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TOPICAL REVIEW

Wireless Antenna Sensors for Biosimilar Monitoring Toward Cyber-Physical Systems: A Review of Current Trends and Future Prospects

MUHAMMAD AZIZ UL HAQ[1], SHAFIQ UR REHMAN[2], HISHAM ABDULRAHMAN ALHULAYYIL[2], TAHER ABDULLAH ALZAHRANI[2], HATOON S. ALSAGRI[2], AND MUHAMMAD FAHEEM[3], (Member, IEEE)

[1]SkyLink Antenna and Wireless Communication Research Center, Pakistan
[2]College of Computer and Information Sciences, Imam Muhammad Ibn Saud Islamic University (IMSIU), Riyadh 11432, Saudi Arabia
[3]School of Technology and Innovations, University of Vaasa, 65200 Vaasa, Finland

Corresponding authors: Shafiq Ur Rehman (srehman@imamu.edu.sa) and Muhammad Aziz Ul Haq (muhammad.azizulhaq@skylinkantenna.com)

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ABSTRACT The integration of wireless antenna sensors for cyber-physical systems has become increasingly prevalent in various biosimilar applications due to the escalating need for monitoring techniques that are efficient, accurate, and reliable. The primary objective of this comprehensive investigation is to offer a scholarly examination of the present advancements, challenges, and potentialities in the realm of wireless antenna sensor technology for monitoring biosimilars. Specifically, the focus will be on the current state of the art in wireless antenna sensor design, manufacturing, and implementation along with the discussion of cyber security trends. The advantages of wireless antenna sensors, including increased sensitivity, real-time data gathering, and remote monitoring, will next be discussed in relation to their use in a variety of biosimilar applications. Furthermore, we will explore the challenges of deploying wireless antenna sensors for biosimilar monitoring, such as power consumption, signal integrity, and biocompatibility concerns. To wrap things off, there will be a discussion about where this subject is headed and why collaborative work is essential to advancing wireless antenna sensor technology and its applications in biosimilar monitoring. Providing an in-depth overview of the present landscape and potential developments, this article aims to be an asset for academics and professionals in the fields of antenna sensors, biosimilar development, wireless communication technologies, and cyber physical systems.

INDEX TERMS Cyber-physical systems, wireless antenna sensors, biosimilar monitoring, real-time data acquisition.

I. INTRODUCTION

In the rapidly developing field of biopharmaceuticals, biosimilar monitoring has emerged as an essential tool for cyber-physical systems. When patents on the primary biologic treatments expire, they are often replaced with biosimilars, often called follow-on biologics [1]. Biosimilars are nearly identical copies of already-approved biological products. A great deal of attention has been paid to medicinal items produced from organisms because of their potential to cure several diseases and ailments, including cancer, autoimmune disorders, and other chronic problems [2]. Biosimilars are gaining popularity because of the hope that they may lower healthcare costs and make more affordable treatments available to more people. Biosimilars provide unique challenges in terms of development, manufacture, and quality control [3] because of their inherent complexity and heterogeneity compared to traditional small-molecule

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pharmaceuticals. Strict monitoring is required from the beginning of the development process all the way through post-market surveillance in order to ensure that biosimilars are safe, effective, and consistent.

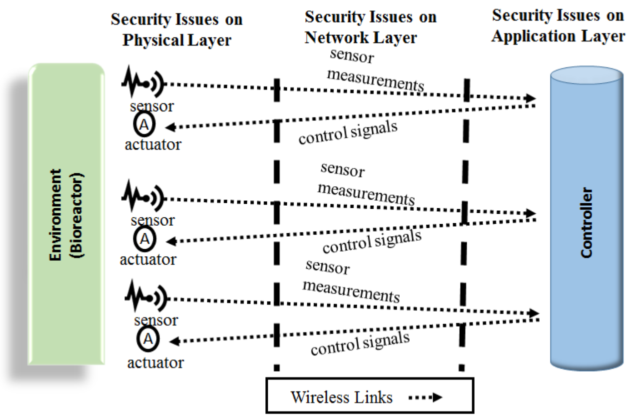


FIGURE 1. A typical layout of cyber-physical systems security.

Biosimilars are biologically like an already-approved biological product, often known as the reference product, and are very comparable to it in terms of quality, safety, and effectiveness. To ensure there are no safety, purity, or effectiveness variations between the reference product and the biosimilar in clinical trials, biosimilars are developed on the basis of a thorough comparison with the reference product [4]. When the patents on the original biologic pharmaceuticals expire, biosimilars provide a cheaper alternative that nevertheless meets the same safety and efficacy standards [5].

Specific rules for the development, approval, and marketing of biosimilars in different countries and regions are provided by regulatory authorities such as the US Food and Drug Administration (FDA), the European Medicines Agency (EMA), and others. To guarantee that the biosimilar product is extremely comparable to the reference product in terms of quality, safety, and effectiveness, these recommendations specify the criteria for showing biosimilarity, which include thorough analytical investigations, non-clinical studies, and clinical trials [6].

The quality, consistency, and effectiveness of biosimilars cannot be guaranteed without rigorous monitoring procedures. Biological products are complicated, thus even when manufactured in labs, there may be some variation. In order to guarantee that the biosimilar product is consistent with the reference product and retains the desirable qualities, it is necessary to keep an intense focus on the manufacturing process [7].

Developing and manufacturing biosimilars is difficult for a variety of reasons, including the medicines' intrinsic complexity and variability. Among these challenges are the identification of appropriate cell lines, the development of a reliable and effective manufacturing method, and the guaranteeing of the requisite quality attributes in the final product. Biosimilar monitoring is essential for overcoming these obstacles because it gives real-time data and insights into the process, allowing researchers and manufacturers to make well-informed decisions and improve the development and manufacturing processes [8].

Biosimilars bring unique challenges and opportunities for pharmaceutical companies implementing Cyber-Physical Systems. CPS is essential for biosimilar medicines made from biological sources, which need tight quality control and stability across manufacturing and supply chain processes. Complex biopharmaceutical production processes and supply networks need CPS integration in biosimilars, emphasizing the need for improved control systems and real-time monitoring. CPS technology connects physical and cognitive elements in biosimilar production and distribution, speeding decision-making, streamlining processes, improving safety, and ensuring regulatory compliance. Stricter regulatory criteria emphasize the need for precise data and quality control. Sensors, actuators, the Internet of Things (IoT), control algorithms, real-time operating systems (RTOS), and data analytics provide real-time changes, predictive maintenance, and anomaly detection in the biosimilar CPS architecture. Pharmaceutical CPS responsibilities include monitoring temperature, humidity, and pressure at production sites and throughout transportation to ensure stability and efficiency. CPS quickly adjusts to environmental circumstances, protecting biosimilar integrity and improving production and distribution. This integration empowers consumers enhances safety, and speeds biosimilar manufacture and distribution, changing the pharmaceutical industry's attitude to issues and possibilities [3], [4], [5].

Biosimilars use cyber-physical systems to secure private data from development through distribution. Intellectual data protection is crucial to the secrecy of unique methods and vital data. Clinical studies generate a lot of data, thus robust cyber security standards are needed to prevent manipulation or malice. From raw materials to delivery, secure digital frameworks prevent biosimilar supply chain disruptions and sabotage. Pharmaceutical infrastructures heavily depend on technology to assist production, underlining the necessity to safeguard them to ensure product safety and efficacy. Cyber security standards are also necessary to comply with data integrity laws. The biosimilar business will gain credibility and reliability. The relationship between cyber security and biosimilars emphasizes the importance of data and system security in the digital era. A block diagram for cyber-physical security is shown in Fig. 1.

The motivation for conducting this review arises from having to improve the monitoring and management of biosimilars within the discipline of pharmaceutical logistics. The development of wireless antenna sensors and their incorporation into Cyber-Physical Systems (CPS) presents a paradigm-shifting technique for addressing the various challenges associated with biosimilar production and distribution. The quality and stability of biosimilars, which are derived from biological sources, are of utmost importance across the whole supply chain. This research aims to investigate the present patterns and potential future opportunities of using wireless antenna sensors in Cyber-Physical Systems (CPS) to facilitate real-time monitoring, data-informed decision-making, and automation. Through enhancements in biosimilar quality and compliance with regulatory standards, this technological advancement has the potential to bring about a transformative impact on the healthcare industry, guaranteeing the secure and effective execution of essential pharmaceuticals.

A. TECHNIQUES AND METHODOLOGIES IN BIOSIMILAR MONITORING

1) ANALYTICAL TECHNIQUES FOR ASSESSING QUALITY, SAFETY, AND EFFECTIVENESS

The quality, safety, and effectiveness of a biosimilar are monitored using an array of tests. Biophysical and biochemical techniques such as mass spectrometry, chromatography, electrophoresis, and many more are included here. The properties of the biosimilar product, its intended use, and the requirements of regulatory agencies all influence the selection of analytical methodologies [9]. Physicochemical property assessment is a crucial part of biosimilar monitoring since it gives insight into the structure, conformation, and stability of a biological product. This is often accomplished by the use of X-ray crystallography, nuclear magnetic resonance (NMR) spectroscopy, circular dichroism (CD) spectroscopy, or Fourier-transform infrared (FTIR) spectroscopy [10]. These techniques provide information about the protein's primary, secondary, tertiary, and quaternary structures, guaranteeing that the biosimilar product has almost identical physicochemical features to the reference product.

Evaluating the biosimilars functional similarity to the reference product by in vitro assessment of biological activity is another important part of biosimilar monitoring. The biological activity of a biosimilar product may be measured using a variety of cell-based, enzymatic, and binding techniques. These tests help find out how effective and safe a product could be [11], by measuring its potency, specificity, and affinity.

An essential aspect of biosimilar monitoring is the assessment of pharmacokinetics (PK) and pharmacodynamics (PD) in vivo. The therapeutic efficacy and possible side effects of the biosimilar product, as well as its absorption, distribution, metabolism, and excretion, are assessed in these trials. PK and PD investigations are often carried out using animal models or clinical trials in humans [12], although this varies depending on the stage of development and the needs of regulatory bodies.

B. CHALLENGES IN BIOSIMILAR MONITORING

Biosimilar monitoring is complicated by the inherent complexity and variety of biological products. Due to their size, complexity of structure, and the participation of live creatures in their synthesis, biological products may display a considerable degree of variability, even when manufactured under controlled settings. Because of the potential impact of this variability on the biosimilars safety and performance, it is crucial to establish monitoring strategies that are sensitive and precise enough to pick up on even the smallest of changes between the biosimilar and the reference product [13].

Another challenge with biosimilar monitoring is the necessity for remote monitoring and real-time data collecting. Manual sampling and off-line laboratory analysis are commonplace in conventional monitoring methods, but they are inconvenient, error-prone, and costly. Improving the efficiency and dependability of biosimilar monitoring [14] requires the creation of cutting-edge technologies that allow for real-time, continuous monitoring and remote data collecting.

The use of wireless antenna sensors has emerged as a potential answer to the difficulties in monitoring biosimilars. These sensors use on electromagnetic pulses, which may be adjusted to detect changes in the characteristics of the target molecule. Wireless antenna sensors are a useful tool for many biosimilar applications because the way electromagnetic radiation reacts with a biosimilar product can indicate a lot regarding its quality, safety, and effectiveness [8].

Wireless antenna sensors may be implemented on a wide variety of platforms, such as implanted gadgets, wearable electronics, and lab-on-a-chip devices. This flexibility permits the development of monitoring systems tuned to the requirements of the biosimilar product and the manufacturing process [15].

C. ADVANTAGES OF WIRELESS ANTENNA SENSORS IN BIOSIMILAR MONITORING

There are several advantages to using wireless antenna sensors for biosimilar monitoring, including higher sensitivity and faster reaction times. These sensors can pick up on even the smallest of changes in the biosimilar product's attributes, enabling immediate feedback and adaptation throughout the research, development, and manufacturing phases [16].

The biosimilar product's quality, safety, and effectiveness may be evaluated comprehensively using wireless antenna sensors that can monitor many parameters at once. This capacity can speed up surveillance and boost biosimilar research and manufacturing efficiency [17]. In addition, wireless antenna sensors may be tuned to detect specific analyses in complicated biological samples by operating at a range of frequencies. By allowing for more precise and trustworthy monitoring findings, this selective detection capacity may help overcome obstacles caused by the complexity and heterogeneity of biological products [18], [19].

Wireless antenna sensors may be improved by integrating with other types of sensors (electrochemical, optical, etc.). The potential uses of wireless antenna sensors in biosimilar monitoring have expanded with the development of wireless communication technologies like Bluetooth, ZigBee, Wi-Fi, and cellular networks. Remote monitoring and control of the biosimilar process is made possible via the use of these communication technologies [20]. Machine learning and other cutting-edge algorithms for processing data Sensors that use wireless antennas are built in.

The development of smart and flexible monitoring systems is facilitated by the combination of wireless antenna sensors, sophisticated data processing algorithms, and machine learning methods. The total efficiency and reliability of substitute research and production may be improved with the help of these technologies, which can give real-time feedback and optimize the biosimilar process [21]. Because of the rising need for efficient, precise, and reliable biosimilar monitoring, researchers have developed wireless antenna sensor technology. These sensors are ideal for use in a wide range of biosimilar applications because to their low cost, high sensitivity, and capacity for real-time data capture and remote monitoring.

II. FUNDAMENTALS OF ANTENNA SENSORS

Wireless communication, radar, and remote sensing are among the few of the numerous applications for antenna sensors. Sensors play a significant role in the system's interface with its surroundings by receiving and transmitting electromagnetic radiation. This detailed explanation aims to shed light on the basics of antenna sensors by focusing on their fundamental principal, classifications, and important performance metrics.

A. WORKING PRINCIPLES

Electrical signals are transformed into electromagnetic waves or vice versa by antenna sensors. There are two main functions performed by antenna sensors: receiving and transmitting.

1) RECEIVING PRINCIPLE

In its receiving mode, an antenna sensor has the ability to capture electromagnetic radiation from wherever it is placed. Electrical signals are produced when these waves move the antenna's conductors and produce currents. These currents have a direct effect on the characteristics of the received signal, and their size and phase are determined by the antenna's shape and structure [22].

Reception theory relies heavily on the radiation pattern of the antenna. The antenna's sensitivity to electromagnetic waves originating from different directions is represented graphically by its radiation pattern. Applications that need for spatial filtering or beam steering are well-suited to antenna sensors with directional radiation patterns, since they may selectively receive signals from certain directions [23].

2) TRANSMITTING PRINCIPLE

During transmission, a sensor antenna converts electrical signals to electromagnetic waves. When the antenna is provided with an input signal, currents will begin to flow throughout its framework. The electromagnetic field generated by these currents is radiated as electromagnetic waves. Even in transmission, the radiation pattern is essential. The amount of power released in each direction is determined by the pattern. Because of this, the effectiveness and coverage area of a wireless communication system, radar, or remote sensing application are all affected by the radiation pattern [24].

B. TYPES OF ANTENNA SENSORS

Antenna sensors come in a few varieties, each with its own characteristics and specific applications. The following are some examples of common types:

1) DIPOLE ANTENNAS

Dipole antennas are among the least complicated and most often used types of antenna sensors. They consist of two conducting parts—typically metal wires—that are physically separated by a very narrow gap. Electric fields are produced in all directions when an input signal is applied over this gap. Due to its omnidirectional emission pattern, dipole antennas may be used for a variety of purposes, such as broadcasting and wireless communication [25].

2) MONOPOLE ANTENNAS

Monopole antennas are a special kind of dipole antenna which employs a single conducting element placed on the ground. The ground plane acts as a reflector, which boosts the output power by a factor of two in the desired direction. Mobile communication devices often use monopole antennas due to their compact size and narrow radiation patterns [26].

3) PATCH ANTENNAS

Planar antenna sensors, also known as patch antennas, are comprised of a small conductive patch—typically a square or a circle—mounted on a dielectric substrate. There is material called a substrate between the patch and the ground plane. Given its compact and lightweight design, patch antennas are well-suited for use in systems where these factors are particularly important, such as those used for satellite communications and aircraft [27].

4) ARRAY ANTENNAS

Multiple antenna elements arranged in a certain design, such a line, a plane, or a circle, make up an array antenna. Beamforming and spatial filtering are both made possible by array antennas, which allow for control of the antenna's emitted pattern by individual element input signal amplitude and phase. Array antennas are often used in radar systems, wireless communication infrastructure, and remote sensing applications [28].

5) FRACTAL ANTENNAS

Fractal antennas are designed using geometric forms based on fractal patterns. At various sizes, these patterns are self-similar and have a persistent structure. Multiband and wideband operation, small dimensions, and better radiation characteristics are all benefits of fractal antennas. They are employed in a variety of applications, such as wireless communication, radar, and satellite systems [29].

6) METAMATERIAL ANTENNAS

In order to achieve improved electromagnetic performance, metamaterial antennas use synthetic substances with novel electromagnetic properties. Because of the unusual features of metamaterials including negative refractive index, near-zero permittivity, and permeability, novel antenna sensors may now be developed. Wireless communication and imaging systems are just two examples of the many places you may find metamaterial antennas being used to shrink size, boost gain, and improve radiation patterns [30].

C. KEY PERFORMANCE PARAMETERS

The efficacy of antenna sensors is measured across several important metrics. Using these metrics, researchers may evaluate and optimize antenna designs for specific uses. Significant indicators of performance include:

1) IMPEDANCE AND BANDWIDTH

How effectively an antenna sensor is matched to its transmission line or system may be determined by measuring its impedance. A well-matched antenna will have minimal signal reflection and high-power transfer efficiency. The bandwidth of an antenna is the frequency range across which it operates optimally. Applications that demand multiband or wideband operation necessitate wideband antennas [31].

2) RADIATION PATTERN

The radiation pattern of an antenna sensor reveals how it responds to electromagnetic waves arriving from different directions. Both the main lobe, which indicates the antenna's highest gain direction, and the secondary lobes, which indicate unfavorable radiation directions, are typical. Applications requiring directional sensitivity, such as radar and remote sensing, rely heavily on the radiation pattern [32].

3) GAIN

Gain quantifies an antenna's capacity to direct its radiated power. Because of their superior range and directionality, point-to-point communication lines and radar systems benefit greatly from the use of high-gain antennas [33].

4) POLARIZATION

Polarization describes the orientation of the electromagnetic wave's electric field vector. Polarization may take on a variety of shapes, but the most frequent are linear, circular, and elliptical. An antenna sensor's performance is maximized when its polarization is in phase with the polarization of the sent or received signals. As polarization may help mitigate the effects of multipath propagation, it is of particular importance in wireless communication systems [34].

5) EFFICIENCY

An antenna's efficiency is measured by how well it disperses the electricity it receives. In order to maximize system performance while minimizing power consumption, high-efficiency antennas that convert the majority of input power into radiated electromagnetic waves are essential [35]. Wireless communication, radar, and remote sensing are just a few of the many applications for antenna sensors. When designing and enhancing systems that rely on antenna sensors, it is essential to have a firm grasp of fundamentals including their working principles, types, and key performance indicators.

III. WIRELESS COMMUNICATION TECHNOLOGIES IN ANTENNA SENSORS

Wireless communication relies on the transmission and reception of electromagnetic waves, which is made possible by antenna sensors. This in-depth discussion will focus on radio frequency identification (RFID), Bluetooth and ZigBee, Wi-Fi and LoRaWAN, cellular networks, and 5G to provide an overview of many wireless communication technologies utilized in antenna sensors. The most recent years' worth of research will be referenced from IEEE journals to keep the discussion up to date.

A. RADIO FREQUENCY IDENTIFICATION (RFID)

RFID stands for radio frequency identification, and it is a wireless communication technology that uses RF signals to identify, monitor, and manage items and individuals. RFID systems include three main parts: RFID tags, RFID readers, and a computer to process the collected data [36].

1) RFID TAGS

RFID tags are tiny electronic devices that may be attached to any number of different objects or people. They can communicate to RFID sensors owing to an integrated circuit (IC) and a sensing antenna. RFID tags may be either passive, active, or semi-passive, depending on how they get and use power. In order to function, active tags need their own power source, whereas passive tags absorb energy from the sensor's radio frequency [37]. Energy harvesting and battery power are combined in semi-passive tags.

2) RFID SENSORS

RFID tags receive radio frequency (RF) signals from RFID readers through antenna sensors. Once the RF signals are received by the tags, they are modulated with the information stored on the tags and re-radiated to the sensor. The device's antenna sensor picks up, demodulates, and extracts the backscattered signals [38].

3) RFID APPLICATIONS

RFID technology has several potential uses, such as in logistics, inventory management, asset tracking, security, and personal identification. Smaller sizes and longer scanning ranges are only two examples of how recent improvements to RFID antenna sensors have expanded their application potential [39]. Bluetooth and ZigBee use the 2.4 GHz ISM (industrial, scientific, and medical) band for their short-range wireless communications. Both rely on antenna sensors to transmit and receive data, making them useful in many electronic devices, automation systems, and manufacturing processes [40].

Bluetooth: Bluetooth is a short-range wireless communication standard that enables devices to exchange data wirelessly. It uses frequency-hopping spread spectrum (FHSS) technology to reduce interference and improve transmission dependability. Piconets are the basic unit of operation for Bluetooth devices [41]. In these ad hoc networks, one primary device communicates with several secondary devices. Often abbreviated as "Bluetooth Smart," Bluetooth Low Energy (BLE) is a variant of Bluetooth designed specifically for use in low-power settings. Because BLE devices may operate for years on very small batteries, they are well suited for IoT uses [42].

ZigBee: ZigBee is a wireless communication technology developed for use in sensor networks and the Internet of Things, where its low power consumption and modest data transfer rates are ideal. It is possible for ZigBee devices to form mesh networks, with data being sent between several nodes along the way. Because of this, self-repairing, scalable networks that can accommodate topological shifts are possible [43].

Both Bluetooth and ZigBee have found widespread use in areas such as home automation, building management, and factory floor control. Bluetooth, a kind of wireless technology, is widely used for short-distance communication among various electronic gadgets. Smart home systems, wireless sensor networks, and building automation are just some of the many low-power, long-range communication applications where ZigBee is widely utilized [44].

B. WI-FI and LoRaWAN

Wi-Fi and LoRaWAN are wireless communication technologies that enable connection for a variety of applications ranging from local area networks to long-range, low-power IoT networks. For sending and receiving data, both methods depend on antenna sensors [45].

Wi-Fi: The IEEE 802.11 standard family is the foundation of Wi-Fi and other wireless networking technologies. It can carry data quickly for LANs and works in the ISM bands of 2.4 and 5 gigahertz. Client devices, including smartphones, laptops, and IoT devices, interface with wireless access points (APs) through antenna sensors [46]. APs are connected to wired networks. Wi-Fi advancements, such as the introduction of Wi-Fi (IEEE 802.11ax), have enabled faster data transfer rates, more efficient use of available spectrum, and wider use of IoT technologies [47].

LoRaWAN: Internet of Things (IoT) applications benefit from LoRaWAN's (Long Range Wide Area Network) low-power, wide-area network (LPWAN) technology for long-range, low-data-rate communication. LoRaWAN uses a novel modulation scheme called Chirp Spread band (CSS) to provide long-distance communication with minimal power consumption in the unlicensed sub-gigahertz band [48]. LoRaWAN networks consist of end devices, gateways, and a network server. A network's server receives data from end devices through antenna sensors sent to gateways. LoRaWAN is suitable for many Internet of Things (IoT) applications because to its long-range communication capabilities and low power consumption [49]. This includes smart agriculture, smart cities, and environmental monitoring. Wi-Fi is widely used for high-speed data transmission at home, in the workplace, and in public places, and it enables a wide variety of devices to establish internet connections. Because of its extended range and low power consumption, LoRaWAN is widely employed in Internet of Things applications that need widespread deployment of battery-operated sensor networks [50].

C. CELLULAR NETWORKS AND 5G

Cellular networks are widespread wireless communication systems that provide data and voice services to mobile devices. These networks include of interconnected base stations that communicate with mobile devices through antenna sensors. Over the years, cellular networks have evolved, with the most current and advanced being 5G [51].

5G Networks: The newest cellular technology is known as 5G (Fifth Generation) networks, and it boasts increased data speed, decreased latency, more network capacity, and improved energy efficiency. In order to facilitate speedy data transmission and increased network capacity, 5G networks use a wide range of frequencies, including those in the millimeter-wave (mm Wave) range [52].

Massive MIMO and Beamforming: Massive MIMO and Beamforming are important technologies in 5G networks that depend on better antenna sensors. Massive MIMO uses large-scale antenna arrays at base stations to serve numerous users at the same time, enhancing network capacity and spectral efficiency. Beamforming is a technology that employs antenna arrays to direct radiated power in certain directions, therefore increasing signal strength and decreasing interference [53], [54].

In conclusion, RFID, Bluetooth, ZigBee, Wi-Fi, LoRaWAN, and 5G are all crucial wireless communication technologies in antenna sensors that enable a wide range of applications, from short-range communication in consumer electronics to long-range IoT networks and advanced 5G services. Developing and improving systems that employ wireless communication technologies requires an understanding of the corresponding antenna sensor requirements.

IV. WIRELESS ANTENNA SENSOR DESIGN AND FABRICATION

Designing and producing wireless antenna sensors is becoming more important as technology advances and the need grows for more efficient, small, and flexible systems. Communication, healthcare, and defense are just few of the fields that make use of antenna sensors. In this study, we'll focus on the most recent developments in the industry as we discuss material preference, design considerations, manufacturing processes, and integration into biosimilar systems.

A. MATERIAL SELECTION

1) CONDUCTIVE MATERIALS

Effective wireless antenna sensor design requires conductive materials. They are responsible for the transmission and reception of electromagnetic waves. Copper, silver, gold, and aluminum are the most commonly used conductive materials in antenna design, and each material has advantages and disadvantages. Recently, researchers have begun exploring alternative materials to enhance antenna performance and reduce production costs.

1. Copper, because of its high electrical conductivity and low cost, is the most commonly used material in antenna construction. Copper is also readily solderable, allowing for strong component connections. Copper, on the other hand, is susceptible to corrosion, which may diminish its performance over time [55].
2. Silver: Silver is a popular material for high-performance antennas because it is the most conductive metal. Silver, on the other hand, is more expensive than copper and is susceptible to tarnishing, which reduces its conductivity [56].
3. Gold is used in certain antenna designs due to its resistance to corrosion and high conductivity. However, it is significantly more expensive than other conductive materials, which limits its widespread application [57].
4. Aluminum is a lightweight, low-cost substitute for copper due to its moderate conductivity. However, it is more challenging to solder and may not produce as robust connections as other materials [58].
5. Researchers are investigating novel materials for antenna design, including graphene and carbon nanotubes. These materials may provide advantages in terms of weight, pliability, and conductivity [59].

2) DIELECTRIC MATERIALS

Dielectric materials are essential for antennas because they affect their efficacy by providing electrical insulation and influencing the propagation of electromagnetic waves. FR-4, Rogers materials, and ceramic materials are frequent antenna dielectric materials.

1. FR-4: FR-4 is a popular dielectric material for printed circuit boards (PCBs) due to its low cost and acceptable performance. However, its dielectric constant and loss tangent may vary significantly, leading to differences in antenna performance [60].
2. Roger's materials are high-performance dielectric materials with more stable dielectric characteristics when compared to FR-4. They are used in situations where precise antenna performance is required, but they are more expensive [61].
3. Ceramic materials: Ceramic materials such as alumina and LTCC are utilized in antennas due to their high dielectric constants and minimal loss tangents. They are suitable for miniature antennas and high-frequency applications, despite being fragile and challenging to fabricate [62].

B. DESIGN CONSIDERATIONS

1) FREQUENCY RANGE

The frequency range is an important consideration in antenna design, as it determines the antenna's size, radiating pattern, and efficacy. The application determines the frequency range, which establishes the antenna's resonance frequency and determines its size [63].

2) POLARIZATION

Polarization is the orientation of the electric field vector of an electromagnetic wave. It is significant in antenna design because it affects the antenna's ability to transmit and receive signals successfully. Depending on the application, an antenna's polarization may be linear, circular, or elliptical; each has advantages and disadvantages [64].

3) GAIN

The gain of an antenna quantifies its ability to direct radiated electricity in a particular direction. For long-distance communications or when a concentrated beam is required, high-gain antennas are utilized, whereas low-gain antennas may be more suitable for short-distance, omnidirectional applications. The gain of an antenna is proportional to its dimensions, radiation pattern, and design [65].

4) IMPEDANCE MATCHING

In antenna design, impedance matching is essential for achieving optimal power transmission between the antenna and the connected system. A disparity in impedance may result in reflected power, reducing the antenna's effectiveness and possibly causing damage to the connected equipment. By designing the antenna's feed structure and employing matching networks, impedance matching is accomplished [66].

5) BANDWIDTH

Bandwidth is a crucial aspect of antenna design because it determines the frequency range over which the antenna can operate effectively. Wide bandwidth antennas can accommodate a greater range of frequencies, making them suitable for multiband or frequency-agile applications. The dimensions, form, and composition of an antenna impact its bandwidth [67].

C. FABRICATION TECHNIQUES

1) PRINTED CIRCUIT BOARD (PCB) FABRICATION

PCB fabrication is a popular method to manufacture antennas, especially planar antenna designs like microstrip patch antennas and printed dipoles. Deposition of conductive material onto a dielectric substrate is followed by etching to form the appropriate antenna pattern in PCB construction. This technology is inexpensive and suitable for mass manufacturing, although the substrate materials available may be restricted [68].

2) ADDITIVE MANUFACTURING

Additive manufacturing, also known as 3D printing, has emerged as a possible method of antenna production. This technology facilitates the creation of intricate three-dimensional structures that would be unfeasible to produce using conventional manufacturing techniques. Material options include conductive polymers, metal particles, and dielectric substances. With additive manufacturing, rapid prototyping and customization are possible, although resolution and mechanical strength may be limited [69].

3) LASER DIRECT WRITING (LDW)

Laser Direct Writing (LDW) is a process that uses a concentrated laser beam to deposit conductive materials onto a substrate to produce the desired antenna pattern. LDW has superior precision and resolution, enabling the production of small antennas and intricate patterns. However, LDW may be a time-consuming and expensive procedure, limiting its use in mass production [70].

4) INKJET PRINTING

Inkjet printing is a non-contact manufacturing process in which conductive ink is deposited onto a substrate by a printer, thereby producing the desired antenna pattern. This method is compatible with a range of materials, including flexible and inexpensive substrates. Although inkjet printing allows for rapid prototyping and customization, the resulting antennas may have lower conductivity and mechanical strength compared to those produced by conventional fabrication methods [71].

D. INTEGRATION WITH BIOSIMILAR SYSTEMS

1) BIOCOMPATIBILITY

Biocompatibility is an important factor when connecting antennas with biosimilar systems. To prevent deleterious effects on biological systems, the antenna and manufacturing process should employ non-toxic, non-immunogenic materials. This may necessitate the application of specific materials or coatings [72].

2) FLEXIBILITY AND CONFORMABILITY

Flexible and conformable antennas are highly desirable for integration with biosimilar systems due to their superior adaptability to the complex, curved surfaces found in biological environments. These properties can be attained by employing flexible substrates, such as polyimide or liquid crystal polymers, and by selecting antenna design and production methods with care [73].

3) MINIATURIZATION

In numerous biosimilar system applications, space constraints require the use of miniature antennas. By using high dielectric constant materials, fractal designs, or the near-field interaction between antenna components, it is possible to reduce the dimensions of an antenna. On the other hand, miniaturization may result in diminished bandwidth and performance. In [74], the effect of various topological modifications on antenna miniaturization is extensively investigated. Numerical studies are conducted with the help of two ultra-wideband monopoles. All geometric parameters are carefully tuned for each antenna topology to have the least feasible footprint while yet having good electrical performance so that the comparison is fair. The findings clearly show that modifying the feed line is preferable to modifying the ground plane or radiator (43% and 2.15%, respectively). The numerical findings are further verified by experimental validations.

4) BIODEGRAD BIODEGRADABLE MATERIALS

In some situations, it may be preferable for the antenna to be biodegradable, allowing transient use in biosimilar systems and eliminating the need for surgical removal. Biodegradable materials, such as polylactic acid (PLA) or polyglycolic acid (PGA), may be used to construct antennas that decompose over time, thereby reducing their long-term impact on biological systems. However, these materials may have inferior electrical efficacy and mechanical robustness compared to non-biodegradable materials [75].

5) WIRELESS POWER TRANSFER AND ENERGY HARVESTING

In such systems, continuous power can be supplied to the antenna and its attendant electronics via wireless power transfer and energy harvesting techniques. Methods for wireless energy transfer include inductive coupling, magnetic resonance coupling, and radiofrequency (RF) energy harvesting. Additionally, energy can be extracted from the biological system via piezoelectric or thermoelectric mechanisms [76].

6) SENSING AND COMMUNICATION

Integration of antennas into biomedical systems frequently necessitates sensing and communication capabilities. These antennas may be programmed to respond to specific biological factors, such as temperature, pH, or the presence of particular proteins. The collected data can then be wirelessly transmitted to an external receiver, enabling continuous monitoring and feedback [77].

Lastly, the design and manufacturing of wireless antenna sensors for integration with biological systems is a complex and diverse field. Material selections, design considerations, manufacturing processes, and integration issues must all be thoroughly examined when developing effective and reliable antennas for a variety of applications. As technology progresses, it is anticipated that novel materials and techniques will improve antenna performance, miniaturization, and biocompatibility, enabling the biomedical industry to develop novel and intriguing applications.

With the advancement of technology, the design and production of wireless antenna sensors have become increasingly essential for a variety of applications, including those in the communication, medical, and military fields. The creation of these antenna sensors is a complex and multifaceted procedure requiring careful consideration of material selection, design features, manufacturing procedures, and integration issues. As new materials and techniques are developed, it is anticipated that the performance, miniaturization, and biocompatibility of these antenna sensors will improve, resulting in enticing and innovative applications beyond the biomedical field.

V. APPLICATIONS OF WIRELESS ANTENNA SENSORS IN BIOSIMILAR MONITORING

In numerous fields, including biosimilar monitoring, wireless antenna sensors have proved to be revolutionary. This in-depth overview examines the applications of wireless antenna sensors in biosensing and diagnostics, drug delivery systems, quality control, environmental monitoring, and bioprocessing.

A. BIOSENSING AND DIAGNOSTICS

In biosensing and diagnostic applications, antenna sensors that operate wirelessly are becoming more widespread. With these sensors, biomolecules, cells, and tissues can be monitored noninvasively and in real time. They can also detect subtle changes in biological systems, making them essential for the early detection and diagnosis of disease.

1) LABEL-FREE BIOSENSING

Wireless antenna sensors have been used in label-free biosensing, which allows for the detection of biomolecules without the need of identification or modification. One example is the employment of metamaterial-inspired sensors to detect DNA hybridization. These sensors, which are based on split-ring resonators, may detect changes in the dielectric characteristics of the material when DNA hybridization occurs [78].

2) IMPLANTABLE AND WEARABLE SENSORS

Both implantable and wearable wireless antenna sensors have increased in prominence for continuous monitoring of physiological parameters such as glucose levels, blood pressure, and pulse rate. These sensors may be embedded in flexible materials, making them comfortable and less intrusive to wear. One example is the development of a textile-based, flexible antenna sensor for continuous glucose monitoring. In [79], a mechanically stretchable, highly sensitive, and long-lasting NPG electrode was designed on a stress-absorbing 3D micro patterned polydimethylsiloxane (PDMS) substrate for non-enzymatic glucose detection as shown in Fig. 2. Sweat collection and passive, accurate delivery from the skin to the electrode surface with excellent replacement capability was achieved by embedding stretchable cotton fabric as a capillary into a thin polyurethane Nano fiber-reinforced PDMS channel. The built-in glucose sensor patch has been proven to have a remarkable ability to track glucose levels in perspiration in real-time and with high accuracy.

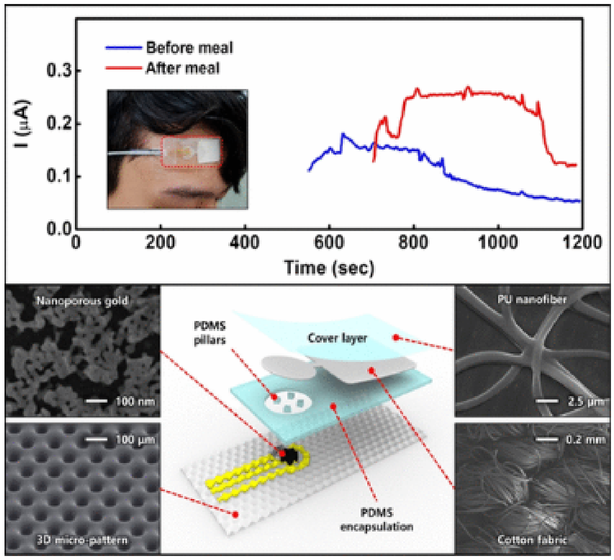


FIGURE 2. A graphical representation of the proposed sensor for glucose level measurements [79].

3) POINT-OF-CARE DIAGNOSTICS

The incorporation of wireless antenna sensors into point-of-care diagnostic instruments has the potential to revolutionize healthcare by providing rapid, precise, and inexpensive testing. These sensors may detect biomarkers related to infectious diseases like influenza, Zika virus, and COVID-19 [80]. In addition, these sensors can be incorporated into handsets and peripheral devices, enabling remote monitoring and diagnosis.

B. DRUG DELIVERY SYSTEM

Wireless antenna sensors have been embedded in drug delivery systems to monitor medication release and ensure proper dosage. These sensors may provide real-time information on the drug's concentration, enabling dosage adjustments as needed. In addition, they can be used to monitor the position and mobility of drug carriers throughout the body, ensuring individualized medication delivery.

1) CONTROLLED DRUG RELEASE

Implantable medication delivery devices may include wireless antenna sensors for real-time drug release monitoring. For instance, a wireless sensor system for monitoring the discharge of medications from biodegradable polymeric micro particles has been developed [81]. In this system, microwave resonators are used to monitor changes in the dielectric properties of the polymer as the medicament is discharged.

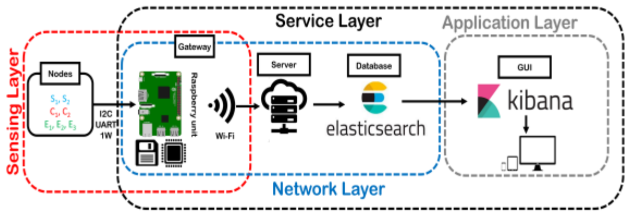


FIGURE 3. A typical architecture layout of wireless sensor network [83].

2) TARGETED DRUG DELIVERY

Wireless antenna sensors may also be used to monitor the movement and position of drug carriers within the body, thereby enabling the administration of medications with precision. For instance, magnetic nanoparticles have been equipped with wireless antenna sensors, enabling remote monitoring of their location within the body via an external magnetic field [82]. This may help ensure that the medication reaches its intended destination, thereby reducing side effects and enhancing therapeutic efficacy.

C. QUALITY CONTROL

Particularly in the pharmaceutical and biotechnology industries, wireless antenna sensors have been used in quality control operations. These sensors can be used to monitor critical factors such as temperature, humidity, and pressure to ensure that the manufacturing process remains within the predetermined parameters.

1) PROCESS MONITORING

Multiple parameters, such as the concentration of active pharmaceutical ingredients (APIs) and the temperature and pressure of the reaction, can be monitored in real time using wireless antenna sensors during the production process. This technology permits the monitoring of microorganism proliferation and the production of the desired product in real time. In [83], authors developed and implemented wireless sensor network architecture as shown in Fig. 3. Automation and continuous monitoring of Sardinian Carasau bread manufacturing are the goals of this architecture. A typical bakery enterprise faces the challenge of sustaining competitiveness in the food industry. Analysis was done to establish the most important elements to monitor throughout product manufacture. To regulate and gather data in real time throughout dough manufacture, sheeting, cutting, and leavening, a heterogeneous, multi-tier wireless sensor network was gesigned. A user-friendly interface improved understanding, control, and process monitoring. Temperature, relative humidity, and gas concentrations may be monitored using the wireless sensor network (WSN). It also measures cinematic belt amounts. A specialist image processing system analyses bread morphology before baking.

2) PRODUCTTESTING AND VALIDATION

Additionally, wireless antenna sensors can be used for product testing and validation to ensure that the final product meets quality standards. For instance, a wireless sensor system has been developed to monitor the disintegration behavior of pharmaceutical tablets [84]. By measuring variations in the dielectric characteristics of the disintegrating medium, the system may provide real-time data on the dissolution of the tablet and the release of the API.

D. ENVIRONMENTAL MONITORING AND BIOPROCESSING

Uses for wireless antenna sensors include environmental monitoring and bioprocessing. They are able to identify and monitor pollutants such as pathogens, heavy metals, and organic compounds, as well as bioprocesses to increase output and decrease pollution.

1) DETECTION OF CONTAMINANTS

It has been possible to detect contaminants in a variety of environmental samples, including water, sediment, and air, using wireless antenna sensors. For instance, a wireless sensor network for monitoring heavy metal ions in water in real time has been established [85]. This device employs an array of antenna sensors equipped with metal-ion-specific receptors, facilitating the detection of trace quantities of multiple heavy metals.

2) MONITORING OF BIOPROCESSES

Fermentation, bioremediation, and bioenergy production are all bioprocesses that may benefit from wireless antenna sensors. These sensors can monitor a variety of variables, including temperature, pH, dissolved oxygen, and substrate concentration, and provide real-time feedback to assist in optimizing the process and achieving maximum product yield. For instance, a wireless sensor system for monitoring microbial fuel cells that provides real-time data on the voltage output and substrate concentration has been developed [86]. In a variety of biosimilar monitoring applications, including biosensing and diagnostics [87], medication delivery systems [88], quality control [89], environmental monitoring [90], and bioprocessing, wireless antenna sensors have demonstrated significant promise. Due to their ability to provide non-invasive [91], real-time monitoring and their compatibility with flexible materials [70], they are ideal for incorporation into peripheral and implantable devices. In addition, its use in point-of-care diagnostics, individualized medication administration, and environmental monitoring has the potential to revolutionize healthcare and environmental management. As technology advances, wireless antenna sensor applications for biosimilar monitoring are anticipated to expand and diversify. Table 1 compares the state-of-the-art sensors related to their advantages along with prospective applications in the context of biosimilar monitoring.

VI. CHALLENGES IN IMPLEMENTING WIRELESS ANTENNA SENSORS FOR BIOSIMILAR MONITORING

In recent years, wireless antenna sensors have made significant advances, especially in biosimilar monitoring.

TABLE 1. A comparison of state-of-the-art sensors.

References	Design	Measurand	Advantages
[78]	Ring-resonator	Chemical and biological sensing	High detection rate
[79]	Flexible Textile-Based	Sweat sensors	real-time noninvasive detection
[80]	Smartphone-based mobile bio sensors	Human metabolites	low-cost, multi-analyses capability
[81]	Electro active material	Drug delivery detection	Non-invasive
[83]	—	Carasau Bread Manufacturing Process	Better control for process monitoring
[84]	—	Physical mechanical properties of tablets	non-invasive characterization

Increasingly, these sensors are being integrated into a vast array of medical applications, from implantable devices to wearable, in order to monitor and diagnose a variety of health issues. However, the use of wireless antenna sensors for biosimilar monitoring faces significant obstacles. The focus of this article will be on power consumption and energy harvesting, signal integrity and interference, biocompatibility and biosafety, as well as data security and privacy.

A. POWER CONSUMPTION AND ENERGY HARVESTING

The power consumption of wireless antenna sensors is a crucial design consideration, particularly when these sensors are used for biosimilar monitoring. High energy consumption may shorten battery life, necessitating frequent battery replacement or recharging. This is particularly challenging for implanted devices, for which battery replacement may require invasive surgical procedures. In designing wireless antenna sensors for biosimilar monitoring applications, it is crucial to reduce power consumption and maximize energy harvesting efficiency.

1) ENERGY HARVESTING TECHNIQUES

Several energy-harvesting approaches have been suggested and implemented to power wireless antenna sensors. These approaches may be generally categorized into the following groups:

1. Solar Energy Harvesting: Solar energy harvesting is the process of transforming sunlight into electrical energy using photovoltaic (PV) cells. Solar energy can extend the battery life of wireless antenna sensors equipped with PV cells, or eliminate the need for batteries altogether [92].
2. Vibration Energy Harvesting: In vibration energy harvesting, piezoelectric or electromagnetic transducers are used to convert mechanical vibrations, typically caused by human motion, into electrical energy. This energy can then be used to power wireless antenna sensors, such as those found on wearable devices [93].
3. Thermoelectric Energy Harvesting: The Seebeck phenomenon, which generates electrical voltage due to temperature differences between two materials, is utilized in thermoelectric energy harvesting. Using the temperature difference between the body and the environment, this technology may be implemented in implanted devices or accessories to generate electricity [94].

2) POWER MANAGEMENT STRATEGIES

Improving wireless antenna sensor energy consumption necessitates efficient power management solutions. These strategies can be categorized as follows:

1. Duty Cycling: To save energy, duty cycling includes frequently turning on and off the sensor's components, such as the radio transceiver. This method is especially beneficial when no continuous monitoring is needed [95].
2. Adaptive Sampling: Adaptive sampling varies the data sample rate depending on the application's needs and the energy limits of the sensor. This method allows wireless antenna sensors to strike a compromise between energy economy and data quality [96].
3. Energy-aware Routing: In wireless sensor networks, energy-aware routing algorithms determine the data transmission channel based on the energy limits of individual sensor nodes. This method may extend the total network lifespan by dispersing energy consumption across nodes effectively [97].

B. SIGNAL INTEGRITY AND INTERFERENCE

Signal integrity and interference are crucial performance issues for biosimilar monitoring wireless antenna sensors. Providing a reliable connection between the sensor and the receiver is essential for accurate data transmission and prompt response to imperative health situations. In contrast, wireless antenna sensors that operate in complex environments, such as the human body or densely populated urban areas, are frequently susceptible to signal degradation and interference.

1) SIGNAL PROPAGATION AND ATTENUATION

Signal propagation and attenuation in wireless antenna sensors may be affected by a number of variables, such as the composition of the human body, the presence of other electronic devices, and environmental factors such as temperature and humidity. These variables may degrade signals, leading to a reduction in communication range and data quality [98].

2) INTERFERENCE MITIGATION TECHNIQUES

Several interference avoidance strategies for wireless antenna sensors used in biosimilar monitoring have been proposed:

1. Frequency Selection: Careful frequency selection can help minimize interference from other wireless devices

or transmissions. Medical device frequency bands, such as the Medical Device Radio communication Service (MedRadio) and the Wireless Medical Telemetry Service (WMTS), may provide protected frequency ranges for wireless antenna sensors [99].
2. Diversity methods, such as spatial, frequency, and polarization diversity, can enhance signal quality by utilizing multiple independent propagation channels or signal characteristics. These strategies have the potential to improve the dependability of wireless antenna sensors in challenging environments [100].
3. Beamforming directs the antenna's emission pattern in a particular direction, thereby enhancing signal intensity at the receiver and reducing interference from other sources. This method may improve the efficacy of wireless antenna sensor communication in biosimilar monitoring applications [101].

C. BIOCOMPATIBILITY AND BIOSAFETY

The biocompatibility and biosafety of wireless antenna sensors for biosimilar surveillance are of the utmost importance. These sensors must be designed so that they have no effect on the body and are also non-toxic and non-allergenic. In addition, the sensors must operate within specific safety constraints to prevent unwanted side effects such as tissue heating or electromagnetic interference with other medical equipment.

1) BIOCOMPATIBLE MATERIALS

Biocompatible materials are critical for the long-term safety and effectiveness of wireless antenna sensors in biosimilar monitoring applications. These substances must be non-toxic, non-allergenic, and chemically stable inside the body. Polymers such as polydimethylsiloxane (PDMS) and metals such as gold or platinum are examples of biocompatible materials often utilized in wireless antenna sensors. A novel strategy for attaining circular polarization (CP) features and gain enhancement of an ultra-miniaturized antenna for biomedical applications is proposed in [102]. The proposed antenna works at 2.4 GHz in the industrial, scientific, and medical (ISM) bands as shown in Fig. 4. The combination of the defective ground structure (DGS) and the Holey superstrate results in a considerable increase in gain with the CP characteristic at the appropriate frequency. As a consequence, not only does the suggested antenna have an ultra-compact size of 2.5 mm 2.5 mm 1.28 mm (8 mm3), but it also has a CP characteristic, a high gain value, and an acceptable radiation efficiency of 0.25%.

2) BIOSAFETY CONSIDERATIONS

Biosafety considerations for wireless antenna sensors include minimizing the body's exposure to potentially harmful effects such as tissue heating and electromagnetic interference. SAR is an essential metric that quantifies the rate at which the body absorbs radiofrequency (RF) radiation. To reduce the potential for harmful effects, wireless antenna sensors should adhere to the SAR limitations [103].

D. DATA SECURITY AND PRIVACY

Installing wireless antenna sensors for biosimilar monitoring is crucial for ensuring data security and privacy, as these devices frequently capture and transmit sensitive health information. It is essential to ensure the security, integrity, and accessibility of these data in order to protect patient privacy and maintain confidence in the technology.

1) ENCRYPTION TECHNIQUES

Encryption methods are crucial for protecting data sent by wireless antenna sensors. To protect the privacy and integrity of transmitted data, symmetric-key encryption, such as the Advanced Encryption Standard (AES), and public-key encryption, such as the Rivest-Shamir-Adleman (RSA) algorithm, may be used [104].

2) PRIVACY-PRESERVING TECHNIQUES

Privacy-preserving approaches may be used to protect patient privacy while permitting data exchange and analysis for research or therapeutic purposes. Techniques such as differential privacy, k-anonymity, and secure multi-party computing may be used to ensure that the obtained data remains anonymous and cannot be traced to specific individuals [105].

3) ACCESS CONTROL AND AUTHENTICATION

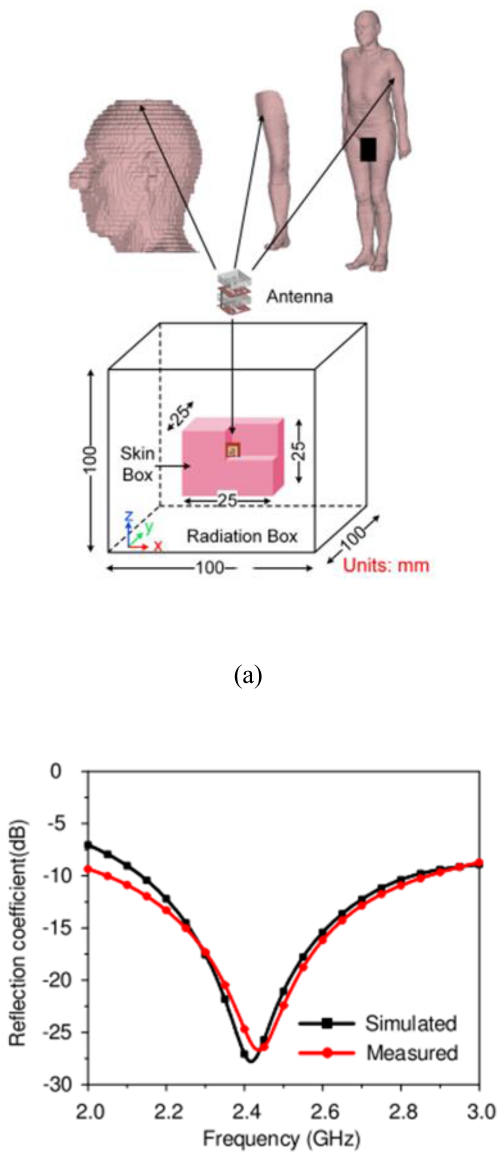
Using access control and authentication procedures, unauthorized access to data sent by wireless antenna sensors may be prevented. Biometric authentication, such as fingerprint or facial recognition, or two-factor authentication, such as combining a password and a physical credential, can be used to ensure that only authorized users can access the data [106].

Wireless antenna sensors offer tremendous potential for biosimilar monitoring applications, but numerous obstacles must be surmounted before this potential can be realized. When designing and implementing wireless antenna sensors for biosimilar monitoring, it is essential to consider power consumption and energy harvesting, signal integrity and interference, biocompatibility and biosafety, as well as data confidentiality and privacy. Recent advancements in energy harvesting techniques, interference mitigation strategies, biocompatible materials, data security and privacy, and data security and privacy have paved the way for new possibilities in biosimilar monitoring; however, ongoing research and development is necessary to overcome remaining obstacles and ensure widespread adoption of these technologies.

VII. FUTURE PROSPECTS AND RESEARCH DIRECTIONS

A. ADVANCEMENTS IN ANTENNA SENSOR DESIGN AND MATERIALS

In recent years, wireless antenna sensors have been widely utilized in biosimilar monitoring, yielding significant benefits in healthcare, environmental monitoring, and other sectors [107]. Antenna sensor design and material advancements



(b)

FIGURE 4. A simulation setup of the proposed antenna sensor, (b) measured and simulated reflection response of the final design at 2.4 GHz [102].

have been instrumental in facilitating these applications, allowing for compact, more efficient, and more reliable sensing devices.

The development of flexible and wearable antennas represents a significant advancement in antenna sensor design. Embedding these antennas directly into garments, textiles, or other flexible substrates enables continuous, noninvasive monitoring of vital signs, biofluids, and other physiological data [108]. This trend is bolstered by the increasing use of advanced materials, such as conductive polymers, graphene, and carbon nanotubes, which possess exceptional electrical and mechanical properties and enable the production of flexible and stretchable antennas with minimal performance loss [109]. Metamaterials, which are synthetic materials with characteristics not found in nature, have also emerged as a viable field for antenna sensor design [110]. Metamaterials can be used to create compact, high-performance antennas that operate at multiple frequencies simultaneously, enabling the simultaneous monitoring of multiple biosignals. In addition, they can be designed with characteristics such as tunability, switchability, and nonlinearity that can be utilized to create more complex and adaptive sensing systems [111].

B. INTEGRATION WITH NANOTECHNOLOGY AND MICROFLUIDICS

In recent years, biosimilar monitoring has made extensive use of wireless antenna sensors, resulting in significant advancements in healthcare, environmental monitoring, and other industries [112]. Significant advancements in antenna sensor design and materials have been essential for the development of these applications, allowing for smaller, more efficient, and more reliable sensing devices.

The development of flexible and wearable antennas marked a major advancement in antenna sensor design. These antennas can be directly implanted into clothing, textiles, or other flexible substrates, enabling continuous, noninvasive monitoring of vital signs, biofluids, and other physiological data [113]. This trend is supported by the increasing use of advanced materials such as conductive polymers, graphene, and carbon nanotubes, which have exceptional electrical and mechanical properties and enable the fabrication of flexible and stretchable antennas with minimal performance loss [114]. Furthermore, metamaterials, which are man-made materials with distinct properties not found in nature, have emerged as a viable topic for antenna sensor design [114]. Metamaterials can be used to construct compact, high-performance antennas that can operate at multiple frequencies simultaneously, enabling the monitoring of multiple bio signals simultaneously. In addition, they can be constructed with characteristics such as tunability, switchability, and nonlinearity, which can be used to create more complex and adaptive sensing systems [115].

C. SMART AND ADAPTIVE BIOSIMILAR MONITORING SYSTEMS

In the domain of wireless antenna sensors, intelligent and adaptive biosimilar monitoring systems are another intriguing research area. These systems can modify their sensing characteristics, such as frequency, bandwidth, and polarization, autonomously in response to changes in the environment, target biosignals, or user requirements, resulting in more accurate, reliable, and customized monitoring [116].

Utilizing cognitive radio (CR) technology, which enables wireless devices to dynamically access and share radio spectrum based on spectrum availability and user requirements, is one method for intelligent and adaptive biosimilar monitoring [117]. Using CR techniques, it is possible to maximize the performance of wireless antenna sensor systems in real time, ensuring that sensing capabilities are maintained despite interference, fading, or other environmental issues [118].

The evaluation and interpretation of data acquired by wireless antenna sensors using machine learning (ML) and artificial intelligence (AI) algorithms [119] is another method for intelligent and adaptive biosimilar monitoring. These algorithms can identify patterns, trends, and anomalies in data, predict future events, and adjust sensor settings accordingly. ML algorithms may be used, for instance, to identify early indicators of illness or physiological changes and to modify monitoring frequency or sensitivity in order to provide healthcare practitioners with more accurate and timely information [120].

Moreover, the integration of wireless antenna sensors with Internet of Things (IoT) and cloud computing technologies has enabled the development of large-scale, distributed biosimilar monitoring systems capable of collecting, processing, and analyzing data from multiple sources, yielding a more complete view of the monitored parameters [121]. These systems may be used for environmental monitoring, precision agriculture, and intelligent healthcare applications where real-time, continuous monitoring of numerous biosignals is essential for decision-making and resource allocation [122].

D. INTERDISCIPLINARY COLLABORATION AND STANDARDIZATION

The development and implementation of wireless antenna sensors for biosimilar monitoring requires the collaboration of academicians and professionals from a variety of fields, including electrical engineering, materials science, biology, chemistry, and computer science. This partnership has the potential to result in the creation of novel sensing techniques, materials, and algorithms, as well as the identification of new applications and use cases for wireless antenna sensors [123].

A lack of uniformity in the design, production, and testing of wireless antenna sensors may impede the flow of information and the reproducibility of findings, which is a significant barrier to facilitating multidisciplinary collaboration. Several organizations, including IEEE, ISO, and the International Electrotechnical Commission (IEC), have been devising standards and guidelines for wireless antenna sensors and their applications in biosimilar monitoring [119] in order to address this issue.

Numerous areas, including performance measures, testing procedures, communication protocols, cyber-physical systems, and data formats, as well as their integration with other technologies such as IoT, cloud computing, and artificial intelligence, have been the focus of efforts to standardize wireless antenna sensors [16], [124], [125], [126], [127], [128]. By establishing a common framework for the development and evaluation of wireless antenna sensors, these standards can promote interoperability, scalability, and reliability, ultimately facilitating the widespread adoption of wireless antenna sensors in various biosimilar monitoring applications [8], [16].

Wireless antenna sensors for biosimilar monitoring will benefit from advances in antenna sensor design and materials, nanotechnology and microfluidics integration, intelligent and adaptive monitoring systems, interdisciplinary cooperation, and regulation. These disciplines hold great promise for the development and implementation of wireless antenna sensors for more precise, dependable, and individualized biosignals monitoring in healthcare, environmental monitoring, and other industries. For biosimilar monitoring, the fields of materials science, nanotechnology, artificial intelligence, and the Internet of Things will likely need to work together. As new technologies and applications emerge, standardization will become more important to ensure that wireless antenna sensors are widely deployed, compatible with each other, and trustworthy.

Biosimilar monitoring system performance, sensitivity, and complexity may be improved by integrating quantum computation and 6G communication networks with wireless antenna sensors. These advancements may allow for the real-time monitoring of additional biological processes and parameters, revolutionizing healthcare, environmental monitoring, and other fields. To maximize the potential of wireless antenna sensors for biosimilar monitoring, interdisciplinary collaboration, industry standards, and novel sensing methods, materials, and algorithms are required.

VIII. CONCLUSION

In recent years, wireless antenna sensors for biosimilar monitoring have advanced significantly due to advancements in materials, design, and integration with other technologies. These devices have the potential to revolutionize healthcare and environmental monitoring by providing non-invasive, real-time, and adaptive sensing capabilities. Advances in antenna sensor design and materials have enabled the development of minuscule, lightweight, and flexible antennas that can be readily incorporated into wearable devices or implants for continuous monitoring. The combination of cognitive radio technologies, machine learning, and artificial intelligence has produced smart and adaptive biomedical monitoring systems that can intelligently adapt to their environments, resulting in improved sensing and communication performance. These technologies have the potential to significantly improve patient care and outcomes by facilitating real-time monitoring, early diagnosis, and individualized treatment plans. Wireless antenna sensors have numerous applications in environmental monitoring, agriculture, food safety, and biosecurity, among others. As the field of wireless antenna sensors develops, it is essential to promote and fund continuous research and development, multidisciplinary collaboration, and standardization initiatives. This will assist in overcoming the limitations and restrictions of existing wireless antenna sensor technologies, allowing them to realize their maximum potential in a variety of applications. Through fostering collaboration between researchers, industry stakeholders, regulatory agencies, and international organizations, standardized procedures, standards, and best practices for the design, implementation, and testing of wireless antenna sensors may be developed. Ultimately, ongoing research on this topic will pave the way for the development of more effective, secure, and efficient wireless antenna sensor systems, thereby enhancing healthcare and environmental monitoring.

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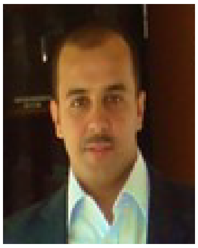
MUHAMMAD AZIZ UL HAQ received the B.S. and M.S. degrees in electronic engineering from Mohammad Ali Jinnah University, Karachi (Islamabad Campus), Pakistan, in 2011 and 2014, respectively, and the Ph.D. degree from the School of Science and Engineering, Reykjavik University, Iceland, in 2019. He was a Postdoctoral Researcher with the Engineering Optimization and Modeling Center, Reykjavik University. He has involved in different projects in the field of contemporary antenna design for microwave imaging, e-health, and future wireless communication systems, such as 5G and the Internet of Things. He has published several articles in ISI indexed journals, book chapters, and some high-ranked international conferences. His research interests include compact antenna design and optimization methods for selected classes of antenna structures.

SHAFIQ UR REHMAN received the M.S. degree in computer science from the Dresden University of Technology, Dresden, Germany, and the Ph.D. degree in computer science from the Department of Software Engineering, Duisburg-Essen University, Germany, in 2020. He is an Assistant Professor with the College of Computer and Information Sciences, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, Saudi Arabia. He was a consultant (requirements engineer) with a well renowned international organizations in Germany. He has involved in different international funded projects in the field of cyber-physical systems and cybersecurity. He has published several research papers in high-ranked international conferences and ISI indexed journals. His research interests include AI, cyber-physical systems, cybersecurity, and requirements engineering.

HISHAM ABDULRAHMAN ALHULAYYIL received the first M.Sc. degree in information security from the University of Pittsburgh, PA, USA, and the second M.Sc. and Ph.D. degrees in computer science from the Computer Science and Engineering Department, University of California, Riverside, CA, USA. He is an Assistant Professor with the College of Computer and Information Sciences, Imam Muhammad Ibn Saud Islamic University. He was a Consultant of planning and development for the higher management with Imam Muhammad Ibn Saud Islamic University and has conducted cyber-security awareness courses for industrial sector. He has published multiple papers in different highly ranked venues in the areas of cyber-security and computer networks.



TAHER ABDULLAH ALZAHRANI received the bachelor's degree in computer science from King Abdelaziz University, Jeddah, Saudi Arabia, in 2002, and the master's degree in cybersecurity and the Ph.D. degree in complex information networks and systems from RMIT University, Australia, in 2011 and 2016, respectively. He has been an Assistant Professor with the Department of Information System, Imam Muhammad Ibn Saud Islamic University, Riyadh, Saudi Arabia, since 2019. He has long experience in government and private sector, where he was a programmer, a web developer, a system administrator, a network administrator, and the Chief of Information Security Officer (CISO) in the Ministry of Finance, Saudi Arabia, for 15 years, from 2004 to 2019. In private sector, he was a cybersecurity consultant and an advisor of many holding companies and medium one. He has published several papers in high-ranked international conferences and ISI-indexed journals. He has involved in different international fund projects. His current research interests include cybersecurity, complex networks and systems, neural networks, bipartite networks, community detection, complexity theory and algorithm, and machine learning.

HATOON S. ALSAGRI received the master's and Ph.D. degrees in information systems from the Department of Information Systems, College of Computer and Information Sciences, King Saud University. She is currently an Assistant Professor and the Head of the Department of Information Systems, College of Computer and Information Sciences, Imam Mohammad Ibn Saud Islamic University. During her graduate studies, she has a opportunity to participate in various conferences and has published various journal articles. Her main research interests lie in the field of artificial intelligence, data science, information diffusion, and the IoT.

MUHAMMAD FAHEEM (Member, IEEE) received the B.Sc. degree in computer engineering from the Department of Computer Engineering, University College of Engineering and Technology, Bahauddin Zakariya University Multan, Pakistan, in 2010, the M.S. degree in computer science from the Faculty of Computer Science and Information Systems, Universiti Teknologi Malaysia, Johor Bahru, Malaysia, and the Ph.D. degree in computer science from the Faculty of Engineering, Universiti Teknologi Malaysia, in 2021. Previously, he was a Lecturer with the Comsats Institute of Information and Technology, from 2012 to 2014, in Pakistan. Also, he was an Assistant Professor with the Department of Computer Engineering, Abdullah Gul University, from 2014 to 2022, in Turkey. Currently, he is a Senior Researcher with the School of Computing Technology and Innovations, University of Vaasa, Vaasa, Finland. His interdisciplinary research interests include the areas of cybersecurity, blockchain, smart grids, smart cities, and industry 4.0. He has authored several articles in refereed journals and conferences, and served as a reviewer for numerous journals in IEEE, IET, Elsevier, Springer, Willey, Hindawi, and MDPI.