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Review Article

Prospective RFID Sensors for the IoT Healthcare System

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The outbreak of COVID-19 has attracted people's attention to our healthcare system, stimulating the advancement of next-generation health monitoring technologies. IoT attracts extensive attention in this advancement for its advantage in ubiquitous communication and sensing. RFID plays a key role in IoT to tackle the challenges in passive communication and identification and is now emerging as a sensing technology which has the ability to reduce the cost and complexity of data collection. It is advantageous to introduce RFID sensor technologies in health-related sensing and monitoring, as there are many sensors used in health monitoring systems with the potential to be integrated with RFID for smart sensing and monitoring. But due to the unique characteristics of the human body, there are challenges in developing effective RFID sensors for human health monitoring in terms of communication and sensing. For example, in a typical IoT health monitoring application, the main challenges are as follows: (1) energy issues, the efficiency of RF front-end energy harvesting and power conversion is measured; (2) communication issues, the basic technology of RFID sensors shows great heterogeneity in terms of antennas, integrated circuit functions, sensing elements, and data protocols; and (3) performance stability and sensitivity issues, the RFID sensors are mainly attached to the object to be measured to carry out identification and parameter sensing. However, in practical applications, these can also be affected by certain environmental factors. This paper presents the recent advancement in RFID sensor technologies and the challenges for the IoT healthcare system. The current sensors used in health monitoring are also reviewed with regard to integrating possibility with RFID and IoT. The future research direction is pointed out for the emergence of the next-generation healthcare and monitoring system.

1. Introduction

The advent of coronavirus disease in 2019, widely known as COVID-19, has caused an epidemic sweeping the world since 2020 [1]. As of 18 April 2022, the cumulative number of cases worldwide is 508million and the number of deaths exceeds 6.2 million. The fast spread of this disease is caused by the extremely contagious nature of the virus and the long incubation period (1-14 days) of the disease. Cutting down the transmission route and controlling the infected patients are the keys to controlling the epidemic. According to current evidence, the COVID-19 virus is mainly transmitted through respiratory droplets and contact routes. Fever is one of the common symptoms of COVID-19 and can be screened with temperature measurement. Thus, the main method of blocking transmission and initial screening is the quarantine of potential carriers and access control based on the temperature measurement in public places. Common temperature measuring devices (infrared thermometers [2], mercury thermometers [3], etc.) have varying degrees of "shortcomings": traditional temperature measuring devices do not automatically record temperature data and are susceptible to ambient temperatures, and direct temperature measurement is prone to cross-contamination and is not suitable for carrying around. These problems have become difficult and painful points for temperature monitoring and crowd control at high risk of the epidemic. Thanks to the advancement in technology, traveller tracking methods such as the health QR code and NHS COVID-19 app have been used to identify the contact people of carriers who did not show symptoms yet. These new techniques which have played an important role in our fight against COVID-19 are all supported by the Internet of Things (IoT) technology.

In recent years, IoT has emerged as a promising technology which extends the concept of the Internet and makes it more pervasive, allowing for seamless interaction between different types of devices. The roles of IoT include identification, information collection, exchange and processing, decision-making, and security, which are aimed at connecting "Everything" together and making them smarter. Cloud computing and artificial intelligence (AI) are two key technologies to enable smart decision-making in various applications, but their accuracy and reliability is based on a huge amount of data from massive sensors, which is only achievable with the introduction of communication technologies, including but not limited to wireless sensor networks (WSN), radio frequency identification (RFID), and 5G. IoT technologies, such as 5G networks [4], radio frequency identification (RFID), and sensor networks, have important applications such as telemedicine, remote surgery, tracking patient activity in healthcare facilities, real-time monitoring using RFID wearable devices [5, 6], and providing ongoing treatment information and support for patients.

Being power hungry has been a challenge for many electronic devices, especially wireless sensor devices, which require long-term monitoring operation with limited charging or battery change. RFID is the key enabling technology for passively providing wireless communication and identification for massive devices in IoT. Thus, the introduction and development of RFID is the key to addressing the challenges of communication and sensing in a number of areas, including healthcare systems. As shown in Figure 1, the RFID-based communication and identification and RFID-based sensing system are two main applications of RFID technology [7]. RFID was first used in aviation for identifying allied and enemy planes. Then, it is introduced for authentication and security in room access, as well as tracing and tracking of targets in different application scenarios, such as goods in supply chains, patients in healthcare systems, or domestic animals in agriculture. From the first decade of the 21st century, the potential of sensing capability in RFID has attracted significant interest from many areas, e.g., supply chains, industrial production, and healthcare.

Recent advancement in RFID-based sensors has proven their capability in many applications. The Wireless Identification and Sensing Platform (WISP) is developed in [8] as a generic identification and sensing platform and can be integrated with low-power sensors including light, temperature, or push buttons. This generic sensing capability has found their application in many industries as well as healthcare systems. More advanced research studies are undertaken for application-specific sensing purposes, e.g., crack, corrosion, and stress sensing in industrial sensing relating to

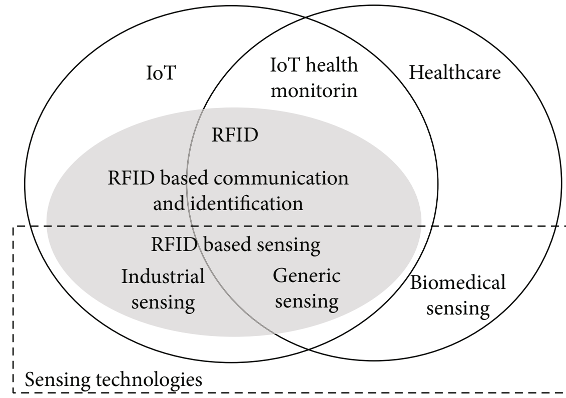

Figure 1: Framework of RFID sensor-based IoT health monitoring applications.

nondestructive testing (NDT) and structural health monitoring (SHM). Conventional research studies in RFID sensors for healthcare systems are limited to generic environmental parameter sensing, such as temperature and humidity. Much key information relating to people's health status such as blood pressure and glucose levels still requires traditional testing methods for collection.

To extend the application of RFID sensors in the healthcare sector, this paper is aimed at providing an in-depth review and summary of the sensing mechanism for RFID-based sensors and the systems and the feature extraction methods. Relevant biomedical sensors are reviewed, and the potential for integration with RFID and IoT is investigated. This paper has been organised into six sections. Section 2 gives the technical background of the RFID sensor-based IoT health monitoring system. Section 3 details the recent development of health monitoring sensors and application scenarios, while Section 4 briefly reviews the security, safety, and compliance of RFID technology. Based on these findings, Section 5 outlines the challenges in RFID sensor developments and future perspectives for biomedical sensing and healthcare applications. Finally, a conclusion is drawn in Section 6 on the findings in RFID sensor-based IoT health monitoring.

2. RFID Sensor-Based IoT Health Monitoring System

2.1. IoT Health Monitoring Systems. IoT has emerged since the beginning of the 21st century and has become the domination mode of wireless communication between electronic devices. The successful application of IoT also gives us a great advantage in the development of modern healthcare [9, 10]. It can also connect numerous objects (e.g., sensors, medical treatments, and devices) [11, 12] to the Internet end, thus allowing users to share personal information, physiological data, and diagnostic resources. The emergence of the IoT has made it an important part of human environmental monitoring and medical applications, as shown in Figure 2, a diagram of a typical IoT health monitoring application architecture. The main challenges are shown below: (1) the efficiency of RF front-end energy harvesting and

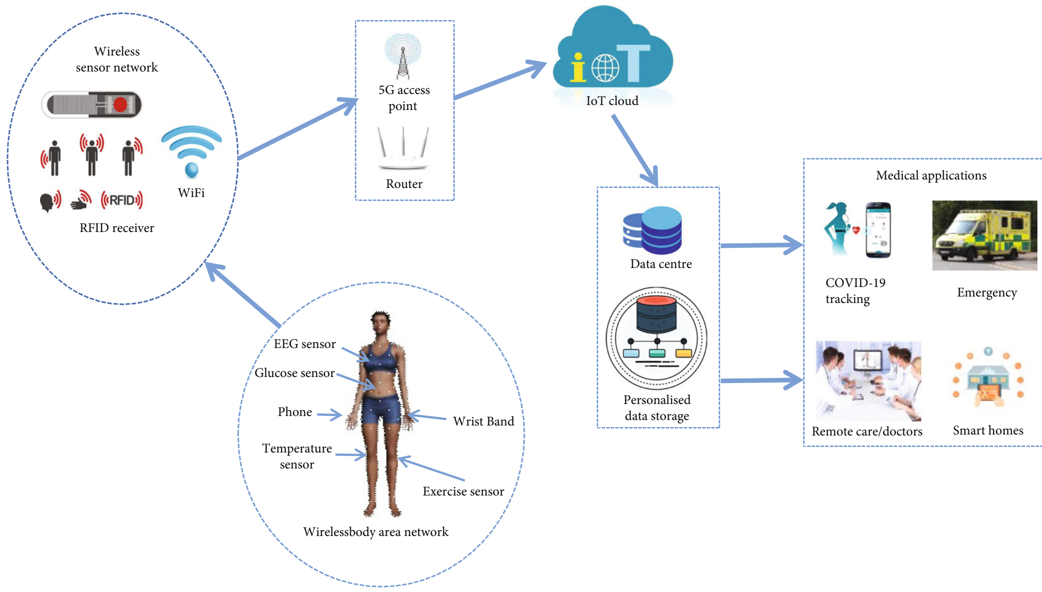

Figure 2: RFID sensor-based IoT health monitoring system and applications.

power conversion is measured; (2) the basic technology of RFID sensors shows great heterogeneity in terms of antennas, integrated circuit functions, sensing elements, and data protocols; and (3) the RFID sensors are mainly attached to the object to be measured for identification and parameter sensing. However, in practical applications, these can also be affected by certain environmental factors. In the figure, different sensors can be deployed at different body locations to monitor physical conditions by applying sensors in wearable and implantable devices as carriers, which can be attached to the subject's body to gauge parameters such as EEG [13], glucose [14–20], heartbeat [21], exercise [22, 23], pH [24–26], pressure [27–30], skin perception [31], breathing [32], and epilepsy [33]. These data can then be transmitted via the device (RFID or WiFi) to the IoT cloud infrastructure and made available to the target user.

These digital signals are relayed via a microcontroller to an RFID device, which transmits these signals wirelessly to a mobile phone, which transmits the data to a specific destination via the Internet. The Internet either uses 5G base stations or is used for transmission purposes. RFID sensors constantly collect information from the patient's body and obtain detailed information about the patient. These wireless devices allow for rapid screening of temperature anomalies and detailed reporting of a patient's physical condition by telemedicine personnel. In the current novel coronavirus outbreak, when a temperature abnormality is detected, the police can make a request for the wearer to go home immediately for isolation. In addition, doctors can receive timely information when a patient's condition deteriorates, in which case they and the hospital can respond to emergency medical services such as ambulances or provide relatives with the necessary action to assist them in helping the patient.

2.2. IoT Technical Background. The key technologies of the IoT are divided into two main parts, communication and network technologies and advanced data and security technologies, which are introduced in detail in the following sections.

2.2.1. Communication and Network Technologies. Main communication and network technologies used in IoT include WSN and RFID. WSN is constructed with massive sensor nodes which are connected with multihop self-organising wireless communication networks to achieve real-time sensing, monitoring, and signal processing from objectives in a designated coverage area. Wireless communication is adopted between sensing nodes in WSN, enabling flexibility in setting up the device locations and ease of connecting the device to the Internet for signal exchange and data transmission. With the rapid development of the IoT in recent years, wireless sensor network technology is an important underlying network technology for achieving a wide range of applications in the IoT and can be used as a nerve-end network for mobile communication networks and wired access networks to further extend the coverage of the network.

RFID uses radio frequency signal space coupling to achieve information transmission for identification technology [34]. The advantages of this technology are that contactless information transfer can be achieved, the identification process does not require human intervention, it can work in a disadvantaged environment, and it can identify objects moving at high speed and carry out signal identification in the field of medical monitoring. Another issue that needs to be considered in constructed IoT applications is the effective identification of objects, and the solution currently used is usually RFID technology. The biggest advantage of RFID systems is that they reduce human intervention and allow objects and people to be tracked and identified.

2.2.2. Advanced Data and Security Technologies. With the rapid development and popularity of ABCDE (artificial intelligence [35], blockchain [36], cloud computing, big data [37], and edge computing [35]), smart technology has become a global choice for rational allocation of medical resources and improving the efficiency and level of health services. They focus on clinical testing, personalised medicine, real-time diagnosis and treatment systems, etc. In parallel with artificial intelligence, medical device intelligence will become a major trend in the next 5 to 10 years. In China, for example, the term “smart healthcare” was introduced in 2009 in line with the new healthcare reform policy, while the first Internet medical consultation was not formally recognised at the policy level until 2020, driven by the new coronary pneumonia outbreak (COVID-19). Since then, the new “fast-forward” button has been pressed for the implementation of digital healthcare for all.

3. RFID Systems and Sensing

RFID sensor systems consist mainly of a transceiver connected to an antenna (called a reader) and a group of transceivers or tags as sensors, with the information stored in the transceiver or tag. The antenna establishes the communication between the transceiver and the transponder. There are two different RFID systems based on the presence or absence of a chip in the tag, namely, chip-based RFID and chipless RFID. Surface acoustic wave- (SAW-) based RFID is also chipless but is based on a piezoelectric phenomenon rather than electromagnetic wave transmission in common chipless RFID. The following content will introduce these RFID technologies and their different sensing principles.

3.1. Chip-Based RFID Sensing. There are active and passive RFID tags based on their powering mode. Active tags are powered by a built-in battery and work over long distances up to hundreds of metres. However, it is large and costly and has limited battery life. Passive tags do not contain batteries and receive power from the reader. When the reader broadcasts its signal, the tag antenna captures the signal and converts the received electromagnetic wave energy into electrical energy and stores it in an internal capacitor. Once the voltage of the internal capacitor reaches a preset level, the tag chip is activated and starts to modulate the backscattered signal with its ID and the stored data. The tag chip switches its internal impedance between two states, thus changing the impedance matching between the tag chip and the antenna. When the impedance is conjugate-matched, the absorption of the reader signal is good and there will be a decrease in the backscattered signal. Vice versa, when the impedance is shift-unmatched, the backscattered signal is stronger. This provides digitised data transmission back to the reader [7]. The passive nature of the RFID tag grants itself several advantages. Due to the simplicity of the circuit, the tag can be designed in a low profile and different shapes to fit different applications. Passive operation also makes the tag have a much longer operating lifetime compared with battery-powered competitors. However, passive RFID is fully dependent on the power from the reader signal and thus has a limited communication distance because of the power loss in the path. Under this condition, semipassive tags are developed using a larger integrated capacitor or rechargeable battery with energy harvesting systems to enable a longer operating range and life. The passive RFID technologies can be further classified based on the operating frequency of the tags, namely, low-frequency (LF) RFID at 125 kHz, high-frequency (HF) RFID at 13.56 MHz, and ultrahigh-frequency (UHF) RFID with the band in the range of 860 to 960 MHz. The UHF band may vary depending on the regulation of the county. LF and HF RFIDs are based on magnetic resonance coupling to transmit the power and data; thus, their operating range is limited to 15 cm. UHF RFID has a relatively longer operating range up to 15 m as the power-and-data link is based on electromagnetic coupling, which operates better in long distances and can achieve directional reading.

For different RFID technologies, there are various methods to integrate sensing capability into the system. For active and semipassive tags, the most common method is integrating digital sensors with the system as its power supply is sufficient for a digital sensor. However, if the digital sensor is used in passive tags, the reading distance is limited; thus, the coverage of each reader is too small for real application. Thus, an analogue sensing method is proposed based on the impedance matching method, as the principle shown in Figure 3. An analogue sensor providing varying impedance with the targeted parameter change is connected to the tag antenna, which is shown as the red load Z_{sense}. It alters the matching condition of the antenna to the tag chip when the targeted parameter changes, which provides an analogue signal mixed with the digital tag response. By extraction of this signal, the parameter can be characterised from the reader end.

With the development in semiconductor design, another digitised analogue sensing method can be achieved with the self-tuning function of the RFID tag. The performance of RFID tags is highly dependent on the environmental conditions, which makes them good sensors but unstable. When a significant change in the targeted parameter happens, the RFID tag antenna could get mismatched with the chip; thus, the tag is unreadable. The idea of self-tuning is enabling the tag chip to change its impedance to achieve the best communication link. The impedance change can also be retrieved in a digital format of the tag status. Thus, this digital impedance change is the digitised analogue sensing signal and can be used for sensing. The limitation of this method is the limited digitisation bit, resulting in low sensing resolution.

The analogue sensing method can transmit rich information with the signal using a much simpler structure as the active RFID; thus, there are wide research studies on retrieving the sensing information using various features and feature extraction methods.

The radar cross-section (RCS) is a commonly used feature in the antennas of RFID systems, which is contributed by two components of scattering, namely, the structural mode and the antenna mode. The structural mode indicates that the physical size of the antenna and the direction of emission affect the scattering effect, whereas the radar cross-section change is constant when the sensor in the tag is at rest. By comparing the former, the latter indicates the magnitude of the load

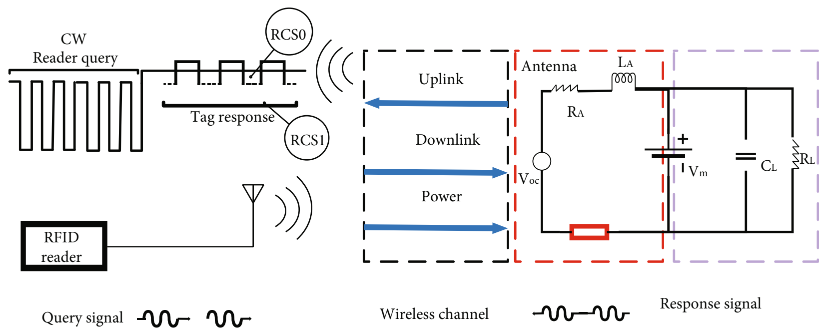

FIGURE 3: Operating principle of analogue sensors based on passive RFID.

misalignment value within the antenna. Thus, the RCS varies with the radiated power and also with the load impedance. In Figure 3, the ID response component can be represented by equation (1), where σ in the equation represents the combined structural and antenna mode backscatter on the RCS.

$$\sigma = \lim_{r \longrightarrow \infty} 4\pi r^2 \left| \frac{\overrightarrow{E_r}}{\overrightarrow{E_i}} \right|^2 = \frac{\gamma^2}{4\pi} G^2 |\Gamma - \mathrm{As}|^2, \tag{1}$$

where $\overrightarrow{E_i}$ is the incident field strength, $\overrightarrow{E_r}$ is the reflected field strength, Γ is the reflection coefficient between the antenna and the sensor input impedance, which favours the "antenna mode" backscatter, and As is a constant, which contributes to the "structural mode" backscatter.

The RSSI value indicates the size of the received signal strength and is also an important RFID sensing method. At present, the industry has applied the RSSI value to judge the distance of the tag from the reader (roughly). The larger the RSSI value received, the closer the tag is to the reader. The smaller the RSSI value, the farther away it is. The RSSI value can also be used to prevent the reader from misreading the prochannel. RSSI can be expressed as

$$\mathrm{RSSI} = 10^{-G_r/10} \frac{1.2567 \times 10^4 V_c}{R^{2B}} \left(\frac{1}{N} \sum_{n=0}^{N-1} |Y_I \text{ or } Q[k, n]| \right)^2 \mathrm{mWatt}, \tag{2}$$

where G_r is the analogue transmission gain from the antenna end to the ADC input. R is the input resistor, and V_c is the input chip level. B is the number of bits in the analogue-to-digital converter. $|Y_I \text{ or } Q[k, n]|$ is the nth sample of the I- or Q-branch ADC output within a single k.

Antennas can be made of conventional dielectric materials or coated with functionalised materials in passive sensor tags. Both options directly and indirectly change the electrical characteristics of the antenna structure and indirectly change the impedance value. In addition, the reader is based on the RCS radio channel actively acquiring the parameters of the antenna and then extracting the eigenvalues from the backscattered signal in order to interpret the defects of the detected thing in question. In particular, the signal processing requires modulation of the interrogation signal received by the tag antenna in order to separate the backscattered signal of the tag antenna from the backscattered signal of the surrounding structure. This is also the part of the process that distinguishes between the chip-based sensor and chipless sensor tags.

3.2. Chipless RFID Sensing. Typically, chipless RFID tags include a set of resonators that interrogate a broadband signal rather than a single continuous tone wave. The resonators produce negative peaks at specific frequencies in the spectrum to encode the data. As it only communicates with the backscattered signal and does not have an internal power source, it is categorised in the passive tags in some classifications. The main disadvantage of this device is its limited operating range, which can be reduced to a few centimetres.

Figure 4 illustrates the workflow of the chipless RFID sensor tag, as well as the reception and signal processing system, where an ultrawideband interrogation signal is required for the chipless RFID signal, mainly by analysing the reflected spectrum signal provided by wearable and implantable devices. In the analysis process, the backscattered chipless sensor tag [38] needs to be preprocessed; then, the feature values are extracted, fused, and sent to the feature similarity metric module to complete the matching and comparison with the corresponding feature values in the database to output the identification results.

The three most commonly used chipless RFID sensing methods are time-domain reflection, spectral signature [39, 40], and amplitude or phase backscatter modulation. The first is the time-domain reflection, which analyses the signal reflected back through the time domain, where information is encoded into the signal based on the feedback characteristics of the tag. By comparing the early and late phases of time-domain reflection, with the former through the response induced by changes in the angle of reflection of the material and the latter through the associated properties of the material, such as geometry and physical properties, the response is induced. Schiavoni et al. [41] successfully monitored skin hydration levels continuously in real time with an innovative wearable skin hydration sensing system based on a time-domain reflectometer. Time-domain reflectance is ideal for tag localisation algorithms but requires high sampling rates and complex algorithms to minimise

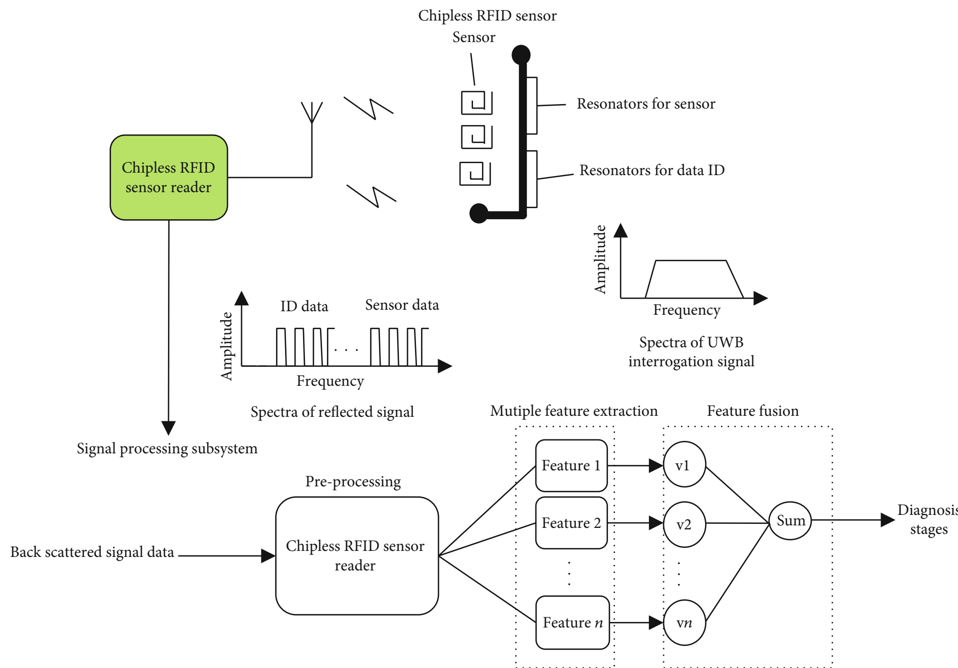

Figure 4: Operating principle of chipless RFID.

noise. The deficiencies of the delayed line signal between the time-domain reflection transceiver and the high power of the early and late signals resulting in susceptibility to noise are recounted in Figures 5(a) and 5(b), respectively. By comparing the two, we can see that the former is less powerful but less sensitive to noise. How to improve the processing of the signal by both will be the topic of our in-depth exploration. The second is spectral characterisation, which uses mainly tags with high Q-factors and selectively attenuated retransmitted or backscattered tag signals [42], to the extent that this allows the unique spectrum to be encoded as a specific signal as the tag's identification (ID). The two commonly used approaches [43, 44] when it comes to circuit design are conventional circuit-based and RF-coded particle-based approaches [45]. The former is the most widely used and popular approach among manufacturers due to the simplicity of the fabrication process. The structure of the spectral signature of this tag is presented in Figures 5(c) and 5(d), respectively, with the former representing a 1-bit inductive-capacitive resonator but with a small localised frequency response. The latter waveform plot shows the resonant minimum produced by this tag. This tag structure is an offset between the minimum frequency and the maximum frequency encoded by the zero and peak or multiple zero and peak offsets. When multiple peaks are encountered, they are encoded and pattern recognition is encoded via binary. Finally, amplitude or phase backscatter chipless sensor tags [46–48] are relatively simple in construction in Figures 5(e) and 5(f) as they have only sensing and coding resonators and no feed lines or antennas which reflect a portion of the electromagnetic wave back to the reader. When the interrogation electromagnetic wave generated by the reader hits the tag, it interacts with the resonator to generate an induced current that reflects a portion of the RF signal back to the reader. In addition, the amount of backscattered energy depends on the efficiency of the resonator.

3.3. SAW RFID. SAWs function by converting acoustic waves in piezoelectric materials into EM signals using a recessed pattern in a conductive medium [34]. SAW structures for sensing are based on two different principles: the first is based on SAW resonators, whose resonant frequency is influenced by external factors being measured. Single-port resonators are directly affected by, for example, temperature and torque, while two-port devices are usually electrically passed through conventional sensors. The second type is the delay line structure, where the measured object affects the velocity v_{SAW} of the surface wave or the geometric length of the propagation path L, both of which produce different round-trip delays $\tau x = L/v_{\mathrm{SAW}}$ readout signals. This conversion is influenced by the propagation time through the delay line and thus allows the information to be encoded. The amplitude of the SAW response signal can be calculated using the following equations:

$$A(t) = A_{\max} e^{-t/\tau_{\mathrm{SAW}}}, \tag{3}$$

$$\tau_{\mathrm{SAW}} = \frac{Q_{\mathrm{SAW}}}{\pi f_0}, \tag{4}$$

where Q_{SAW} is the quality factor of the loaded resonator and $A_{\max}$ is the response signal of the maximum amplitude. In the literature [49], SAW resonators have the advantage that

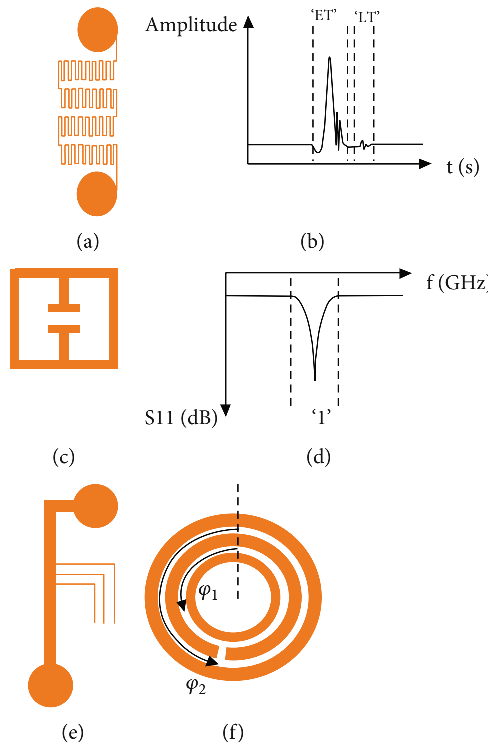

Figure 5: (a) Delay line labels using TDR. (b) The terms “ET” and “LT” refer to early and late reactions. (c) LC resonator coded using SS. (d) Expected coding of “1” in return loss. (e) LH delay line labels using A/PB coding through complex impedance loading. (f) Polarisation diversity tag with A/PB coding through time slot rotation [41].

they have a lower insertion loss compared to reflective delay lines. In addition, the high-quality factor (Q_{SAW}) in the literature [36] may ensure higher resolution.

3.4. Comparison of Parameters and Features in RFID-Based Sensing. In different RFID sensor-based IoT health monitoring applications, feature extraction methods are very important for reducing the noise and amplifying the sensitivity of the raw data from the sensors. The latest developments in terms of sensing principles, sensing variables, characteristics, and advantages and disadvantages can be summarised in Table 1. In terms of sensing principles, the table describes the frequency selective surfaces, scattering behaviour of electromagnetic waves and measurement of coupling coefficients, “truncated C”-shaped planar coupled line resonators (retransmission), fingerprint recognition (RSS), modified complementary split ring resonators (MCSRR), and retransmission of the third L-shaped multiple resonators. The second focus on sensing variables includes the RCS, variables for octagonal RFID tags, reflection coefficient (S21), power variables, and log-periodic antennas. Secondly, in terms of feature extraction, coded data bits, code verification and bending analysis of the tag, coded bit density and size, RSSI, range distance and power variation, and relative antennas are commonly used. Finally, by comparing these six papers, the main findings of the different sensing variables and feature value extraction are compared with their advantages and disadvantages, such as in anechoic chambers, for incompatibility with Gen2 conditioning, some researchers improve the sensing distance, but they need to be related to the conditioning of dedicated receivers. With this section of the review of RFID sensing principles and feature extraction methods, a closer look at the application of RFID-based sensors in healthcare systems is to follow.

4. Health Monitoring Sensors and Application Scenarios

As the product of evolution for as long as four billion years, the human body is one of the most complicated systems known to us. To sense and monitor the operating condition of this system is vital for maintaining the health of people, which is the main purpose of the healthcare system. This section will introduce the sensing methods used in healthcare systems and the state-of-the-art RFID-based sensors in health-related sensing applications, together with the application scenarios of IoT healthcare systems.

4.1. Health Monitoring Sensors. The first type is electrochemical sensing, which is an important part of the flexible sensing type recently. It converts the physical quantity to be measured into an induced electric potential (electromagnetic signal into current); this sensing method is in the middle waveform of the current or surface acoustic wave transmission. Sensors based on EM transduction have a large number of sensing parameters that require further

Table 1: Comparison of parameters and features in RFID-based sensing.

Refs.	Sensing principle	Sensing variables	Feature	Pros	Cons
[60]	Frequency selective surface (FSS)	RCS	The encoded data bits	Accurately retrieved up to 1.8 m with the tag at 0 dBm power	Inside an anechoic chamber
[61]	Scattering behaviour of the electromagnetic wave and the measurement of coupling coefficients	Variables of the octagonal-shaped RFID tag On-body RCS	Code verifications and the bending analysis of the tag	Accurately retrieved up to 1.8 m with the tag at 0 dBm power On-body RCS down to 7 mm	Not compatible with Gen2 regulation
[62]	"Truncated C"-shaped planar coupled line resonator (retransmission)	Reflection coefficient (S21)	The encoded bit density and size	A maximum reduction of 86.7% for the area of the resonator	VNA is required
[6]	RSS fingerprinting method	Power variables	RSSI	Using the Euclidean distance model achieves an accuracy of 98% for most sampled ADLs	The accuracy of the activity recognition algorithm performs below the threshold
[63]	The modified complementary split ring resonator (MCSRR) (retransmission)	The log-periodic antenna	Range distance Power variation	Maximum range distance of 30 cm and a power transmitted level of 30 dBm	Regulation dedicated receiver
[64]	3rd L-shaped multiresonator	RCS	Relative frequency shift (RFS)	RFS compared with the simulation results are 0.99%, 0.88%, and 2.26%	Regulation dedicated receiver
[65]	Feeding loop and the radiating antenna	Backscattered power	Power variation	Backscattered power up to 10–12 dB change in home	Regulation dedicated receiver

delineation. Due to its distinctive chemical and electronic properties, the flexible sensor is ideal for the realisation of various kinds of biosensing. Some common types of electrochemical sensing include monitoring glucose [14–19] and pH [24–26]. Carbon nanotubes [50, 51] have been developed as glucose and pH sensors because of their curved sidewalls and hydrophobicity that provides strong interactions through π-bonds. Another type of electrochemical sensing is the monitoring of cholesterol [52, 53], which is based on the principle of a kind of grease on the membrane of animal cells. These sorts of sensors are fabricated using both SWCNTs and MWCNTs in combination with lysogels [54]. SWCNTs and MWCNTs integrated with sol-gels are used in the fabrication of these types of sensors [54]. These techniques involve the immobilisation of a separate enzyme film, such as cholesterol esterase [55] and cholesterol oxidase [56], on the sensing surface. Biomedical signal sensing and monitoring is another area that has been developed through wearable flexible electronics [57, 58]. Chen et al. [59] described the monitoring of human bioelectrical signals such as the common EEG, ECG, body temperature, pressure, sweat, and tissue fluids was achieved.

Pressure [27, 29] and strain [28, 30] sensors are among the most standardised applications of flexible sensors. To date, the monitoring of various physiological parameters, such as medical bandages and gloves, is successfully demonstrated with various piezoresistive and piezoelectric sensors [66, 67]. Some pressure sensors [68] form the electrodes by coalescing two nanoparticles as electronic bandages, allowing operation in different media. Other research on these pressure sensors is in tactile perception [31] and artificial intelligence [30]. Smart materials attract intensive interest due to their great potential. One of the major advantages is the sensitive environmental parameters that can be measured under specific conditions and the selection and design of special smart material sensors under specific conditions. Magnetic field sensors [69] are a class of sensors developed using inorganic functional nanofilms and polymer films. The Hall effect principle was used to form a linear array of eight sensors to achieve high body sensing. We have also developed wearable electronic noses using CNTs and sensor arrays prepared from PEN nanocomposites. Hydrogel systems and electrophysiological sensors use polymethyl methacrylate (PMMA) layers as the base and are made from spin-coated and PI heat-cured layers on the top [70]. Electrodes were formed from Cr and Au bilayers evaporated by the electron beam. Another investigation for biomedical sensors is based on alloys in WFS for applications such as electrocardiography and stress-strain measurements. Flexible organic electrochemical transistors (OECTs) [71–74] can be used as sensors used for saliva detection as they convert biochemical signals into electrical signals.

4.2. Intelligence for IoT Healthcare. The authors [75] aim to extract and give analytical results from the data at the input side through a deep learning IoT monitoring system, with different levels of nonlinear variation of the corresponding neural networks. The framework of this deep learning model has four aspects, namely, automatic compilation, convolutional neural networks, recurrent neural networks, and Boltzmann machine restrictions. This study gives the reader deep learning in health monitoring systems that do not require large amounts of training and eigenvalue information. In Ref. [76], deep learning techniques are used in wearable sensor devices to automatically extract the corresponding feature values. Deep learning techniques are mainly classified into generative, discriminative, and hybrid models. Among these three models, the reader can find generative and discriminative models to improve feature extraction. For moving sensor data, it can save some computation time and identify parameters accurately. But there are also some big research challenges that lie in the fusion of deep learning and mobile learning for decision-making in wearable devices due to the mobility of these data. In the study by [77], it reduced downtime for data collection, storage, processing, and display in the health IoT, followed by a more efficient allocation of resources. This facilitates the merging of key hospital metrics to the extent that the patient's physical condition is more easily understood. In [78], the main focus is on medical data fusion through computers, mathematical techniques, and medical data. The most important aspect of data fusion is the designation of the IoT environment (the environment in which the objects are propagated and tracked) with the aim of improving the quality of the data and the accuracy of the decisions. Unfortunately, however, some data fusion is associated with ambiguity and irrelevance of the data, which ends up with results that do not match reality.

4.3. Application Scenarios. The use of RFID technology in healthcare applications is not without its requirements for frequency and reliance on different devices. Several frequency bands in which radio frequency identification operates have been studied [33]. Many RFID antennas have been investigated for wearable and implantable scenario applications in the body area operating in these health bands. In particular, wearable chipless sensors have several applications including the low-frequency band [40, 79], the UHF band [80–82], and the 26.5-40 GHz band [83].

The current research topic is on the application of electromagnetic and biomedical sensing modalities in combination with RFID sensing on human skin. In Table 2, the main contributions of their team are summarised in terms of sensing modalities, eigenvalue extraction, sensing materials, etc. In terms of sensor types and methods, the main types are textile humidity sensors, epidermal sensors, biointegrated RFID sensors, conformal space-filling curve sensors, and novel biosensors. By combining these types of sensors, different sensing methods can be used, such as humidity sensing, biomedical sensing, skin temperature sensing, and electromagnetic sensing. We found that not only RSSI and power variation but also sensor code (SC), potential processing, calibrated thermocouples, broadside realisation gain, and spatial sensitivity were achieved by comparing feature extraction with conventional RFID sensing. Typically, these antennas are copolar, and then the choice of material is often different, as the material is highly responsive to sensitivity.

Implantable chipless tags are more ambitious from a technical and specification point of view. Although there have been a couple of implantable RFIDs introduced in the literature [84–86], reporting on chipless equipment has so far been fairly sparse. While the benefits of this technology in terms of eliminating transcutaneous wires and batteries are obvious, the complexity of the wireless operating system and the interference of various parameters lead to other shortcomings that increase the total size of the embeddable device [87].

The first limitation is that the antenna size depends on the operating frequency so that higher frequencies work very well. Unfortunately, this is a phenomenon in biotissues, where RF damage is lower at lower working frequencies. This necessitates a balance between the frequency of the antenna designed for a particular implant and its function. However, it is clear that with today's research techniques, remote detection is not possible and readings from internal devices are limited to a few centimetres. A final limitation relates to the amount of microwavable energy required to monitor the signal. The wide range of microwave readings requires much more power, not least in a medium as lossy as the human body, which means that the body parts around the implant are going to inevitably heat up. This is not only dangerous for the body's own mechanisms, but it may also alter the body's sensory nerves. RFID sensing in body domain networks is a very important application in wearable devices and human implants. This section summarises some of the recent research directions and sensing methods used by researchers in these two large applications.

4.3.1. Wearable RFID Device. This section details some of the wearable applications for the body area, and Table 3 presents some of the literature research on the most advanced wearables.

As can be seen from this table, the tag types are divided into passive and chipless, and in the sensing principle section, multiple resonators, intelligent material sensing, frequency selective surfaces, and electromagnetic sensing are used. The sensing variables are also the RCS, resonant frequency, distance variable, and pH variable. In the feature extraction section, the main features are S-parameters and polarisation and symmetry are considered primarily. In the literature [95], a 2-bit implementation is introduced, with the integration of multiple resonators. Corchia et al. [96] avoided the use of electronic chips by using appropriate coding techniques. Dang et al. [97] introduced the modularity of the sensor and the textile antenna by means of a convenient snap-on connection method for the calculated RFID module, as well as this literature [98], where we have the range in which the device is able to detect ambient relative humidity values (65%-95%). Khan et al. [60] were able to accurately retrieve 4-bit data code words at 0 dBm at varying distances up to 1.8 m. In addition, in Singh et al.'s study [99], dipole and loop antennas were combined into a quasi-Yagi structure that could be placed on the back of the hand. The biggest drawback is the adjustment of the dedicated receiver; the number of bits is limited by the number

Table 2: List of types of sensing methods used in health monitoring.

Refs.	Sensor type	Sensing methods	Feature	Tag type	Cross/ copolar	Sensitive material	Application
[88]	Textile moisture sensor	Moisture sensing	Sensor code (SC)	Active	Copolar	Twill woven fabric	Sensorized facemask
[24]	Epidermal sensor	Biomedical sensing	Potential treatment	Passive	Copolar	Ag/AgCl ink	pH monitoring in sweat
[89]	Epidermal sensor	Skin temperature sensing	RSSI	Passive	Copolar	Polyethylene substrate	Monitoring of axilla temperature
[90]	Epidermal sensor	Embedded temperature sensing	Turn-on power	The dual-chip epidermal tag	Cross	Carved copper	On-body dual-temperature test
[91]	Biointegrated RFID sensor	Electromagnetic sensing	Calibrated thermocouple	Active	Copolar	Polyurethane film	Reliable skin temperature monitoring
[92]	Biointegrated RFID sensor	Electromagnetic sensing	Broadside realised gain	Active	Copolar	PVC (polyvinyl chloride)	During human gestures
[93]	Conformal space-filling curve sensor	Electromagnetic sensing	Space sensitivity	Active	Copolar	Teflon spacer and insulated	Detection of microcracks in orthopedic implants
[94]	Novel biosensor	Biomedical sensing	Interrogation distance	Passive	Copolar	Conjugated anti-rabbit IgG	Human sign detection

Table 3: State-of-the-art research into the design of wearable chipless RFID tag antennas.

Refs.	Tag types	Sensing principles	Sensing variable	Feature	Pros	Cons
[95]	Frequency signature	Multiresonator	RCS	|S11 | |S21 |	A 2-bit implementation, integration with the multiresonator	Performance depends on the properties of the materials used and the manufacturing process
[96]	Resonance-based	Multiresonator	Resonance frequency (f_{res})	|S21 |	By using appropriate coding techniques, the use of electronic chips is avoided	The number of bits is limited by the number of resonators (limited by size)
	Frequency shift					
[97]	—	Smart material sensing	Distance variable	RSSI	Modularity of sensors and textile antennas is introduced by the convenient snap-on connection method of the calculated RFID module	Regulation dedicated receiver
[98]	Frequency signature	Multiresonator	pH variable	|S21 |	The equipment is capable of detecting ambient RH values in the range (65%-95%)	Regulation dedicated receiver
[60]	Chipless	Frequency selective surface (FSS)	RCS	Polarisation and symmetry	Accurate retrieval of 4-bit data code words up to 1.8 m at 0 dBm with varying distances	Regulation dedicated receiver
[99]	Single- and dual-band	Electromagnetic sensing	Distance variable	|S11 | RSSI	Dipole and loop antennas are combined into a quasi-Yagi structure to be placed on a hand back	Regulation dedicated receiver

of resonators (limited by size) and finally the difficulty of choosing the inherent properties of the material.

The biggest disadvantages are the tuning of the dedicated receiver, the number of bits limited by that of oscillators (limited by size), and finally the difficulty of selecting the inherent properties of the material.

4.3.2. Implant RFID Device. Embedded biomedical equipment is without doubt one of the most sought-after fields of application for RFID, as its inherent wireless power and data communication capabilities offer great potential in this area (see Table 4). This section focuses on antennas for implantable devices, divided into five sections: planar, wire, conformal, spiral, slot, and planar inverted F antennas (PIFA). The literature is mainly studied through magnetic and electric field sensing, followed by biomedical sensing, smart material sensing, split ring resonators (SRR), and pin ring resonators (PLAR), as well as the finite element method

TABLE 4: State-of-the-art research into the design of implant RFID tag antennas.

Types of implantable antennas	Refs.	Sensing principles	Sensing variable	Feature	Pros	Cons	Efficiency
Planar antennas	[107]	Biomedical sensing	Voltage standing wave ration	|S11 |	The radiation efficiency of 80% is observed	Regulation dedicated receiver	High (80%)
	[108]	Smart material sensing	Distance variable	Power variable	The tested tag has a reading range of over 0.7 m and an immersion depth of 30 mm	Only at the simulation and laboratory stage	High
	[109]	Electromagnetic sensing	Skin thickness variable	|S11 |	Length (L_s) and width (W_s) of the substrate have been reduced by 36.84% and 40%, respectively	Regulation dedicated receiver	High
Wire antennas	[110]	Magnetic field sensing	Radiation efficiency responses	|S11 |	The QFHA radiated a maximum gain of −19.83 dBi with 290 MHz circular polarisation bandwidth	Regulation dedicated receiver	High
	[111]	Magnetic field sensing	Distance variable	S -parameters	−10 dB impedance bandwidth of 48.91%	Only at the simulation and laboratory stage	Low
Conformal antennas	[112]	Electric field sensing	Axial ratio (AR) band	|S11 |	The measured 10 dB impedance BW is 39.21%	Only at the simulation	Low
	[113]	Split ring resonator (SRR)	Thickness variable	Reflection coefficient	Reflection coefficient of -11.83 dB at the desired frequency of 900 MHz	The ultrawideband nature of the antenna will tolerate detuning effects	High
Spiral antennas	[114]	Pin-loaded annular ring (PLAR) resonator	Axial ratio (AR) band	|S11 |	Impedance bandwidth of 8% and a wide axial ratio (AR) bandwidth of 19.1%	Regulation dedicated receiver	Low
	[115]	Finite element method (FEM) and the finite difference time domain (FDTD)	Maximum power variable	|S11 |	Specify the range for biotelemetry at data rates of 7 and 100 kB/s	Regulation dedicated receiver	High
Slot antennas	[116]	Electric field sensing	Axial ratio (AR) band	|S11 |	Axial ratio bandwidths of 22.2% and 31.5%	Only at the simulation	Low
Planar inverted F antennas (PIFA)	[117]	Electric field sensing	Power	S -parameters	Wide bandwidth of 27.8%, ranging from 1.92 to 2.60 GHz	No integration with RFID technology	High (80%)

(FEM) and finite difference time domain (FDTD). In terms of feature extraction, it is essentially by S-parameters, except for power variations. The table compares the strengths and weaknesses of each in terms of high and low efficiencies and experimental conditions.

4.4. Healthcare-Related RFID Technology for Patient Care. In the past, healthcare-related RFID technology was implemented through passive tags, which were worn on the patient's wrist, where the tag detailed the patient's name, year, blood type, and information about the treatment given [100]. The security of this information is enhanced by an intelligent identification system. Patients in neurological hospitals, who are often difficult and do not actively cooperate, need to be combined with camera systems, in which case the nurses can access the information via wall receivers and sensors [101].

In some specific cases, hospitals will be designed with active tags for monitoring the patient's body temperature, which can reduce costs. In [102], a combination of electromagnetic-based near-field coherent sensing and RFID is proposed for monitoring vital signs, mainly by generating a backscattered signal from within the body and from the remote movement of the device. Its amplitude and phase are measured to analyse contact with the skin, body movement, and patient comfort. As the system relies on the reflection and projection of light, this improves the accuracy of monitoring heart and respiratory rates. It is also used for sleep monitoring as a polysomnogram. The tag, which is embedded inside the patient's clothing and placed in the heart position, is the main indicator for assessing the heart rate, respiratory rate, and upper body movement. However, hospitals currently provide remote monitoring conditions for doctors and nurses, and the data collected relies heavily on manual collection, which would take a significant amount of time to deploy in a clinical environment, and the lack of timely feedback leads to some misjudgements. Therefore, based on the current combination of IoT and RFID for remote monitoring, it is more valuable for the patient's activities and vital signs under real clinical conditions.

5. Safety, Security, and Compliance

The application of technology should consider safety, security, and compliance with rules and policies, especially in healthcare applications. This section will introduce the safety and security considerations in RFID sensing technology and related policy compliance.

5.1. Safety. Similar to mobile phones, the 5G base stations containing electromagnetic fields for transmitting and receiving devices and the wearable and implantable RFID devices are subject to international and national safety guidelines for specific absorption rates (SAR) between the electromagnetic radiation and the human body [103–105]. Assessing SAR levels and related parameters for RFID devices in human body areas is therefore an important part of the process. For example, when monitoring intracranial pressures at 868 and 915 MHz [106], elevated intracranial pressures are usually the result of cerebral oedema, cerebrospinal fluid disturbances, head injuries, or limited intracranial mass lesions. Figure 5 shows the regional SAR response induced by a subscale anatomical model of an implanted RFID antenna. To assess the potential risk of exposure to RFID antenna radiation, the authors of [106] investigated the impact of exposure to RFID at 915 MHz on the metabolic system's secretory function.

In this study, reverberation chambers were used for whole-body exposure for eight hours per day, five days per week, for sixteen weeks. There were no significant effects on the productive function of the pituitary gland. The effect of the antenna operating frequency on SAR was discussed in [106]. The results showed that for 402, 433, 868, and 915 MHz, the SAR decreased and the field distribution expanded with increasing frequency for implanted antennas with the same physical dimensions (but different effective dimensions).

Another issue that arose from the introduction of RFID to the healthcare system is the electromagnetic interference (EMI) caused by the reader and tag signals, which could lead to the disruption of medical devices, including pacemakers and dialysis machines, potentially endangering the patients who depend on those devices [118]. van der Togt evaluated 2 RFID systems (active LF and passive UHF) with 41 different medical devices and reported 34 EMI incidents among 123 total tests, while 22 were classified as hazardous. Thus, it is important to consider EMI effects in the process of sensor design and system integration for healthcare.

5.2. Security. User health information must be kept highly confidential in the healthcare sector to avoid data breaches. Any breach of patient health information could lead to a loss of integrity and result in legal and loyalty issues; thus, the deployment of RFID applications must comply with the legal right to privacy. Mutual authentication is a basic requirement to ensure secure communication between the RFID tags, the readers, and the server.

The main categories for RFID authentication include nonpublic key cryptosystem- (NPKC-) based schemes and public key cryptosystem- (PKC-) based schemes. NPKC-based schemes are easy to implement due to the simple operation used and have better performance, such as nonpublic cyclic redundancy code (NPCRC) checksum-based schemes, simple bitwise operation-based schemes, one-way hash function-based schemes, and symmetric encryption algorithm-based schemes. It is demonstrated that secure communication in RFID systems requires PKC-based authentication schemes to ensure that security attributes are implemented. A work in [119] shows that the elliptic curve cryptography (ECC) system is more suitable for the RFID system because it can achieve a similar security level as PKC-based schemes but has a shorter key size.

5.3. Compliance. Safety limits for exposure to electrical and magnetic time-varying effects are based on the established health effects of electromagnetic fields (EMFs) (see the International Commission on Protection against Ionising Radiation and different ethnic considerations). Exposure to EMFs affects internal body currents and energy absorption by tissues. The prevention of adverse health effects requires that the electrical and magnetic effects do not exceed the basic limits proposed.

The basic limits of exposure to EMFs set by the guidelines and laws and regulations [120] define two types of groups of the occupational open-air groups consisting of adults, who usually have considerable experience in known conditions, are aware of the potential risks, and take appropriate precautions. The other group is the general public, which includes individuals of different ages and different health conditions and perhaps also groups or individuals who are particularly susceptible to diseases, such as children, women, and people with chronic illnesses, and therefore, it is recommended that the general public have more stringent exposure limits than the occupationally exposed group, which are taken into account in this discussion. The basic limits based on the physical quantities of the frequency domain used to specify exposure in the EMF are as follows:

(i) Current density (J) for the frequency range 1 Hz-10 MHz

(ii) Energy absorption rate (SAR) for the specified frequency range 100 kHz-10 GHz

(iii) Power density (S) for the frequency range 10-300 GHz

6. Challenges and Future Trends in Perspective

Summarising the review of the state-of-the-art RFID sensing technologies above, the challenges for developing the next-generation RFID sensing systems for IoT-based health monitoring systems can be identified in the following fields. The future trends for mitigating these challenges are discussed at the end of this section.

6.1. Sensitivity. The sensitivity of tags as sensors in RFID is mainly dependent on the ability to resolve the received RF signal and the matching of the frequency. The sensitivity and linearity of sensors are the most important performance characteristics of sensors, especially for implanted microsensors. The sensitivity and linearity of microsensors with small ranges have been a major factor hindering the development of microsensors. While the issue of sensitivity has been a key metric for researchers to consider, the current mainstream research direction is to improve sensitivity by means of smart materials; e.g., novel sensing methods have been adopted, using materials and manufacturing techniques (body-conforming electrodes, conductive screen printing of sensors and antennas), as well as embroidered wires in textiles or flexible/stretchable electronics [97, 108].

6.2. Stability. RFID signals with body area network (BAN) sensing information are backscattered or retransmitted way into the WSN channel, and the associated sensors in the BAN, which combines sensing and communication in the system, need to address the RF channel to mitigate path loss and multipath effects [121]. Although there is some relevant research on the simulation of RFID sensors in healthcare, there is currently no relevant literature to support whether and under what conditions the variability of the measured signal associated with the sensing activity can be distinguished from the measurement instability [93]. Power measurements [63, 65] are also very important in the extraction of eigenvalues as an indication of the sensing capability through tag antenna impedance mismatch and high efficiency as a cost. To some extent, the modulation characteristics of the propagation channel and tags, which are frequency and power dependent, are of great relevance to the phase measurements. Furthermore, in the sensing path of the forward and backward scattering signals, it is subject to the variability of the environment in which it is located to be very severe, and therefore, when tags in different environments are used in healthcare applications, they are affected by environmental parameters that bring instability to the sensing variables, measurements, and feature extraction. Finally, there is insufficient literature to support the challenge of what instabilities are introduced to sensing parameter measurements when applied in healthcare from the convergence of other related complex sensing modalities and RFID sensing, such as electromagnetic sensing, medical sensing, SAW sensing, and smart material sensing.

6.3. Communication. In the second part of the review of the RFID sensing section, the line-of-sight data transmission route between the tag and the reader changes as the transceiver power of the two sections changes. This is referred to as small-scale fading due to interference from object waves during propagation. In addition, during the communication process, the data transmission on the upstream and downstream links is asymmetrical; often, the data on the downstream link (tag) is much worse. In the upstream and downstream communication process, mainly through the unidirectional and bidirectional transmission, for unidirectional communication, small-scale fading is serious. For bidirectional communication, which mainly comes from the superposition of scattered components near the tag, the main observation is even the product of independent small-scale fading effects [7]. How to improve this part of the link range is a great challenge, and the existing literature draws attention to the problem of communicating information transmission in WBNs. In analysing the communication process, the focus needs to be on accurate link budget equations, as well as modulation factors, path blocking losses, polarisation mismatch losses, impedance mismatch losses, and small-scale fading losses.

6.4. Energy. Tags as sensors are made of special materials and therefore require a different amount of energy. Existing RFID system tags are mainly passive tags, which are required to be placed within the range of the reader; otherwise, the relevant data would not be sensed. The relevant devices on passive tags are powered by the RF energy on the transmitter side, which transmits the communication by backscattering the incoming signal; however, the communication sensing capability is subject to the power requirements on the transmitter side. When the logic of the components in the sensor is functioning properly, this energy comes from the RF energy at the receiving end only. Currently, most of the power-affected sensing for implantable devices stays at the simulation stage, especially [108]; when the sensor is implanted in the WBN, the RF signal is attenuated by the surrounding environment, and it is difficult to run both power supply and implantable depth information communication at the tag end; therefore, the energy for the communication range of passive tags is limited.

6.5. Signal and Data Processing. Due to the user identification and low cost of RFID tags, RFID systems are very widely used in healthcare to monitor human vital signs. The tags are read continuously to capture the instantaneous state of the signal and the sequence of signal characteristics. However, the reader can only read at a limited rate from the collected information and very subtle motion-induced vital signatures cannot be extracted in time. Furthermore, due to the limited signal processing power, the extracted physiological features cannot be accurately recorded to match the user's physical signs (e.g., heart rate and respiration). However, there are currently some scholars who perform matching authentication of vital features through mechanical learning [122] and voice [123] methods.

Another major challenge is the acquired medical data which is haphazard. At the most basic level, despite efforts to standardise medical terminology, diagnostic coding, etc., there is a great deal of variation in how individual providers describe, conceptualise, and articulate their observations of patients. Often, the exploration, discovery, and analysis of all data are only as valid and valuable as the clarity and validity of the underlying dataset. These issues relate only to the volume and speed of the data collected, which must be interpreted. In the related literature, artificial intelligence and machine learning [124] can now provide statistical tools to identify measurements to fill in data gaps and synthetically construct "controls" for comparison with real-world experience. These tools provide a way forward to compare observations from a given intervention with expected outcomes in the absence of an intervention so that we can model testing paradigms that allow for assumptions about certainty and causality.

6.6. Future Trends in RFID-Based IoT Health Monitoring. There are a few research directions towards a smart health monitoring system for healthcare applications. This section introduces the research trends in RFID-based IoT health monitoring systems.

6.6.1. New Material. The material used in sensors determines the base sensitivity of the system. Emerging materials, such as graphene, nanomaterial, and metamaterial, have attracted attention in various sensing applications. Nanomaterial sensors achieve high sensitivity to temperature, electrophysiological parameters, strain, and electrochemical parameters [125] and bring benefits for tracking key health indicators and environmental parameters. Graphene has been investigated for highly sensitive pressure sensors [126] as well as smart tactile sensors and e-skins. A graphene oxide-based printed RFID antenna is investigated for humidity sensing in [127], achieving a battery-free humidity sensor.

Emerging materials not only boost the sensitivity of sensors but can also be used to enhance the performance of RFID systems. A UHF RFID tag antenna made with highly flexible graphene assembly film (GAF) is presented in [128], showing equivalent performance to commercial tags with high mechanical stability. The metamaterial is used in [129] for a broadband low-profile reconfigurable antenna.

6.6.2. Passive Biomedical Sensor Development Based on RFID. The development trend of RFID-based biomedical sensors is mainly in the three areas: the development of reliability, passive tags, and multisensor information fusion. In the development of reliability, the RFID technology biomedical field is still in the early stages, and its reliability is dependent on the anti-interference ability of electronic equipment, and the next work, wherein the use of traditional sensors is generally nonelectricity for power conversion, cannot be separated from the power supply, so we have the use of passive tags in biomedical applications, but also the future of large-scale use is an important direction; the last direction on the multisensor information fusion refers to the data from multiple tags for multilevel and multifaceted processing so as to produce new meaningful information; however, this information is not available to any single tag.

6.6.3. Data Analytics. The introduction of data science technologies to data analytics will be one of the major advancements in IoT healthcare. Studies have shown the advantages of AI and ML in the aspect of intelligence in monitoring and decision-making. Further studies will focus on the wider application scenarios such as the diagnosis, prevention, and prognosis of disease, modelling disease progression, analysis of the genetic and environmental influence on phenotypes, identification of the target in drug development, improvement of the health process, and disease phenotyping [130].

7. Conclusion

This paper further reviews the state-of-the-art RFID sensor technology in IoT health monitoring, focusing on sensor design, communication, and sensing capabilities in different environments and artificial intelligence for RFID-based IoT healthcare. Although sensor technology is used in body area networks, it also poses challenges and issues such as communication in the human environment, sensing capabilities, accuracy and reliability, security, and compliance. It is hoped that this comprehensive review and discussion of the application of different frequency, wearable, and implantable RFID devices in different recent scenarios will lead to more innovative research and interesting applications.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] V. Chamola, V. Hassija, V. Gupta, and M. Guizani, "A comprehensive review of the COVID-19 pandemic and the role of IoT, drones, AI, blockchain, and 5G in managing its impact," *IEEE Access*, vol. 8, pp. 90225–90265, 2020.

[2] M. Ndiaye, S. S. Oyewobi, A. M. Abu-Mahfouz, G. P. Hancke, A. M. Kurien, and K. Djouani, "IoT in the wake of COVID-19: a survey on contributions, challenges and evolution," *IEEE Access*, vol. 8, pp. 186821–186839, 2020.

[3] J. Li and G. Xu, "Lessons from the experience in Wuhan to reduce risk of COVID-19 infection in patients undergoing long-term hemodialysis," *Clinical Journal of the American Society of Nephrology*, vol. 15, no. 5, pp. 717–719, 2020.

[4] J. D. Hughes, C. Occhiuzzi, J. Batchelor, and G. Marrocco, "Twin-grid array as 3.6 GHz epidermal antenna for potential backscattering 5G communication," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 12, pp. 2092–2096, 2020.

[5] A. Ennajih, B. Nasiri, J. Zbitou, A. Errkik, and M. Latrach, "A wearable UHF RFID tag antenna-based metamaterial for biomedical applications," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 2, pp. 676–684, 2020.

[6] W. Shuaieb, G. Oguntala, A. AlAbdullah et al., "RFID RSS fingerprinting system for wearable human activity recognition," *Future Internet*, vol. 12, no. 2, p. 33, 2020.

[7] J. Zhang, G. Tian, A. Marindra, A. Sunny, and A. Zhao, "A review of passive RFID tag antenna-based sensors and systems for structural health monitoring applications," *Sensors*, vol. 17, no. 2, p. 265, 2017.

[8] R. Angeles, "Understanding the RFID deployment at Sacred Heart Medical Center: using technology-organization-environment framework lenses," *Procedia Computer Science*, vol. 196, pp. 445–453, 2022.

[9] A. Rahaman, M. Islam, M. Islam, M. Sadi, and S. Nooruddin, "Developing IoT based smart health monitoring systems: a review," *Revue d'Intelligence Artificielle*, vol. 33, no. 6, pp. 435–440, 2019.

[10] H. Landaluce, L. Arjona, A. Perallos, F. Falcone, I. Angulo, and F. Muralter, "A review of IoT sensing applications and challenges using RFID and wireless sensor networks," *Sensors*, vol. 20, no. 9, p. 2495, 2020.

[11] M. Bouklachi, M. Biancheri-Astier, A. Diet, and Y. Le Bihan, "NFC/RFID patch coil curvature effect and shielding for medical applications wirelessly powered," *IEEE Journal of Radio Frequency Identification*, vol. 4, no. 2, pp. 107–114, 2020.

[12] Q. Liu, W. S. Zhao, and Y. Yu, "RVFID-based bidirectional wireless rollover sensor for intelligent wheelchair," *Microwave and Optical Technology Letters*, vol. 63, no. 2, pp. 504–509, 2021.

[13] K.-P. Gao, G.-C. Shen, N. Zhao, C.-P. Jiang, B. Yang, and J.-Q. Liu, "Wearable multifunction sensor for the detection of forehead EEG signal and sweat rate on skin simultaneously," *IEEE Sensors Journal*, vol. 20, no. 18, pp. 10393–10404, 2020.

[14] M. Tanaka, "Improving obesity and blood pressure," *Hypertension Research*, vol. 43, no. 2, pp. 79–89, 2020.

[15] H. Koshimizu, R. Kojima, K. Kario, and Y. Okuno, "Prediction of blood pressure variability using deep neural networks," *International Journal of Medical Informatics*, vol. 136, p. 104067, 2020.

[16] T. K. Dhiman, G. B. Lakshmi, R. Kumar, K. Asokan, and P. R. Solanki, "Non-enzymatic detection of glucose using a capacitive nanobiosensor based on PVA capped CuO synthesized via co-precipitation route," *IEEE Sensors Journal*, vol. 20, no. 18, pp. 10415–10423, 2020.

[17] D. A. Kumar and T. Jayanthy, "Non-invasive monitoring of blood glucose concentration based on insulin secretion level using NIR spectroscopy for diabetes detection," *Medico-Legal Update*, vol. 21, pp. 1259–1266, 2021.

[18] M. Dautta, M. Alshetaiwi, J. Escobar, and P. Tseng, "Passive and wireless, implantable glucose sensing with phenylboronic acid hydrogel-interlayer RF resonators," *Biosensors and Bioelectronics*, vol. 151, p. 112004, 2020.

[19] T. Athauda, P. C. Banerjee, and N. C. Karmakar, "Microwave characterization of chitosan hydrogel and its use as a wireless pH sensor in smart packaging applications," *IEEE Sensors Journal*, vol. 20, no. 16, pp. 8990–8996, 2020.

[20] T. Jahana and H. Higa, "Non-invasive blood glucose monitoring device using photoacoustic spectroscopy," in *2020 5th International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS)*, pp. 66–70, Okinawa, Japan, 2020.

[21] T. Arikawa, T. Nakajima, H. Yazawa et al., "Clinical usefulness of new R-R interval analysis using the wearable heart rate sensor WHS-1 to identify obstructive sleep apnea: OSA and RRI analysis using a wearable heartbeat sensor," *Journal of Clinical Medicine*, vol. 9, no. 10, p. 3359, 2020.

[22] D.-H. Choi, G. B. Kitchen, M. T. Jennings, G. R. Cutting, and P. C. Searson, "Out-of-clinic measurement of sweat chloride using a wearable sensor during low-intensity exercise," *NPJ Digital Medicine*, vol. 3, no. 1, pp. 1–4, 2020.

[23] F. H. Guillot, P. G. Jacobs, L. M. Wilson et al., "Accuracy of the Dexcom G6 glucose sensor during aerobic, resistance, and interval exercise in adults with type 1 diabetes," *Biosensors*, vol. 10, no. 10, p. 138, 2020.

[24] V. Mazzaracchio, L. Fiore, S. Nappi, G. Marrocco, and F. Arduini, "Medium-distance affordable, flexible and wireless epidermal sensor for pH monitoring in sweat," *Talanta*, vol. 222, p. 121502, 2021.

[25] L. Ding, X. Li, L. Hu et al., "A naked-eye detection polyvinyl alcohol/cellulose-based pH sensor for intelligent packaging," *Carbohydrate Polymers*, vol. 233, p. 115859, 2020.

[26] A. Majumder, S. K. Pradhan, K. Saha, and S. Tallur, "Low-cost passive pH sensor fabricated on Scotch™ tape," *IEEE Sensors Letters*, vol. 4, no. 4, pp. 1–4, 2020.

[27] X. Pei, H. Zhang, Y. Zhou, L. Zhou, and J. Fu, "Stretchable, self-healing and tissue-adhesive zwitterionic hydrogels as strain sensors for wireless monitoring of organ motions," *Materials Horizons*, vol. 7, no. 7, pp. 1872–1882, 2020.

[28] C. Yang, X. Huang, X. Li et al., "Wearable and implantable intraocular pressure biosensors: recent progress and future prospects," *Advanced Science*, vol. 8, no. 6, p. 2002971, 2021.

[29] Y. Zhang, Y. Huang, Y. Ge, and N. Bao, "A master–slave hand operation cooperative perception system for grasping object via information fusion of flexible strain sensors," *Measurement*, vol. 169, p. 108437, 2021.

[30] A. Fatema, S. Poondla, R. B. Mishra, and A. M. Hussain, "A low-cost pressure sensor matrix for activity monitoring in stroke patients using artificial intelligence," *IEEE Sensors Journal*, vol. 21, no. 7, pp. 9546–9552, 2021.

[31] J. H. Lee, J. S. Heo, Y. J. Kim et al., "A behavior-learned cross-reactive sensor matrix for intelligent skin perception," *Advanced Materials*, vol. 32, no. 22, p. 2000969, 2020.

[32] J. Wang, S. Soltanian, P. Servati, F. Ko, and M. Weng, "A knitted wearable flexible sensor for monitoring breathing condition," *Journal of Engineered Fibers and Fabrics*, vol. 15, 2020.

[33] M. Thompson and A. Ackroyd, "Biosensor technology in diagnostics and mechanistic studies of epilepsy," *Proceedings of The 1st International Electronic Conference on Biosensors*, vol. 60, no. 1, p. 20, 2020.

[34] A. Abugabah, N. Nizamuddin, and A. Abuqabbeh, "A review of challenges and barriers implementing RFID technology in the healthcare sector," *Procedia Computer Science*, vol. 170, pp. 1003–1010, 2020.

[35] L. Sun, X. Jiang, H. Ren, and Y. Guo, "Edge-cloud computing and artificial intelligence in Internet of Medical Things: architecture, technology and application," *IEEE Access*, vol. 8, pp. 101079–101092, 2020.

[36] S. Jangirala, A. K. Das, and A. V. Vasilakos, "Designing secure lightweight blockchain-enabled RFID-based authentication protocol for supply chains in 5G mobile edge computing environment," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 11, pp. 7081–7093, 2020.

[37] G. Aceto, V. Persico, and A. Pescapé, "Industry 4.0 and health: Internet of Things, big data, and cloud computing for Healthcare 4.0," *Journal of Industrial Information Integration*, vol. 18, p. 100129, 2020.

[38] V. Mulloni and M. Donelli, "Chipless RFID sensors for the Internet of Things: challenges and opportunities," *Sensors*, vol. 20, no. 7, p. 2135, 2020.

[39] J. Aliasgari, M. Forouzandeh, and N. Karmakar, "Chipless RFID readers for frequency-coded tags: time-domain or frequency-domain?," *IEEE Journal of Radio Frequency Identification*, vol. 4, no. 2, pp. 146–158, 2020.

[40] A. J. Healey, P. Fathi, and N. C. Karmakar, "RFID sensors in medical applications," *IEEE Journal of Radio Frequency Identification*, vol. 4, no. 3, pp. 212–221, 2020.

[41] R. Schiavoni, G. Monti, E. Piuzzi et al., "Feasibility of a wearable reflectometric system for sensing skin hydration," *Sensors*, vol. 20, no. 10, p. 2833, 2020.

[42] F. Babaeian and N. C. Karmakar, "Development of cross-polar orientation-insensitive chipless RFID tags," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 7, pp. 5159–5170, 2020.

[43] T. Tang, M. Olaimat, M. Aldhaeebi, G. Wen, and L. Xiao, "Circular multiusage RFID tag antenna with coding ability for chipless application," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 30, no. 12, 2020.

[44] C. Herrojo, J. Naqui, F. Paredes, and F. Martin, "Spectral signature barcodes implemented by multi-state multi-resonator circuits for chipless RFID tags," in *2016 IEEE MTT-S International Microwave Symposium (IMS)*, pp. 1–4, San Francisco, CA, USA, 2016.

[45] B. Lopes, T. Varum, and J. N. Matos, "Use of FrFT in an indoor scenario for chipless RFID tags ID recovery," *IET Microwaves, Antennas & Propagation*, vol. 14, no. 12, pp. 1316–1322, 2020.

[46] F. Pereira, R. Correia, M. Jordao, and N. B. Carvalho, "Chipless strain sensor using phase modulation," in *2020 IEEE Wireless Power Transfer Conference (WPTC)*, pp. 420–423, Seoul, Korea (South), 2020.

[47] A. DiCarlofelice, E. DiGiampaolo, and P. Tognolatti, "mm-Wave chipless RFID tag for healthcare applications," in *2020 XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio Science*, pp. 1–3, Rome, Italy, 2020.

[48] J. Zhao, J. Li, and D. Li, "Effective decoding and ambient backscattering phase cancellation mitigation in tag-to-tag communication," *International Journal of Systems, Control and Communications*, vol. 12, no. 1, p. 12, 2021.

[49] A. Abuelkhail, U. Baroudi, M. Raad, and T. Sheltami, "Internet of Things for healthcare monitoring applications based on RFID clustering scheme," *Wireless Networks*, vol. 27, no. 1, pp. 747–763, 2021.

[50] M. B. Azizkhani, S. Rastgordani, A. P. Anaraki, J. Kadkhodapour, and B. S. Hadavand, "Highly sensitive and stretchable strain sensors based on chopped carbon fibers sandwiched between silicone rubber layers for human motion detections," *Journal of Composite Materials*, vol. 54, no. 3, pp. 423–434, 2020.

[51] M. F. Hossain and G. Slaughter, "PtNPs decorated chemically derived graphene and carbon nanotubes for sensitive and selective glucose biosensing," *Journal of Electroanalytical Chemistry*, vol. 861, p. 113990, 2020.

[52] S. Mehtab, M. G. H. Zaidi, and P. Joshi, "Metal nanoparticles based electrochemical biosensors for cholesterol," *Journal of Nanomedicine & Nanotechnology*, vol. 11, no. 1, p. 540, 2020.

[53] N. Agrawal, B. Zhang, C. Saha, C. Kumar, X. Pu, and S. Kumar, "Ultra-sensitive cholesterol sensor using gold and zinc-oxide nanoparticles immobilized core mismatch MPM/SPS probe," *Journal of Lightwave Technology*, vol. 38, no. 8, pp. 2523–2529, 2020.

[54] M. Feroz and P. Vadgama, "Molecular imprinted polymer modified electrochemical sensors for small drug analysis: progress to practical application," *Electroanalysis*, vol. 32, no. 11, pp. 2361–2386, 2020.

[55] F. C. Petry and A. Z. Mercadante, "Addition of either gastric lipase or cholesterol esterase to improve both β-cryptoxanthin ester hydrolysis and micellarization during _in vitro_ digestion of fruit pulps," *Food Research International*, vol. 137, p. 109691, 2020.

[56] M. S. Perdani, M. Sahlan, M. Yohda, and H. Hermansyah, "Immobilization of cholesterol oxidase from Streptomyces sp. on magnetite silicon dioxide by crosslinking method for cholesterol oxidation," *Applied Biochemistry and Biotechnology*, vol. 191, no. 3, pp. 968–980, 2020.

[57] X. Pu, S. An, Q. Tang, H. Guo, and C. Hu, "Wearable triboelectric sensors for biomedical monitoring and human-machine interface," *Iscience*, vol. 24, no. 1, p. 102027, 2021.

[58] A. Spanu, G. Casula, P. Cosseddu et al., "Flexible and wearable monitoring systems for biomedical applications in organic flexible electronics: fundamentals, devices, and applications," in *Organic Flexible Electronics*, pp. 599–625, Woodhead Publishing, 2021.

[59] Y. Chen, Y. Zhang, Z. Liang, Y. Cao, Z. Han, and X. Feng, "Flexible inorganic bioelectronics," *NPJ Flexible Electronics*, vol. 4, no. 1, 2020.

[60] M. U. Khan, R. Raad, J. Foroughi, P. I. Theoharis, S. Liu, and J. Masud, "A silver-coated conductive fibre HC12 sewed chipless RFID tag on cotton fabric for wearable applications," in *2020 IEEE 23rd International Multitopic Conference (INMIC)*, pp. 1–5, Bahawalpur, Pakistan, 2020.

[61] M. U. Khan, R. Raad, J. Foroughi, M. S. Raheel, and S. Houshyar, "An octagonal-shaped conductive HC12 & LIBERATOR-40 thread embroidered chipless RFID for general IoT applications," *Sensors and Actuators A: Physical*, vol. 318, p. 112485, 2021.

[62] A. K. Hossain, M. I. Ibrahimy, S. M. Motakabber, S. M. Azam, and M. S. Islam, "Multi-resonator application on size reduction for retransmission-based chipless RFID tag," *Electronics Letters*, vol. 57, no. 1, pp. 26–29, 2021.

[63] M. E. Jalil, M. K. Rahim, H. Mohamed et al., "High capacity and miniaturized flexible chipless RFID tag using modified complementary split ring resonator," *IEEE Access*, vol. 9, pp. 33929–33943, 2021.

[64] H. Tu, Y. Zhang, H. Hong, J. Hu, and X. Ding, "Design and characterization of novel fabric-based multi-resonators for wearable chipless RFID applications," *Textile Research Journal*, vol. 91, pp. 1830–1840, 2021.

[65] A. Mehmood, H. He, X. Chen et al., "Body movement-based controlling through passive RFID integrated into clothing," *IEEE Journal of Radio Frequency Identification*, vol. 4, no. 4, pp. 414–419, 2020.

[66] A. Jovanovski and B. Stappenbelt, "Measuring the boxing punch: development and calibration of a non-embedded in-glove piezo-resistive sensor," *Multidisciplinary Digital Publishing Institute Proceedings*, vol. 49, no. 1, p. 13, 2020.

[67] W. Dong, L. Yang, and G. Fortino, "Stretchable human machine interface based on smart glove embedded with PDMS-CB strain sensors," *IEEE Sensors Journal*, vol. 20, no. 14, pp. 8073–8081, 2020.

[68] P. Escobedo, M. Bhattacharjee, F. Nikbakhtnasrabadi, and R. Dahiya, "Smart bandage with wireless strain and temperature sensors and batteryless NFC tag," *IEEE Internet of Things Journal*, vol. 8, no. 6, pp. 5093–5100, 2021.

[69] S. Zuo, H. Heidari, D. Farina, and K. Nazarpour, "Magnetomyography: miniaturized magnetic sensors for implantable magnetomyography," *Advanced Materials Technologies*, vol. 5, no. 6, p. 2070033, 2020.

[70] D. Murzin, D. J. Mapps, K. Levada et al., "Ultrasensitive magnetic field sensors for biomedical applications," *Sensors*, vol. 20, no. 6, p. 1569, 2020.

[71] W. Ji, D. Wu, W. Tang et al., "Carbonized silk fabric-based flexible organic electrochemical transistors for highly sensitive and selective dopamine detection," *Sensors and Actuators B: Chemical*, vol. 304, p. 127414, 2020.

[72] Y. Liang, T. Guo, L. Zhou, A. Offenhäusser, and D. Mayer, "Label-free split aptamer sensor for femtomolar detection of dopamine by means of flexible organic electrochemical transistors," *Materials*, vol. 13, no. 11, p. 2577, 2020.

[73] X. Wu, J. Feng, J. Deng et al., "Fiber-shaped organic electrochemical transistors for biochemical detections with high sensitivity and stability," *SCIENCE CHINA Chemistry*, vol. 63, no. 9, pp. 1281–1288, 2020.

[74] M. Galliani, C. Diacci, M. Berto et al., "Flexible printed organic electrochemical transistors for the detection of uric acid in artificial wound exudate," *Advanced Materials Interfaces*, vol. 7, no. 23, p. 2001218, 2020.

[75] R. Zhao, R. Yan, Z. Chen, K. Mao, P. Wang, and R. X. Gao, "Deep learning and its applications to machine health monitoring: a survey," *Mechanical Systems and Signal Processing*, vol. 14, no. 8, 2018.

[76] H. F. Nweke, Y. W. Teh, M. A. Al-garadi, and U. R. Alo, "Deep learning algorithms for human activity recognition using mobile and wearable sensor networks: state of the art and research challenges," *Expert Systems with Applications*, vol. 105, pp. 233–261, 2018.

[77] F. Pasluosta, B. Eskofier, D. B. Da Silva, and R. da Rosa Righi, "Internet of Health Things: toward intelligent vital signs monitoring in hospital wards," *Artificial Intelligence in Medicine*, vol. 89, pp. 61–69, 2018.

[78] F. Alam, R. Mehmood, I. Katib, N. N. Albogami, and A. Albeshri, "Data fusion and IoT for smart ubiquitous environments: a survey," *IEEE Access*, vol. 5, pp. 9533–9554, 2017.

[79] A. Motroni, A. Buffi, and P. Nepa, "A survey on indoor vehicle localization through RFID technology," *IEEE Access*, vol. 9, pp. 17921–17942, 2021.

[80] A. J. Mugisha, A. Rigi, R. Joshi, A. Tsiamis, S. Podilchak, and S. Mitra, "Towards a compact UHF RFID reader for wearable bio-sensing devices," in *2020 5th International Conference on Smart and Sustainable Technologies (SpliTech)*, Split, Croatia, 2020.

[81] S. Ahmed, S. T. Qureshi, L. Sydanheimo, L. Ukkonen, and T. Bjorninen, "Comparison of wearable e-textile split ring resonator and slotted patch RFID reader antennas embedded in work gloves," *IEEE Journal of Radio Frequency Identification*, vol. 3, no. 4, pp. 259–264, 2019.

[82] R. Singh, A. Michel, P. Nepa, and A. Salvatore, "Compact quasi-Yagi reader antenna for UHF RFID smart-glove," in *2020 5th International Conference on Smart and Sustainable Technologies(SpliTech)*, pp. 1–4, 2020.

[83] J. G. Hester and M. M. Tentzeris, "Inkjet-printed flexible mm-Wave Van-Atta reflectarrays: a solution for ultralong-range dense multitag and multisensing chipless RFID implementations for IoT smart skins," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 12, pp. 4763–4773, 2016.

[84] Y. Zhang, C. Liu, X. Liu, and K. Zhang, "A miniaturized circularly polarized implantable RFID antenna for biomedical applications," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 30, no. 3, 2019.

[85] G. Scotti, S.-Y. Fan, C.-H. Liao, and Y. Chiu, "Body-implantable RFID tags based on Ormocer printed circuit board technology," *IEEE Sensors Letters*, vol. 4, no. 8, pp. 1–4, 2020.

[86] A. Schiffmann, M. Clauss, and P. Honigmann, "Biohackers and self-made problems: infection of an implanted RFID/NFC chip," *JBJS Case Connector*, vol. 10, no. 2, 2020.

[87] C. M. Boutry, H. Chandrahalim, P. Streit, M. Schinhammer, A. C. Hänzi, and C. Hierold, "Towards biodegradable wireless implants," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 370, no. 1967, pp. 2418–2432, 2012.

[88] G. M. Bianco and G. Marrocco, "Sensorized facemask with moisture-sensitive RFID antenna," *IEEE Sensors Letters*, vol. 5, no. 3, pp. 1–4, 2021.

[89] F. Camera, C. Miozzi, F. Amato, C. Occhiuzzi, and G. Marrocco, "Experimental assessment of wireless monitoring of axilla temperature by means of epidermal battery-less RFID sensors," *IEEE Sensors Letters*, vol. 4, no. 11, pp. 1–4, 2020.

[90] C. Occhiuzzi, S. Parrella, F. Camera, S. Nappi, and G. Marrocco, "RFID-based dual-chip epidermal sensing platform for human skin monitoring," *IEEE Sensors Journal*, vol. 21, no. 4, pp. 5359–5367, 2021.

[91] F. Camera and G. Marrocco, "Electromagnetic-based correction of bio-integrated RFID sensors for reliable skin temperature monitoring," *IEEE Sensors Journal*, vol. 21, no. 1, pp. 1–1, 2020.

[92] C. Miozzi, G. Diotallevi, M. Cirelli, P. P. Valentini, and G. Marrocco, "Radio-mechanical characterization of epidermal antennas during human gestures," *IEEE Sensors Journal*, vol. 20, no. 14, pp. 7588–7594, 2020.

[93] S. Nappi, L. Gargale, P. P. Valentini, and G. Marrocco, "RF detection of micro-cracks in orthopedic implants by conformal space filling curves," in *2019 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, Pisa, Italy, 2019.

[94] M. Yuan, E. C. Alocilja, and S. Chakrabartty, "A novel biosensor based on silver-enhanced self-assembled radio-frequency antennas," *IEEE Sensors Journal*, vol. 14, no. 4, pp. 941-942, 2014.

[95] L. Corchia, G. Monti, and L. Tarricone, "A frequency signature RFID chipless tag for wearable applications," *Sensors*, vol. 19, no. 3, p. 494, 2019.

[96] L. Corchia, G. Monti, E. De Benedetto et al., "Fully-textile, wearable chipless tags for identification and tracking applications," *Sensors*, vol. 20, no. 2, p. 429, 2020.

[97] Q. H. Dang, S. J. Chen, D. C. Ranasinghe, and C. Fumeaux, "Modular integration of a passive RFID sensor with wearable textile antennas for patient monitoring," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 10, no. 12, pp. 1979–1988, 2020.

[98] L. Corchia, G. Monti, E. D. Benedetto, and L. Tarricone, "A chipless humidity sensor for wearable applications," in *2019 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, pp. 174–177, Pisa, Italy, 2019.

[99] R. K. Singh, A. Michel, P. Nepa, and A. Salvatore, "Wearable dual-band quasi-Yagi antenna for UHF-RFID and 2.4 GHz applications," *IEEE Journal of Radio Frequency Identification*, vol. 4, no. 4, pp. 420–427, 2020.

[100] X. Liu, J. Yin, Y. Liu, S. Zhang, S. Guo, and K. Wang, "Vital signs monitoring with RFID: opportunities and challenges," *IEEE Network*, vol. 33, no. 4, pp. 126–132, 2019.

[101] Australian Commission on Safety and Quality in Health Care2020, https://www.safetyandquality.gov.au/.

[102] J. J. Kim, L. M. La Porte, M. P. Saleh et al., "Suicide risk among perinatal women who report thoughts of self-harm on depression screens," *Obstetrics and Gynecology*, vol. 125, no. 4, pp. 885–893, 2015.

[103] S. Amendola, R. Lodato, S. Manzari, C. Occhiuzzi, and G. Marrocco, "RFID technology for IoT-based personal healthcare in smart spaces," *IEEE Internet of Things Journal*, vol. 1, no. 2, pp. 144–152, 2014.

[104] M. Wang, X. Wang, L. T. Yang, X. Deng, and L. Yi, "Multisensor fusion based intelligent sensor relocation for health and safety monitoring in BSNs," *Information Fusion*, vol. 54, pp. 61–71, 2020.

[105] I. Awolusi, C. Nnaji, E. Marks, and M. Hallowell, "Enhancing construction safety monitoring through the application of Internet of Things and wearable sensing devices: a review," *Computing in Civil Engineering*, vol. 2019, pp. 530–538, 2019.

[106] R. Deepa, "IoT based health and safety system for manual scavengers and miners," 2020, https://www.irjet.net/archives/V7/i5/IRJET-V7I51223.pdf.

[107] K. Jaiswal, A. K. Patel, S. Yadav, S. Singh, R. S. Yadav, and R. Singh, "Probe-Fed wideband implantable microstrip patch antenna for biomedical and telemetry applications," in *Soft Computing and Signal Processing*, pp. 635–642, Springer, Singapore, 2019.

[108] S. Ma, T. Bjorninen, L. Sydanheimo, M. H. Voutilainen, and L. Ukkonen, "Double split rings as extremely small and tuneable antennas for brain implantable wireless medical microsystems," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 2, pp. 760–768, 2021.

[109] N. H. Sulaiman, N. A. Samsuri, M. K. A. Rahim, F. C. Seman, and M. Inam, "Compact meander line telemetry antenna for implantable pacemaker applications," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 10, no. 3, p. 883, 2018.

[110] S. H. Zainud-Deen, H. A. Malhat, and A. A. Balabel, "Octafilar helical antenna for circular polarization wireless capsule endoscopy applications," *Wireless Personal Communications*, vol. 108, no. 1, pp. 569–579, 2019.

[111] X. Wang, J. Shi, L. Xu, and J. Wang, "A wideband miniaturized implantable antenna for biomedical application at HBC band," in *2018 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, pp. 1–3, Xuzhou, China, 2018.

[112] R. Li, Y.-X. Guo, and G. Du, "A conformal circularly polarized antenna for wireless capsule endoscope systems," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 4, pp. 2119–2124, 2018.

[113] A. Khan, D. Wen, Y. Liu, G. Sukhorukov, and Y. Hao, "An ultrawideband conformal antenna for implantable drug delivery device," in *2020 14th European Conference on Antennas and Propagation (EuCAP)*, pp. 1–3, Copenhagen, Denmark, 2020.

[114] Y. Xu, W. Bo, L. Lu, L. Zhu, and C. Guo, "Circularly polarized annular ring antenna with wide axial-ratio bandwidth for biomedical applications," *IEEE Access*, vol. 7, pp. 59999–60009, 2019.

[115] A. Shah, M. Zada, and H. Yoo, "Design and analysis of a compact-sized multiband spiral-shaped implantable antenna for scalp implantable and leadless pacemaker systems," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 6, pp. 4230–4234, 2019.

[116] K. Saraswat and A. R. Harish, "A dual band circularly polarized 45° rotated rectangular slot antenna with parasitic patch," *AEU-International Journal of Electronics and Communications*, vol. 123, p. 153260, 2020.

[117] L. Luo, B. Hu, J. Wu, T. Yan, and L. J. Xu, "Compact dual-band antenna with slotted ground for implantable applications," *Microwave and Optical Technology Letters*, vol. 61, no. 5, pp. 1314–1319, 2019.

[118] R. van der Togt, "Electromagnetic interference from radio frequency identification inducing potentially hazardous incidents in critical care medical equipment," *JAMA*, vol. 299, no. 24, p. 2884, 2008.

[119] D. He and S. Zeadally, "An analysis of RFID authentication schemes for Internet of Things in healthcare environment using elliptic curve cryptography," *IEEE Internet of Things Journal*, vol. 2, no. 1, pp. 72–83, 2015.

[120] S. Tayyaba, W. Khalid, M. W. Ashraf, and V. E. Balas, "Principles and paradigms in IoT-based healthcare using RFID," in *Healthcare Paradigms in the Internet of Things Ecosystem*, pp. 251–269, Academic Press, 2021.

[121] J. S. Jung, J. N. Lee, J. M. Kim, and J. K. Park, "An UHF RFID reader antenna with multitag identification for extremely low-temperature medical systems," *International Journal of Antennas and Propagation*, vol. 2020, 11 pages, 2020.

[122] F. Al-Turjman, M. H. Nawaz, and U. D. Ulusar, "Intelligence in the Internet of Medical Things era: a systematic review of current and future trends," *Computer Communications*, vol. 150, pp. 644–660, 2020.

[123] L. Lu, L. Liu, M. J. Hussain, and Y. Liu, "I sense you by breath: speaker recognition via breath biometrics," *IEEE Transactions on Dependable and Secure Computing*, vol. 17, no. 2, pp. 306–319, 2017.

[124] X. Tao, T. B. Shaik, N. Higgins, R. Gururajan, and X. Zhou, "Remote patient monitoring using radio frequency identification (RFID) technology and machine learning for early detection of suicidal behaviour in mental health facilities," *Sensors*, vol. 21, no. 3, p. 776, 2021.

[125] S. Yao, P. Swetha, and Y. Zhu, "Nanomaterial-enabled wearable sensors for healthcare," *Advanced Healthcare Materials*, vol. 7, no. 1, p. 1700889, 2018.

[126] C. B. Huang, S. Witomska, A. Aliprandi et al., "Molecule-graphene hybrid materials with tunable mechanoresponse: highly sensitive pressure sensors for health monitoring," *Advanced Materials*, vol. 31, no. 1, p. 1804600, 2019.

[127] X. Huang, T. Leng, T. Georgiou et al., "Graphene oxide dielectric permittivity at GHz and its applications for wireless

humidity sensing," *Scientific Reports*, vol. 8, no. 1, pp. 1–7, 2018.

[128] B. Zhang, Z. Wang, R. Song et al., "Passive UHF RFID tags made with graphene assembly film-based antennas," *Carbon*, vol. 178, pp. 803–809, 2021.

[129] P. Liu, W. Jiang, S. Sun, Y. Xi, and S. Gong, "Broadband and low-profile penta-polarization reconfigurable metamaterial antenna," *IEEE Access*, vol. 8, pp. 21823–21831, 2020.

[130] S. Smadar, H. Rossman, and E. Segal, "Axes of a revolution: challenges and promises of big data in healthcare," *Nature Medicine*, vol. 26, pp. 29–38, 2020.