Medical Sensors and Their Integration in Wireless Body Area Networks for Pervasive Healthcare Delivery: A Review

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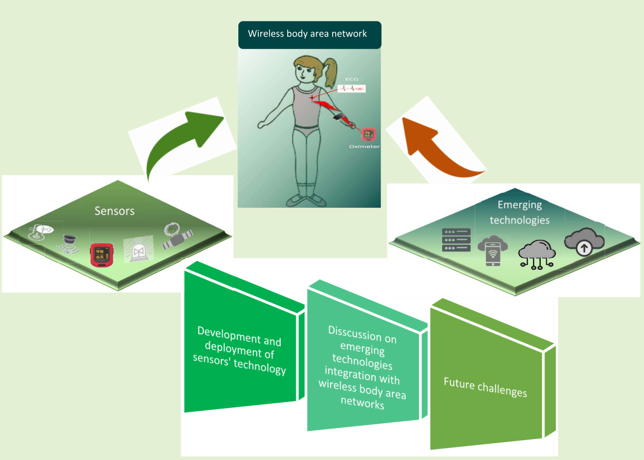
***Abstract*—The introduction of sensor technology in our daily lives has brought comfort, convenience, and improved health over the past few decades. Technological advances further expanded the use of medical sensors by reducing their size and costs. Medical sensors improve the intelligence and capabilities of healthcare services including, remote health monitoring, surgical procedures, therapy, and rehabilitation. We present a comprehensive review of medical sensors in the last 50 years focusing on their deployment in healthcare applications. The review also discusses the role of Internet of Things (IoT) technology in enhancing the capabilities of sensor technologies for the healthcare domain. Moreover, we also investigate the benefits and challenges of various integrated architectures which have been proposed recently to seamlessly integrate heterogeneous medical sensors with emerging technologies and paradigms that include edge, Mobile Cloud Computing (MCC), fog, and cloud computing technologies. Finally, we identify future challenges that must be addressed to achieve the maximum potential and benefits of medical sensor technologies and ultimately provide robust, scalable, reliable, and cost-effective healthcare delivery.**



***Index Terms*—Body area network, cloud, edge, fog, healthcare, Internet of Things (IoT), sensing, sensor.**

I. INTRODUCTION

THE development of the first sensor-based thermostat in 1883 by Warren Johnson to avoid hourly janitor interruption for temperature adjustment in the classroom is considered the first modern sensor in history [1], [2]. Since then, numerous types of sensors have emerged for different purposes leading to many technological developments such as remote sensing [3]–[5], mechanical design [1], robotics [6] and space exploration [7], [8]. In 1956, the first biosensor was developed by Leland C. Clark, Jr for oxygen detection that brought the concept of biosensing to healthcare [9]. Later, Clarke and Lyone [1] introduced the first glucose sensor in 1962 that further extended the scope of sensor technology for medical applications and commercialized it in 1972, leading to a multi-billion-dollar industry. Likewise, in the 20th century, sensor technology strongly influenced the monitoring of healthcare parameters (such as temperature, heart rate, glucose level, and so on) [10]–[12], surgical procedures [13]–[15], and diagnosis [15], [16] (such as biopsy, endoscopy and prenatal testing) pertaining to healthcare.

In mid-1980s, sensors' design began to incorporate digital signal processors, microcontroller units, and application-specific integrated circuits which transformed the traditional sensors into smart sensors with better computation, storage, and energy management capabilities [17], [18]. Later,

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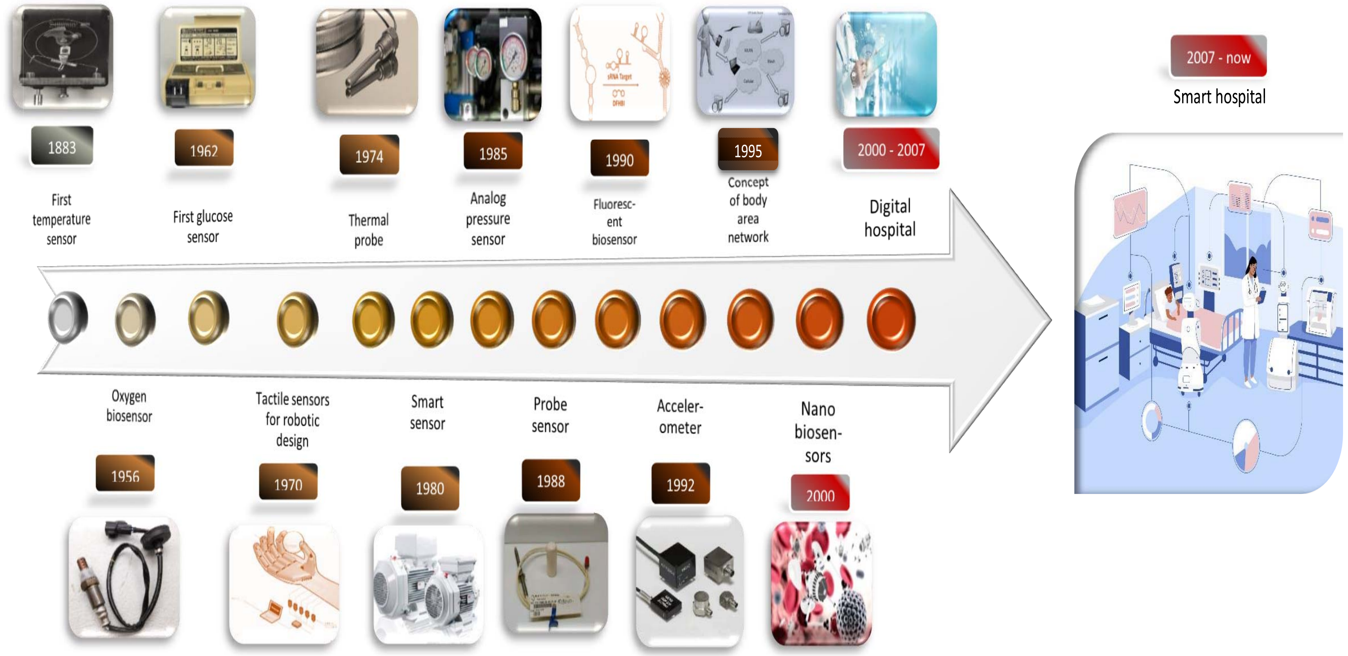

Fig. 1. Integration of sensor technologies in healthcare over time.

the end of the 20th century witnessed a rapid acceleration in the development of cost-effective and small form factor MicroElectroMechanical Systems (MEMS) based sensors that can measure physical parameters such as acceleration, temperature, and pressure [19], [20]. The unique design of MEMS-based sensors allows the integration of electronic components onto a single chip that can measure different phenomena, perform signal processing, and enable wireless communication. These types of smart sensors also enable the design of various devices ranging from sports' watches to cars. The rapid evolution and ease in adapting sensors quickly led to their use in a wide range of health-related applications, including home pregnancy testing [21], allergy detection [22] or HIV self-testing [23], [24]. Following the rapid technological sensor developments over the last 50 years, patients, individuals, and healthcare providers adapted the sensing technology to a wide range of healthcare and facility management applications. This led to the concept of Wireless Body Area Networks (WBAN) in 1995 [25].

A WBAN consists of several micro-sized medical sensors (due to their small sizes and their ability to measure different biological parameters accurately) and a gateway that connects the WBAN with an external healthcare system. Micro-medical sensors can be easily placed on the patient's body without causing any discomfort. Micro medical sensors are generally manufactured using flexible materials such as semiconductors, ceramics, hydrogels, polymers, and alloys that generate mechanical, electrical, chemical or magnetic responses to the external stimuli [26]. The primary components of a medical sensor include a microcontroller, an on-chip memory or flash memory, a miniaturized power source, a transceiver and a sensor to detect physiological parameters (such as temperature, heartbeat, and oxygen level). The microcontroller also includes an integrated Analog to Digital Converter (ADC) and a digital signal processor. The ADC converts the sensor's measured analog output into a digital signal, and the digital signal processor performs various signal operations on the digital signal to execute quick mathematical functions such as addition, subtraction, multiplication, and division [27]. Sensing devices use transceivers to communicate the detected information wirelessly with other sensing devices and a gateway. Gateways transmit the retrieved data to an external computing device for analysis and timely decisions by healthcare professionals.

At the start of the 21st century, advances in nanotechnology sped up the development of nanomaterial-based nano biosensors that have high sensitivity and specific functionalities for performing cellular-level monitoring and diagnosis [28]. Furthermore, Graphene-based nanoantennas support electromagnetic communication in the Terahertz band with very high speed that enable nano biosensors' applications for various medical applications such as early cancer detection [29], initial stage kidney damage diagnosis [30], improved oxygen level measurements, localized and non-invasive surgical procedures [31], [32].

Furthermore, in public areas such as hospitals, biosensors can provide inexpensive, quick detection of bacteria strains for infection control and prevention [33], [34]. Figure 1 highlights the integration of sensor technologies in the healthcare domain and demonstrates the development of different types of sensors and nano biosensors which led to the concept of WBAN, digital hospital, all of which paved the way toward a new era of smart hospitals for continuous healthcare monitoring and delivery.

A. Research Contributions of This Work

In this work, we explored the state-of-the-art literature to review the following three aspects: (1) The evolution of medical sensors over time and the types of sensors available to

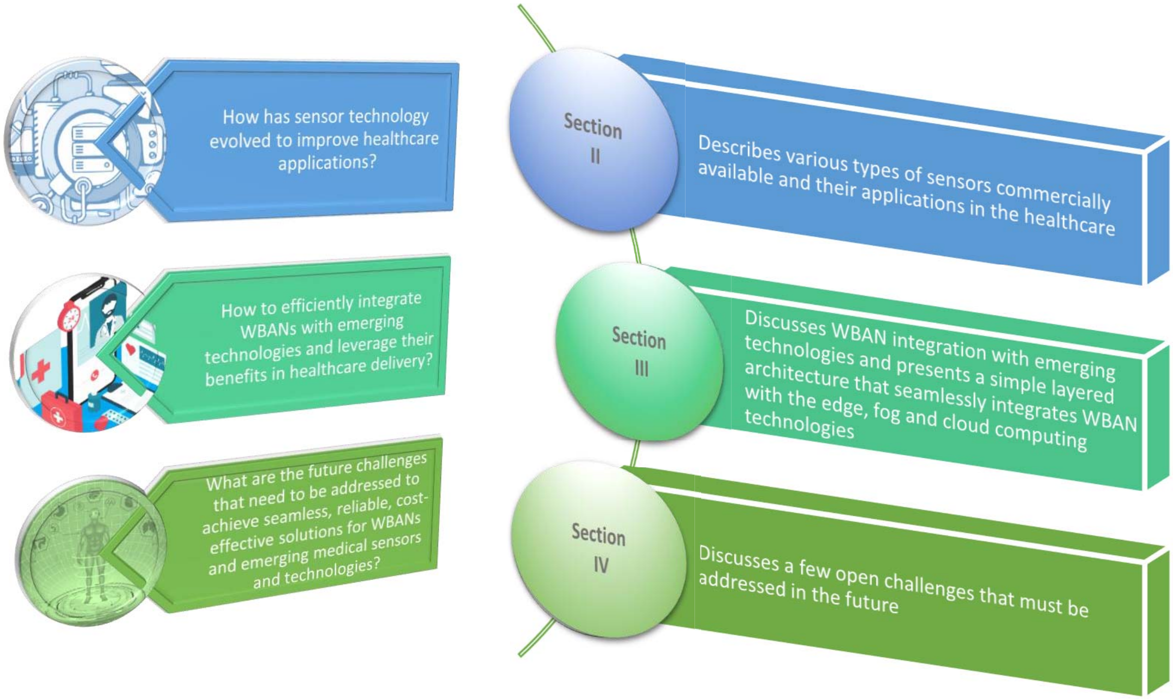

Fig. 2. Layout of the presented review framework.

practitioners for improving the various healthcare applications. (2) Solutions which integrate the WBAN environment with emerging technologies (such as edge, fog, cloud, and Mobile Cloud Computing (MCC)) to deliver high performance, cost-effective healthcare delivery. (3) Challenges that must be addressed in the future to improve the applicability of WBAN in a heterogeneous environment. To address the aforementioned aspects, we summarize the main contributions of this work as follows:

- We reviewed state-of-the-art medical sensor technologies that have been developed and deployed in the last few decades, focusing on their main features and healthcare applications where they are deployed.
- We described the functionalities of sensing, networking, and application layers and we present a cohesive architecture that shows how technologies (such as edge, fog, cloud, and Mobile Cloud Computing (MCC)) can be integrated at the different layers in a WBAN environment.
- We discussed future challenges that must be addressed to achieve the maximum potential and benefits of medical sensor technologies especially when they are deployed in highly heterogeneous networked WBAN environments.

Figure 2 also visually describes the questions that proposed review framework solves.

We organize the rest of this paper as follows. Section II describes different types of medical sensors along with their applications in healthcare and discusses contributions and limitations of existing related surveys. Section III discusses WBAN and IoT integration with emerging technologies and describes a simple layered architecture that can seamlessly integrate emerging technologies with a WBAN. Section IV discusses a few open challenges that must be addressed in the future. Finally, Section V concludes the paper.

II. BACKGROUND ON MEDICAL SENSORS AND REVIEW OF EXISTING SURVEYS

This section focuses on advances in medical sensors technology. It reviews the evolution of medical sensor technologies and highlights the medical sensors used in healthcare applications. This section also discusses existing relevant surveys and identifies their limitations which we addressed in this review.

A. Sensor Applications in Healthcare

Over the past several decades, the integration of sensors in medical applications has significantly improved the quality and safety of many healthcare applications including remote patient monitoring [11], [35], medical imaging [36], [37], improved diagnosis [15], [29], and childbirth care [38]. The advent of sensor-based minimal invasive surgery techniques in the 1990s also extended the use of sensors to different surgical procedures such as remote surgical tool positioning [39], [40], anesthesia [41], endoscopy [42], [43], and advanced cardiac surgery [44].

The last few decades have also witnessed rapid developments of nano biosensors in medicine where nano biosensors with better sensitivity and functionalities can be implanted inside the human body for early cancer detection, targeted drug delivery, and non-invasive surgical procedures. In remote healthcare applications, various sensors such as oximeter, humidity, ECG, temperature, position and glucose sensors can be worn by the patient to send remote updates to the healthcare provider when needed. Similarly, force, airflow, temperature and flow sensors are used in anesthesia delivery, dialysis, endoscopy and different surgical equipments and procedures.

In addition to enhanced healthcare deliveries, wearable and implanted sensors also play a significant role in reducing medical costs by enabling remote monitoring, diagnosis, and treatment. Figure 3 presents a detailed taxonomy of widely used sensors deployed in a broad range of applications. The deployment of these sensors demonstrates the pivotal role that sensors play in medical applications today.

B. Types of Sensors Used in Healthcare

Sensors used in medical applications can be broadly classified as physical sensors [45], electrochemical sensors [46], optical sensors [47], and magnetic sensors [34]. These different types of medical sensors mainly differ from other sensors in terms of their characteristics and sizes. For instance, medical sensors have better sensitivity for detecting specific physical, chemical or biological processes with enhanced accuracy. Moreover, the integration of medical sensors in medical devices requires highly miniaturized sensors that can be easily integrated into the medical devices and easily worn/carried by patients for various applications. For example, physical sensors such as temperature, pressure and ECG sensors, can be worn by the patients for monitoring the body or skin temperature, oxygen saturation level, or the blood flow [48]–[50]. Table I summarizes different types of sensors used in medical applications or the healthcare industry.

In the context of optical sensors, they have many applications for non-invasive surgical procedures, including endoscopy [42], [51], radiography [52], [53], artificial retinas [54], ocular surgery and observation. In contrast, chemical sensors can detect the presence and concentrations of different substances in the body, such as glucose concentration, PH value, and so on. Magnetic biosensors are considered important for various applications such as magnetocardiography, magnetomyography, and point-of-care devices. Ultrasonic sensors can measure flow rates and monitor fluid levels. They can accurately detect air bubbles or the presence of blood in the dialysate.

Furthermore, various healthcare projects have been undertaken to improve emergency medical care. For example, In the CodeBlue project [55], different wearable sensors perform remote physiological monitoring and notify the healthcare providers in an emergency. Another project called LOBIN [56] also monitors the health of the patients and locates their positions in a hospital environment. In the MEDiSN project, the system monitors the health of injured people during a disaster. The MEDiSN project [57] also integrated a back-end server that persistently stores the healthcare history of monitored patients and makes it available to authenticated users. Another body-inertial healthcare project [58] also uses WBAN for healthcare management for emergencies and daily physiological monitoring. Moreover, recently, The Guangdong Second Provincial General Hospital in China has also announced a comprehensive smart hospital project to enable advanced real-time healthcare monitoring and data processing [59].

C. Existing Surveys

Over the years, several surveys have comprehensively reviewed state-of-the-art literature to summarize communication technologies [92], routing protocols [93], [94], WBAN applications in healthcare [95], [96], reliability and trust issues [97], [98], security and privacy concerns of WBANs [99]–[101]. However, in this survey, we focus primarily on advances in medical sensors and WBAN integration with emerging technologies. This section briefly analyzes the most relevant state-of-the-art surveys and summarizes their main contributions and shortcomings which motivated this review.

In [102], authors briefly reviewed medical sensors, healthcare applications, and services. However, it lacks an in-depth discussion related to medical sensor design and deployment challenges. Another survey [103] solely focused on the data fusion techniques and limitations of sensors in carrying out the data fusion operations without properly reviewing the WBAN architecture and related components. In [104], Sneha. *et al.* discussed the patient monitoring models and decisions protocols from a smart home perspective, leaving other important applications of a WBAN.

Similarly, the authors of [105] provided insights into future intelligent monitoring of children, elderly, and chronically ill patients for easy and independent living. Their intelligent monitoring is enabled using RFID tags or by placing ECG sensors, accelerometers or posture sensors on the body of the patients or children to monitor their movements and physical conditions. Another survey [106] only summarized existing application layer protocols for healthcare applications. Pantelopoulos *et al.* [107] also only reviewed the developments in medical sensors for healthcare applications.

In the context of temperature-aware and energy-efficient routing, Oey *et al.* in [108] solely focused on the temperature rise challenge in WBAN's routing and summarized the temperature-aware routing schemes in WBANs. In contrast, the survey presented in [109] focused on energy-efficient routing schemes for WBANs. Similarly in [110], Jijesh. *et al.* also discussed recently proposed routing schemes by classifying them into various categories in a WBAN environment. In [111], the authors reviewed the state-of-the-art literature on various aspects of a WBAN, including communication architectures, applications, programming frameworks, security issues, and energy efficiency.

Additionally, the current literature also reviewed energy harvesting and wireless transfer opportunities to prolong the lifetime of WBAN. For example, Huang *et al.* in [112] discussed wireless information and power transfer technologies that enable the transfer information and energy simultaneously using electromagnetic waves. The authors of [113] also provided an overview of wireless power transfer for WBAN to transfer energy to the medical sensors that have low energy. In [114], various energy harvesting options such as glucose, heartbeat, lactate, blood pressure, and breathing are briefly discussed that can provide energy to the sensors placed over the body or implanted inside the human body.

Egbogah *et al.* [115] also comprehensively described the existing healthcare system and discussed various protocols that can enhance the performance of the healthcare system. Another survey [116] broadly reviewed IoT-based healthcare systems and described various applications that IoT healthcare architectures can support but it lacks a thorough demonstra-

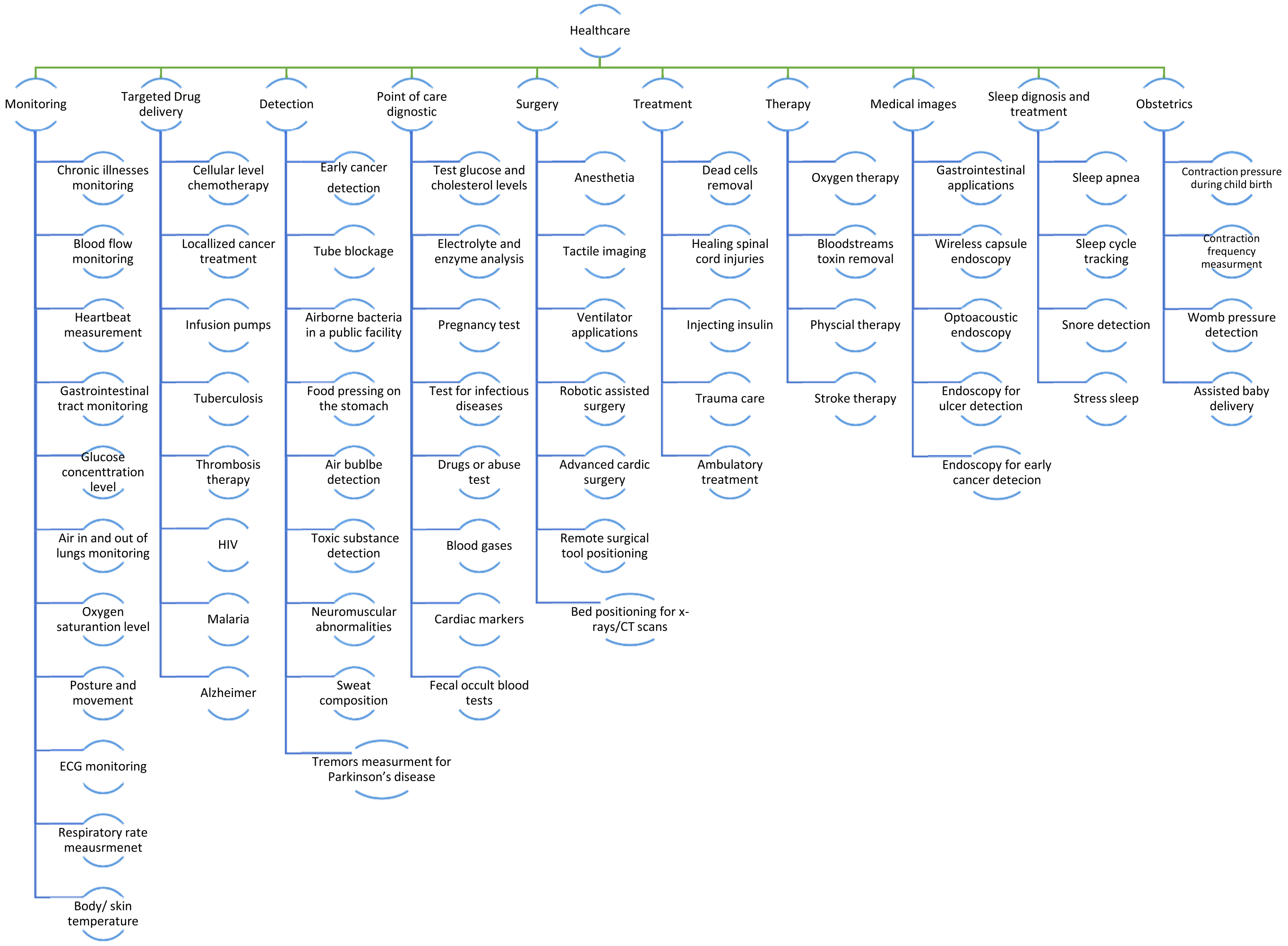

Fig. 3. Taxonomy of sensors deployed in the healthcare domain.

tion of different layers and protocols comprising the IoT architecture. Uslu *et al.* [116] also reviewed IoT architectures for healthcare applications and discussed various factors that affect IoT-based healthcare architectures.

The primary improvements in the presented review framework over current review works and surveys that have been published include:

1) In contrast to other existing surveys, the presented review explores the developments in the design of medical sensors over the last 50 years. In addition, we also provide a detailed taxonomy (Figure 3 and Table I) that highlights different types of medical sensors and their use in various healthcare applications.
2) This survey thoroughly discusses the WBAN architecture and its integration with IoT and other technologies. Moreover, unlike other surveys, it also describes the IoT layered architecture to better understand the integration of WBAN with IoT technologies.
3) In this review, we also introduce a new simple layered architecture that cohesively integrates emerging technologies at various layers of the IoT architecture for efficient resource consumption and data processing.
4) Finally, this review identifies future research directions that need further attention by researchers.

Table II also summarizes the current surveys that are related to this review and highlights their limitations which we consider in this work.

III. WBAN INTEGRATION WITH INTERNET OF THINGS (IOT) AND EMERGING TECHNOLOGIES

An operational healthcare system requires the interconnection of WBAN (consisting of implanted or wearable sensors) and various heterogeneous smart objects (such as IoT devices) to support multiple applications for elderly, infants or chronically ill patients. The devices placed outside the body or implanted inside the body generate a large amount of physiological data for improved diagnosis and medical decisions. However, the vast amount of data produced by sensing devices also requires efficient and cost-effective management for an advanced and smart healthcare system.

Emerging technologies such as edge computing, MCC, fog computing, or cloud computing, can provide low-cost storage and computational solutions to meet the requirements of a cost-effective healthcare system. In addition, new wireless technologies such as Ultra Wide Band (UWB) [118],

TABLE I
SENSOR TYPES AND THEIR APPLICATIONS

Reference	Sensor type	Application	Reference	Sensor type	Application
[41], [60]–[66]	Pressure sensors	1. Anesthesia delivery machines 2. Oxygen concentrators 3. Sleep apnea machines 4. Ventilators 5. Kidney dialysis machines 6. Infusion and insulin pumps 7. Blood analyzers 8. Respiratory monitoring and blood pressure monitoring equipment 9. Hospital beds 10. Surgical fluid management systems 11. Pressure-operated dental instruments	[41], [62]–[66]	Temperature sensors	1. Anesthesia delivery machines 2. Sleep apnea machines 3. Ventilators 4. Kidney dialysis machines 5. Blood analyzers 6. Medical incubators 7. Humidified oxygen 8. Heater temperature monitoring and control equipment 9. Neonatal intensive care units 10. Organ transplant system temperature monitoring and control
[6], [14], [44]	Tactile sensors	1. Knee motion monitoring 2. Emotion recognition 3. Voice monitoring 4. Pulse monitoring 5. Wound heal monitoring 6. Breath monitoring 7. Prosthetic limb 8. Electronic signature	[41], [60]–[67]	Flow sensors	1. Anesthesia delivery machines 2. Oxygen concentrators 3. Sleep apnea machines 4. Ventilators 5. Respiratory monitoring 6. Gas mixing 7. Electro-surgery
[10], [68]	Oximeter/ Sp02	1. Oxygen saturation level monitoring 2. Alert about the low oxygen levels in newborns 3. Continuous care for patients with chronic respiratory or cardiovascular conditions	[69], [70]	Skin sensors	1. Monitor body parameters such as temperature, heartbeat, sweat composition, and alcohol intake etc. 2. Skin wounds monitoring 3. Provide personalized skincare
[70]–[73]	Humidity sensor	1. Personal care 2. Disease diagnostics 3. Breath rate monitoring 4. Touch-free examination of skin moisture	[9]	Fluorescent biosensors	1. Early detection of biomarkers in molecular and clinical diagnostics 2. Monitoring disease progression and response to treatment therapeutics, for intravital imaging and image-guided surgery
[43], [74], [75]	Force sensors	1. Fluid monitoring applications 2. Dialysis machines 3. Endoscopic surgery 4. Physical therapy equipment 5. Orthopedics and MRI devices	[76], [77]	Electromyography sensors	1. Measure the electrical activity of muscles 2. Detect neuromuscular abnormalities 3. Postural control 4. Physical therapy 5. Neuromuscular physiology
[40], [41]	Airflow sensors	1. Anesthesia delivery machines 2. Laparoscopy 3. Heart pumps	[78]	Activity sensors	1. Monitor heart activity and position of the upper trunk 2. Monitor position and activity of upper and lower extremities
[38], [49], [79]	ECG sensors	1. Measurement of electrical activity of the heart	[50], [80]	Heart rate sensors	1. Count the number of heart contractions per minute.
[81], [82]	Intraocular pressure telemetric sensors	1. Continuous intraocular pressure (IOP) monitoring for glaucoma patients	[83]	Electromyogram sensors	1. Records the electrical activity produced by skeletal muscles.
[84]	Pyroelectric infrared sensors	1. Movement detection 2. Infrared radiation level detection	[85]	pH sensors	1. Monitor wound healing 2. Infection identification
[86]	Photoplethysmographic biosensors	1. Advanced monitoring of patient’s cardiovascular state	[87]	Plethysmographic sensors	1. Continuous measurement of weak blood flow signals
[88]	Intrauterine pressure sensors	1. Measurement of contraction pressure and frequency during childbirth	[89]	Ultrasonic proximity sensors	1. Count the chest rises in a minute 2. Respiration rate management
[90]	Electroencephalogram sensors	1. Measurement of electrical activity of the brain	[91]	Glucometer	1. Blood glucose concentration

6G [119] and Wi-Fi 6 (802.11ax) [120] technologies are also considered key enablers for transforming the healthcare system by supporting new healthcare monitoring, evaluation, and treatment services. For example, UWB technology enables data communications at very high data rates (up to 500 Mega bits/second) with low cost, reduced power consumption, and enhanced reliability within the surrounding area of the human body [121]. Thus, UWB technology can substantially enhance WBAN’s functionality for a wide range of applications such as assisted living for seniors, continuous remote monitoring for chronic patients, and physical posture monitoring to avoid muscle strain or injury.

6G communication technology is also envisioned to support AI-driven solutions for advanced healthcare systems and enable real-time communication of human body information to the edge devices and cloud servers for short-term and long-term healthcare analysis at high data rates [122]. Furthermore, Wi-Fi 6 technology (802.11ax) also supports higher networking capabilities, including enhanced reliability, connectivity, efficient data handling and power utilization. Accordingly, Wi-Fi 6 provides fast hospital-wide access to medical data and imaging systems such as radiography, magnetic resonance imaging, and ultrasound leading to reliable and efficient patient care and healthcare delivery.

However, the integration of sensors with other technologies also requires the consideration of several factors, including sensors’ battery power, robustness, wireless connectivity, computational speed, and portability at a low cost. In this section, we briefly discuss recent integration WBANs architectures with IoT and the benefits of integrating WBAN with emerging technologies (i.e., cloud, MCC, fog and edge computing) to provide efficient resource management, additional storage, and cost-effective services for pervasive healthcare applications.

A. WBAN and IoT

Sensors worn by the patient or implanted inside the patient’s body perform continuous vital monitoring functions and execute important operations such as storage, computation, or transmission. However, the resource constraints faced by sensing devices means that they can only carry out limited operations. A smart IoT gateway can extend the applications of WBAN for diverse operations by efficiently analyzing the detected data and carrying out complex functions that cannot be fully performed at the sensor devices. Figure 4 shows that smart gateways can connect a WBAN with emerging technologies such as edge, MCC, fog and cloud computing for enhancing WBAN’s functionalities.

Furthermore, the integration of new technologies at different layers in the IoT ecosystem also improves storage and data availability while reducing data transmission latency. State-of-the-art schemes [123]–[125] have implemented WBANs using an IoT architecture to improve communication, data analysis, and scalability among heterogeneous devices. Numerous [126]–[129] existing IoT architectures for

TABLE II
COMPARISON OF THIS SURVEY WITH RELEVANT PAST PUBLISHED SURVEYS

Ref.	Description	Comments	Improvements of this survey over previously published surveys
[102]	Describes various services, applications, and systems based on medical sensors and briefly discusses their design goals and challenges	Challenges associated with the design, development, and implementation in medical healthcare systems are not fully explored	This survey differs from existing surveys in the following aspects: 1. It thoroughly reviews different types of sensors and their applications in healthcare that are not included in many current surveys 2. It presents a comprehensive discussion on WBAN architecture and its integration with IoT and other technologies Moreover, unlike other surveys, it also describes the IoT layered architecture to better understand the integration of WBAN with IoT 3. Unlike existing surveys, it presents an in-depth discussion on the integration of emerging technologies with WBAN, including the introduction of a simple layered architecture that cohesively integrates emerging technologies at various layers of the IoT architecture 4. It identifies research directions that require more attention in the future
[103]	Mainly focuses on sensor data fusion operations and network communication schemes to minimize energy consumption	Does not provide a detailed discussion on communication protocols and architectures	
[104]	Discusses a ubiquitous patient monitoring model and decisions protocols by demonstrating the complex processes, parameters, and decision criteria for patient monitoring	Lack of design goals and challenges for smart home application development	
[105]	Presents future intelligent monitoring applications from a smart home perspective	Does not provide a detailed information about the types of sensors that need to be used in a smart home environment. Only focuses on daily healthcare activity monitoring at home, such as movement and fall detection, medical status checking and location tracking.	
[106]	Reviews state-of-the-art technologies and techniques for using constrained application protocol for connecting and monitoring medical sensors	Focuses only on application layer protocols	
[107]	Studies the current developments of wearable biosensor systems for health monitoring	Focuses on sensor design issues such as inadequate energy and power without discussing sensor communication issues and existing architectures	
[108]	Reviews and compares existing routing protocols and discusses their challenges in designing temperature-aware routing protocols	Only focuses on temperature aware routing protocols without discussing WBAN architectures and other communication challenges	
[111]	Review state-of-the-art WBAN architectures, including communication architectures, applications, programming frameworks, security, and energy efficiency issues	Does not discuss future challenges and improvements	
[110]	Discusses existing WBAN routing protocols in terms of their energy, bandwidth, and power usage	Communication architectures are not discussed	
[115]	Presents an extensive discussion on existing healthcare models and characteristics of Media Access Control (MAC), routing, and transport layer protocols for healthcare applications	Lack of discussion on the limitation and improvements for healthcare systems	
[109]	Comprehensively reviews existing energy-based routing schemes for WBANs	Does not provide an in-depth discussion of WBAN architectures and energy consumption issues	
[117]	Reviews IoT-based healthcare systems, including IoT technologies, services, and applications	Does not describe the IoT layered	
[116]	Comprehensively discusses an IoT architecture for a smart hospital design	Does not describe the WBAN communication architecture	

healthcare systems have considered the three main layers (i.e., sensing, networking, and application) and use different communication technologies such as IEEE 802.15.4 and 802.15.6, Bluetooth, Zigbee, or radio frequency identification according to the application requirements.

Wu et.al [130] proposed an IoT architecture for healthcare applications consisting of WBAN, IoT gateway, and a cloud server. Sensing devices in the WBAN monitor different physiological parameters and communicate with each other using a Low-Power Wide-Area Network (LPWAN) while the data transfer between the IoT gateway and the cloud server is carried out using a Message Queuing Telemetry Transport Protocol (MQTT) [131]. In [132], the authors implemented a WBAN integrated with IoT wherein sensor nodes in the WBAN monitor the temperature, heartbeat, and fall and communicate the collected information to the IoT gateway using Bluetooth Low Energy (BLE) [133] transmissions.

In another work [134], the authors integrate cloud services with a WBAN to improve the emergency response in a disaster situation, resulting in real-time data processing and efficient management. In [135], Bhardwaj *et al.* proposed an experimental framework for cloud and WBAN integration. In [136], the authors also integrated a cloud server for disaster healthcare management, in which sensor nodes placed over the body of the patient transfer physiological data to the local data processing unit. The local processing unit performs the initial data processing and sends the data to the cloud servers for advanced data management operations.

Various existing architectures [137]–[140] have also integrated cloud servers for addressing security and privacy issues in a healthcare environment. Since the service-oriented architecture of IoT enables communication and interoperability among heterogeneous devices, there are multiple challenges at the sensing, communication, and application level that require

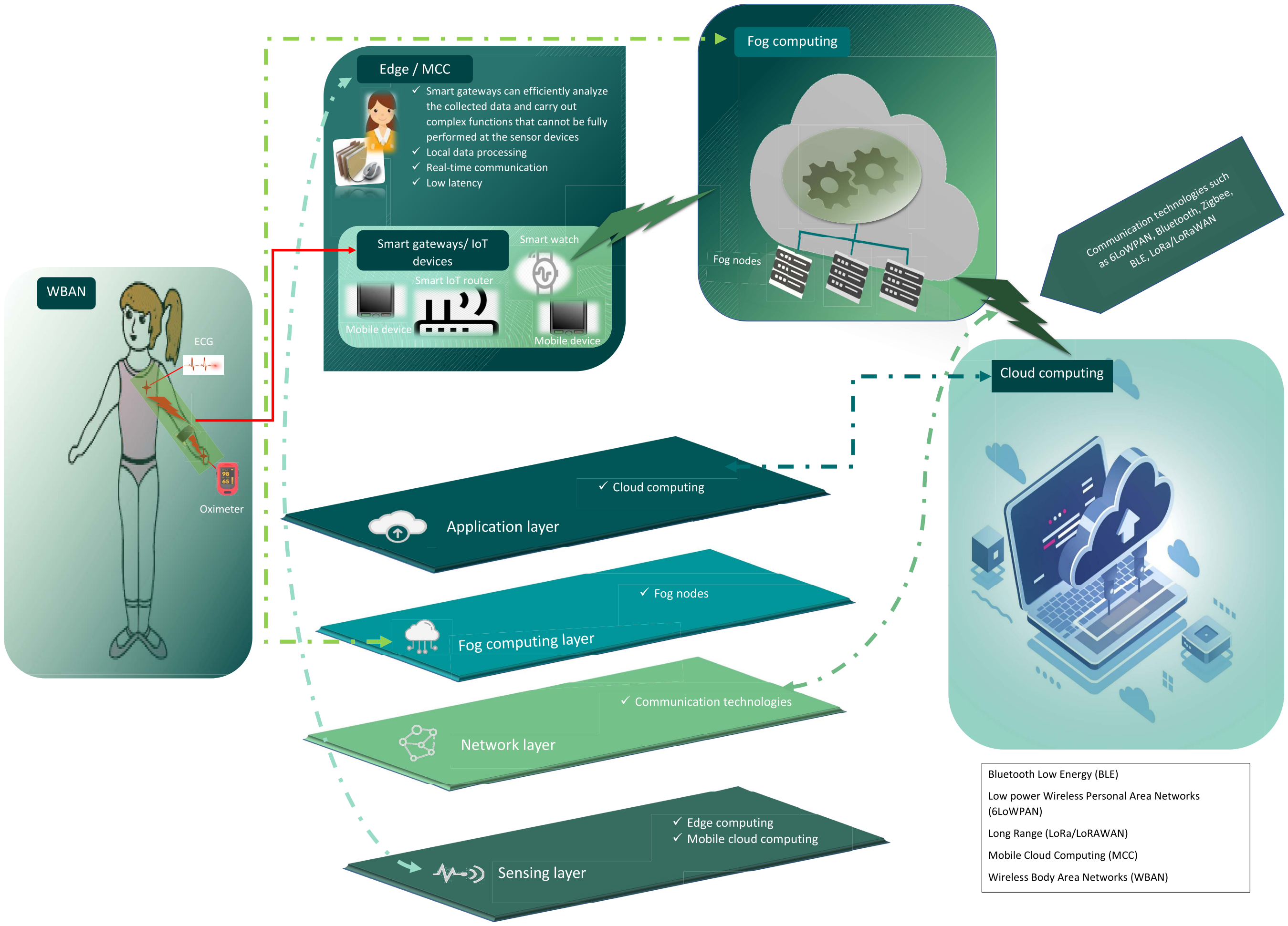

Fig. 4. Architecture integrating a WBAN with technologies such as edge, fog, and cloud.

further attention. According to the existing literature [116], [127], [134], [141], [142], requirements and integration challenges at various levels must be addressed when medical sensors are integrated with the IoT ecosystem. Table III presents various existing integration architectures along with their advantages and limitations.

B. Integration of Emerging Technologies at the Sensing Layer for the WBAN-IoT Architecture

The sensing layer deals with data monitoring aspects, such as data collection, storage, and analysis [154]. This layer needs efficient resource management for sensing devices during vital parameter monitoring, analysis, and transmission to the smart gateway which can then preprocess the raw sensor data collected and satisfy the integration and transmission requirements of using different integration platforms (such as satellite and crowd sensing) [116].

The sensing layer also needs to support data storage and distribution to store patient's physiological information and share it with medical, insurance, or healthcare personnel. In this section, we discuss the benefits and challenges of integrating edge computing and Mobile Cloud Computing (MCC) at the sensing layer.

1) Edge Computing Integration at the Sensing Layer: The integration of edge computing services at the sensing layer can reduce the data manipulation complexity and optimize security services because smart gateways or edge devices can process and analyze the original information collected locally without requiring the transmission of all the information to the remote servers. In this paradigm, [35], [155] end-devices placed at a nearby location, minimizes data latency and improves the data communication speed between senders and receivers. Thus, edge-computing-assisted WBAN can provide real-time communication with low latency and resource consumption of sensing devices.

The emergence of edge computing also offers an excellent opportunity for smart localized healthcare applications to reduce the data propagation load and improve QoS with minimal cost. In [150], Oueida *et al.* proposed a resource reservation system, integrated with edge computing for efficiently managing the hospital resources (such as the number of available beds, patient's duration of stay, and average patient waiting time). In this resource reservation system, each resource (such as available beds and devices used for monitoring patients' conditions), has its own edge node that communicates with the cloud to notify the hospital management team about the status of the resource. In [151],

TABLE III
PROPOSED INTEGRATED ARCHITECTURES ALONG WITH THEIR ADVANTAGES AND LIMITATIONS

Integrated technology	Ref.	Advantages	Limitations
Cloud computing architectures	[130]	1-Low power communicationamong the sensing devices and WBAN connected to the cloud serverssaves energy 2- Cloud server provides datastorage, website display, and mobileuser interface	1. Require high CPU storage and cost 2. High WBAN's resource consumption
	[135]	1. Support Cloud-WBAN computing scenarios 2. Efficient resourceutilization and allocation 3. Optimal resource provisioning	1. High-level architecture does not thoroughly focus on WBAN challenges such as limited energy and low complexity
	[134]	1. Efficient management of large amounts of data 2. Real-time powerful data processing and storage	1. Requires high processing power, large memory capacity 2. Needs trust management schemes
	[136]	1. Efficient data aggregation andtransmission to the cloud servers based on data priority	1. Cloud server require high data storage and computation power 2. Frequent data exchange between the WBAN and cloud servers
Mobile cloud computing architectures	[143]	1. Reduces power consumption 2. Save mobile storage by executing complex tasks at the cloudserver.	1. High bandwidth consumption 2. Increased cost and latency
	[144]	1. High flexibility and reliability 2. Low computational power and cost-effective implementation for pervasive healthcare delivery	1. Interoperability and latency issues 2. Support application-specific design
	[145]	1. Optimizes the real-time query processing 2. Minimizes energy consumption and query latency	1. Lack of mobility as patients who wore sensors need to be on bed or not moving 2. Limited scalability
	[79]	1. Sensing data collected by the sensing devices can be accessed by the medical or healthcare staff anytime, anywhere from any device	1. Real-time data uploaded at the cloud server requires a lot of resources 2. Inadequate security and privacy
Fog computing architectures	[146]	1. Introduces an intermediary layer of intelligence between sensor nodes and the cloud for enhanced energy efficiency and reliability	1. Interoperability and security concerns
	[147]	1. Embedded data mining, storage and notification service at the edge of the network	1. Requires QoS provisioning and interoperability
	[148]	1. Allows patients to monitor and share information with their physicians independently 2. Enables rapid notifications to the authorities in emergencies	1. Lack of scalability and security
	[149]	1. Provides logical intelligence to the end devices 2. Filters the collected data with low latency.	1. High processing and storage complexity 2. High bandwidth consumption
Edge computing architectures	[150]	1. Efficient management of hospital resources.	1. Requires high storage and computational power 2. High resource consumption
	[151]	1. Reduces the cost and improves data processing at the edge of the network for remote monitoring applications	1. Low complexity solutions are required for data processing and management at the edge devices
	[152]	1. Monitors and analyzes the physical health of users using cognitive computing for optimal resource consumption	1. High resource consumption and complexity
	[153]	1. Real-time low latency voice disorder detection and treatment.	1. Lack of interoperability and standard design framework

Dong *et al.* reduced the system-wide cost by using edge computing wherein edge devices handle the data processing based on the criticality of data. This reduces the processing burden on the WBAN, and improves the video streaming quality for remote monitoring applications.

In another work [152], Chen *et al.* proposed an edge cognitive computing architecture to monitor and analyze a patient's health. In [153], Muhammad *et al.* used edge computing for detecting voice disorder (such as laryngitis, muscle tension dysphonia and spasmodic dysphonia due to neurological voice illnesses). The voice samples were collected using the sensing devices and then distributed over several clouds for parallel processing. The final results obtained from the clouds were processed by medical specialists for ultimate decision and treatment recommendations such as distance voice therapy or medicine.

However, edge computing is a relatively new concept that does not have a standard design framework. Therefore, research communities are developing different hardware-dependent platforms and lightweight solutions to design edge computing applications to improve edge-computing assisted WBAN healthcare systems.

2) Mobile Cloud Computing Integration at the Sensing Layer for WBAN-IoT Architecture: The integration of mobile cloud computing [156] at the sensing layer alleviates computation-intensive operations off resource-constrained sensor nodes and transfers resource-intensive (storage, computation) tasks to the cloud for additional real-time processing. The seamless integration of MCC with WBANs also brings several inherent advantages of cloud computing, such as cost-effective data management, easy integration, and dynamic resource provisioning. Data storage on the cloud servers also improves data reliability because patients' data is saved on multiple servers, and it can be easily retrieved in case of device failure and loss. In addition, MCC provides enhanced functionalities and services that deliver cloud services to the mobile devices with better speed for QoS-enabled medical video streaming and it also provide personalized applications for patients, doctors, healthcare providers, or emergency unit personnel when they access the patients' data.

In the existing literature [157]–[159], several healthcare solutions integrate WBAN with MCC for continuous secure vital monitoring. For instance, in [144], the authors developed a cloud-enabled pervasive healthcare system that provides energy-efficient data communications among the WBAN, mobile computing devices, and cloud servers. In another work [143], Lo'ai *et al.* developed a cloudlet-based efficient and secure mobile cloud computing model that allows mobile devices in the healthcare environment to directly connect with the cloud using Wi-Fi technology. In [79], Fong *et al.* proposed a MCC integrated healthcare solution for noncontact ECG monitoring wherein mobile devices collect ECG measurements for analysis and the collected information can be accessed by the medical or healthcare staff anytime, anywhere from any device. In another work [145], Diallo *et al.* developed a real-time querying system that uses cloud-based WBANs that make use of statistical modeling techniques to provide approximate answers to queries with reduced energy consumption to optimize the performance of cloud-based WBANs.

However, due to the participation of different types of sensors and IoT devices, the sensing layer needs to address crucial issues such as primary data processing, data filtering, complexity, reliability, low cost for energy consumption, storage, computation, and security mechanisms for reliable and optimized healthcare system performance [160]–[162]. In the existing literature [163], [164], various data filtering strategies and sensor data processing mechanisms have been discussed. For example, dong *et al.* in [165] reviewed current filtering methods which address received sensor data's coupling issues as data obtained from a sensing device consist of its own sensed data and the data received from other neighboring nodes. Therefore, the data received at the sensing node needs to be filtered to avoid any inconsistencies from the sensor's measurements. In another work [166], the authors studied multi-data fusion and consensus filtering mechanisms to understand their impact on the improved (after taking into account delay and other network factors which may affect the sensed data) received data estimation. In another recent work, the authors of [167] reviewed sensors' data processing that lack generality and flexibility for ambulatory monitoring in the outpatients settings (such as medical offices, clinics, dialysis centers and hospital outpatient departments).

The Raspberry embedded card system [168] is considered to be an optimal solution for decreasing the cost at the sensing layer that allows saving patients' data, including real-time photos and diagnostic information [169]. In the context of privacy and security, considerable attention has been given to the design of authentication and authorization approaches using blockchain to develop optimal security approaches that consume low energy [170], [171].

C. Network Layer Support for Seamless Integration of WBANs With Emerging Technologies

The network layer enables heterogeneous devices to communicate with each other using different protocols and communication technologies while addressing crucial requirement such as interoperability, standardization, low cost, optimal data delivery, security and privacy [116]. Various communication technologies have already been presented in the existing literature to standardize communication among heterogeneous devices and networks. Internet Protocol Version 6 (IPv6) over Low power Wireless Personal Area Networks (6LoWPAN) [172] is the most common communication standard for low-power short-range networks. This standard introduces an adaptation layer between the MAC and the network layers for interoperability.

ZigBee [173] is another popular technology that enables low power communication over a longer distance to improve the lifetime of resource constrained devices. BLE [133], [174] is also a good alternative for short-range, low bandwidth, and low power communication. However, BLE and Zigbee technologies have limited performance for advanced healthcare applications that require an extended communication range for cooperation among doctors, patients, and other stakeholders. LPWAN technologies can provide optimal solutions to meet

TABLE IV
COMPARISON OF VARIOUS STATE-OF-THE-ART COMMUNICATION TECHNOLOGIES

Technology	Zigbee	6LoWPAN	BLE	LoRA	Sigfox	NB-IoT
Communication range	10-100 meters	116 meters	100 meters	About 5 km	About 30-50 km	About 10 km
Transmission power	20 dBm	3 dBm	20 dBm	15 dBm	14 dBm	20 dBm or 23 dBm
Data rate	250 Kbps, 100 Kbps, 40 Kbps, and 20 Kbps	250 Kbps	1 Mbps	Up to 27 Kbps	600 bps	26Kbps
Latency	Below 140 Milliseconds	In miliseconds	In Miliseconds	10 seconds	10 seconds	1.5 to 10 seconds
Mobility support	Limited	Yes	Yes	Yes	No support	Limited
Deployment cost	Low	Low	Low	High	High	Low
WBAN support	High	High	High	Moderate	Low	High for low mobility WBAN

medical device requirements for extended coverage with limited power consumption [175].

LPWANs technologies, Long Range (LoRa) LoRa/LoRaWAN has significantly reduced cost and communication latency, which is highly suitable for chronic disease monitoring and treatment [176]. Narrow Band-IoT is also an LPWAN technology that improves energy and reduces device cost [177]. SigFox [178], [179] experiences low interference due to its narrow bandwidth use and consumes low power. In addition, Sigfox enhances the lifetime of the sigfox devices up to 14.6 years when a low data rate is used [180].

Based on recently published state-of-the-art surveys on communication technologies [92], [173], [176], [178], [179], Table IV summarizes the transmission range of communication technologies in meter and Kilo Meter (KM), transmission power in Decibel MilliWatts (dBm) and data rate in Kilobits/second (Kbps) and Megabits/second (Mbps).

D. Fog Computing Integration With WBAN

Fog computing is regarded as one of the most promising advances of traditional cloud computing. This new paradigm provides distributed services and bridges the gap between the WBAN and cloud servers. The primary benefits of fog computing include low latency, efficiency, security, and resiliency of many applications and services including those deployed in healthcare systems [181], [182].

In [147], the authors leveraged fog computing at the smart gateways between the WBAN and the cloud server to provide distributed storage, embedded data mining, and advanced services that are not supported at the cloud server. In [146], Rahmani *et al.* implemented fog computing by introducing an intelligent layer between the sensing devices and cloud servers to improve the energy efficiency, latency, and reliability of healthcare systems. In [183], Vora *et al.* introduced fog computing to reduce the delay for ambient assisted living. In [184], Tanwar *et al.* also improved WBAN performance using fog computing for monitoring and treating chronic arthritis disease.

The existing literature [148], [185] promotes that fog computing has strong potential for assisting doctors in making smart, timely decisions during critical situations (such as stroke or respiratory failure) and providing faster responses securely than standalone cloud-based applications.

E. Cloud Computing Integration With WBAN at the Application Layer

The application layer primarily deals with application-layer design aspects (to provide edge/fog/cloud computing support), healthcare application design (such as data management, authorization and authentication), and application-level services for healthcare providers, patients, and other stakeholders. Moreover, different healthcare technologies such as mobile health, electronic health [186], telemedicine [187], and P4 (a framework that combines prediction, prevention, personalization, and participation to detect and prevent diseases using extensive biomarker testing, close monitoring, deep statistical analysis, and patient health coaching) medicine [188] are supported by the application layer based on the information retrieved from the lower layer.

In addition, the application layer design requires a Graphical User Interface GUI to provide a seamless representation of the information collected from the lower layers, and a platform for doctor and patient interaction [189]. The current literature [141], [190] includes numerous application-layer communication protocols, including machine-to-machine communication protocols or messaging protocols to address cloud and fog computing integration challenges.

Application layer protocols are based on request/response, publisher/subscriber, or both request/response and publisher/subscriber interaction models; for instance, the Hypertext Transfer Protocol is the most common client/server-based application-layer communication protocol that can run over many existing networks. However, it has high complexity due to long header files that increases the energy consumption during network communications. The constrained application protocol is also based on the client/server architecture, and it is a lightweight protocol that significantly reduces power consumption [191]. MQTT protocol [131] is a messaging protocol that is based on the publisher/subscriber interaction model, and it is considered to be an excellent solution for transferring a large number of sensors messages to the cloud solutions.

In another work [192], the authors proposed the extensible messaging and presence protocol that uses both the request/response and the publisher/subscriber model, and it runs over distributed networks. Websockets presented in [190] is best suited for real-time medical applications because it is a simple message queueing protocol that minimizes communication latency. Another scheme presented in [193] improves Quality of Service (QoS) and scalability. The digital data service [194] is a publisher/subscriber model protocol but it suffers from high bandwidth consumption. However, it is suitable for real-time, low latency applications. Figure 5 shows the WBAN benefits and challenges when WBANs are integrated with IoT and emerging technologies.

IV. FUTURE CHALLENGES AND RESEARCH OPPORTUNITIES

The 21st century has witnessed significant advances in the healthcare domain and the integration of WBANs with emerging technologies along with the development of cost-effective sensors used by many healthcare applications today. However, there are still several open challenges that must be addressed to reap the full benefits of medical sensors and improve the performance of WBANs for a wide range of healthcare applications. In this section, we discuss some of these challenges.

A. Energy Consumption

Energy consumption is a fundamental design consideration of sensor networks, particularly for a WBAN where sensors (both on-body or in-body) are equipped with limited battery supplies for enabling continuous healthcare monitoring and data transmissions. Several research efforts [114], [144], [170], [195] have developed energy-efficient schemes at various layers for smart utilization of energy resources to avoid frequent battery replacements. However, the high data communication requirements associated with healthcare applications still drain the power in a short period of time and requires battery replacement that can be prohibitive. To address this basic concern of energy consumption, energy harvesting and wireless power transfer techniques are gaining significant attention [196], [197].

For energy harvesting, the human body itself contains several energy harvesting resources broadly classified as biochemical (such as glucose and lactate) and biomechanical energy sources (including heartbeat, breathing, blood pressure or other muscular movements) that can recharge the batteries of both on-body or implanted sensors. However, we need to address energy harvesting design issues that limit the incorporation of energy harvesting modules into small-sized sensors. There is also a lack of simulation tools to effectively and rigorously evaluate energy models according to human body energy harvesting features, and energy-harvesting-aware hybrid solutions to enable energy harvesting from multiple sources simultaneously [114].

In the context of wireless energy transfer, they involve energy transmission to the resource-constrained sensor networks using radio frequency signals. For example, ECG sensors and blood glucose sensors can harvest different amounts of energy according to their location and transmission capabilities, and sensors with high energy resources can transfer some parts of their energy to those sensors that have minimal power left and do not have energy harvesting sources [113]. However, when wireless energy transfer is adopted, the spectrum used for communication purposes is inevitably occupied for energy transfer which affects the information transmission efficiency because the resource-constrained sensors are powered at the expense of information transfer quality.

Multiple Input and Multiple Output (MIMO) technology can provide promising solutions but issues such as channel fading and interference must be addressed. In addition, relay-assisted information and energy transfer are also considered an optimal solution for multi-hop networks for efficient data and power transmissions. However, this still needs further research [113].

B. Interoperability

The integration of heterogeneous devices in large-scale distributed networks still has unresolved interoperability issues due to the lack of standards. New solutions and protocols are necessary to enable communication among heterogeneous devices and make them interoperable. Several communication technologies such as LPWAN, LoRa, Bluetooth and Zigbee have been extensively explored to satisfy the minimum level of technical interoperability [198].

While semantic technology inclusion (the development of a rich language that can help artificial intelligence systems to understand and process information the way humans do) has also been explored in the literature to enable seamless integration and interoperability [199]. However, high level of syntactic and semantic interoperability are still major challenges that require close collaboration among the vendors to enable seamless integration and interoperability.

C. Security

Security in WBANs for healthcare applications is vital because sensor nodes collect and transmit highly sensitive patient data, and any security vulnerabilities may affect the patient's privacy and endanger patients' lives. For instance, a compromised command can be sent to an automated insulin pump to inject insulin into the patients' bloodstream causing an insulin overdose. Therefore, many security solutions such as authentication and encryption, intrusion detection systems and trust management systems, have been used to mitigate various types of attacks [200].

Additionally, various security solutions have been proposed for WBANs to enforce anonymity, mutual authentication, forward key secrecy, session key establishment and revocability [201]. Although several cryptographic, non-cryptographic and authentication schemes have been extensively investigated in the literature, there are still numerous open research challenges that must be addressed. These include designing lightweight-secure communication mechanisms at each tier of

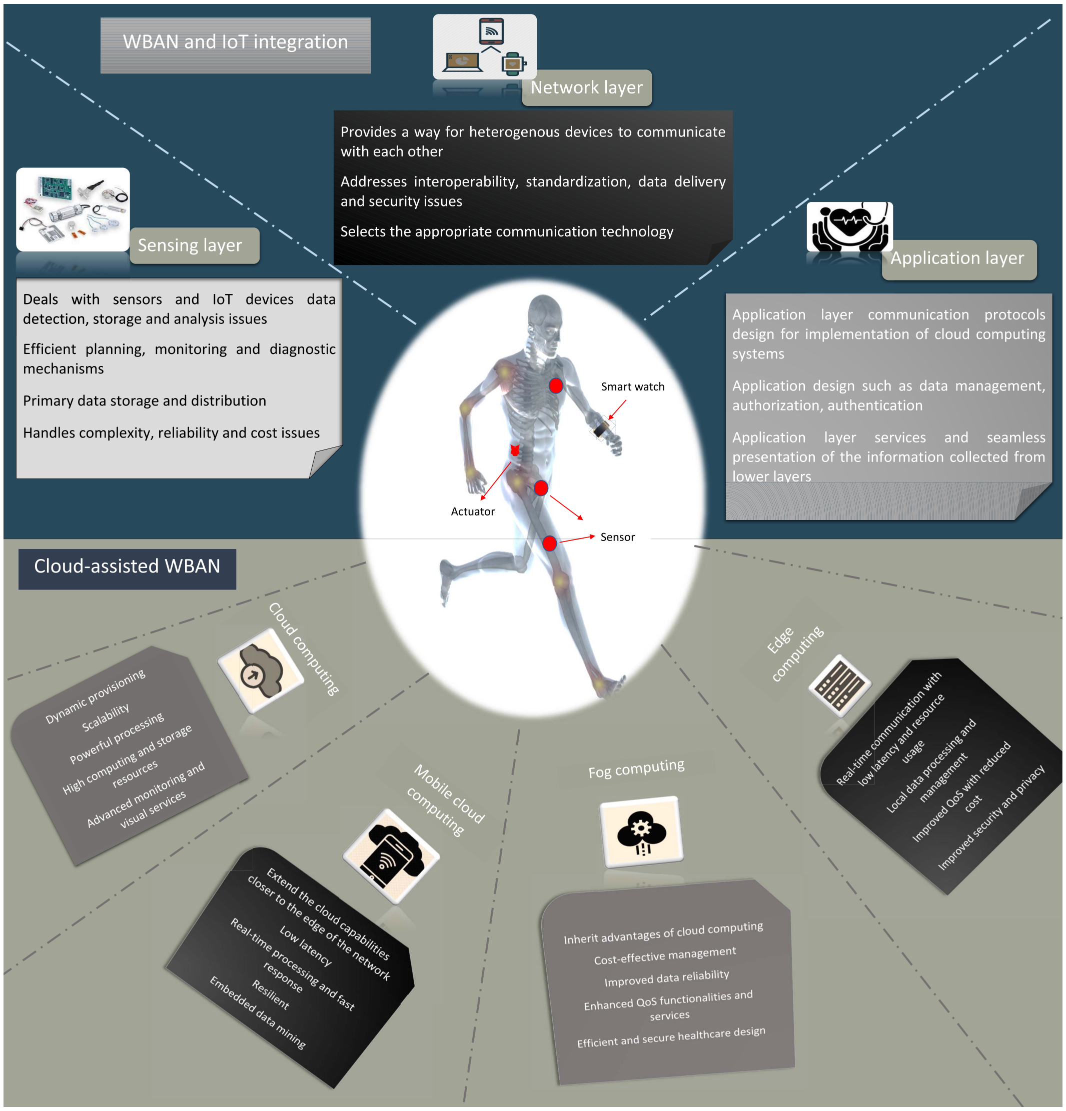

Fig. 5. Benefits and challenges of WBAN integration with IoT and emerging technologies.

the underlying WBAN architecture and novel authentication schemes that also consider the primary energy consumption concerns of WBANs.

D. Biocompatability

On-body and implanted sensors biocompatibility (i.e., biofunctionality and biosafety) require further investigation for gaining clinical approval from health agencies. Unfortunately, although biocompatibility is a key concern for healthcare applications, it is still an open challenge. The failure of wearable devices in providing safety and reliability in daily activities for real clinical applications has increased the biocompatibility requirement of sensing devices. For example, the direct contact of ECG electrodes with the skin for more than 7 days causes skin irritation and requires replacement [1].

Furthermore, implanted sensors lose their functionality over time, and immune cells fight the implanted sensors as foreign bodies [202]. In these areas, when wearable and implanted sensors are deployed in healthcare applications, we need to ensure biocompatibility and flexibility of sensors to enable man-machine interaction with high safety and reliability.

E. Complexity

The growing demand for sensing devices for real-time healthcare applications is being challenged by the low complexity requirement of WBANs. Since sensors have limited memory and computational power, they cannot perform computation or memory intensive tasks (e.g., robust route selection, route failure identification, heavy data processing). Thus, storage and computational power limitations affect the design of efficient data fusion and management schemes for both on-body and in-body sensor networks.

The benefits of sensor technologies in healthcare applications have motivated researchers to investigate the integration of AI and deep learning approaches with WBANs to improve their computational intelligence with minimal complexity. For example, optimal route selection and data collection mechanisms can integrate simple AI algorithms to perform data collection with reduced complexity. Recently proposed data communication schemes for WBAN have adopted several metaheuristic and machine learning approaches such as artificial bee colony [203], firefly algorithm [195], [204], annealing algorithm [205], and feedforward neural networks [206] to reduce the storage and computational complexity of data communication mechanisms.

However, to meet the requirements of real-time healthcare applications, we need robust and low complexity schemes to collect and manage sensor data. More research is needed to investigate how deep learning approaches can be integrated with WBANs in order to design low complexity data fusion, data processing, and data management mechanisms which will enable timely, real-time medical decisions.

V. CONCLUSION

Today, medical sensors are being used for a wide range of functions in healthcare applications. Advances in hardware, software, and communication technologies are enabling the cost-effective development of powerful medical sensors with diverse capabilities all of which aim to provide scalable, cost-efficient, and reliable healthcare delivery to many stakeholders in the healthcare industry. In this work, we reviewed developments in medical sensors in the last few decades. We describe the benefits of various integration architectures of WBANs (making use of different types of medical sensors) with recent computing paradigms such as IoT, edge, mobile cloud computing, fog, and cloud. Finally, we discussed some future research opportunities that should be further investigated.

In this review, we did not cover other emerging technologies such as UWB, 6G, and Wi-Fi 6 (802.11ax) at the same depth as cloud, MCC, fog, and edge computing because this review has mainly focused on advances of medical sensors in healthcare and WBAN integration with the cloud, MCC, fog, and edge computing. In the future, we will review these other emerging technologies not included in this review, and we will discuss IoT-based WBAN architectures that integrate other communication technologies and advanced healthcare applications.

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