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Radio Sensing Using 5G Signals: Concepts, State-of-the-art and Challenges

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***Abstract*— Radio sensing has become increasingly important, as the demand for "smartness" is drastically increasing. Unlike conventional sensing, radio sensing uses existing radio signals or devices to passively sense the ambient environment for low cost and wide deployment. In this paper, a comprehensive overview of radio sensing using the recent fifth generation (5G) signals is provided. 5G systems have many merits, such as high frequency, large bandwidth, massive antenna array and dense network, making them ideal for radio sensing. In the overview, basic theories and concepts of 5G radio sensing are first introduced. Then, different state-of-the-art 5G sensing works are discussed based on their applications. These applications show that 5G radio sensing represents a step change in radio sensing. After that, several open challenges in 5G radio sensing are illustrated with relevant insights. These insights manifest that 5G radio sensing has great potentials to explore.**

***Index Terms*— 5G, activity recognition, cellular signal, detection, healthcare, localization, radio sensing, safety.**

I. INTRODUCTION

A. Radio Sensing Concept

Radio sensing has attracted great research interest recently [1], [2]. Traditional sensing often requires dedicated sensing devices or signals, such as cameras and tags, to perform the sensing tasks [3]. Such methods could be costly, inefficient or inconvenient. For example, cameras require line-of-sight (LOS) so that they perform poorly with obstruction or in case of low visibility. Also, in health monitoring, it is inconvenient to wear tags. These problems can be solved by using radio sensing. A radio receiver is intrinsically a sensor. The radio signals in the ambient environment can be blocked, reflected and diffracted by objects inside it. The presence, the movement or any other changes caused by these objects will lead to variations in the propagation of radio signals. Hence, the received radio signals containing these variations can be used to detect the changes in the ambient environment.

Radio sensing leverages reflection, diffraction and scattering of radio signals for ubiquitous sensing. Compared with traditional sensing, radio sensing has several advantages. Firstly, its operation is sensor-less, that is, no extra dedicated sensing devices are needed. The radio receiver can work as the sensor. Secondly, it is contactless, and does not require the sensed objects to cooperate. Thirdly, its hardware cost could be low, as one only needs to reuse existing or off-the-shelf radio receivers. Other benefits include privacy protection of object (video or audio could expose personal identity while radio will not) and efficiency (such as working in non-line-of-sight (NLOS) conditions or in the dark). In Issac Asimov's 1983 science fiction book *"The Robots of Dawn"*, he cited *"Every time I lift my arm, it distorts a small electromagnetic field that is maintained continuously across the room. Slightly different positions of my hand and fingers produce different distortions and my robots can interpret these distortions as orders"* [4]. Radio sensing is making this a reality.

Different radio signals can be used for radio sensing, including FM radio, WiFi, Bluetooth, ZigBee, and cellular. A detailed review of these methods can be found in [2] and [5]. Many of these previous works use WiFi signals due to its low cost and wide availability [6]. However, compared with WiFi signals, cellular signals have several advantages, including wider coverage for both indoor and outdoor applications, longer operational time of base stations, and licensed frequency bands with less interference. These advantages are increasing the popularity of cellular sensing to turn all mobile devices and base stations into distributed sensors for unprecedentedly ubiquitous environment perception [7], [8].

B. 5G for Radio Sensing

The fifth generation (5G) cellular system adopts a wide range of state-of-the-art technologies, such as massive multiple-input-multiple-output (MIMO), millimeter-wave (mmWave) communications, network densification and device-to-device (D2D) communications, to enable a variety of use cases [9]. These application scenarios can be mainly summarized into three categories: enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (URLLC), and massive machine type communications (mMTC). For example, eMBB aims to provide high-data-rate seamless mobile services for improved user experience, URLLC enables applications requiring stringent latency and reliability, such as autonomous driving and smart manufacturing [10], while mMTC enables Internet of Things (IoT)

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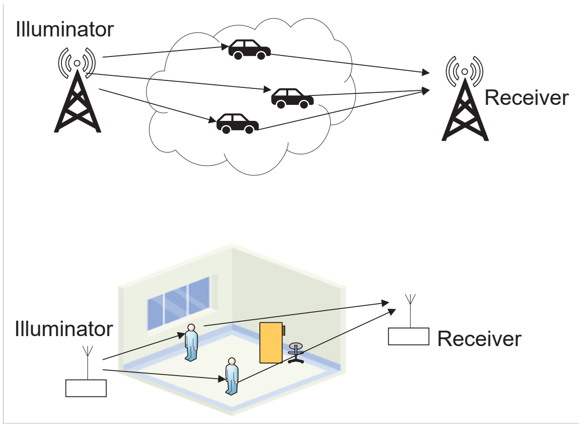

Fig. 1. Diagram of 5G radio sensing for outdoor and indoor applications.

as another important development in wireless communications [11]. Owing to these attractive applications, 5G is being rolled out around the world to provide better cellular access. Fig. 1 shows a diagram of 5G radio sensing for both outdoor and indoor scenarios, where a 5G base station or small cell can transmit the radio wave that propagates through the environment to be sensed and the radio receiver is used to extract the environment information from the received signals.

The advent of 5G makes the advantages of using cellular signals for radio sensing even more attractive. 5G signals have several unique merits that are ideal for reliable and accurate pervasive radio sensing.

1) High Carrier Frequency: 5G uses very high carrier frequency reaching the mmWave bands. The 5G frequency range one (FR1) includes all existing and new bands below 6 GHz, while the 5G frequency range two (FR2) covers 24.25 - 52.6 GHz (albeit quite energy-consuming for a terminal) [12]. The high carrier frequency leads to high ranging resolution to capture more and finer changes in the received signal for better sensing. For example, the velocity resolution in ranging is inversely proportional to the carrier frequency [15]. The high carrier frequency also makes the radio signals more sensitive to absorption loss in the propagation, such as water and chemicals, to allow the sensing of more environmental parameters. Also, high frequency yields smaller antennas to allow for more antennas equipped at the mobile device or base station. The high frequency comes with high penetration loss, reducing multi-path components in the channel to make it sparse and more dependent on the ambient environment, in contrast to previous cellular systems with rich multi-path components. This increases the signal-to-interference ratio of individual multi-path components to make radio sensing easier and better.

2) Large Channel Bandwidth: 5G signals have large channel bandwidth, up to 400 MHz in some cases [13]. This improves radio sensing by increasing its accuracy. For time-critical sensing, large bandwidth gives shorter symbol interval to reduce latency and increase accuracy of time measurements. This is beneficial to time-delay estimation used in some radio sensing applications, as its estimation accuracy is proportional to the bandwidth so that large bandwidth gives very high accuracy. Using time-of-flight (ToF) and time-of-arrival (ToA), the time-delay estimate can be directly transformed to distance estimate. It was shown in [14] that a bandwidth of 100 MHz can achieve a ranging error on the order of centimeters, in contrast to the commonly used global navigation satellite system (GNSS)-based method on the order of meters. The large bandwidth also contributes to finer multi-path resolution to separate closely spaced components from nearby objects.

3) Large Antenna Array: 5G systems use large antenna arrays to implement massive MIMO. For example, Nokia AirScale 64T64R uses 64 antennas. The massive number of antennas or antenna elements provides great spatial flexibility for radio sensing. It enables real-time software-defined reconfiguration of radiation pattern using beam-steering or beamforming. This ability of dynamically changing the radiation pattern allows radio sensing to use different spatial configurations to "view" the same environment or object from different angles, and by comparing or stitching these "views", it can extract the location information of the objects for movement tracking or activity discrimination. The massive number also generates near-pencil beams to increase directivity. The use of large arrays is also well known for directly improving the accuracy of angle-of-arrival (AoA) estimation [16]. The angle resolution is inversely proportional to the number of antennas. It has been reported that, for a bandwidth of 40 MHz, it is also possible to achieve a ranging error on the order of centimeters if multiple antennas are used [16].

4) Dense Network: 5G systems have dense deployment of base stations and user equipment, as network densification is a key technology to support large volume of traffic. In an ultra-dense network, a mobile device often has connection to several base stations, at the cost of reduced battery life. This provides spatial diversity for radio sensing, as several reference points will be available. High density also means the availability of a number of neighboring mobile devices to perform collaborative sensing. This is possible for 5G, as it supports D2D communications allowing data exchange between mobile devices directly. High density also gives a high probability of LOS for sensing signals with better qualities.

5) Other Aspects: 5G signals also have other benefits for sensing. For time-non-critical sensing applications, 5G allows the use of cloud radio network for centralized processing of the received signals from different radio heads for spatial processing gain [17]. This is not available in previous cellular systems or in WiFi. For time-critical sensing applications, 5G supports ultra-reliable and low latency communications for fast response, such as collision avoidance. Nevertheless, 5G has limited range and coverage. Also, it has high energy requirement. These might delay the development of 5G sensing.

Table I gives a list of 5G characteristics and their advantages and disadvantages for sensing. There has been increasing interest in 5G radio sensing. For convenience, a list of frequently used abbreviations are summarized in Table II. The main contributions of this work can be summarized as follows:

- A detailed overview of state-of-the-art works on 5G radio sensing is provided with insightful discussion based on their applications.
- It is the first time that different works using 5G radio

TABLE I
SUMMARY OF 5G CHARACTERISTICS AND ADVANTAGES

Characteristics	Advantages	Disadvantages
High frequency	higher ranging resolution for finer sensing, smaller antenna and higher sensitivity to environment	limited range, coverage
Large bandwidth	higher ranging accuracy, shorter latency, easier separation of multi-path components	energy-consuming
Antenna array	adds degrees of freedom, increases delay and angle estimation accuracies	high complexity
Dense network	increase the number of reference points and collaborators, higher probability of LOS	energy-consuming
Cloud radio	centralized processing of signals from multiple radio heads for diversity gain	high overhead
Fog computing	distributed processing to reduce latency and offload computing tasks	high complexity

TABLE II
LIST OF FREQUENTLY USED ABBREVIATIONS

5G	Fifth generation
AoA	Angle-of-arrival
AP	Access point
CPCL	Cooperative passive coherent location
CSI	Channel state information
CSQ	Cellular signal quality
DKA	Diabetic ketoacidosis
DT	Decision tree
D2D	Device-to-device
eMBB	Enhanced mobile broadband
FOG	Freezing of gait
FR1	Frequency range one
FR2	Frequency range two
GNSS	Global navigation satellite system
IoT	Internet of Things
KNN	K-nearest neighbor
LOS	Line-of-sight
LSTM	Long-short term memory
MIMO	Multiple-input-multiple-output
mMTC	Massive machine type communications
mmWave	millimeter-wave
NLOS	Non-line-of-sight
NB	Naive Bayes
OFDM	Orthogonal-frequency-division-multiplexing
RRSS	received raw signal sample
RSS	Received signal strength
SNR	Signal-to-noise ratio
SVM	Support vector machine
ToA	Time-of-arrival
ToF	Time-of-flight
UE	User equipment
URLLC	Ultra-reliable and low latency communications
USRP	Universal software radio peripheral

sensing are compared in terms of methods and results based on their applications. The comparison shows the pros and cons of the relevant works to suggest possible future improvements.

- Open challenges in 5G radio sensing are outlined based on the overview to point out the shortcomings of existing works and therefore, the future research directions.

C. Structure of the Paper

This paper provides a comprehensive overview of the growing field on 5G radio sensing. It focuses on sensing using the 5G signals only. State-of-the-art works up to December 2020 will be reviewed. To start with, we will discuss several fields related to 5G radio sensing to distinguish them and to define the scope of this paper. Then, several basic but important theories and concepts for signal processing in different sensing applications will be introduced. After that, state-of-the-art works on 5G radio sensing will be discussed based on their applications, including healthcare, safety and positioning. Finally, open challenges in this relatively new field will be outlined, followed by concluding remarks. Fig. 2 gives the structure of the paper.

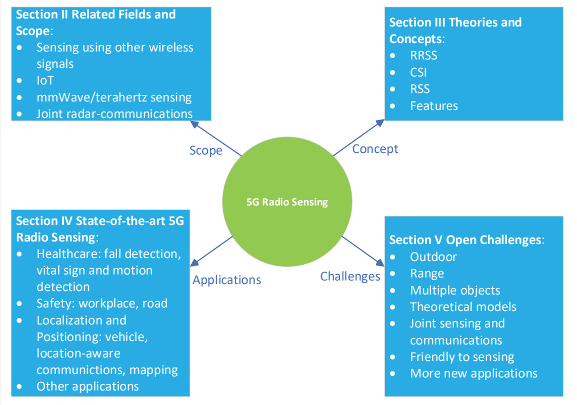

Fig. 2. Structure of the survey.

II. RELATED FIELDS AND SCOPE

Before we proceed to discussing 5G radio sensing, it is important to distinguish it from several relevant fields that are similar to 5G radio sensing.

The first field is radio sensing using other wireless signals, such as WiFi, Bluetooth and previous generations of cellular signals. For example, WiFi sensing is a very active research field [18]. Interested readers are referred to [18] and the references therein for WiFi sensing. They are not the focus of this paper. First, there have already been quite a few comprehensive overviews on WiFi sensing, and there is no need to repeat them here. Second, despite some disadvantages, 5G has many unique advantages over WiFi signals, such as higher frequency and larger bandwidth, as discussed in Section I and Table I. In this sense, 5G sensing is distinct from radio sensing using WiFi or other wireless signals. Hence, this paper will only discuss 5G sensing.

The second field is IoT supported by 5G. A typical IoT framework is made of three main steps: data collection, data transmission and data processing. Among them, data transmission refers to the process of transmitting the field measurements from the remote nodes to the access point, and it can be implemented by using any wireless systems, including 5G. Indeed, one of the most important applications of 5G is mMTC that supports low-power wide-area networking for IoT. In this case, 5G provides the network for data transmission but is not involved in data collection. However, in 5G radio sensing, the 5G signal is used as the sensing signal to collect data. Hence, the two fields are different and this paper will not discuss any works on IoT supported by 5G network.

The third field is mmWave sensing. The similarity of the two fields comes from the fact that the 5G FR2 uses frequency bands in the mmWave spectrum. However, mmWave sensing has been adopted long before 5G systems were deployed, due to its high resolution [19]. For example, mmWave radar was used to acquire real-time visualization of 3D images [20] or see through walls [21]. This field is different from 5G radio sensing discussed here. First, mmWave sensing uses a mmWave waveform dedicated for sensing, while 5G radio sensing uses 5G waveforms designed for communications. For example, 5G signals use orthogonal-frequency-division-multiplexing (OFDM). Second, mmWave sensing in the literature uses specialist equipment, while 5G radio sensing uses existing 5G communications signals or devices for passive and opportunistic sensing. Hence, this paper will not discuss any works on mmWave sensing. Another related field is terahertz sensing. Similar to mmWave sensing, it uses active terahertz signals dedicated to imaging or sensing [22]. Recently, the interest in terahertz sensing grows due to the development of terahertz communications [23]. The terahertz band is expected to be an important enabler for the sixth generation [24]. Hence terhertz signals can be used for both sensing and communications [25]. However, 5G signals have not reached the terehertz band yet so this will not be discussed in the paper.

The last field is joint radar-communications for 5G. Joint radar-communications has become important in recent years for two reasons: the lack of spectrum for communications and the demand for both radar sensing and data communications in emerging applications [26] - [28]. Radar and communications could co-exist, co-design, or integrate [26]. If they co-exist or co-design with each other, the radar sensing part of the joint system still uses radar waveforms for sensing and mutual interference between radar and communications exists. This can be mitigated via beamforming [31] - [33] or null space projection [34]. If they integrate with each other, dual-functional [35] or duplexed waveforms [29], [30] are often used, which require changes to the 5G systems. For example, the same carrier could be modulated by both radar and communications signals, or waveform diversity could be used where the main lobe is used for radar and side-lobes are used for communications, or certain antennas in MIMO systems or certain subcarriers in OFDM systems are used for radar while others are used for communications. The 5G radio sensing focuses on sensing only instead of joint designs. Hence, this paper will not discuss any works on joint radar-communications for 5G.

In summary, this paper does not discuss any works on radio sensing using other wireless signals, IoT utilizing 5G network, sensing using dedicated mmWave signals, or 5G joint radar-communications. These fields are related but including them in this survey will make it excessively long. Moreover, there have already been survey papers on these relevant fields, such as [26] on joint radar-communications, and [18] on WiFi sensing. To the best of the authors' knowledge, there have been no surveys on 5G radio sensing. For this reason and to fill the gap in the literature, this survey will only focus on 5G radio sensing. Next, we will introduce some basic theories and concepts used for signal processing in 5G radio sensing. Table III summarizes the difference of these fields from 5G radio sensing.

TABLE III
SUMMARY OF DIFFERENCES OF RELEVANT FIELDS

Relevant Field	Difference
Other wireless signals	The unique characteristics of 5G systems, such as high frequency, large bandwidth and massive array, make 5G sensing a step change compared with radio sensing using WiFi and other cellular signals.
IoT	It uses the 5G network to transmit measurements from remote sensors to the access point but the 5G signal itself is not used in data collection.
mmWave/terahertz sensing	It uses unmodulated waveforms and requires specialist equipment for active sensing.
Joint radar-communications	It focuses on the interplay between radar and communications and requires changes to 5G systems.

III. THEORIES AND CONCEPTS

Signals transmitted by one radio device and received by another radio device contain variations caused by objects in the ambient environment between the transmitter and the receiver. Hence, measurements of these signals can be used to sense the environment. There are several widely used types of measurements: received raw signal sample (RRSS), radio channel state information (CSI), received signal strength (RSS), or cellular signal quality (CSQ) indicator. RRSS is the raw sample of the received signal that directly reflects the signal variations. Hence, it contains all propagation characteristics. RRSS often uses signals received from references or beacons. CSI is a physical layer type of measurement to track the variations at the symbol level. It is able to discriminate multi-path components for high sensing accuracy. RSS is a link layer type to track the variations at the frame level. It is commonly used for link adaptation and transmission scheduling in wireless systems. CSQ is also a link layer type that is generated by mobile devices during idle mode to monitor radio link propagation from different base stations for possible cell reselection [8]. Other measurements include packet error rates, time-delay [36], Doppler [37] and link quality information [38].

A. RRSS

We discuss RRSS first. For 5G signals, assume that the OFDM waveform is used with a number of N sub-carriers and a fixed frequency spacing of Δf. The transmitted signal after the inverse fast Fourier transform (IFFT) is

$$S(t) = \sum_{n=1}^{N} s_n(t) = \sum_{n=1}^{N} A_n e^{j2\pi n \Delta f t}, \qquad (1)$$

where $s_n(t)$ is the signal on the n-th sub-carrier and $A_n = a_n e^{j\theta_n}$ is the transmitted data symbol on the n-th sub-carrier with amplitude a_n and phase θ_n.

This signal is transmitted in an environment with K objects. The RRSS on the n-th sub-carrier after going through the environment is given by

$$\begin{aligned} Y_n(t) &= \sum_{k=1}^{K} \alpha_k A_n e^{j2\pi n\Delta f(t-\tau_k)} e^{j2\pi f_k t} + W_n(t) \\ &= \sum_{k=1}^{K} \alpha_k e^{j2\pi f_k t - j2\pi n\Delta f\tau_k} s_n(t) + W_n(t), \end{aligned} \tag{2}$$

where α_k is the effective attenuation from the k-th object, τ_k is the time delay of the k-th object, f_k is the Doppler of the k-th object if it is moving, and W_n is the white noise.

In practice, more than one OFDM symbols will be used. Denote $T_s = \frac{1}{\Delta f} + T_{cp}$ as the interval of the OFDM symbol, where T_{cp} is the length of the cyclic prefix. Thus, by substituting $t = mT_s$ in (2), one has the received m-th OFDM symbol on the n-th sub-carrier as

$$Y_{m,n} = \sum_{k=1}^{K} \alpha_k e^{j2\pi f_k mT_s - j2\pi n\Delta f\tau_k} s_{m,n} + W_{m,n}, \tag{3}$$

where $m = 1, 2, \cdots, M$ index the OFDM symbols, $W_{m,n} = W_n(mT_s)$ and $s_{m,n} = s_n(mT_s)$. According to the radar range equation, one has $|\alpha_k|^2 = \frac{G_t G_r \lambda^2 \sigma_k}{(4\pi)^3 d_k^4}$, where G_t and G_r are the transmitting and receiving antenna gains, respectively, λ is the wavelength of the signal, σ_k is the mean radar cross section related to the reflection area of the object, and d_k is the distance between the transmitter and the k-th object in the case when the transmitter and receiver are collocated. Thus, the attenuation is determined by the range or the distance. One sees from (3) that the time delay τ_k causes different phase shifts for different sub-carriers, and the Doppler causes different phase shifts for different OFDM symbols.

If the transmitted symbol is known, such as references or beacons, one has

$$Q_{m,n} = \frac{Y_{m,n}}{s_{m,n}} = \sum_{k=1}^{K} \alpha_k e^{j2\pi f_k mT_s - j2\pi n\Delta f\tau_k} + W'_{m,n}, \tag{4}$$

where $W'_{m,n} = \frac{W_{m,n}}{s_{m,n}}$ and $Q_{m,n}$ contains the information on the objects. This RRSS can be used for radio sensing.

For example, if ranging and localization are performed, one can calculate the periodogram as the range-Doppler profile to give [39] $P(i,k) = \left|\sum_{m=0}^{M'-1} e^{-j2\pi\frac{im}{M'}}\left(\sum_{n=0}^{N'-1} Q_{m,n} e^{j2\pi\frac{nk}{N'}}\right)\right|^2$, where $M' \geq M$ and $N' \geq N$. Using the range-Doppler profile, the presence of the object is detected by comparing $P(i,k)$ with a predetermined threshold. Ranging and localization are important applications of 5G radio sensing and they often use RRSS measurements. The ranging resolution is given by $\Delta d = \frac{c}{2B}$ and the velocity resolution is given by $\Delta v = \frac{c}{2T_f f_c}$, where c is the speed of light, B is the channel bandwidth, T_f is the time duration of one frame and f_c is the carrier frequency [39]. Fig. 3 shows how they change with bandwidth and carrier frequency, respectively, when $T_f = 5ms$. Since 5G signals have a bandwidth of up to 400 MHz and carrier frequency of 26 GHz, it has great advantages in ranging and localization over WiFi signals.

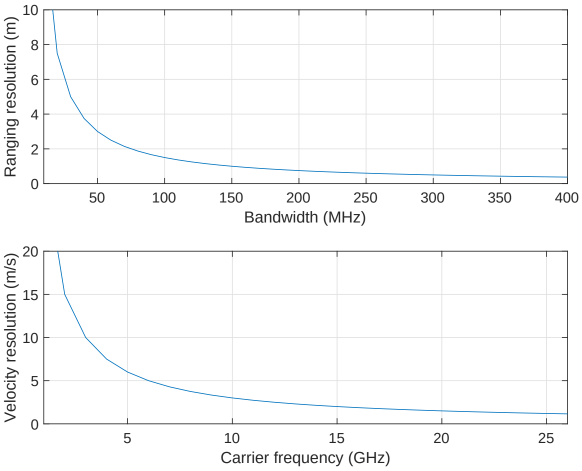

Fig. 3. Ranging resolution versus bandwidth and velocity resolution versus carrier frequency.

B. CSI

CSI is another widely used type of measurement for 5G radio sensing. Assume that the CSI representing the static ambient environment is given by

$$h(\beta, \phi|\emptyset) = \sum_{p=1}^{P} \beta_{p|\emptyset} e^{-j\phi_{p|\emptyset}}, \tag{5}$$

where P is the total number of multi-path components, $\beta_{p|\emptyset}$ is the gain of the p-th component, $\phi_{p|\emptyset}$ is the phase of the p-th component and $\emptyset$ represent the channel state in the static case with no changes or events happening. Note that the model in (5) describes the multi-path components in the channel, while the model in (2) describes the reflections caused by multiple objects in the ambient environment. They are related to each other but not necessarily the same.

When one or more objects enter the environment or perform activities, such as a car driving into a street or a human in a room raising the arm, the state of the channel will change due to these changes or events. In this case, the CSI becomes

$$h_n(\beta, \phi|\amalg) = \sum_{p=1}^{P} \beta^n_{p|\amalg} e^{-j\phi^n_{p|\amalg}}, \tag{6}$$

where $n = 1, 2, \cdots, N$ denote different time instants, $\beta^n_{p|\amalg} = \beta_{p|\emptyset} + \Delta\beta^n_{p|\amalg}$, $\phi^n_{p|\amalg} = \phi_{p|\emptyset} + \Delta\phi^n_{p|\amalg}$, $\Delta\beta^n_{p|\amalg}$ and $\Delta\phi^n_{p|\amalg}$ are the amplitude and phase changes induced by event $\amalg$ at time n for the p-th multi-path component, and $\amalg$ represents the channel state with event $\amalg$. The amplitude change and the phase change contain information on the event. In practice, the amplitude information is often used for sensing. However, the amplitude information is suitable for detection but not for discrimination of different activities. Thus, other applications use phase or both amplitude and phase for sensing.

When multiple carriers or multiple antennas are used, the CSI is similar, except that frequency diversity gain or spatial diversity gain will be achieved by having independent measurements on different frequencies or antennas. In this case, (5) and (6) become vectors. They are not repeated here for compactness.

C. RSS

The RSS can be expressed as

$$S_n(\Pi) = S(\emptyset) + \Delta S_n(\Pi), \tag{7}$$

where $S(\emptyset) = E\{S_T(\emptyset)\}$ is the average RSS observed over a certain period of time T when the channel is in static state with no events and $\Delta S_n(\Pi)$ is the additional RSS induced by event Π at time instant n. For IEEE 802.15.4, the RSS indicator (RSSI) can be used with an 8-bit resolution. For WiFi, RSS can be obtained using the received channel power indicator (RCPI). For 4G systems, RSS can be obtained from the reference signal received power (RSRP). For 5G, there are several RSS that can be used: synchronization signal reference signal received power (SS-RSRP), new radio received signal strength indicator (NR-RSSI) etc. Activity and behavior recognition is an important part of healthcare monitoring applications using 5G radio sensing, and they often use CSI and RSS. In this case, machine learning is often applied.

D. Features of Measurements for Machine Learning

In machine learning, features are often calculated and selected from the raw measurements before learning. This subsection introduces commonly used features in 5G sensing. Assume a window size of W. Commonly used features include the following. The mean or average of the measurements is $\mu = \frac{1}{W}\sum_{w=1}^{W} d_w$, where d_w represents either RSS, CSI or RRSS discussed in the previous subsections. The variance of the measurements is $\sigma^2 = \frac{1}{W}\sum_{w=1}^{W}(d_w - \mu)^2$. The n-order central moment is $\gamma = \frac{1}{W}\sum_{w=1}^{W}(d_w - \mu)^n$. These are time-domain features of the received radio signal. Assume $D_q = \sum_{w=1}^{W} d_w e^{-j\frac{2\pi}{Q}qw}$ as the FFT of d_w, where $q = 1, 2, \cdots, Q$. The spectral energy is [40] $E = \sum_{q=1}^{Q}|D_q|^2$. Let $P_q = \frac{|D_q|^2}{\sum_{q=1}^{Q}|D_q|^2}$. The entropy is $H = \sum_{q=1}^{Q} P_q \ln P_q$. These are the frequency domain features.

Other features include root mean square, median, minimum, maximum, standard deviation, auto-correlation, zero crossing rate, Kurtosis, and skewness.

E. Downlink- and Uplink-based Sensing

Downlink-based sensing uses the 5G signals transmitted by the base station, while uplink-based sensing uses the 5G signals transmitted by the user equipment (UE). Downlink-based sensing has long range and large coverage but the propagation environment is more complicated due to more interference and objects. Uplink-based sensing has short range and small coverage but the propagation environment is less complicated due to the short range. Most works using RRSS and CSI are downlink-based, while those using CSQ are uplink-based.

IV. STATE-OF-THE-ART 5G RADIO SENSING

5G radio sensing extracts important information about the ambient environment from the received 5G signals. These information can be human-centric. For example, 5G radio sensing recognizes the presence and motion of humans [41], [42], [43], the fall [44], [45], gait [46], walking speed [47], [48], gesture, vital signs [49], [50]. These information can be object-centric. For example, 5G radio sensing can detect the presence and motion of objects to localize and track objects [52] - [57], and image the objects [58]. These information can be scene-centric. For example, 5G radio sensing can count the crowd size or perform mapping and positioning [59] - [61].

The extracted information has enabled a wide variety of applications using 5G radio sensing. For example, the presence and motion detection of humans can be used for human safety in industrial workspace or on the roads for safety and surveillance [62] - [71]. The human fall and emotion detection can be used for ambient assisted living, the human gait, sleep and vital sign monitoring for patient recovery or treatment, the gesture recognition for home automation to provide context-aware services, while the human activity and behavior recognition for intrusion detection. The detection of objects can be used for material identification [73], [74]. The localization and tracking of objects can be used in warehouses and see-through-walls imaging. The crowd counting can be used in social mass gathering for security and surveillance or for heating, ventilation and air-conditioning controls. The indoor positioning and mapping can be used to map the layout of a room [75] - [79].

Next, we will discuss the state-of-the-art works on 5G radio sensing based on their applications, as most of these works are application-oriented. Nevertheless, this categorization may lead to cross-overs between applications and we will minimize the cross-overs in the discussion.

A. Healthcare

5G radio sensing used in healthcare helps to analyze and understand human behavior or patient's daily activities and syndromes to improve reliability of diagnosis and decrease working load for healthcare workers.

1) Fall Detection: Fall detection is one of the most important applications of 5G radio sensing in healthcare. It is critical for life-or-death and cost reasons, especially for elderly people who live alone or for vulnerable people who suffer from certain diseases. Without prompt response and emergency care, the fall could develop into life-threatening conditions. Timely detection of a fall is thus of great importance. There has been a large amount of literature on fall detection (see [44] and references therein but they mainly use WiFi sensing), and 5G radio sensing can play an important role with its merits.

In [45], the authors studied fall detection using the 5G C-band (3.3 - 4.2 GHz, 4.4 - 5.5 GHz) for patients after surgeries. The patients after surgeries are often vulnerable. A fall could lead to many injuries or even to death, such as bruises, bone fractures, neurological disorders or reopening of wounds. Reference [45] provided a low-cost solution. They used a Rhode & Schwartz SMBV 100B signal generator to generate 5G signals at a frequency of 4.8 GHz and a transmission power of 20 dBm, which was radiated using an omnidirectional antenna. The CSI was received by an ASUS PCE-N15 NIC connected to a desktop PC. The fall, slow walking, fast walking, lying, squatting and sitting were monitored from 8 subjects of different ages located 4 meters away from both the transmitter and the receiver. The CSI measurements were organized in packets from 30 sub-carriers and eventually the 15-th sub-carrier was chosen due to its good accuracy. Three machine learning algorithms were used to process data: support vector machine (SVM), Naive Bayes (NB) and decision tree (DT). The experiments showed that SVM has the best performance. Tests using three kernels of polynomial, linear and radial basis function (RBF) showed that RBF has the best performance for SVM. The highest accuracy reaches more than 95%. The Kappa value or Cohen's Kappa score compares the expected accuracy with the observed accuracy for a classifier [80]. The closer it is to 1, the better the classifier will be. In this case, the Kappa value for SVM is 0.98, very close to the upper limit of 1.

2) Vital Sign and Motion Detection: Vital signs, such as respiration rate, heart rate or pulse rate, are direct indicators of health. Gait and other motions have also been shown as an important indicator and predictor of the health status, especially in the elderly.

In [49], the authors studied the use of 5G C-band signals operating at 4.8 GHz to detect the tremors and breathing activities for multiple sclerosis (MS) patients. MS is a motion-related neuro-degenerative disease. It causes mobility impairment and many functional disabilities. One syndrome of this disease is tremor due to muscle weakness, spasm and ataxia, which could lead to paralysis. Another syndrome related to this is the lost control of breathing, due to weak respiratory muscles. The authors used the same equipment as [45] to capture CSI at 4.8 GHz from 30 sub-carriers. Three machine learning algorithms were used: SVM, K-nearest neighbor (KNN) and random forest (RF). Their performances were examined in terms of accuracy, precision, recall, specific, Kappa and F-measure. Four motions: sitting, lying, falling and tremors, were detected, where the transmitter and receiver were 4 to 5 meters away. Breathing detection was performed when they were 1 to 1.5 meters away, and compared with a respiratory sensor. Features used include root mean square, square root of amplitude, mean, Kurtosis, crest factor, skewness, impact factor, peak-to-peak, standard deviation, marginal factor. Overall, SVM has the best performance with an accuracy of 95% for sitting, 98% for lying, 100% for falling and 96% for tremor, and its Kappa value is 0.96. Its recall, precision, specificity and F-measure values are also higher. For breathing detection, the correlation between 5G sensor and a wearable respiratory sensor is 0.88 for normal breathing and 0.87 for abnormal breathing, showing the effectiveness of 5G sensing. The same authors also worked on body motion detection for Huntington disease (HD) [42]. HD commonly affects people in their thirties and forties. The most common symptom is chorea, where patient feels uncontrollable jerky moving or body twitching. Monitoring body motion is therefore essential to discover and treat HD. They focused on SVM to give an accuracy of 96% to 99%.

In [50], the authors proposed a breathing monitoring system using 5G C-band at 4.8 GHz to capture breathing-induced chest movements in diabetic ketoacidosis (DKA) patients. Typical signs of DKA include Kussmaul breathing, a deep and labored breathing pattern, and a fruit-scented breath. Their experiments showed that, in normal breathing, the respiratory rate is 17 breaths/minute and extent is between -1 and 1. In Kussmaul breathing, the rate is 32 breaths/minute and extent is larger than 1. Thus, the respiratory rate and extent were used to diagnose and monitor DKA. The amplitude of the CSI was used and the data was first pre-processed using wavelet transform to remove outliers and then peak detection was used to calculate respiratory rate and extent. The distance between transmitter and receiver was 2 to 3 meters. Ground truth was obtained using HKH-11C digital respiratory sensor. Out of 30 sub-carriers, the 13-th was chosen as the best. SVM was used to classify normal breathing or Kussmaul breathing. The accuracy is 98.75%.

In [46], the authors used 5G C-band signals to detect the freezing of gait (FOG) episodes experienced by Parkinson's disease (PD). They used a signal generator DSC3000 series, two dipole antennas, TP-link (PCE-AC68) NIC, and a desktop to capture the amplitude of CSI, which was then converted into time domain features of mean, standard deviation, skewness, Kurtosis, mean absolute deviation, interquartile range and peaks. Then, these features were used in a multi-layer perception neural network with a single input layer, single hidden and output layer using Levenberg-Marquardt training to classify between sitting, slow walk, fast walk, voluntary stop and FOG episodes. Details of these neural network methods can be found in [81]. The classification for FOG is 99.3%, better than any existing methods.

In summary, 5G radio sensing has great potential in healthcare applications to save and protect lives. It allows the identification of key symptoms of various diseases that are related to human body movements. The identification often uses the CSI or the amplitude of CSI. It requires comparison between normal people and patients for training. The classification is performed by using machine learning. SVM has the best overall performance in many cases so far. Neural networks offer an alternative. Table IV summarizes the application of 5G radio sensing in healthcare. Several lessons are learned. Firstly, it is observed from [46] that the neural networks methods can greatly improve the accuracy of 5G radio sensing. However, very few works used these methods. Thus, the detection in [45], [49], [42], [50] could be further improved by using neural networks, at the cost of much longer data records for training. Secondly, these works overwhelmingly used CSI. However, as discussed in Section III, RRSS contains more information about the objects and could be used to improve accuracy. Finally, most of these works used the 4.8 GHz band. Higher 5G frequencies could be used to improve performance. For healthcare applications, detection accuracy is critical.

B. Safety

The ultimate goal of safety is to protect lives from danger. In this case, 5G radio sensing can acquire an environmental

TABLE IV
HEALTHCARE APPLICATIONS OF 5G RADIO SENSING

Ref.	Diseases	Detectors	Frequency	Bandwidth	Antenna	Metrics	Methods	Accuracies
[45]	post-surgical patient	fall	4.8 GHz	30 sub-carriers	single omni	CSI	SVM, NB, DT	>95%
[49]	multiple sclerosis	tremor, breath,	4.8 GHz	30 sub-carriers	single omni	CSI	SVM, KNN, RF	>95% for tremor, 0.88 correlation for breathing
[42]	Huntington disease	body motion	4.8 GHz	30 sub-carriers	single omni	CSI	SVM	96% to 99%
[50]	Diabetic ketoacidosis	breathing	4.8 GHz	30 sub-carriers	single omni	amplitude of CSI	SVM	98.75%
[46]	Parkinson's disease	freezing of gait	4.8 GHz	30 sub-carriers	single omni	amplitude of CSI	neural networks	99.3%

perception and use this perception to make critical decisions on how humans should act and behave within safe limits.

1) Workplace Safety: In a smart factory, humans often work together with robotics, such as on a car assembly line. In this case, 5G radio sensing can perform human activity recognition to enhance the transparency of human-machine interaction. This allows a robot to follow human movements without obstructing human operations. For example, near hazardous machinery, a virtual fence could be built by using 5G radio sensing so that an alert will be made if humans get too close.

To realize this, the non-cooperative detection of human presence is important so that human operations will not be disrupted. Human activity recognition is also important. One area related to human activity detection is human gesture and pose detection. Also, human activity recognition in surveillance systems tracks individuals and crowds to support the security guard to monitor suspicious activities and detect possible hazards or anomalies.

In [8] and [43], the authors used CSQ measurements from mobile devices, including 5G networks, to detect body movements near smartphone. Even in idle mode, smartphone carries out continuous and autonomous measurements of the downlink channels from different base stations for cell reselection. Any fluctuation in these measurements reflects body movement or scene change in the surrounding. In these works, when the body is less than 0.5 meter away from the device, CSQ measurements were taken for one month from 2 to 4 smartphones, and then processed using a sequential change detection algorithm based on cumulative sum to isolate changes due to body motion from changes due to network. Then, machine learning was applied to these detected changes using Bayesian classification based on Dirichlet-Compound Multinomial model, SVM, and long-short term memory (LSTM), to identify the body motion. Off-the-shelf smartphones were used. SVM has an accuracy of 80%, Bayesian has an accuracy of 90%, while LSTM has comparable performance with Bayesian.

In [5], 5G sensing was used for workplace safety. For a typical human-robot collaborative scenario with one robot handling tasks and located inside an open workspace that is shared with one human worker. Both were moving so that the position of human must be tracked continuously. The authors studied three methods: WiFi passive sensing with 16 industrial standard wireless nodes, fast beam-steering and passive sensing using 100 GHz. In the last case, a virtual safety fence was implemented to discriminate safe and unsafe activities within 0.5 to 2 m of the robots. CSI measurements were used in maximum likelihood estimation, LSTM, and a deep neural network. The deep neural network achieves an accuracy of 99% for recognizing standing, moving arms and crossing fence. A similar study was done in [64]. Considering a human-robot collaborative workspace, a mixture of 6 frequency modulated continuous wave radars in sub-THz band, 3 infrared sensors, one radio transmitter for opportunistic sensing at 100 GHz, and a sub-THz camera, with 1024 detectors, were deployed to detect and track human operators in a virtual fence system. CSI was used. The classification accuracy is larger than 96% with a latency less than 150 ms.

In [41], the authors used a prototype 5G system with 52 OFDM sub-carriers and a large sub-carrier spacing of 240 kHz at a center frequency of 3.45 GHz to detect presence and walking speed. In presence detection, two universal software radio peripheral (USRP) devices (USRP X310) were used as transmitter and receiver in two rooms, a TP-LINK omni-directional antenna with a gain of 18 dBi for both transmitter and receiver and a window of 60 ms equivalent to 300 OFDM symbols. In walking speed detection, two USRP NI 2932 devices were used as transmitter and receiver. The transmitter used TP-LINK omni-directional antenna with 18 dBi, while the receiver used a planar antenna with 5 dBi. They were 20 meters away from each other. A window of 20 ms was used. They used both time and frequency domain features, including mean, standard deviation, variance, root mean square, frequency spectral entropy, Kurtosis, skewness from the RSS measurement applied to KNN. The best accuracies were 92.8% and 95% for presence and walking speed, respectively, in comparison with 70% by using a sensor. References [47] and [48] give more details on walking speed recognition performed in [41]. A similar study was done in [62].

Reference [65] studied the use of beam-steering to recognize distinct activities from multiple humans. This task is much more challenging than recognition of a single human but is necessary in workplaces where multiple human operators work with robots. They used receiver-side beamforming and beam-sweeping over different azimuth angles to detect human presence. Beamforming is very energy-consuming and hence, will not be constantly available in the environment, unless the receiver is customized for sensing instead of using existing 5G terminals. Thus, this method has limited use. The experiment used the sub-6 GHz band and a USRP X300 with one antenna as transmitter and three USRPs as receivers each with phase synchronized 4 antennas and having 52 OFDM sub-carriers in a 22.4 m^2 semi-anechoic chamber. The method can detect 0 to 4 persons within one person error in 100 experiments, 5 persons in 43 out of 100 experiments, 6 persons in 50 out of 100 experiments, without any prior training. It can also extract 20 gestures out of 21 from one person when up to three were simultaneously there. CSI was used. A similar study was performed in [63] and [66], where receiver-side beamforming was able to detect the direction-of-arrivals for up to four stationary humans and track the direction-of-arrival of up to two walking humans at the same time.

2) Road Safety: Road safety is another important application of 5G radio sensing. This is particularly useful because 5G is chosen as the backbone to support vehicle-to-everything communications and hence, future vehicular networks are likely to be built within 5G networks to use ambient 5G signals for road sensing [67]. With the advent of autonomous driving, this application becomes critical, as driver-less cars need to sense the driving environment not only for efficiency, such as route planning and energy saving, but also for safety to protect other road users as well as avoid any accidents. Traditional methods often adopt radars, lidars, cameras or sonars. However, most of these methods require LOS, which is not possible in some cases. 5G radio sensing could be a useful complement to active radars.

In [71], a detector for crossing a curb was proposed to protect pedestrians, as they may be crossing the road between two parked cars without being noticed by drivers on the road. First, a context filter based on human activity recognition was designed to detect the pedestrian's position, movement direction and acceleration to determine if the pedestrian is stepping on the road. Then the result will be communicated to the nearby cars via 5G internet and D2D communications. The study used sensor data from smartphones carried by pedestrians but it could also use 5G signals from road side units. In the detection, the curb crossing is made of three steps: standing at or walking to the curb, crossing the curb and standing or walking towards the road. Three curb heights were tested based on German standards. Five activities were considered from standing, slow walking, fast walking, running to crossing. The accelerometer and gyroscope were used to acquire data. Machine learning algorithms including KNN, C4.5, RIPPER2, NB, sequential minimal optimization (SMO) were applied to features of mean, variance, standard deviation, energy, entropy and integral. KNN has the best overall performance of a missed alarm rate between 19% and 33%. In [72], the authors focused on the recognition of crossing curb or stepping down alone. They proposed a frequency domain method to analyze the frequency components of the data followed by low-pass and high-pass filters, and a grouping method to improve recognition by grouping similar activities in the data. The new method improved the F-measure by 20%, precision by 18.7% and recall by 20.9%, compared with state of the art method, for crossing curb recognition. A detailed discussion of pedestrian safety was given in [70].

In [61], the authors proposed a new concept of cooperative passive coherent location (CPCL) scheme to support road safety using 5G radio sensing. Its novelty is to extend traditional passive radar using one node to cooperative passive radar involving several nodes. In CPCL, any radio acts as an illuminator or observer. Locally estimated object parameters were exchanged and fused, creating a powerful radar network. The authors discussed possible issues in radar signal processing, networking, synchronization, and data fusion. Finally they showed an initial example using one transmitter and two receivers to prove that cooperation is beneficial.

In [68], the authors proposed a new road surveillance system using 5G OFDM signals. The surveillance was enabled by using the combination of delay and Doppler estimates from multiple bistatic passive radar links. The Cramer-Rao lower bounds for joint estimation of delay and Doppler were derived. A parameter set for low signal-to-noise ratio (SNR) applications was obtained to satisfy the accuracy requirement while reducing the bandwidth requirement on delay estimation. The minimum required observation time was also determined for Doppler estimation.

In summary, 5G radio sensing has an important use in road safety. This is driven by the adoption of 5G networks in future vehicular networks for smart traffic as well as the pervasiveness of smart phones. The targets of sensing in this use are pedestrians to protect vulnerable road users and vehicles for road surveillance. However, due to the complexity on the road, this sensing is challenging and therefore, requires cooperation sometimes to improve accuracy and reliability. Table V summarizes the applications of 5G radio sensing to enhance safety. The lessons learned can be summarized as follows. Comparing these works, it is concluded that high frequency leads to high accuracy, as in [5] and [64]. Thus, other works could also explore the high frequency to achieve better accuracy. Also, the foundation of these applications is motion detection. Motion detection requires the decomposition of the whole process into several typical stances. This decomposition is the key and could seriously affect the sensing accuracy.

C. Localization and Positioning

Localization and positioning are important applications of radio sensing. There have been a lot of works on device-free localization even before 5G was deployed [69]. The deployment of 5G systems makes these applications extremely attractive, as 5G radio sensing can achieve an accuracy of centimeters, a much better result than the commonly used GNSS-based method with an accuracy of several meters. In 5G radio sensing, the localization is device-free or sensor-less.

1) Vehicle Positioning: Similar to road safety, vehicle localization is an important application of 5G sensing, because the vehicular networks are inherently built within the 5G networks. For autonomous driving, finding where the vehicle is determines all the following actions, such as route planning and traffic monitoring. 5G signals have many unique characteristics that make them suitable for vehicle positioning.

In [15], a feasibility study was performed to use the 5G communications waveforms as radar signals. Different 5G frequencies and bandwidths were discussed. Three scenarios

TABLE V
SAFETY APPLICATIONS OF 5G RADIO SENSING

Ref.	Application	Detectors	Frequency	Bandwidth	Metrics	Methods	Accuracies
[8], [43]	surrounding	body movement	unknown	unknown	CSQ	SVM, DCM, LSTM	90%
[5]	human-robot	standing, arm-moving, crossing	100 GHz	unknown	CSI	MLE, LSTM, Deep Neural	99%
[64]	virtual fence	body motion	100 GHz	unknown	CSI	machine learning	96%
[41], [47], [48], [62]	workspace	presence, walking speed	3.45 GHz	12.48 MHz	RSS	KNN	92.8% - 95%
[65], [63], [66]	workspace	presence and activity from multiple	3.42 GHz	12.48 MHz	CSI	MMSE beamforming	high
[71], [72]	pedestrian	crossing curb	unknown	unknown	accelerometer and gyroscope	KNN, C4.5, RIPPER2, Bayes, SMO	80%
[61]	road safety	car locations	unknown	80 MHz	RRSS	Bayesian fusion and MEC	unknown
[68]	road surveillance	range and velocity	5.2 GHz	10 MHz to 1 GHz	RRSS	Delay, Doppler estimation	unknown

of 5G radar in vehicle radar, marine radar and aviation radar were described. For adaptive cruise control, a range resolution of less than 0.5 meter is required and can be satisfied using a bandwidth of 400 MHz as in 5G new radio. The related operation ranges for radar and communications are 90 meters and 150 meters, respectively, which could be further increased by increasing the transmission power within FCC limits. Also, a SNR higher than 15 dB is required to satisfy the velocity resolution requirement. A joint receiver for radar parameter estimation and timing synchronization was also proposed and the simulation of mean squared errors showed that coarse range and velocity estimates can be achieved.

In [51], 5G mmWave communications signals were proposed for vehicle positioning to replace GNSS-based positioning. GNSS is limited by blockage, and it treats multi-path as interference, while 5G localization utilizes multi-path for simultaneous localization and mapping based on time of arrival measurements. Assuming both reflecting surfaces and scattering points, the work proposed a Bayesian 5G tracking filter followed by a brief propagation filter. The tracking filer performed data association to match paths to map entries. The propagation filter computed posterior distributions over vehicle state and map entries, and distinguished different sources without prior knowledge. This algorithms gave an average tracking error of 0.5 meters, 0.02 radians, and 0.3 meters for the vehicle location, heading and clock bias, respectively. Reference [59] gave an overview of vehicle positioning using 5G signals.

In [54], the authors studied the use of 5G signals transmitted by the base station as a monostatic radar for ranging in a time-division multiplexing systems. First, they analyzed the range and velocity estimation resolutions for different bandwidths and observation time. 5G FR1 and 5G FR2 can give a range resolution of around 1.5 meters and 0.4 meters, respectively. The best option is FR2 with bandwidth 400 MHz and sub-carrier spacing 120 kHz. For the velocity resolution, FR2 is an order of magnitude better than FR1. In their experiments, they used a NI PXIe-5840 vector signal transceiver as transmitter and receiver at 3.5 GHz and then two Keysight N5183B-MXG signal generators to up-convert and down-convert them to 28 GHz. The system verified the proposal for indoor and outdoor sensing. A similar study was also performed in [60] by the same authors with more emphasis on self-interference removal.

2) Location-aware Communications: The UE location is important in cellular communications for many location-based services, but it is even more important in 5G systems, as it can improve the radio access network, for example, by enabling location-based beamforming to reduce interference and strengthen signals or location-based mobility and radio resource management to improve spectral efficiency. If the UE is the vehicle, then the methods in the previous subsection may also be used for UE positioning and tracking.

In [53], the advantages of UE positioning in 5G were first reviewed. Then, using LOS, an extended Kalman filter was used to track its directional parameters for positioning performed at the base station. A ultra-dense network with 74 access points (AP) was used. The APs use circular arrays with 20 elements and transmission power of 23 dBm. The UE uses circular arrays with 4 elements and transmission power of 10 dBm. The UE travels between 30 km/h to 50 km/h. The system operated at 3.5 GHz with OFDM for both up and down links. Sub-carrier spacing is 240 kHz and transmission interval is 200 micro-seconds using Zadoff-Chu sequence. Both centralized and distributed tracking were performed. The error in azimuth angle at AP is less than 0.1 degrees and in elevation angle at AP is less than 3 degrees, in all cases. Tracking at UE has larger errors. The authors also compared traditional CSI-based beamforming with location-based beamforming and showed that receiver side location-based beamforming has excellent throughput performances. This saves the overhead for channel estimation, which is a serious issue in massive MIMO due to pilot contamination.

In [55], the authors studied different approaches of the UE positioning for mmWave communications using LOS, NLOS, combined LOS and NLOS. Using a transmission power of 10 mW and a frequency of 60 GHz, trilateration methods using RSS, ToF and AoA were compared. It was shown that RSS is generally poor, while ToF and AoA have good performances with LOS, with possible more improvement by combining ToF and AoA. For small spaces, combining LOS with the 1st order reflection signals and using both ToF and AoA give decimeter level accuracy. For large spaces, LOS with ToF shows good promise.

In [52], the authors compared indoor localization using RFID, unmanned aerial vehicle (UAV), and 5G. For 5G, they used a carrier of 60 GHz and a bandwidth of 2 GHz and compared three conditions: LOS, obstructed LOS and obstructed LOS using beamforming. The results showed a localization error of only 2 cm for the LOS and 3 cm for the obstructed LOS. Beamforming made it more robust with only one anchor required. This problem was further studied in [57], where multi-path components in a 5G signal were used to localize indoor objects for assisted living.

3) Mapping: Mapping is useful in many applications, such as autonomous driving and geographical survey. Traditional methods use X-ray or radar [20]. They require dedicated hardware with high frequency, large bandwidth and antenna arrays. Consequently, they are extremely expensive and usually bulky. 5G signals can be used to capture the positions and shapes of objects in the environment for mapping at low cost but with sufficient accuracy, due to their mmWave carrier frequency and bandwidths of hundreds of MHz.

In [75], an indoor mapping method was proposed using 5G new radio signals at 28 GHz. Phased arrays at both transmitter and receiver were steered towards different directions and the reflections from objects were used to reconstruct the environment. The processing is similar to that in Section III.A, where the periodogram was calculated and smoothed using a Gaussian kernel to map a corridor with 2 meters width and 60 meters length. The measurements were taken and processed by using a vector signal transceiver PXIe-5840 as RF transmitter and receiver at 3.5 GHz and two signal generators N5183B-MXG with external mixers to up and down convert to 28 GHz for OFDM signals with bandwidth 400 MHz and sub-carrier 120 kHz. The results showed impressive mapping performance.

In [76], joint localization and mapping was studied, where 5G signals were used in a message-passing method to jointly estimate the position, orientation of the UE, as well as the locations of any scatters or reflectors. With no prior knowledge assumed, the estimator was able to provide accurate single-snapshot simultaneous localization and mapping even without LOS. In particular, the root mean squared error of the proposed method was much lower than the least squares method proposed in [77] and [78].

In [79], environment mapping was also studied for a 2D surface and a 3D space where 5G signals at 60 GHz was transmitted as illuminator in a bistatic mode to perform mapping at the receiver. They used Analog Devices HMC6350 evaluation kit with HMC6300 board as transmitter and HMC6301 as receiver. Tektronix TSM4102A signal generator and DPO70404C oscillator were used to generate and record signals. The performance depends on the number of antennas, measurement noise, sparsity of signals etc. In [58], mapping for a 3D space was studied using reflected 5G OFDM system at 2 GHz with a 64-element array at both transmitter and receiver. Similar to other works in this subsection, no changes to the existing 5G system were required for the mapping. They first proposed a FFT-based ranging method similar to frequency modulated continuous wave radar. Then ranging data from different channels were stitched to improve ranging resolution by increasing bandwidth. To verify this, they built a 5G prototype base station. Using a channel bandwidth of 100 MHz, 8192 sub-carriers with spacing 12.2 kHz to achieve 3D images of indoor scenes with angular resolution of 2 degrees and range resolution of 15 cm, without affecting 5G communications.

In summary, the applications in this subsection are related to positioning and localization. These applications are related to each other, for example, outdoor environment mapping could be used for vehicle positioning while indoor environment mapping could be for UE positioning. Table VI summarizes application of 5G radio sensing in localization and positioning. The lessons learned can be summarized as follows. These works overwhelmingly use the RRSS measurements for high accuracy. However, further improvements could be achieved by using higher frequency or larger bandwidth, especially in [79] and [58]. Also, the stitching method from [58] suggests that, instead of using omni-directional antenna to cover the whole area, one may consider the use of directional antenna or beamforming to focus on different parts of the area and then stitch them together for better accuracy. Finally, very few of these works use machine learning or deep learning but these methods have been proved effective in other applications. Thus, they may be considered in localization and positioning.

D. Other Applications

Identification or detection of materials is an exciting use of 5G radio sensing. It has wide applications, such as concealed weapon detection or expired milk warning. Existing methods overwhelmingly use X-rays, radar, computed tomography (CT) or magnetic resonance imaging (MRI), which adopt extremely high frequency and large bandwidth signals for sensing. Hence, they are often expensive and require specialist

TABLE VI

LOCALIZATION AND POSITIONING APPLICATIONS OF 5G RADIO SENSING

Ref.	Application	Detectors	Frequency	Bandwidth	Methods	Accuracy
[15]	5G radar	range, velocity	all 5G frequencies	all 5G bandwidths	correlator	varies
[51]	vehicular tracking	location	mmWave	unknown	Bayesian tracking filter	0.5 meters for location, 0.02 radians for heading, 0.3 meters for clock bias
[54], [60]	mapping	range, velocity	28 GHz	400 MHz	periodogram, self-interference cancellation	unknown
[53]	UE positioning	location	3.5 GHz	200 MHz	Extended Kalman, beamforming	0.1 degrees error in azimuth angle, 3 degrees error in elevation angle
[55]	UE positioning	location	60 GHz	2.16 GHz	RSS-, ToF-, AoA-trilateration	varies with parameters
[52], [57]	assisted living	location	60 GHz	2 GHz	ML, tracking filter	0.02 meters for LOS, 0.03 meters for NLOS
[75]	indoor mapping	location	28 GHz	400 MHz	periodogram and Gaussian kernel	unknown
[76]	mapping	position, orientation	mmWave	unknown	message passing estimator	error of 1.8 degrees in orientation, 7 meters in position
[79]	imaging	region	60 GHz	900 kHz	scalar potential	varies with parameters
[58]	imaging	region	28 GHz	100 MHz	radar processing and stitching	angular resolution 2 degrees and range resolution 0.15 meters

training for operation. The use of 5G signals opens another horizon, as objects of different sizes, shapes and materials cause different reflection or diffraction of the 5G signals. In [73], liquid detection was studied using 5G C-band at 4.8 GHz. First, they used CSI to distinguish between suspicious and non-suspicious liquids. Then, they identified the type of liquid. Finally, they distinguish different concentrations of alcohol. The transmitter and receiver were 1 meter away using signal generator and spectrum analyzer. The bandwidth was 100 MHz and transmission power was -5 dBm. KNN was used to achieve an accuracy of 98% to detect suspicious liquids, 97% to identify the type and 94% to recognize the concentration of alcohol. In [74], a liquid-sensing ring resonator was designed at 36 GHz. It measured and analyzed the dielectric constant of the liquid to identify the liquid.

Humidity detection is another application of 5G radio sensing. In [82] and [83], on-body humidity sensing antenna was designed at the 38 GHz frequency by detecting the dielectric constant of polyimide and changes in resonant frequency. UAV detection becomes a popular area in recent years, due to many unauthorized UAV flights and safety concerns. In [84], a 5G-based phased-array was designed for passive detection of UAVs. It used radar waveforms to detect a DJI Phantom 3 UAV with a range of more than 250 meters and SNR larger than 10 dB and an angular resolution of 8 degrees.

In summary, the high carrier frequency and the large channel bandwidth have equipped 5G signals with many benefits. In fact, the high frequency and large bandwidth of 5G have made 5G signals similar to conventional custom-made high-resolution radar sensing signals. Thus, the 5G signals can be used to either detect and recognize large objects at fine resolution or small objects that are otherwise not possible using other wireless signals. The advantages and disadvantages of the works discussed above are self-evident from Tables IV - VI. For example, the approaches in [52], [57] require large bandwidth and high frequency to achieve high localization accuracy but the approach in [51] has low accuracy but less requirements on frequency and bandwidth. Thus, these advantages and disadvantages are not repeated here.

V. OPEN CHALLENGES

To improve the accuracy of existing 5G radio sensing methods and to widen the use of 5G radio sensing in various applications, further investigation is required. Some open challenges in 5G radio sensing are discussed as follows. These challenges stem from the limitations of existing works that have been discussed above.

1) Outdoor Sensing: Most of the existing 5G radio sensing methods discussed above aim at indoor scenarios, except vehicle positioning. Indoor environments are more controllable with less uncertainty and higher probability of LOS in many cases. However, 5G provides coverage not only for indoors but also for outdoors. Thus, outdoor 5G radio sensing also requires attention, such as construction site safety and traffic monitoring. This is a challenge because outdoor environments are more complicated and more diversified and therefore, less controllable due to more scatters and higher dynamics. Intelligent reflecting surfaces could offer a solution for small areas by customizing the propagation environment [85].

2) Range: Related to the first challenge, most of the existing 5G sensing methods discussed above are only developed for uses in short range, when transmitter and receiver are separated a few meters away or at most tens of meters apart. This may be enough for indoor sensing. However, for outdoor applications and for large indoor venues, the sensing range needs to be increased, as the signal strength decays quickly with the distance. This could be achieved by increasing the transmission power but as the distance increases, it is likely to have more dynamics and the increased transmission power will increase interference too. Thus, 5G radio sensing will become more complicated for long range. This may require deep learning and data mining to extract as much information from the measurements as possible. Also, network densification in 5G alleviates this problem by increasing the density of access nodes.

3) Multiple Objects: Most of the existing 5G sensing works sense a single object. This is relatively easy, as the received signal is only affected by one object. However, there are scenarios where multiple objects need to be sensed in the same area, such as [65], [63] and [66]. Sensing multiple objects in the same area is relatively difficult, as their information is mixed in the received signal, but is necessary for some applications. References [65], [63] and [66] provided very elegant solutions by taking advantage of beam-steering to scan the space. However, this applies to multiple objects in a homogeneous environment. If they are in a heterogeneous environment, such as different persons staying in different rooms with different materials, 5G radio sensing will be difficult, as the propagation information for different persons may have different strengths so that one is stronger than the other in the same received signal. In this case, a scheme similar to successive interference cancellation may be useful.

4) Theoretical Models: Most existing 5G sensing works have studied the effects of different sensing parameters on the sensing accuracy. However, a systematic study of these effects is missing, as parameters could be correlated with others but these relationships are unknown. Also, most of these studies are heuristic via computer simulation. There is no theoretical model describing the explicit relationship between the sensing performance and sensing parameters. The lack of such model makes most 5G radio sensing designs ad hoc using trial-and-error. This issue is similar for WiFi sensing. However, since 5G uses the mmWave band, there are less multi-path components and hence, a more in-depth analysis may be possible by adopting the most recent advances in electromagnetic theories.

5) Joint Sensing and Communications: Most existing works consider 5G radio sensing only. However, in some applications, both sensing and communications functions may be required. It will be useful to develop joint sensing-communications to improve efficiency. Sensing can use either ambient 5G signals dedicated to communications or 5G signals custom-made for sensing. The use of ambient 5G signals dedicated to communications makes sensing sub-optimal, as the optimal sensing waveform is different from the optimal communications waveform. The use of the optimal sensing waveform will require changes to existing 5G communications. Hence, a joint dual-functional or time-duplexed waveform design for 5G radio sensing and 5G communications may be useful to reap the benefits of both radio sensing and communications.

6) Friendly to Sensing: Current 5G systems are designed for communications, not for radio sensing. Consequently, it is difficult for the sensing services to extract the RRSS, CSI or RSS measurements from the off-the-shelf 5G devices, as users are not expected to have access to these measurements. Currently, specialized hardware is required to retrieve these measurements. Thus, future 5G systems can be made more friendly to radio sensing by providing these measurements at the top layer for any users that require sensing services. This problem could be addressed in beyond 5G systems by upgrading the protocols.

7) Lack of Sensing Applications: Although many important applications of 5G radio sensing have been developed, as discussed before, there are still more to develop. For example, there has been no work on crowd counting using 5G signals. There has been no emotion recognition using 5G radio sensing. This is not surprising, as the 5G system has only been deployed recently, while WiFi and other generations of cellular signals have been in existence for a long time and therefore has more mature hardware and software. Nevertheless, given the many advantages that 5G signals have, it is expected that this area will attract more attention to develop more sensing applications. The quick roll-out of 5G systems and publications in this area, including this paper, may help tackle this.

8) Beamforming: Beamforming has played an important role in several 5G radio sensing works, such as [63], [65], [66] and [75], and may continue to play such a role in the future. 5G radio sensing uses the 5G signals that propagate through a changing environment to detect and classify such changes. Beamforming achieves additional spatial gain at the sensor by steering the beam pattern of the 5G signals to different directions for high-resolution sensing. It can be implemented by either reconfiguring the radiation pattern of an array via phase and amplitude adaptation or by physically steering the array to scan the space. Although its efficiency has been proven in [63], [65], [66] and [75], many 5G sensing works have not considered it, as beamforming is very energy-consuming and could incur high running cost. As the hardware cost reduces in the future, this problem will alleviate. Also, applications requiring high security and safety, such as collision avoidance and workplace safety, may adopt beamforming first.

9) Beyond 5G Sensing: The research on beyond 5G or 6G systems has recently started [86]. Although the key technologies for 6G are still under investigation, it is widely agreed that intelligent surfaces, artificial intelligence, mobile edge computing [87], fog computing [88], larger bandwidth and higher carrier frequency up to terahertz could be adopted. Thus, the open challenges of 5G radio sensing discussed above could be partly addressed in the evolution from 5G to 6G. For example, the use of terahertz signals in 6G will make radio sensing even more accurate by having higher ranging resolution. The use of artificial intelligence will improve outdoor radio sensing. The use of mobile edge computing or fog computing will widen and ease the deployment of radio sensing services at

TABLE VII

OPEN CHALLENGES AND POSSIBLE SOLUTIONS

Challenges	Solutions
outdoor sensing	intelligent reflecting surfaces
range	deep learning, network densification
multiple objects	successive cancellation
theoretical models	advanced electromagnetic theories
joint sensing and communications	dual-functional designs
friendly to sensing	protocol upgrades
lack of sensing applications	roll-out of 5G
beamforming	reduced hardware cost
beyond 5G sensing	combined radio sensing and 6G

the edge to relieve computational load and reduce latency. For these reasons, radio sensing will become even more important in 6G systems due to the increased demand for "smartness" in future networks and the increased accuracy of 6G radio sensing albeit more localized due to their larger bandwidth and higher frequency.

6G also offers a great opportunity for radio sensing by making the cellular systems more friendliness to sensing with easier access to measurements in the protocols and the development of joint sensing and communications to have higher integration of sensing and communications. Future 6G standards should include radio sensing to diversity its killer applications and to increase its efficiency. The main application scenario of radio sensing in 6G is localization and sensing, as outlined in the 6G white paper [89]. Other applications scenarios of radio sensing include joint sensing-communications and autonomous driving. Table VII gives a list of the challenges and possible solutions discussed above.

VI. CONCLUSION

This paper has provided an overview of most works on 5G radio sensing completed so far. Different sensing works have been discussed based on their applications in healthcare, safety, localization and others. This covers most works in the literature but is no complete list for all possible areas 5G radio sensing can help in the future. Hence, open challenges in 5G radio sensing have been discussed at the end. Moreover, future 6G systems will use even higher frequency and larger bandwidth to provide global wireless connection. These features will improve radio sensing further. Since the aim of this work is to provide an overview of existing works, no new simulation or experimental results have been provided and interested readers can refer to the references listed for such results.

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