signs, location, and gestures. One of the most common ways for RF monitoring of human subjects is based on low-power radars, which sends out an RF signal toward the subject and captures the return signal that is reflected by the subject. Physiological motion (e.g., respiration and heartbeat), location, and gesture information can be obtained by comparing the transmitted and received signals.

A. Human Vital Signs Detection

Human vital signs in the form of physiological motions can be identified by analyzing the interaction between radiofrequency signals and physiological motions, without requiring any sensor to be attached to the body. For example, interferometry-mode radars compare the phase of the transmitted and the received signals. The dynamic phase change due to physiological movements can thus be detected with a simple coherent RF architecture. This leads to a large variety of potential applications including sleep study [15]–[17], baby monitors [18], [19], and searching for survivors after disasters. While the noncontact vital signs detection concept was proposed by pioneers in this field a few decades ago [20]–[24], recent advancement in semiconductor technology and embedded computation are trying to enable the technology for practical use (e.g., in home and clinical environment) with portable operation, higher accuracy, and more reliable operation. In recent years, other approaches to radiofrequency non-contact vital signs detection have also been developed. For example, [25] used a time-reversal system to estimate breathing rate within a short period of time using off-the-shelf WiFi devices. The system exploits the channel state information to capture the miniature variations in the environment caused by breathing.

Recent studies have also demonstrated that the interferometry radar could even assist medical linear accelerator to track a mobile tumor during cancer radiotherapy, and thus eliminate the side effect due to tumor motion caused by respiratory movement [26]–[28]. Instead of measuring the target movement frequency, this application requires accurate measurement of the movement pattern, which is critical for the radiotherapy dose to be effectively delivered to tumor. Since a respiratory signal has low-frequency and DC components (e.g., the stationary moment after exhalation), an AC-coupled architecture with a capacitor between the mixer and baseband amplifier will distort the signal. Simply connecting the mixer output and baseband amplifier would not work because the baseband circuit will be saturated due to the DC offset produced by down-conversion of clutter reflection and TX-to-RX leakage. To resolve the problem, a DC-coupled radar with dynamic tuning solution was developed based on a coarse tuning that cancels clutter reflection at the receiver input and a fine tuning that further adjusts the DC bias point of the baseband circuit [26].

However, the tradeoff found in a DC-coupled radar with dynamic tuning is the necessity of monitoring the baseband output DC level and performing tuning in real time, which increases the operation cost. An alternative based on a post-distortion algorithm was developed to compensate for the frequency-dependent distortion in the baseband output of an AC-coupled radar [29].

B. Human Localization and 2-D Environment Mapping

Localization of human subjects and mapping of environment are another important area of RF non-contact sensing. Typically, a signal with a bandwidth need to be sent and received to obtain the key information of target range. To that end, frequency-modulated continuous-wave (FMCW) and ultra-wideband (UWB) architectures are frequently adopted. By steering the signal beam either mechanically or electronically, an RF sensor can map a 2-D indoor environment.

Furthermore, since interferometry mode offers very high motion detection sensitivity (i.e., millimeter or sub-millimeter motion sensitivity with GHz carrier signals) at a low computational load, a hybrid mode that integrates both FMCW and interferometry operation was proposed to not only map the environment, but also differentiate humans from other objects based on a human subject's physiological motions. Based on this, [30] demonstrated a portable system for 2-D human-aware indoor mapping. The system operates in a "burst-FMCW" fashion, which, for most of the time, uses a single-tone signal to track physiological motion for human identification. When large displacements of human subjects are detected, it sends out short individual FMCW bursts to update the range information, achieving "human-aware" localization. Similar method was also implemented on a K-band beamforming radar shown in Fig. 4 [31]. The beamforming radar uses an array of RF vector controller on printed circuit board (PCB) to achieve dynamic control of both the amplitude and phase of each RF channel around 24-GHz. Fig. 4 (c) illustrates an example of the synthesized radiation pattern steered to $-45°$, $-30°$, $-15°$, $0°$, $15°$, $30°$ and $45°$ at 23.75 GHz. The radar was used for simultaneous mapping of objects including a car, a lamp post, and a human subject as shown in Fig. 5 (a).

(a)
(b)
(c)

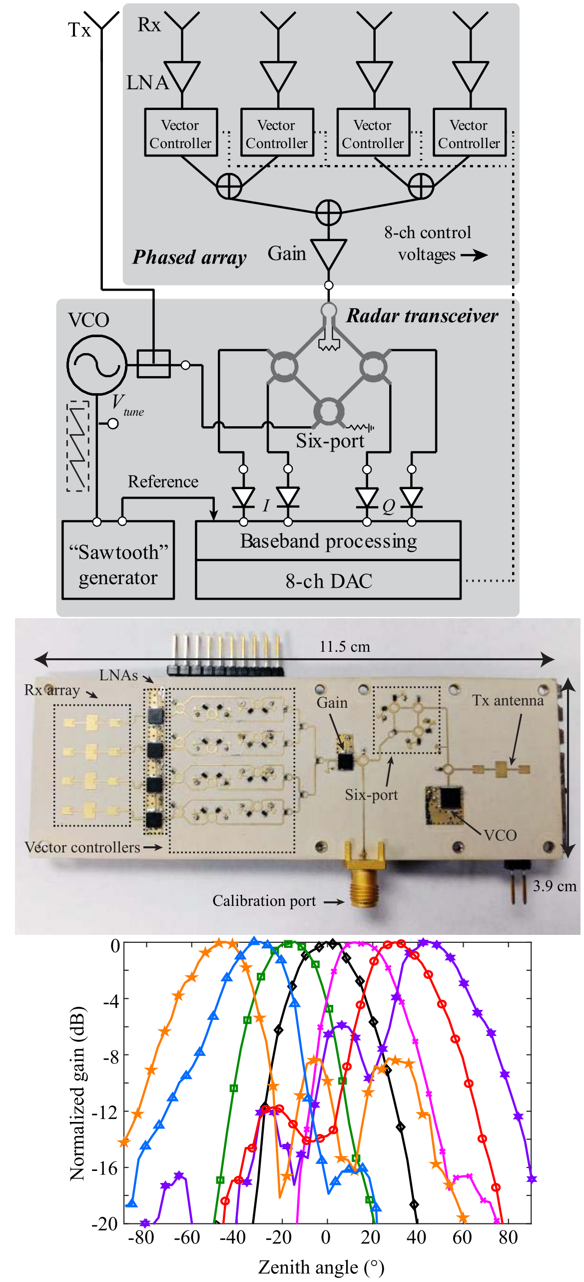

Fig. 4. (a) Block diagram of a K-band beamforming radar for "human-aware" 2-D environment mapping. (b) Top layer of the beamforming radar prototype. (c) Measured patterns of the beamforming array steered to different angles at 23.75 GHz with phase and amplitude beamforming. From [31].

Taking advantage of electronic beamforming, it was able to map the environment within a 90° region in front of the radar, which is shown in Fig. 5 (b). Due to the 0.3-m range resolution limit of the 500-MHz RF signal bandwidth and the wide beamwidth, the mapping resolution was not as high as optical mapping technologies. However, since the incorporated RF sensing mechanism can easily pick up millimeter-scale human physiological motion, the portable system can identify the location of the human subject based on his physiological signal pattern even when the car engine was turned on. Fig. 5 (c) shows the extracted human target by analyzing the standard deviation of sequential scans from the 2-D mapping

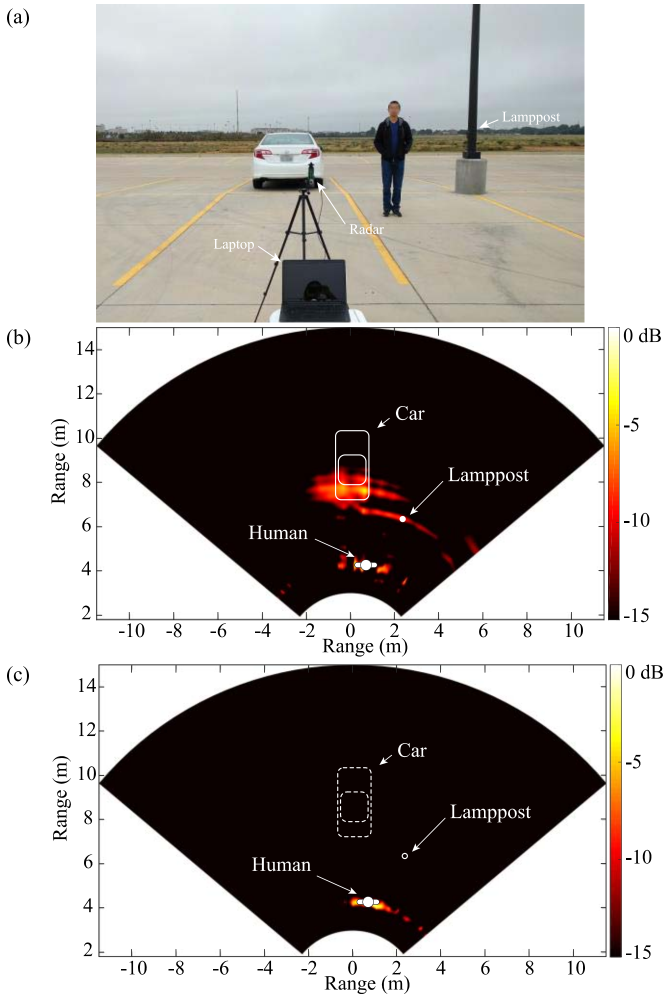

Fig. 5. (a) Short-range localization with a human subject and two objects using the K-band beamforming radar. (b) 2-D mapping results. (c) Human target extracted with standard deviation of sequential scans from the 2-D mapping results. From [31].

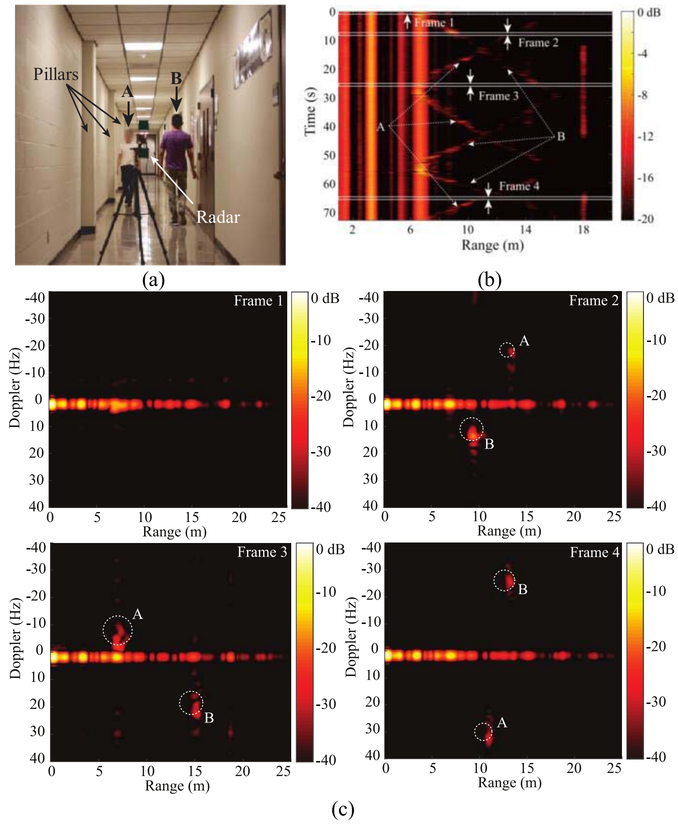

Fig. 6. (a) Experimental setup for Range-Doppler tracking of two human subjects. (b) Range-profile matrix. (c) Range-Doppler frames at different moments. From [35].

results [31]. Although the experiment in Fig. 5 was performed in outdoor environment, the beamforming technology to quickly scan a space and localize human subjects is valuable for many indoor healthcare applications such as senior care, patient rehabilitation, and fall detection.

C. Range-Doppler Tracking and Fall Detection

Range-Doppler imaging is a useful technique for target identification and tracking [32]–[34]. Traditionally, the principle of simultaneously analyzing Doppler- and range- histories of a target were used mainly for tracking of large targets such as ships and airplanes. The mechanism, however, can be easily adopted to tracking of human subjects. A coherent FMCW radar note only detects range history, but also the Doppler information by performing Fourier transform to the range history along the slow-time, resulting in a series of range-Doppler history.

Figure 6 presents an example of a 5.8-GHz portable radar detecting two human subjects who walked back and forth in opposite directions in a narrow corridor [35]. The radar-detected range-profile in a 73-second interval is shown in Fig. 6(b). Many strong vertical strips, which correspond to nearby stationary clutters, can be observed. Although the traces of the two moving human subjects are noticeable as indicated by A and B, they are much weaker than the clutter returns. Fig. 6(c) plots four frames of the real-time range-Doppler video. Frame 1 shows the beginning of the experiment, when both subjects were standing stationary. Frame 2 corresponds to the 7-second moment of the acquisition time, when subject A was walking towards the radar, while subject B was walking away from the radar. Frame 3 corresponds to the 26-second instant, when subject A was close to the radar and about to turn around with a near-zero velocity, while subject B was still walking away from the radar system. Frame 4 at the 64-second moment shows subject A walking back to the radar and subject B walking away from the radar. It should be noted that all the stationary clutter returns in a complex indoor environment are compressed into the zero-Doppler line in range-Doppler graph. This leads to the advantage of easy isolation of moving human targets from surrounding clutters.

It has been further demonstrated that analyzing the echoes in the range-Doppler image and the micro-Doppler features [36], gait information and fall events can be detected. For example, [37] presents a case study demonstrating a 5.8-GHz portable FMCW radar sensor that uses the Doppler, range, and radar cross section (RCS) information to detect fall events and differentiate falls from other activities such as a sudden jump.

D. Hand Tracking and Gesture Recognition

Analysis of the radar-detected signal in both time and frequency domains can reveal features of a movement for classification purposes [38]–[41]. In recent years, miniaturized radar circuits and systems have emerged as a good candidate to analyze motion features in time-frequency domain for the Internet of Things (IoTs) applications that can benefit senior people and people with special needs. In [42], a portable smart radar gesture recognition sensor achieved 96.7% accuracy for identifying different types of hand and head movements. Large interests have also been drawn from the industry. For example, based on an integrated millimeter-wave radar sensor chip and powerful machine learning, Google launched to public the project *Soli*, which develops high-resolution and low-power miniature gesture sensing technology for human-computer interaction [43]. The solution achieved a sub-millimeter accuracy and a speed of 10000 frames per second on embedded hardware. NVIDIA Research developed an FMCW monopulse radar for hand-gesture sensing to serve intelligent driver assistance systems [44].

In addition, linear time-domain motion tracking based on CW radar sensors can also be used in hand tracking, gesture classification, and recognition. A recent example was reported in [45], and [46], where the feasibility of human hand gesture recognition was investigated. This work tried to realize the basic "moving" and "click" functions of a mouse by remotely tracking the hand and finger actions based on a single-input multiple-output (SIMO) Doppler radar sensor. The system consists of one transmitting and two receiving channels designed to operate at 5.8 GHz. The antennas were placed on the lower side of a computer's display to detect the hand actions in front of them.

E. Recent Advancements in Millimeter-Wave Region

As the carrier frequency increases to millimeter-wave region (Ka-band and beyond), the sensitivity of radar systems is improved due to shorter wavelength and the radiation beam can be more easily configured because of the increased number antenna elements that can be accommodated with a given device size. Therefore, millimeter-wave portable radar has gained much attention for remote indoor monitoring of vital signs [47]–[49], detection of small mechanical motion, and precise localization. In [47] a Ka-band Doppler radar non-contact heartbeat detection has been demonstrated in experiment with a high accuracy and low-power. In [48] a W-band (75 to 110GHz) continuous wave (CW) radar in GaAs mHEMT technology is demonstrated to determine respiration and heart beat rate of a human target at 1-meter distance by a combined time and frequency domain analysis.

IV. Wireless Neural Interfacing and Prosthesis

Understanding how the brain represents, transforms, and communicates information requires large-scale, simultaneous recordings from distributed neuronal networks at a cellular-level resolution. In the brain, neurons communicate with each other by firing action potentials (spikes), with each spike lasting 1 to 2 milliseconds. In practice, to characterize brain activities at single-spike resolution and distinguish spike shapes, electrical recording technologies are necessary to work at higher sampling rates (e.g., 10∼40 kHz). This would generate a high-speed data stream, posing significant challenges to designing data links of neural recorders.

In large-scale recordings, transmitting high-speed data streams routinely adopts wired connection. However, a wired connection increases the risks of tissue infection, breakage, interference coupled through the wires, and motion artifacts. Furthermore, it restricts the spectrum of the accessible experimental protocols and clinical translations. Specifically, a successful implementation of wireless neurotechnology will tremendously benefit the design and application of neural prosthetic devices that are frequently used to restore/improve lost body functions, by allowing more flexible and unconstrained movements of subjects.

Many factors contribute to the complexity of the design of wireless neurotechnologies, including wireless interface, power supply and dissipation, packaging, biocompatibility, and so on. One critical design challenge is the trade-off between high data rate and low power consumption, as increasing wireless transmission bandwidth would require proportionally higher power consumption. To this purpose, in recent years there has been mainly two lines of research efforts that aim to balance this trade-off, following the approaches of 1) designing low-power wireless transmission technologies to transfer raw neural data, and 2) compressing neural data before transmission, as shown in Fig. 7.

In the first line of researches, the common choice of wireless interface for data transmission has been through a transition from inductive coupling to radio frequency (RF) antenna communication, as inductive coupling typically has slow data rates and high sensitivity to misalignment between coils. In RF communication technologies, industrial, scientific, and medical (ISM) radio bands and ultra-wideband (UWB) are popularly used in biomedical/neural electronics. For example, Schwarz et al. proposed a wireless recording system based on 2.4GHz-ISM and demonstrated chronic recording from 512 channels in freely moving monkeys [50]. The system was built with commercially available components (Intan Technology chips for recording and Nordic radio chips for wireless communication), and supports a 2Mbps data rate. Constrained by the transmission bandwidth of 2.4GHz-ISM, only spikes are recorded in the wireless mode. In comparison, UWB can offer a much higher data rate, as well as less interference, feasibility for real-time peer-to-peer communication, and implantable antenna size. Ando *et al.* [51] designed a multichannel neural recorder with a 128-Mbps UWB transmitter for brain-machine interfaces (BMI), which can support 64-4096 channels simultaneously at a power consumption no more than 1376mW. In another recent work of UWB-based wireless neural recorders, Yin et al. proposed a 100-channel hermetically sealed implantable headstage for chronic wireless neurosensing applications [52], [53]. The wireless links in this device support data transmission at up to 48Mbps as well as inductive charging of internal Li-on battery at 150 kHz. This headstage was later commercialized by Blackrock Microsystems, USA, and adopted in a design

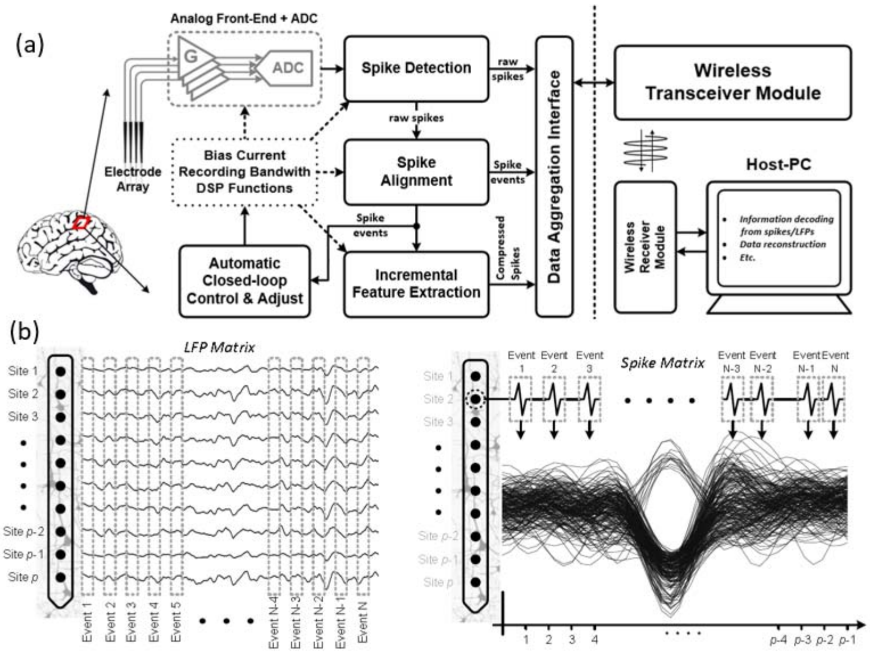

Fig. 7. (a). A neural recording system amplifies and digitizes weak neural signals on the electrode sites implanted in the brain. The raw data rate is as high as 500kbps to 1Mbps per channel. As a result, it requires pre-processing and compressing the neural signals on-chip before wireless transmission. (b) Example neural signals appearing on electrode sites. Left, local field potentials; right, neural spikes.

of a brain-spine interface to alleviate gait deficits after spinal cord injury (SCI) in primates [54]. UWB has also shown potentials in enabling gigabit data telemetry for large-scale neural recording at ultra-low power consumption (data rate of 6Gbps, energy cost of 2.08pJ/bit in [55]).

Though seemingly promising, power consumption and scalability constitute primary concerns of wireless neurotechnologies that aim to transfer raw data. To alleviate the burdens brought by the exploding data volumes in large-scale recording, on-chip data compression is becoming indispensable to transmit data from an increasing number of channels without consuming excessive power. As a common way to reduce data rate, spikes are often extracted from raw data, with local field potentials (LFPs) discarded [50]. However, LFP may contain vital information regarding motor planning, sensory processing, and higher cognitive processes. In [56], an algorithm that can effectively and efficiently compress multichannel LFPs was proposed. With this method, up to 100× data reductions for LFPs as well as 25× for spikes can be achieved at the cost of ultra-low power consumption, thus facilitating wireless data transmission. To further compress spikes, wavelets, compressive sensing (CS), and feature extraction based approaches are actively explored in recent years and implemented into VLSI circuits [57]–[62]. Among them, CS is attractive due to its computational simplicity in the implant side and the capability to facilitate direct feature extraction in the compressed domain [63]. The signal reconstruction in CS entails expensive computations to perform optimizations, thus posing great challenges to downstream real-time signal processing that demands original signals [64], [65]. Discussed throughout these works, a key design challenge of on-chip data compression lies in the trade-off between functionality, complexity, and scalability, which is further complicated by the requirement of on-chip integration with analog circuits as a system-on-chip (SoC) solution. Due to these difficulties, the development of large-scale, low-power neural recording system with extensive on-chip data compression is still in its infancy.

To include wireless neural recording into prosthetic devices poses rigid requirements on safety, stability, portability, and functionality, and is also highly application-specific. In the treatment of SCI, it is essential for prosthetic devices to have recording capability to on-the-fly evaluate the effectiveness and optimize the protocol of the spinal cord stimulation. Lo *et al.* [66] proposed a fully integrated wireless SoC for motor function recovery after SCI, supporting 16-channel recording, 160-channel stimulation, and data telemetry at 2Mbps, and demonstrated its functionalities on a rat model. In the treatment of brain damage, the work presented in [67] validates that a neural prosthesis can serve as a communication link between distant locations in the cerebral cortex by applying activity-dependent stimulation in the targeted area. In this work, a 16-channel wireless recording and stimulation prosthesis was developed and used to bridge the premotor cortex and the somatosensory cortex on a rat model, with both recorded signals and stimulation patterns wirelessly retrieved for observation. Significant efforts will be needed to build the next-generation wireless neural interface for prostheses that is robust, lightweight, low-cost, and of high performance.

V. Non-Contact Characterization of Biological Materials

Electromagnetic waves and their underlying physical principles can be exploited for the characterization of biological materials. In future-medicine environments, this

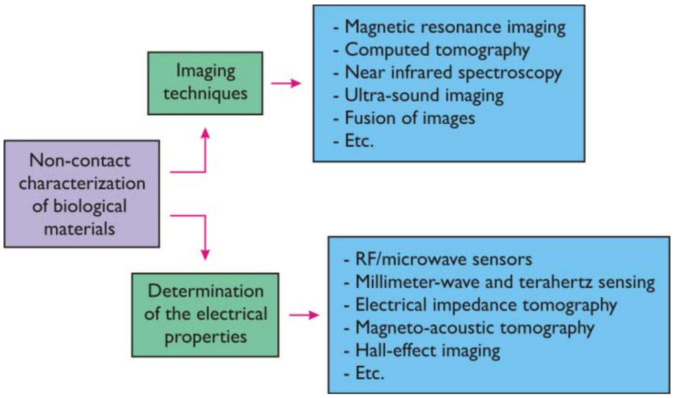

Fig. 8. Solutions to non-contact characterization of biological materials.

characterization or diagnosis of biological tissues is going to be connected with the therapy, so that theranostic devices or systems to come will allow a fully-personalized treatment for each individual patient [68], [69]. To this aim, RF/microwave, infrared, or optical techniques offer key advantages in terms of their contactless and non-destructive sensing features. In the existing techniques, the frequencies of the employed electromagnetic fields are chosen to have good penetration properties into the biological tissues [68], [69]. A graphical overview of the solutions reviewed in this section is provided in Fig. 8.

A. Imaging Techniques

Non-contact imaging techniques provide the medical professionals with imaging tools to analyze the internal structure, composition, and physiological processes of biological tissues and organisms [70].

Magnetic resonance imaging (MRI) employs strong magnetic fields, radio waves, and field gradients to generate images of the organs in the body [70], [71]. MRI scanners are based on the phenomenon of nuclear magnetic resonance (NMR), by which hydrogen atoms of the under-test tissue are excited by the generated strong magnetic fields. These excited atoms produce detectable radio-frequency signals (of frequencies in the ranges of HF and UHF spectra). By means of the spatial resolution of induced magnetic field gradients, it is possible to construct images with the internal structure of the analyzed organs, in which the appearing contrast between their different parts are associated with the different concentrations of excited atoms [70]. MRI scanners do not make use of dangerous ionizing X-rays, contrary to the case of conventional computed tomography (CT) [72]. In addition, MRI is a very versatile technique, since it enables to produce chemical and physical data for many different structures inside the body, mainly used in diagnostic medicine and biomedical research [70], [71].

In addition to the imaging based on RF/microwave waves (like in MRI) and on high-frequency X-rays (like in CT), it is also to emphasize the imaging technique centered on near infrared spectroscopy (NIRS) [73]. NIRS is a non-contact spectroscopic method that exploits the near region of the infrared spectrum (i.e., wavelengths from about 700 nm to 2500 nm) for the imaging of the internal structure of biological tissues, especially those related to vascular medicine. The absorptivity of biological tissues is very small for near-infrared electromagnetic waves, thus providing NIRS with penetration capabilities when compared, for example, with the mid-infrared radiation [73].

Contactless imaging techniques for healthcare applications based on electromagnetic waves are under continuous research. The investigations are not only centered on the improvement of the scanners and spectroscopes, but also on the signal-processing algorithms for the formation of the images and the exploitation of the outputs for diagnosis purposes [74]–[76]. One interesting active area is the combination of imaging information from multiple sensors and subsequent image registration, leading to the desired advantage of improved overall available diagnostic information [77]. For example, the combination of ultra-sound imaging (USI) with MRI information adds together the benefits of improved spatial resolution of USI and enhanced contrast resolution in the discrimination of the kind of tissues of MRI [77].

B. Determination of Electrical Properties

An accurate estimation of the electrical properties of biological mediums is found to be very beneficial, because these properties are related to the physiological and/or pathological state of the tissues [78]–[81]. Indeed, some tissue pathologies can be connected with variations of both the electrical conductivity σ and the dielectric permittivity ε. In particular, these electrical properties vary as a function of the relative intra- and extra-cellular fluid volumes and ionic concentrations and the cellular extent in the tissue [81], [82].

Contactless techniques based on electromagnetic waves have been proposed for the determination of the conductivity and the permittivity and their variations within biological tissues. While contact-type approaches that are usually based on open-ended coaxial probes have been reported in the literature [83], they are commonly not convenient for their use in vivo [82]. A contactless determination of the electrical properties of tissues usually employs RF/microwave devices which may have a high sensitivity. For example, miniature high-temperature superconducting surface coils, multi-turn split-conductor transmission-line resonators, or flexible polymeric antennas have been proposed to determine the conductivity σ and the dielectric permittivity ε of in-vivo biological tissues [84]–[86].

Point-of-care diagnosis cell characterization and tissue sensing, characterization of biomaterial, microfluidic bio-sensing have been active research areas in the field of millimeter-wave and terahertz sensing. In [87] a rapid and energy-efficient spectrometer architecture has been proposed, based on dual-frequency-comb scanning. The spectrometer consists two identical comb chips with a fixed intermediate frequency offset. In a conventional single-tone spectrometer, the maximum scanning speed with certain sensitivity is fundamentally limited by the population saturation of molecular states. However, the dual-frequency-comb scanning as proposed in [87] overcomes the limitation by a much shorter total scanning time through parallel operation. In [88] and [89], millimeter-wave and terahertz are demonstrated for dielectric characterization of biomaterials. In [88], a co-planar waveguide (CPW) based sensor on LTCC substrate is used to characterize the dielectric properties (e.g. ε_r and loss tangent) of biological liquids and tissues up to 110GHz, which can be used as an invasive detection. In [89], a low-power miniaturized K-band sensor is demonstrated for minimally invasive dielectric characterization of biomaterials using an open stub, a short stub, and a combination of both. The different stub types combined with a sensing oscillator translates the characteristics of dielectric material into the oscillation frequency and the output power. In [90] three different architectures of millimeter-wave and terahertz reflectometer and their circuit implementations have been compared. These three architectures are homodyne or heterodyne lock-in detection, six-port passive networks, and sampled-line approaches. In [91] a novel non-invasive device has been demonstrated with glucose concentration detection in the frequency range of 56-61GHz. A potential change in the glucose concentration translated into a change in the relative permittivity of the blood, which in turn affects the electromagnetic field distribution and the transmission coefficient [92] and [93] focus more on the terahertz sensing for biomedical applications [92] introduces a sensing technology using terahertz wave with metal mesh resonant filters. The work studies the terahertz wave absorption and propagation characteristics in metallic meshes designed for terahertz sensing and for application to biomedical related specimens. In [93] the terahertz imaging system has been compared to millimeter-wave reflectometer for acquiring images and point measurements, respectively. It is shown that the millimeter-wave has 10 times higher sensitivity for thickness correlation than terahertz [94] presents the modeling and characterization of an interesting BiCMOS embedded microfluidic platform. This microfluidic platform provides very flexible size of microchannels in BiCMOS chip and can bring the fluid very close to the sensor. A fully integrated 120GHz dielectric sensor has been used for demonstration of the platform.

Beyond the employment of RF/millimeter-wave/terahertz circuits and systems, there have been some additional efforts to derive the electrical properties of tissues from other primary measurements, such as electrical impedance tomography, magnetic induction tomography, magnetic resonance electrical impedance tomography, or Hall-effect imaging, magneto-acoustic tomography with magnetic induction [95]–[99]. From these mapping techniques, the solution that exploits the MRI output with some specific reconstruction algorithms, in which the wavelength of the RF radiation is of the order of the body size, must be emphasized [82], [100].

VI. Other Wireless Sensing Technologies

Driven by the ever-increasing demand of higher life quality and personal care, both the academia and industry are experiencing rapid advancements in wireless sensing and detection solutions. The previous sections have reviewed some of the recent developments on circuits and systems for applications such as data communication and powering of wireless implantable devices, non-contact sensing of human physiological signals, biological material characterization, and neural recording. There are many other wireless sensing circuits and systems for healthcare and biomedical applications. For example, wearable health-monitoring systems are becoming more and more popular, especially for noninvasive diagnosis and long-term monitoring [49], [101]. These sensors are physically worn on human body to collect and wirelessly transmit data. One challenge for wearable monitoring is how to deploy the sensors without interfering the subject's regular activities. Therefore, it is highly desirable to minimize such sensors with highly integrated circuits and systems. Besides, low power consumption is another important requirement to allow a longer operation period. The propagation of electromagnetic waves can be largely influenced by the patients' movements too [101]. Additional challenges include privacy concerns and wireless link reliability [49]. Wearable sensors using millimeter-wave spectrum provide advantages of miniaturization and better protection of privacy because of short data transmission range. However, the patients' regular movements can have a larger influence on the wireless link.

Optical technology serves as another important tool for non-contact healthcare and biomedical applications. For example, human respiration and heartrate can be measured using imaging photoplethysmography (PPG), which measures the small changes in skin color due to changes in blood volume in arteries and capillaries during a cardiac cycle. Imaging PPG utilizes devices such as cameras to measure these changes. The detection is based on the fact that blood absorbs more light than its surrounding tissues. Vital signs detection have been successfully demonstrated using different types of cameras [33], [34]. The technology can also detect multiple subjects' vital signs [35]. However, optical technologies still suffer from certain limitations such as being sensitive to ambient light and requiring more computation resources to extract the feature of interest. Therefore, sensor fusion has been proposed to combine the advantages of radio frequency and optical technologies. For example, [36] integrated a Doppler radar with an iPhone camera to build a vital sign detection system. The camera measures a subject's random body movement, and feed that information to the radar system to cancel the noise caused by random body motion. As the cost and size of different types of sensor circuits reduce, it is expected that more systems with sensor fusion will be developed as practical healthcare and biomedical solutions [102]–[106].

VII. Conclusion and Outlook

For wireless sensing circuits and systems to meet the high demand in biomedical applications, advanced semiconductor technologies with a low cost and high integration capability are the driving force. Silicon technologies such as CMOS and BiCMOS are ideal for their low cost and high integration capability. Furthermore, in the performance aspect, both deep submicron CMOS and advanced BiCMOS technologies with high cut-off frequencies have been demonstrated for various millimeter-wave and terahertz applications [87], [107], [108]. Innovation and dedicated modeling and characterization of semiconductor technologies for biomedical sensing are key to accelerate researches in applications.

Although lots of progress has been made by engineers and researchers to enhance the performance while reducing the hardware cost and power consumption, there are still great potential to be explored further. Breakthroughs are expected because of the rapid advancement in semiconductor technologies, embedded systems, as well as other fields such as machine learning and big data science. The continued contributions from members in the circuits and systems society in collaboration with researchers from other disciplines will be greatly valued and appreciated.

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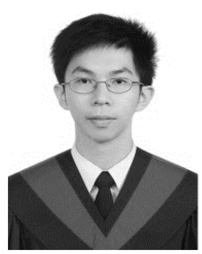

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