IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 7, 2022, accepted May 4, 2022, date of publication May 9, 2022, date of current version May 13, 2022.

*Digital Object Identifier 10.1109/ACCESS.2022.3173643*

# Key Wearable Device Technologies Parameters for Innovative Healthcare Delivery in B5G Network: A Review

**SIMEON OKECHUKWU AJAKWE[1], (Member, IEEE), COSMAS IFEANYI NWAKANMA[2], (Member, IEEE), DONG-SEONG KIM[1], (Senior Member, IEEE), AND JAE-MIN LEE[1], (Member, IEEE)**

[1]Department of IT Convergence Engineering, Kumoh National Institute of Technology, Gumi 39177, South Korea
[2]ICT Convergence Research Center, Kumoh National Institute of Technology, Gumi 39177, South Korea

Corresponding author: Dong-Seong Kim (dskim@kumoh.ac.kr)

This work was supported in part by the Ministry of Science and ICT (MSIT), South Korea, under the Grand Information Technology Research Center Support Program through the Institute for Information & Communications Technology Planning & Evaluation (IITP) under Grant IITP-2022-2020-0-01612; and in part by the Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology under Grant 2018R1A6A1A03024003.

**ABSTRACT** The future of healthcare relies heavily on the connection of humans to intelligent devices via communication networks for rapid medical response. Hence, the evaluation of the performance of smart wearable devices as veritable tools for prompt, pervasive, and proactive healthcare delivery to end-users in response to socio-economic dynamics is imperative especially as 5G unwinds and B5G emerges. Despite the boom in the wearable market and significant improvement in communication technologies, the translation of wearable data from clinical trials to valuable assets for practical medical application is burdened with varying challenges. This review provides an introspective analysis of the performance of unobtrusive wearable devices based on identified key performance indicators (KPIs) in relation to evolving generation networks in achieving innovative health care delivery. A total of 2751 articles pooled from 5 digital libraries were screened and 16 were selected for this review using PRISMA. The identified E-DISC wearable KPIs; energy efficiency, discretization, intelligence, secured network, and customizable standards are currently engrossed with both reliability and real-time issues that undermine its performance, perceptibility, and acceptability by end-users. The transformation of smart wearable devices' data from clinical trials into intangible resources for medical application is the fulcrum of innovative healthcare actualization. Further insight on how the identified challenges can be streamlined for smooth device alignment and transition to the emerging B5G network and its eco-friendly environment is also discussed. It is hoped that this will serve as a rallying point for research direction in translating prospective wearable solutions into a valuable resource for actualizing p-health.

**INDEX TERMS** Artificial intelligence, B5G network, healthcare, wearable, sensing, 5G network.

## I. INTRODUCTION

Improvement in wearable device technologies is anticipated as 5G unwinds and B5G (otherwise called the sixth-generation (6G)) network emerges with emphasis on throughput, improved capacity (speed), network densification, reduced latency (security), and safety-consciousness [1]. This is to ensure that the future pervasive healthcare system (referred to as "p-health") is proactive, precise, patient-centered, preventive, participatory, predictive, pervasive, preemptive, and personalized, to meet the global dynamics in disruptive technologies' demands and delivery [2]. Innovative healthcare delivery is an emerging interdisciplinary area that cuts across the acquisition, processing, transmission, storage, retrieval, and use of health and biomedical information [3]. Wearable technologies, communications, and applications are at the heart of p-health actualization otherwise called connected health (CH) [4]. Wearable applications include wireless health monitoring through physical activities, predictive health, assisted living, etc. Sensing and

The associate editor coordinating the review of this manuscript and approving it for publication was Razi Iqbal.

imaging technologies are the two main technologies deployed in p-health.

Due to recent advancements in sensing, networking, and data fusion, the features of unobtrusive wearable devices have undergone tremendous transformation in their usage [5]–[7]. First, the provision of real-time health-related information through wireless networks has facilitated real-time attention to acute scenarios (such as cardiac arrest, epilepsy, stroke), especially in rural settings and suburbs where expert services were previously inaccessible is now made possible through the availability of 5G network [8] as these devices transmits data over 5G network [9]–[12]. Also, unobtrusive wearable monitoring provides precise information for evaluating the health and fitness of a person at any instance. Data can be transmitted through mobile phones or on flexible displays allowing for closer monitoring of the users. This has resulted in the promotion of an active and healthy lifestyle. In addition, it helps to detect any potential health risk and facilitates the implementation of preventive measures at an earlier stage. Furthermore, with the global outbreak of the Coronavirus (COVID-19), the demand for contactless medical delivery surged sporadically to reduce the spread of the virus [13], [14] through physical contact.

However, as 5G unwinds and 6G emerges, there is the need to review introspectively through empirical evidence the performance of the existing wearable devices based on their technological parameters otherwise known as key performance indicators (KPI) to ascertain the level of innovativeness of these devices in response to the envisaged characterization of B5G to guarantee seamless operations for innovative p-health care.

Previous reviews in this area only covered fundamental issues on wearable device designs and sensors without a didactic connection to its technological parameters as it relates to the B5G network. Authors [15] and [16] provided in-depth insight into the various materials used in constructing wearable healthcare systems, and identified improvements in its unique properties (such as self-heal ability, stretchability, biodegradability, etc.) needed for integration in B5G networks. Also, the works of [17]–[19] focused on wearable sensors with emphasis on the different autonomous flexible sensor approaches in wearable designs and their characteristics. These works, however, did not take into perspective the KPIs and the impact of B5G on its transformations. Authors [20] presented a detailed review on fog computing in healthcare. This work, however, focused only on fog computing tasks without adequate discussion of the determinants affecting the overall performance of these devices in healthcare delivery.

Recently, Aleksandr, *et al.* [7] presented a state-of-the-art review of the historical background of the wearable device market with a shallow discussion of its underlying communication technologies. Similarly, in a survey carried out by Apeksha *et al.* [21], their work focused on determining to what extent wearable technologies with integrated artificial intelligence (AI) solutions have helped in predicting user's health status and its consequence. Furthermore, authors [22] reviewed the different techniques for tracking and recording various human body movements using wearable technology to ascertain the quality of service (QoS) of these devices. Though authors [3] carried out a review of key parameters of unobtrusive sensing and wearable devices for health informatics in 2014, their work however demands an upward empirical review considering the dramatic technological transformations witnessed globally in recent times due to the upsurge in disruptive technologies and breakthroughs in science and technology.

Despite the significant progress achieved in developing p-health systems as highlighted by previous reviews, issues such as user acceptance, user-inclusiveness, distributed interference in wireless networks, safety, on-node processing, data privacy, reduction of motion artifact, low power design, etc., need to be addressed to enhance the usability of these devices (especially unobtrusive wearables) in B5G. These reviews had only concentrated on identifying these problems without specifically outlining how the identified issues are linked with their core performance parameters as well as providing sound technical insights on how B5G networks can address these underlying technological bottlenecks.

Is B5G the answer to curbing the identified problems and transiting from clinical trials to data usability from the wearable device for practical purposes? How have wearable designs responded to 5G networks? Undoubtedly, the ubiquitous and futuristic use of wearable devices for p-health is invariably dependent on issues associated with its core performance parameters. Therefore, an upward constructive review of these KPIs is imperative to ascertain the extent 5G network has impacted the advancement of unobtrusive wearable devices and the set the path for 6G integration in actualizing innovative healthcare delivery. Hence, this review is timely given the fact that the window period for the unwinding of 5G is in sight and the emergence of 6G (otherwise known as B5G) unarguably promises greater expectations.

On this premise, this review critically examines unobtrusive wearable devices deployed in health care delivery to ascertain the extent to which their developmental strides match up with improved speed, security, smartness, and safety concerns of the B5G network. The main goal of this review is.

- To examine perspectives and trends in unobtrusive sensing wearable devices and designs with an emphasis on emerging technological dimensions based on network evolution and socio-economic dynamics.
- To identify key technological performance indicators (KPIs) and drivers of unobtrusive wearable devices in response to advancements in communication networks and highlight associated challenges.
- To provide an evidence-based technological approach for assessing the performance of wearable devices in a B5G environment.
- To provide an in-depth analysis of the convergence of B5G network characterization, wearable devices, and

p-health, and outline possible research directions in addressing identified concerns.

The rest of this paper is arranged as follows: Section II presents the systematic review methodology adopted in this study. Section III discusses socio-economic dynamics propelling the advancement of wearable device technologies. In Section IV, unobtrusive wearable device designs and technologies are explored highlighting the impact of technology on transformative wearable designs. Section V presents the performance parameters and KPIs of wearable devices and discussed associated issues and challenges. While Section VI explored the link between wearable device KPIs and the unique characterization of emerging B5G networks, Section VII provides hints on the potential of B5G KPIs to support wearable device technology for the advancement of p-health. Section VIII concludes the paper with promising directions for future research.

## II. METHODOLOGY

In this study, the preferred and meta-analysis (PRISMA) systematic review methodology is adopted [23]. In all, five databases were adequately searched including IEEE Xplore, MDPI, SpringerLink, PubMed, and Scopus digital library. The search was carried out on each of the databases using keywords "wearable device" and "health care" or "wearable technologies" and "5G health care service", or "unobtrusive wearable" and "5G technologies", or "innovative health care" and "5G wearable technologies". The choice of these keywords is for an exhaustive search to reflect the PICOS approach (participants, interventions, comparators, outcomes, and study design/limitations) thereby providing enough information about the study scope. In addition, the search is limited to 2014 to 2022.

### A. CRITERIA FOR ARTICLES SELECTION AND EXCLUSION

First, the authors performed a preliminary screening of all searched articles. Articles with duplicate titles and content were excluded after glancing through the titles and abstract. Thereafter, the authors evaluated the full article content and check its eligibility. The inclusion criteria for an article to be reviewed based on eligibility include:

- That the article is published in a reputable journal or conference proceedings.
- That the publication year of the article spans between 2014 and 2022.
- That wearable device technologies and parameters for innovative health care were the primary subject matter for the article.
- That the article content is targeted towards both wearable device growth and next-generation communication network.
- That the article is written and published in the English language.

All articles that were considered not original research (such as comments, letters to editors) and that did not meet the above criteria were forthwith rejected and excluded from the list of reviewed papers.

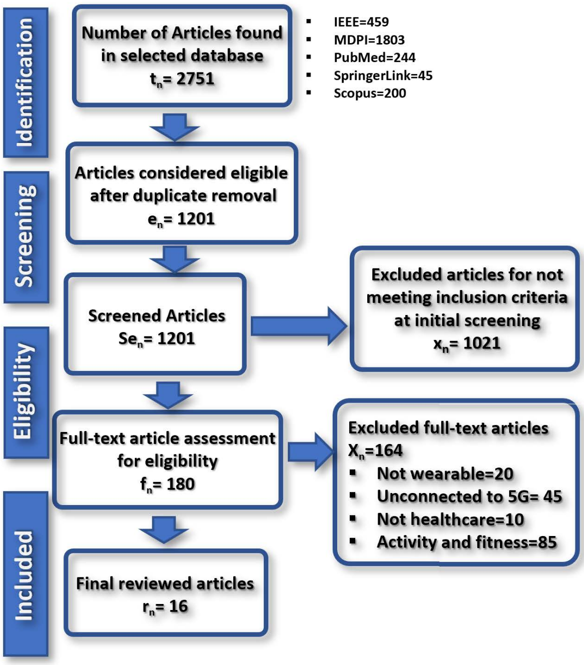

**FIGURE 1.** The study paper selection process highlighting the eligibility criteria for both inclusion and exclusion.

### B. ARTICLE SEARCH RESULT

In the first instance, 2751 articles were identified from the selected digital libraries. 1201 articles were considered eligible for screening after excluding 1550 duplicated articles. After initial screening, 1021 articles that did not meet the inclusion criteria based on initial screening were excluded. Thereafter, 180 included articles were subjected to a full-text article eligibility assessment by two authors. Having excluded 164 irrelevant studies, 16 articles were used for the final review. Fig. 1 depicts the study selection process while Table 1 summarizes the description of articles included in the final analysis and selection for review in this work.

## III. SOCIO-ECONOMIC DYNAMICS TRIGGERING WEARABLE DEVICE TECHNOLOGIES ADVANCEMENT

Wearable technologies are electronic devices or computers incorporated into clothing or other accessories and worn comfortably on the body. It consists of two different components; wearable and body sensors [27]. Major application areas of wearable technologies include health and medical, fitness and wellness, infotainment, industrial, and military. In healthcare, wearable devices help to monitor vital signs, and augment senses. Though medical wearable device used for monitoring physical and physiological vital signs has proven to be reliable, most people are hesitant to attach physiological sensors to their body due to safety concerns and discomforts [3].

Despite the evolution of generation network (2G-B5G), there is still a shortfall in the expansion and marketability of

**TABLE 1.** Comparison of selected Wearable Device Technologies for Innovative Health care services.

| Author and Year | Target Area or Population | Study Aims | Outcomes/Findings | Platform/Suggestions |
|---|---|---|---|---|
| Zheng *et al.* 2020 [15] | Evolution of unobtrusive wearable designs and construction materials | To explore the narratives of wearable features designs in response to more unobtrusiveness | Explored the design strategies of for emerging features of unobtrusive wearable in response to advancement in technology | Flexible sensors for integration of wearables into medical platforms. |
| Mardonova *et al.* 2018 [16] | Wearable technologies and applications in Mining Industry | To review trends in wearable device technology and features of sensors advancement | Advancement in wearable sensor technology improved safety and efficiency of mining sites | Mining and industrial sites |
| Wu *et al.* 2018 [17]<br>Seshadri *et al.* 2016 [19] | wearable sensors and applicability in biomedical and emergency medicine | To review the utility and application constraints of biomedical sensors as used in medicine, sports, etc. | Need for better AI algorithm to translate large datasets into useful assets for practicable use. | Need for more non-intrusiveness of wearables to increase derivable utility |
| Kraemer *et al.* 2017 [20] | Fog computing task and network level in pervasive healthcare | To review of healthcare applications and fog computing for real-time data transmission | Data aggregation issues and network overhead, privacy and dependability issues in wireless networks | Need for flexible computation approach for data transmission in cloud deployment |
| Aleksandr *et al.* 2021 [7] | Wearable market and technology, timelines and trends | To review wearable market based on various factors | Wearable technology is in infancy stage and encumbered with myriads of challenges | Wearable technology is an essential building block for future innovations and systems |
| Apeksha *et al.* 2021 [21] | Smart wearable technology applications in health insurance | To determine the extent AI integration into wearables helped to improve healthcare status | Use of AI can create value in health care delivery through real-time reliable feedback | Privacy concerns, securing issues in sharing sensitive health record. |
| Zheng *et al.* 2014 [3] | emerging unobtrusive and wearable technologies for health informatics | To provide overview of wearable technologies in the realization of pervasive health data acquisition | Though significant progress has been recorded, most wearable are in prototype stages with concerns. | Need to advance wearable designs to enhance usability and address emerging technological concerns |
| Sun *et al.* 2018 [24]<br>Kazim *et al.*2021 [9] | Wearable communications and requirements in 5G network for future health care | Evaluation of design challenges in wearable communications | Spotlighted critical issues such as energy, latency, spectrum, etc. | Need for multi-layer communication architecture and edge technology in wearable designs. |
| Lin *et al.* 2020 [25]<br>Loncar *et al.*2019 [4] | Wearable sensing, information, and communication technologies for connected healthcare model | Review of clinical usefulness of wearable devices for medical diagnosis and treatment | Difficulty in achieving user-friendly designs, technical issues, and data management concerns | Need for cost-effective, stake holders inclusive, and clinical usable solutions |
| Dimauro *et al.* 2021 [10]<br>Sharifi *et al.*2021 [11] | Bioelectronic and AI-wearable tech. for medical diagnosis and healthcare | Review of AI integration into wearable designs to achieve improved health care | AI improved the smartness of wearable technologies for medical care albeit challenges | Privacy, security, cost, legal, user-engagement, data management concerns, etc. |
| Mechanick *et al.* 2020 [12]<br>Said *et al.*2021 [26] | Wearable technologies in lifestyle medicine and biomedical applications | To review the clinical concepts of wearable tech. in medicine and biomedicals | Wearable tech. application in biomedical and medicine has considerably improved. | Translating generated data into usable resource for practical usage rather than clinical trials |

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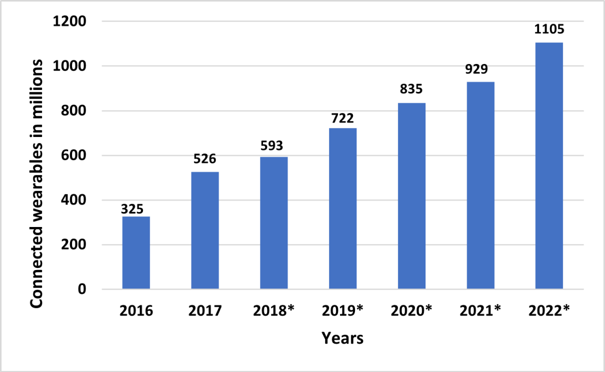


**FIGURE 2.** Global connected devices 2016 to 2022 in millions.

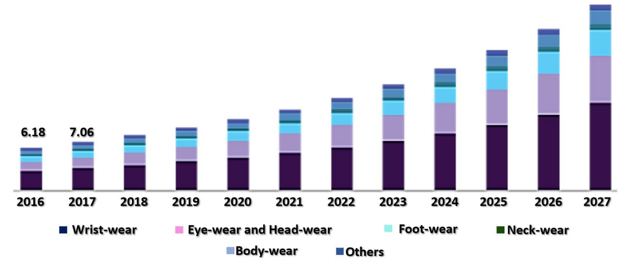


**FIGURE 3.** Number of connected wearable device in the United States of America.

**TABLE 2.** Forecast for Wearable Devices Worldwide [31].

| Wearable Devices | Period under Review | | | |
|---|---|---|---|---|
| | *2016* | *2017* | *2018* | *2021* |
| Smart watch | 34.80 | 41.50 | 48.20 | 80.96 |
| Wristband | 34.97 | 44.10 | 48.84 | 63.86 |
| Sports watch | 21.23 | 21.65 | 21.65 | 22.31 |
| Bluetooth headset | 128.50 | 150.00 | 168.00 | 206.00 |

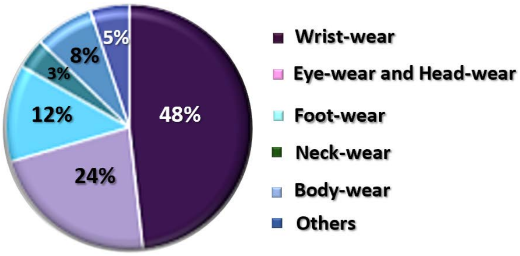


**FIGURE 4.** Global wearable technology market share (Grand View Research, 2020).

wearable devices for healthcare purposes partly due to the primitive approach in semiconductor production [15]. However, with breakthroughs in material science and innovative technologies, wearable technologies have significantly improved resulting in better wearable designs [6]. In recent times, there has been an astronomical growth of wearable devices and their associated technologies [28], [29]. Fig. 2 and Fig. 3 respectively show the increase in the number of connected wearable devices from 325 million in 2016 to 722 million in 2019 indicating a more than double increase within the space of three years. This number is forecast to reach more than one billion by 2022 [28].

However, with the outbreak of COVID-19 globally, the industrial production process was disrupted across the globe, with the wearable device market inadvertently affected in the first half of 2020 resulting in the shut down of production units due to governments imposed restrictions [30]. The pandemic notwithstanding, fostered the role of wearable technologies and devices in the healthcare sector with a surge in demand for contactless healthcare delivery to cushion virus spread [30]. As a result, some players in the wearable technology industry that had developed innovative systems for virus infection detection and possible curtailment [31] witnessed unprecedented patronage as shown in Table 2.

The projected global market demand for wearable device technologies in medical applications was set to be about 17% higher in 2019. Besides, the smart-eye technology was expected to be 40% more in sales than now [31]. In 2019, an increase in demand by millennial consumers led to computer electronics applications making a whooping 45% contribution to the market share index (see Fig. 4). These gave rise to the development of devices that can maintain luxury standards and meets users' demands by utilizing the advantage of high-end machine-to-machine seamless communications and connections occasioned by the 5G network. With the expected advancement in the 5G and B5G networks, the global wearable technology market size valued at USD 32.63 billion in 2019 is projected to expand by 15.9% using the compound annual growth rate (CAGR) [30].

As of 2019, the dominant key players of the wearable technology market globally are Alphabet, Apple Inc, Fitbit Inc., Garmin Ltd., Huawei Device Co., HTC Corporation, Samsung, Sony Corporation, Xiaomi Global Community [31] as shown in Table 3, with each player having its market share index and segment. These market players continuously undertake strategic initiatives such as new product/service launch, outsourcing of certain processes and functions, mutual contracts and agreements, mergers and collaborations, etc., to sustain their market position, maintain global relevance, and maximize profits. These initiatives are geared toward meeting the demands of millennial end-users [30]. Also, the advancement in network infrastructures, use of sophisticated sensors, AI abilities, and big-data velocity contributed to the upsurge of wearable devices, with the desire to improve the safety, productivity, and decision-making capacity of these devices to accommodate futuristic demands and scenarios [32].

Though Fitbit Sense fitness watch, band, and other similar smartwatches are not intended for medical diagnosis and cannot be classified arbitrarily as medical devices, these devices can track in real-time useful metrics (such as body fat estimates, blood oxygenation, etc) that hitherto required the physical presence of a doctor or special equipment [33]. Hence, most wearable companies have only succeeded in flooding the wearable market with enablers of pervasive healthcare service delivery and not necessarily medical devices. This concern has questioned the reliability

**TABLE 3.** Major Players in Wearable Device for Healthcare.

| Devices | *Target Area* | *Major Market Players* |
|---|---|---|
| Hearable | Tech<br>Healthcare | Apple,Bose,Google, Huawei,Samsung, Sony<br>Jabra,Lifebeam, Nuheara, Vinci |
| Smart watches | Tech<br>Healthcare | Apple, FitBit, Garmin, Sony, Samsung, Xiaomi<br>Alivecore, Empatica, KinesiaU, Nemaura, Omron, Onepulse, PKvitality, Verily |
| Fitness Trackers | Tech<br>Healthcare | Samsung, FitBit, Garmin,Nike, Xiaomi<br>iHealth, Alivecore, BrainSentinel,Misfit,SpireHealth |
| Eye Wear | Tech<br>Healthcare | Google, Samsung, Microsoft<br>Vusix, Epson,Virtamed, eSight, OssoVR, Immersive solutions, Medical Realities, VirZOOM |
| Body Device | Tech<br>Healthcare | Google, Athos, Sensoria, OM Signal<br>Siren, Bonbouton, NeuroMtric, Hexoskin,Sensoria, Infineon, Owlet, Neofect |
| Skin Patch | Tech<br>Healthcare | N/A<br>Eccrine systems, BioTelemetry, Epicore, PKVitality, Biolinq, Theranica, Gentag,iRhythm, Medtronic, Nemaura |

of these devices in providing biased information that makes consumers resort to self-medication rather than seeking medical help [34].

Furthermore, the constant need for an improvement in the real-time p-health system; increase in preventive care; intuitive monitoring of patients' compliance remotely (through real-time data collection and analysis); decrease in readmission rates; as well as acceptance of seamless real-time remote-based professional advice and treatment; and more drives the wearable technology market volatility [29]. A real-time p-health system refers to the provision of real-time contactless medical support to users with specific time-sensitive conditions. Moreover, the end user's preference for a compact but reliable product (hybrid and multi-functional) that would integrate and fuse all functions seamlessly is also a factor propelling wearable technology development [29], [35].

In addition, demographic and social trends such as the increased prevalence of chronic disease; rising average life expectancy, the need to decrease the length of hospital stay; the higher ratio of seniors; the larger proportion of patients requiring long-term care; etc. also drive this technology [36]. Finally, the need to cut down the global public and private expenditure on health services estimated at **USD** 7.2 trillion in 2012 is also a critical factor driving accelerated advancement of the sensing wearable market [29]. With all the considered factors and consequent advancements in the Internet of Things (IoT), wearables are expected to bring about high growth opportunities in all sectors of the economy including healthcare as reported by authors [35] that the size of the wearable market grew from USD 1.4 billion in 2013 to USD 19 billion in 2018.

## IV. UNOBTRUSIVE WEARABLE DEVICE DESIGNS AND SENSING APPROACHES

Though the wearable device market is experiencing a boom, the development of unobtrusive wearable devices for practical healthcare purposes is relatively slow [15]. This is relatively due to the infeasibility of brittle material and integrated circuit technology used in the production of the semi-conductors as well as the complex nature of the human body requiring different monitoring devices to be attached to it at the same time [18]. Innovation in telehealth is closely linked to advancement in electronics technology as shown in Fig. 5 and Fig. 6 respectively. The core technologies of sensing wearable devices have evolved from water buckets and bulky vacuum tubes to the benchtop, and from portable devices with discrete transistors to the recent small and compact wearable devices with integrated circuits [27].

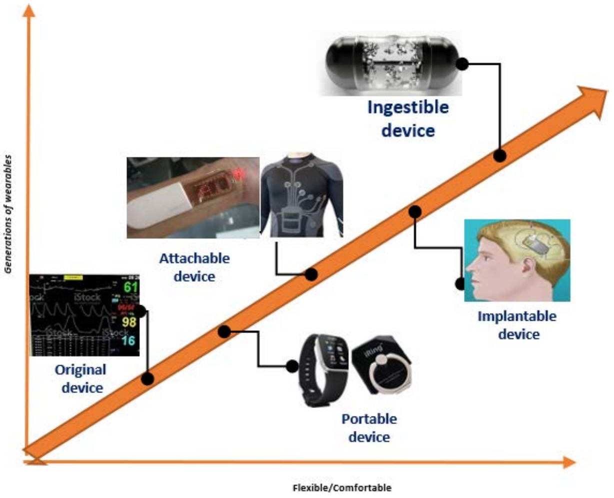


**FIGURE 5.** Timelines of Medical Devices with Technology Evolution representing the different milestones in wearable technological advancement.

Unobtrusive wearable device design is targeted at non-stop real-time measurement, monitoring, recognition, and analysis of physical signs, behavioral patterns, and physiological and biochemical activities of the user using some predefined parameters. The most commonly measured signs are blood oxygen saturation ($SpO_2$), blood pressure (BP), heart rate, electrocardiogram (ECG), ballistocardiogram (BCG), posture, core/surface body temperature, etc. [37]. Unobtrusive wearable sensing is implemented as sensors worn by users (such as in the form of ear-ring, clothing, shoes, gloves, eyeglasses, watches, etc.), sensors embedded into an ambient environment, or as smart objects interacting with users (such as a chair [38], car seat [39], mattress and mirror [40], steering wheel [41], mouse [42], toilet seat, and bathroom scale [43]).

Over the years, unobtrusive wearables are designed with two sensing approaches namely; capacitance-coupled sensing, and photoplethysmography (PPG) [38].

**TABLE 4.** Unobtrusive Wearable Devices for various Physiological and Physical Measurement.

| Device Category | Examples | Monitoring | Physiological and Physical Measurement |
|---|---|---|---|
| **Ingestible** | Bioink | Interstitial fluid | Glucose, pH and electrolytes (such as sodium). |
| | Smart pill | Medicine | Medicine when drug reaches stomach with patch. |
| **Implantable** | Pacemakers | Cardiovascular signal | Heartbeat for treating arrhythmias. |
| | Tattoo | Salivary Sweat | Monitoring respiration and pathogenic bacteria detection with tooth enamel Lactate, glucose, alcohol, and electrolytes (such as ammonium) with skin worn tattoo. |
| **Attachable** | Wearable Skin Patches | Cardiovascular signal | Blood pressure and heart rate by measuring of ECG, BCG and pulse transit time with a thin, flexible patch. |
| | | Body temperature | Sweat volume and sweat components like hydration, glucose, lactate, pH and electrolytes. |
| | Contact Lens | Chemicals | Glucose and lactate in tear fluid. |
| **Portable Device** | Wrist-Mounted Devices | Cardiovascular signal | Heart rate, blood pulse etc. (wrist band or watch). |
| | | Sweat contents | Glucose, sodium etc. (wrist band or watch). |
| | Head-Mounted Devices | Salivary contents | Lactate, uric acid and glucose etc. (mouth guard). |
| | | Sweat contents | Lactate and potassium etc. (eyeglasses). |
| | | Cardiovascular signal | Heart rate (eyeglasses). |
| | E-Textiles | Sweat contents | Glucose and lactate etc. (textiles with electrode). |
| | | Cardiovascular signal | Heart rate and temperature etc. (leg calf). |
| | | Physical activity | Foot motion (footwear). |
| | Others | Physical activity | Sleep, daily activity etc. (ring, necklace, and clip etc.). |
| | | Physical activity | Step count and sitting time (belt worn on waist). |
| | | Physiological signal | ECG and direct current (belt worn on chest). |

**FIGURE 6.** Varieties of Medical Wearable Devices highlighting their contact points on the body.

Capacitance-coupled sensing is a sensing technique that uses a transmitter and a receiver electrode to measure the distances of nearby conductive objects by determining the capacitance between the sensor and the object (see Fig. 7). Once the transmitter is excited by a wave signal, the receiver picks up this wave. This method is deployed for measuring biopotentials like electromyogram (EMG), ECG, and electroencephalogram (EEG) [44]. The major challenge in capacitance-coupled sensing designs is high contact impedance due to indirect contact and capacitive mismatch caused by motion artifacts. However, with the recent introduction of gradiometric measurement by Pang *et al.* [45], motion artifacts can be considerably reduced.

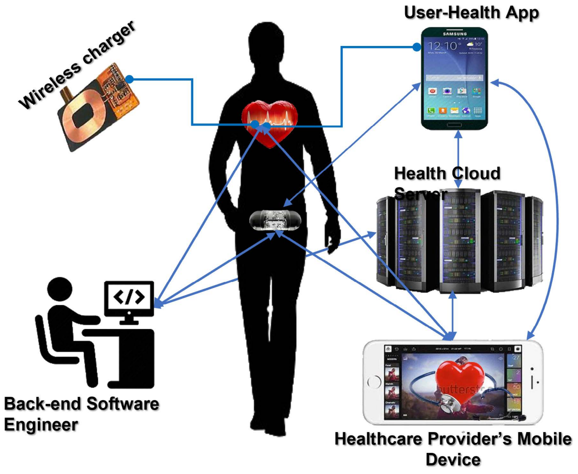


**FIGURE 7.** Components of Unobtrusive Wearable Device System.

Conversely, photoplethysmography (PPG) sensing is a method that uses a simple optical technique to detect volumetric changes in blood circulation. It is widely used to measure vital signs such as blood pressure, respiration rate, heart rate, $SpO_2$, etc. Varieties of unobtrusive and ubiquitous wearable devices have been developed over the years. Some are worn on the body while others are implantable in the body using varied state-of-the-art emerging technologies, wiith the majority applied in healthcare [7]. For example, the deployment of wearables for neurological rehabilitation, monitoring of long term chronic diseases, posture, and activity monitoring of the elderly and the disabled, etc [46].

Generally, wearable devices for healthcare delivery are categorized into portable devices, attachable devices, implantable devices, and ingestible devices [46] as succinctly presented in Table 4. Smart sensing and implantable devices

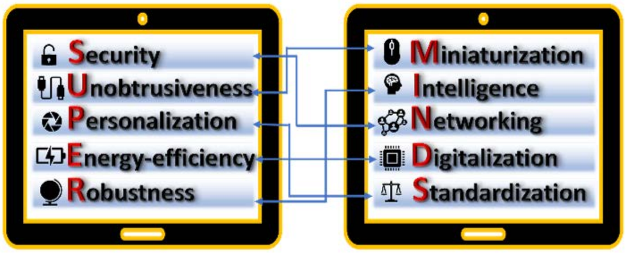


**FIGURE 8.** Sensing Wearable Device KPIs based on advancement in core technologies indicating their interdependence in operations and developmental changes.

help to manage critical and chronic diseases, proactive diagnoses of health status, prediction of possible causes of the ailment, and minimize post-operative complications that require patient's readmission [47]. However, despite these pluses, statistical evidence reveals that implanted wearable devices accounted for 17% of acquired infections, 2-5% of hospitalization, and 20% surgical flaws, which is far from the desire to achieve flawless result [47] as earlier report [48].

The key enabling technologies behind unobtrusive wearable device design is summarized as MEMS; (Multi-sensor hybrid packages, Easy to implement, 9-axis IMU, and Sensor fusion software algorithms), with smart-optimized support of sensor power requirement and Long Term Evolution (LTE) for energy harvesting [49]. These core technologies have key performance indicators (KPIs) that play a key role in the design and development of unobtrusive wearable devices. These indicators otherwise known as core performance parameters are the metrics for measuring the re-inventiveness and performance efficiency of wearable devices in relation to technological advancement [15].

## V. KEY PERFORMANCE INDICATORS IN UNOBTRUSIVE SENSING HEALTH WEARABLE DEVICES

The ubiquitous use of wearable devices is highly dependent on issues associated with its KPIs. According to authors [50], the key technologies that need to be developed for improve implementation of unobtrusive wearable device is summed as "MINDS"; miniaturization, intelligence, networking, digitization, standardization. However, Zheng *et al.* [3] in their work expanded the list of key technologies to include unobtrusiveness, security, energy-efficiency, robustness, and personalization. With the advancement in technology, the parameters that determine and drive the innovation and performance of unobtrusive sensing wearable devices can be comprehensively summed as SUPER MINDS as seen in Fig. 8 namely; security, unobtrusiveness, personalization, energy-efficiency, robustness, miniaturization, intelligence, networking, digitization, and standardization.

Fig 8 shows that the performance of an unobtrusive wearable device is a cumulative function of these core technology parameters as expressed in equation (1).

$$\Longrightarrow Device_p = f[\Sigma(\Delta S_p, +\Delta U_p, \ldots + \Delta St_p)], \qquad (1)$$

where $Device_p$ is wearable device performance, $\Delta S_p$ is change in device's security feature, $\Delta U_p$ is change in device's unobtrusiveness, and $\Delta St_p$ is change in device's standardization factor respectively.

However, a closer look at Fig. 8 indicates that these parameters are interwoven in their operation and developmental changes, in determining the overall quality of experience (QoE) and QoS witnessed by users of these devices. This inter-relationship is technology-driven and multi-dimensional as changes in one parameter result in changes in another closely related parameter. For instance, the advancement in networking protocols and topologies is a function of response to changes in security architectures. Also, the increase in digitalization is a function of better energy-efficient and conservative mechanisms. Based on this intertwined relationship, these parameters are condensed into 5 (five) major KPIs using discriminant factor analysis in response to the 5G network. Hence, these KPIs are summed as "E-DISC"; **E**nergy-efficiency, **D**iscretization, **I**ntelligence (Robust and Scalable), **C**ustomizable Standards, and **S**ecured network. Therefore, the innovativeness and developmental transformation of any wearable device in response to technological dynamics is a function of these textbf E-DISC parameters or technological factors as given in equation (2).

$$\Delta Wearable_k = f\Sigma(E_e, D_l, I_r, S_n, C_s)], \qquad (2)$$

with $\Delta Wearable_k$ representing dynamic wearable innovation in response to technological advancement, $E_e$ stands for device energy-efficiency rate, $I_r$ is the device's intelligence robustness, $S_n$ represents the device's network security strength, and $C_s$ is the device's customization flexibility and interoperability. An empirical and introspective review of these KPIs in relation to the 5G network provides an insight into pervasive issues in wearable devices that demands technological upgrades for a seamless transition from 5G to B5G.

### A. ENERGY-EFFICIENCY

Energy-efficiency is the number of bits that can be transmitted per joule of energy. Energy-efficiency (minimal energy consumption) is critical in the design and optimal utilization of wearable devices for innovative healthcare delivery. Several innovative strategies have been developed over time to improve energy-efficiency of wearable device designs with the purpose of meeting advances in communication networks as shown in Fig. 9. These innovative strategies include power management and energy-efficiency awareness approach and improving energy-efficiency of existing storage technologies [51], development of a novel structure of $ZnCo_2O_4$-urchins-on-carbon-fibers matrix [52], and development of commercial pen ink [53] to improve the efficiency of existing storage technology.

Also, the scavenging energy approach from either the ambient environment or human activities [54]–[56] using piezoelectric harvesters is gaining stunning popularity in achieving minimal energy-consumption of wearable devices.

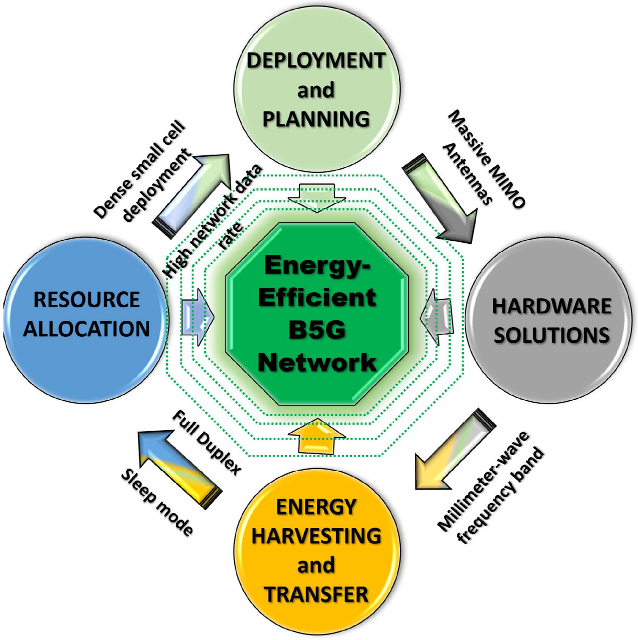


**FIGURE 9.** B5G Energy Efficient Compliance highlighting its parameters.

With the heterogeneous network in place which emphasizes power savings, wider coverage, and increased capacity [57], wireless communication and data transmission via unobtrusive wearable devices will be significantly impacted to meet the much-anticipated increase in network traffic.

The information in Fig. 9 clearly indicates that an energy-efficient B5G network leverages deploying hardware solutions with massive Multi-Input Multi-Output (MIMO) antennas, the millimeter-wave frequency band for ease of access and communication, full-duplex and high network dense data rate for fast data transmission, and sleep modes for efficient resource usage. These characterizations ensure ultra-reliable low latency connectivity (URLLC) of devices. As such, unobtrusive wearable device connected to such a network guarantees real-time access and transmission of health-related data irrespective of data variability, velocity, or volume. Also, with an energy-efficient B5G network, it is guaranteed that there will be a reduction in the total cost of ownership [58] which is a critical cost component in determining the overall cost per unit product of any information technology resource [59], including wearables. TCO includes the initial costs to implement an IT project with the associated continuing costs to maintain, modify, train staff, house, deploy, and provide infrastructure or any other cost associated with the project, including final decommissioning.

TCO is an estimate which includes all direct and indirect costs over the useful life of the IT product which is commonly used in full cost accounting systems. This total Cost analysis is also known as life cycle cost analysis [59]. Also, TCO reflects not just the balance of the direct qualities of competing for IT products (price, functionality, reliability, etc.) but also its relationship to a broader set of technology platforms, as well as its ability to access market and community-based services and support. Hence, achieving energy efficiency will facilitate minimization of TCO which ultimately will bring about a reduction in the cost per unit product of unobtrusive sensing wearable devices as currently witnessed in the market (see Fig. 2 and Fig. 3) [28]. Hence, this will bring about a reduction in the cost of unobtrusive sensing wearable devices as currently witnessed in the market (see Fig. 2 and Fig. 3) [28]. While improving energy efficiency, there is constant flexibility by B5G operators to maintain a reasonable trade-off between device overall performance and energy consumption level.

Digitization, on the other hand, is closely connected to energy-efficiency as the analog signals from the body need to be digitally analyzed, stored, and transmitted by these wearable devices. Maintaining accurate diagnostic measurements with minimal power consumption, therefore, requires critical innovative measures to be in place as an inaccurate medical diagnosis can be fatal. Proper presentation of the relayed message via wearable devices is key to increasing user-acceptability of such devices. Hence, an increase in digitization ensures that physiological and physical activity readings from wearable devices are presented in a user-friendly manner. Several novel attempts made in this regard include band-limited functions approximate reconstruction, heartbeats' classification, and compression using a time-based approach [60]. Millimeter-wave telecommunication as used in 5G provides extremely high speeds (Gbps) for Device-to-Device (D2D) communication [61].

### B. DISCRETIZATION

According to Brigante *et al.*, the development of compact and lightweight wearable devices with optimized layout design is proportionate to the increase in comfort derivable from such devices which are made possible by the size of processing electronics and inertia measurement unit (IMU) [62]. Hence, the more unobtrusive a wearable device is, the higher its user acceptability and QoS. Miniaturization or discretization is also achieved via sensor inductive powering [49]. Discretization can be seen in the capacitive coupling sensing method used for unobtrusive capturing of bio-electrical signals, as well as textile sensing for unobtrusive monitoring of physiological parameters, PPG for unobtrusive cardiovascular assessment [15].

The sophistication and miniaturization of sensors are significantly dependent on the improvement of battery solutions, and the advancement of wearable biosensors and material science to enhance durability and robustness in the future [47]. Hence, wearable sensors are expected to be inconspicuous and minimally cumbersome to reduce fears associated with putting on medical wearables in public. According to Andreau *et al.*, the major challenge with unobtrusiveness (as regards to chronic implants) are power management, stability of sensor in the long term, and biocompatibility of materials [47].

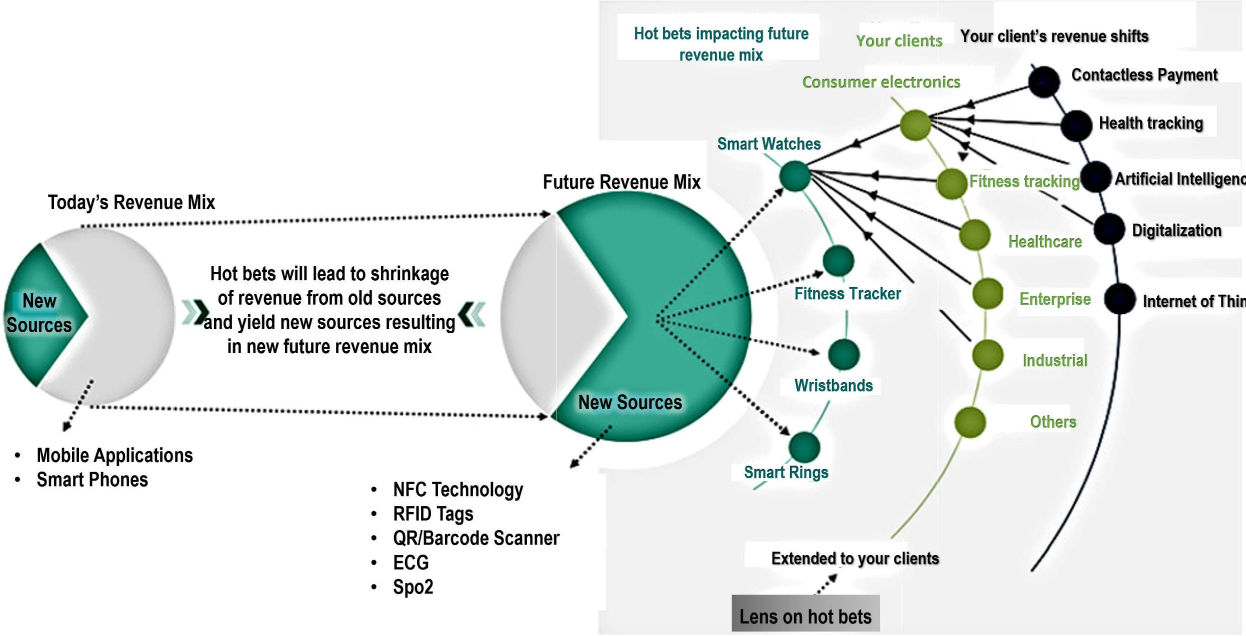


**FIGURE 10.** Disruptive Technologies and Global Wearable Device Demand [63].

Consequently, with the advancement in material science and communication technology, improved implantable wearable device technologies have resulted in better management of many chronic diseases like cancer, hypertension, cardiac arrest, diabetes, etc [16]. According to Zheng *et al.*, with the potentials of transient electronic technology, biocompatibility, biodegradability, and self-heal ability, a fully integrated electronic and optoelectronic multi-functional system, an unobtrusive wearable device can retain its electronic functions, restore its electrical/mechanical characteristics after slight medical damage, robust in meeting complex human body needs, and possesses high ductility characteristics [15]. Transient electronic technology as an emerging technology emphasizes the need to develop systems that can be absorbed by human organisms and surrounding environmental micro-organisms at ultra-fast programmed speed without homeostatic imbalance and discomfort [64].

However, with miniaturization and unobtrusiveness comes the need to take into cognizance the health implication associated with long-term exposure of vital organs of the body to ultraviolet rays emitted by these devices through constant usage [49]. Therefore, advancement in unobtrusiveness and miniaturization must continuously guarantee widespread user acceptance through safety-sensitive innovations to avoid public disapproval [24].

### C. ROBUST INTELLIGENCE

Wearable devices are designed to adjust to various environmental needs and respond to the dynamic homeostatic of patients with accurate details. AI components allow autonomic functions such as sending alerts and taking informed support decision [20], [65]. AI also provides user-adoption and context-awareness features in wearable devices [66]. Several AI approaches developed and extensively applied in various healthcare applications include the hidden Markov model, artificial neural networks, random forests, support vector machines, convolutional neural networks, and neuro-fuzzy inference systems.

The reduction of motion artifacts of wearable sensors is still a challenging problem for the development of wearable systems. Motion artifact in wearable sensors is due to the overlapping of wearable systems' frequency band with the desired signal. Some of the proposed methods for reducing motion artifacts include; adaptive neuro-fuzzy interference system (ANFIS), adaptive filtering method without additional sensors [67], adaptive noise cancellation method with the use of an embedded accelerometer [40]. The adaptive filtering method is not impressive in real-time applications due to its extensive processing time. The lack of large-scale studies in real-world situations, the need for individualized training data in supervised learning, and the high rate of false alarms, are some of the major obstacles that hinder the widespread adoption of sensing technologies in clinical applications [3].

Available statistics indicate that there is a significant increase in the adoption of AI [10], IoT [12], and mobile edge computing [20] in wearable devices for contactless healthcare delivery and health-status tracking which has disrupted the global demand for wearable devices, and in turn impacted on the growth of the wearable market (see in Fig. 10). This upsurge in wearable device demand occasioned by disruptive is however not unconnected to the ultra-reliable low latency communication characterization that 5G networks offer as most of these devices are designed with the capacity to run on 5G networks.

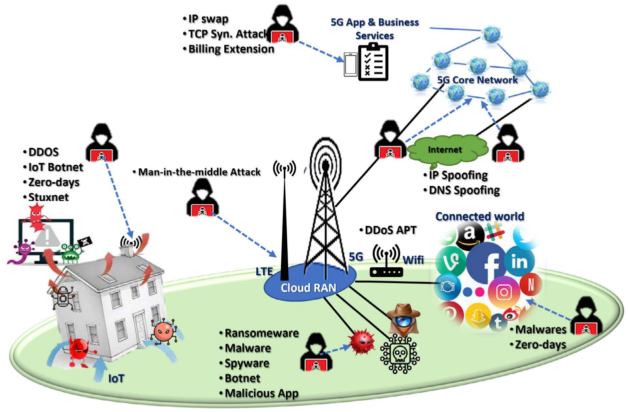


**FIGURE 11.** Security Threats and Attacks in 5G Networks.

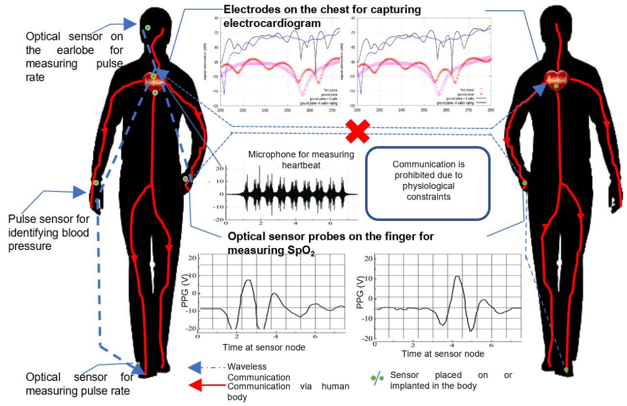


**FIGURE 12.** Illustration of secure inter-sensors communication for wearable health monitoring [71].

### *D. SECURED NETWORK*

Due to the expected roles B5G guarantees and its influence on changing lifestyles, the security of the network and reliability of the transmitted data over it is very important [1]. To deliver high efficiency and quality p-healthcare via unobtrusive wearables, efficient security and seamless network configuration are critical indicators that determine viable deployment [68]. The upsurge of wearable and other handheld device development has generated multiple security concerns with privacy issues as the most palpitating and resurfacing problem [69]. Without adequate security, the transmitted data over a wearable device via a wireless sensor network is vulnerable to different cyber-threats and attacks as seen in Fig. 11.

The challenge to guaranteeing security lies in three (3) aspects: how to protect user's privacy (confidentiality), how to prevent the disclosure of patient's data (trustworthiness), and the right of access to the system (authenticity) [44]. Hence, the improvement in data encryption, information confidentiality, and authentication strategies of wearables are of immense necessity. Data transmission security between wearable sensors for inter-sensor communications requires designing a key agreement for encryption. Various approaches have been proposed to handle this issue such as certificateless conditional privacy-preserving authentication scheme for wireless body area networks big data services [70], Identity-based symmetric cryptography and asymmetric key cryptography for Body Sensor Network (BSN), use of impulse intervals (IPIs) [71] as shown in Fig. 12, and the use of PPG as bases for key agreement.

To further enhance security of data transmission between wearable devices and communication networks, the mostly deployed B5G security technology strategies to track and curtail attacks are massive MIMO, physical layer coding, non-orthogonal multiple access technology, heterogeneous networks, millimeter wave communication, and full duplex networks [72]. Consequently, networking protocols and approaches utilized in the development of medical wearable device contributes significantly in guaranteeing security of vital medical information transmission between remote location and its eventual destination.

One of the most popular wearable technology networks is the BSN [73]. It is an inter-connectivity of allied technologies for the development of pervasive sensing for healthcare and other applications requiring widespread and persistent monitoring of physical, physiological, and biochemical parameters in any environment, without activity restriction, and any form of behavioral modification [73]. Sensing networks also include Wireless Personal Area Network (WPAN), Wireless Local Area Network (WLAN), cellular networks (3G/4G/5G network, GPRS), Wireless Wide Area Network (WWAN). These are deployed in transmitting acquired data from wearable devices to data servers for storage and subsequent analysis and processing [73].

The major challenge of wearable networks includes network security, network topology optimization, multiple sensor fusion, user mobility, and communication protocols for energy-efficient transmission [73]. Other issues of consideration are the guarantee of QoS, transmission power, reliability (i.e., error control), latency, and bandwidth reservation [74]. Ultimately, wearable devices for innovative p-health will largely depend on incorporating supreme-built-in security paradigms, flexible network mechanisms, and AI embedded security automation that requires minimal human intervention to retain its patronage from users.

### *E. CUSTOMIZABLE STANDARDS*

Customization of wearable devices for innovative healthcare delivery entails tweaking the device ergonomics, sensor calibration, disease detection, medical diagnosis, and treatment to meet up with technological dynamics while satisfying the varying ecstasies and demands of the targeted market audience. In 5G networks, tracking a person's physiological (oxygen level, body temperature, ECG, etc.) and physical (activity, posture, etc.) signs with varied details/patterns between devices and cloud-based platforms at various locations to guarantee precise personalized management, requires seamless data transmission and optimized intelligence from distributed database [36]. Therefore, customization to each user's needs and specifications demands an intuitive, robust, and scalable interoperability across health service platforms.

Reviewing the existing interoperability protocols as standard procedure in the design and development of wearable devices that meets 5G network demands is crucial in the wave of geometrical increase in cyber-attacks and security vulnerabilities across the globe due to the premium attached to the privacy of health records.

Despite the proliferation of wearables, statistics show that only a few interoperable standards are available for evaluating the accuracy and reliability of health wearable devices. Among notable ones are ISO/IEEE 11073 [71], an extension of ISO/IEEE 1103 to accommodate wireless wearable devices at home [68]. Recently, the X73PHD standard (a micro-controller-based platform with low-voltage and low-power constraints) was established [68]. Though the standardization process is often time-consuming and complicated, there is an urgent need to improve on the existing standards to meet the demands of disruptive technologies and guarantee the safety of users as 5G unwinds and B5G emerges with promises of more flexible and user-friendly options such as open-networking in radio access networking (O-RAN) across multiple support services.

Hence, wearable designs that will operate in a B5G networked environment for future p-health care delivery should consider meeting the standard requirements for integrating a device into a networked control system architecture namely dependability, interoperability, scalability, and composability (DISC). Composability refers to the modularity of subsystems designed for easier integration. Scalability refers to the extensibility of the system to accommodate emerging functionalities due to dynamic operational changes in the environment. Hence, scalable and composable architectures allow for the building of an operational environment that not only supports dynamic and flexible changes, but also adaptive behaviors under resource and timing constraints. On the other hand, interoperability and dependability emphasize the need for flexible integration of components and reliable (fault-tolerant) output.

## VI. B5G NETWORK AND WEARABLE DEVICE TECHNOLOGIES: FUTURE DIRECTION

The unobtrusive wearable device has contributed immensely to p-health service delivery due to advancements in its underlying technologies. However, data from these devices that are applicable for clinical trials has not genuinely solved real-world practical concerns as its fails to meet up with expected requirements [75]. This according to authors [75] is due to bias (selective) and under-reporting of outcomes, the use of proxy, complex, and prejudiced endpoints for predictions, failure of incorporating end user's viewpoint in device designs, misleading and ambiguous suggestions, inconsistent and multi-variant outcomes, use of complex metrics and scales for result interpretation, amongst others. Thus, it undermines the reliability of the results from these devices. Such unreliable results create anxiety in its users and affect the reliance on such results by both the end-users and the physicians in drawing factual conclusions about medical decisions and treatments. Thus, poor data representation for digital health management is a critical issue that demands a closer consideration in wearable designs for innovative healthcare delivery. Furthermore, wearable device makers need to be concise and clear about how these devices should be used.

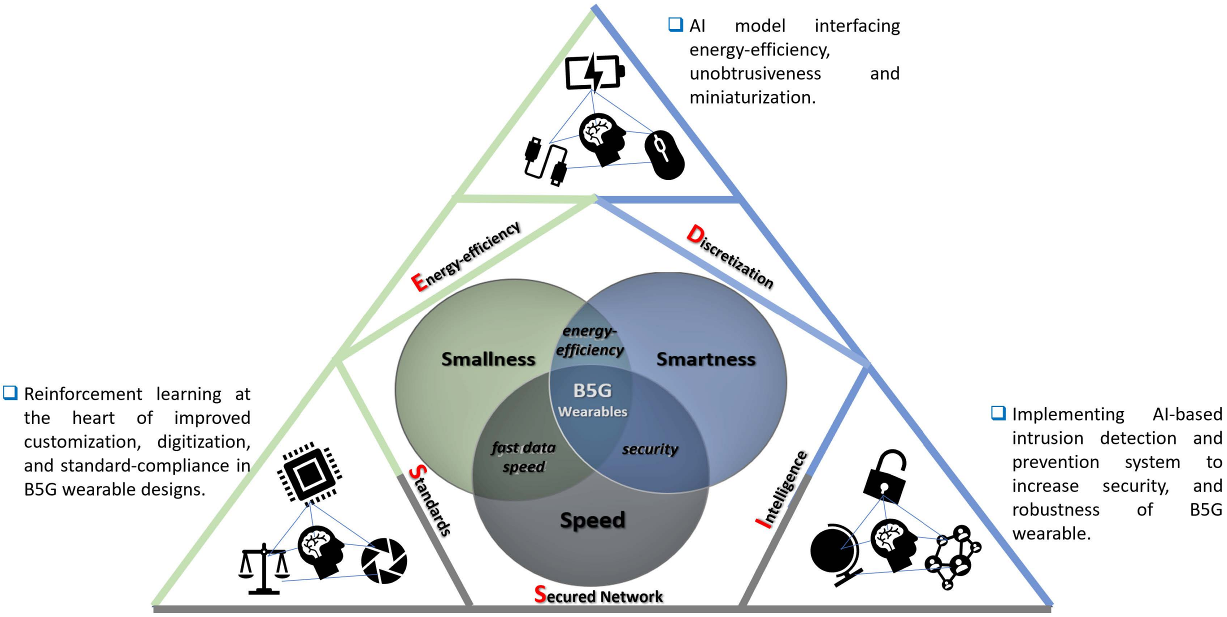
Also, most of the applications deployed on wearable devices for tracking and monitoring different physical and physiological parameters have not been cleared by the relevant regulatory and medical agencies due to several reported cases of inconsistent and unreliable readings and recommendations from the devices. These unreliable recommendations have resulted in patients seeking unwarranted medical attention. To be precise, a study shows that only 11.4% of 264 patients who received abnormal pulse reading from their apple smartwatch sought medical cardiovascular diagnosis [75]. These statistics reveal the extent these users trust the readings from these devices.

Hence, qualitative and unbiased data collection techniques, inclusive participation of end-users in the device design process, transparency and trustworthiness in reporting outcomes, and self-explanatory but delimited sensitivity consciousness when transmitting certain information to users to avoid abuse, agitations, and addictions, are key to remedying these identified flaws. This will help in translating health records meant for clinical trials into real-time real-world applications. By incorporating these essentials in the design and development process of a wearable device and integrating it into B5G network capabilities, these identified flaws can be remedied.

The ultimate goal of 5G and B5G wireless networks is ultra-fast network connectivity and data transmission (speed to support disruptive technologies of 10Gbps and above), incredibly low latency (miniaturized and energy-efficiency), substantial rise in base station's efficiency (especially security), and improved QoS through reliable feedback [2]. This implies that the 5G network and beyond focuses on delivering IT products that run seamlessly and are secured across terminals irrespective of destination. Hence, the critical issue demanding innovative engineering is the development of an unobtrusive wearable device with improved data security, privacy, and the digitalization of healthcare data [76]. Leveraging on the potentials of B5G in transforming healthcare delivery, the future of wearable healthcare devices for p-health that will align with the B5G network is anchored on three (3) interconnected core pillars; speed (personalized standards), smartness (secured networks with robust intelligence), and smallness (energy-efficiency and discretization) as expressed in equation (3) and depicted in Fig. 13.

$$\Delta Device_p = f[\Sigma(Ss_p, Sm_p, Sp_p)], \tag{3}$$

where $\Delta Device_p$ is B5G wearable device performance, $Ss_p$ is device size, $Sm_p$ is device smartness, and $Sp_p$ is device speed of feedback. From Fig. 13, AI is at the hub of the operations of



❑ AI model interfacing energy-efficiency, unobtrusiveness and miniaturization.

❑ Reinforcement learning at the heart of improved customization, digitization, and standard-compliance in B5G wearable designs.

❑ Implementing AI-based intrusion detection and prevention system to increase security, and robustness of B5G wearable.

FIGURE 13. B5G Wearable Device Paradigm highlighting the sync. of E-DISC KPIs with 6G core objectives with AI at the hub of its operations.

B5G wearable devices in transforming outcomes into usable assets for reliable medical decisions. Therefore, equation (3) can be re-expressed as

$$\alpha Device_p = \Delta Device_p + \Delta\Theta_{ai}, \tag{4}$$

with $\Delta\Theta_{ai}$ representing the dynamic impact factor of AI in the operations of the B5G wearable device. With the increase in trustworthiness and transparency in the design and development of AI products such as unobtrusive wearable devices, the inherent lapses in the existing wearable devices can be curbed.

### A. SMALLNESS

The expected wearable technology in 5G and B5G environments is predicated on the creation of an intelligent virtual power plant that optimizes resource usage, incorporates efficient-energy usage, compact and precise production, and trading in a highly secured channel. As seen in Fig. 13, actualizing smallness largely depends on increased energy-efficient paradigm, discretization, and improved standards. Hence, energy efficiency and its derivatives in wearable devices are anchored on a heterogeneous B5G network with enhanced capacity, coverage, and power savings [13] for reliable transmission of health data.

The parameters for checkmating energy efficiency in 5G and B5G networks include but are not limited to sleep mode [77], high network data rate [78], [79], dense small cell deployment [80], full duplex [81], massive MIMO antennas [80], [82], millimeter-wave frequency band [83]. Millimeter-wave telecommunication deployed in 5G networks provides extreme high speeds (Gbps) for D2D communication [84]. The contending issue in millimeter waves is that at higher frequency bands, signal attenuation occurs; limiting the strength of signal reception. Also, oxygen molecules and water vapors affect mm-wave energy. Hence, maintaining a trade-off between performance and energy efficiency is considered very critical in the development of wearable devices that will meet QoS [1]. Channeling research efforts to address the identified lapses inhibiting miniaturization to gain speed is a necessity.

In addressing surrogate and composite outcome issues, wearable device designs should focus on real-time patient-relevant and expert-agreeable outcomes. To achieve this, AI-driven wearables should consider the correlations and inter-relationships of aggregated features in datasets used for predicting results and making recommendations. This feature aggregation principle should be done with full consultation of relevant medical experts and following established clinical records and procedures. It will further ensure that the problem of non-inclusion, non-representativeness, and lopsided and biased wearable device outcomes are avoided. Only with 5G and B5G can the domain of AI devices transit from artificial normal intelligence to real human intelligence where irrationality blends with rationality in proffering reliable dynamic solutions in a complex environment like the human body. With this aggregation of features through feature engineering, the low device computational cost is guaranteed, which ultimately translates to more speed and encourages more unobtrusiveness in wearable devices. This simplicity in wearable designs will further motivate hybrid digital and analog antenna development [24] for ultra-reliable connectivity.

### B. SMARTNESS

The blending of disruptive technologies that are capable of meeting user traffic (security), dynamic demand-oriented services (intelligence), and scalable growth of IoT and Industrial Internet of Things (IIoT) (robustness) are considered the core strengths of 5G and B5G networks. Smartness and security are two inseparable interwoven components because smartness is a function of high-security alertness and sensitivity in situation-based decision-making with high precision. Integration of large-scale IoT and IIoT with new technology concepts that demand high precision feedback, real-time proactive decision-making, ease of use, and optimum confidentiality and trustworthiness; creates smartness-based security constraints [65], [85], [86], especially in unobtrusive wearable devices. These characterizations are achievable in a system driven by AI as shown in Fig. 13.

According to International Telecommunication Union (ITU-T), security features in B5G security architecture are divided into separate architectural components [87]. This is to guarantee systematic end-to-end security of services, help in planning means to assess the security of current networks, and facilitate new security solutions, in a bid to improve the alertness and rationality of the devices that use these security models. Thus, security in the B5G network focuses on supreme-built-in encryption (security as software); versatile security systems (AI-based security and applying AI in cyber-security); and various manufactured based-automation (security automation) [88]. This has resulted in the development of various AI-based intrusion detection systems for wearable devices [89]–[92]. It also ensures data confidentiality and privacy is maintained in wearable devices resulting in increase in the trustworthiness and reliability of the end-users in the system.

Smartness also entails real-time transmission of intelligent and secured information remotely between the end-users and its needed destination; detection of data patterns from large-scale dynamic sources, and recommendation of intelligent action to be taken forthwith via artificial intelligence paradigms [90]. Hence, wearable devices that will operate effectively in 5G and transit seamlessly into B5G should consider incorporating features that not only mitigate futuristic threats but also provide trustworthy real-time intelligent feedback that will satisfy users' expectations [93]. With the internet of humans, a novel concept in healthcare that connects, monitors, and records patients' health status in real-time via the internet and other disruptive technologies [9], rapid medical response is guaranteed through B5G.

Leveraging on the potentials of AI and B5G, the use of complex scale and ambiguous relaying of results that instills anxiety in end-users of wearables can be curbed. AI-driven and B5G compliant wearable device designs should also incorporate features for relaying user-centric results that are concise, self-explanatory, and specifies asymptotic condition rather than average score/ratings. Furthermore, there should be a paradigm shift from wearable device results interpretation that are statistically significant to results that are clinically beneficial; to serve as benchmarks for predicting the future. With an AI-based security approach, information censoring can be achieved in wearable devices. Hence, the B5G complaint wearable device should consider delimiting the transmission of precarious medical details to end-users and leverage the edge network to transfer such complex prescriptions to medical practitioners to avoid frustration and self-medication.

### C. SPEED

Due to the constant high demand on latency, computation resources, and efficiency, even 5G networks may not be able to help the development of wider application of future technologies [94]. Hence, the discretization, networking, and standardization of antennas and sensors expected to work in B5G must correspond to the speed of data transmission across connected devices with unobtrusive wearable devices included. Speed in this context cuts across network bandwidth (the rate of data transfer in any given network signifying its capacity), throughput (the amount of data moved at any given time), and latency (time taken for a data packet to get its intended destination).

Notably, antenna from previous mobile communication technologies (1G-4G) is passive and uses capacitors, conductors, and metal rods which inadvertently affect data transmission speed across connected devices with wearables inclusive. However, 5G and B5G compliant antennas are active in nature with high speed (frequency ranging between 30 to 300GHz), low latency (up to 1ms to 100$\mu$s end-to-end device latency), bandwidth (connection capacity measuring in multiples of Gbps), and possesses AI-based security features [95], [96]. Other approaches deployed to boost performance, coverage, reliability, and user experience in 5G and emerging B5G networks include but are not limited to advanced antenna system (AAS), beamforming, and MIMO strategies [97].

Undoubtedly, these characteristics will boost real-time streaming and transmission of reliable data (structured and unstructured) over wearable devices between end-users and medical experts. Thereby reducing ambiguity hitherto experienced in results' interpretation of previous devices due to weaknesses in their underlying communication technologies such as network traffics, propagation delays, hardware issues, etc.

Therefore, reinventing more innovative approaches to enhance antenna performance to achieve more speed and incorporating such features into wearable devices will help actualize innovative healthcare delivery. Also, to meet user expectations, wearable devices should be designed to efficiently communicate with antennas with geometrical adjustment parameters to obtain multi-band response. Furthermore, deployed antennas should be MIMO-based with mmWave spectrum. Lastly, there is the need to take adequate steps to prevent and protect against signal loss caused by rain, fog, or snow, which is a clog in communication technology advancement. Addressing the outlined issues will automatically translate to making wearable devices an asset for actualizing innovative p-healthcare delivery.

## VII. POTENTIALS OF B5G KPI TO SUPPORT WEARABLE DEVICE TECHNOLOGY

Consequent to the unwinding of the 5G network, research efforts shifted to focus on the practical implementation of B5G or 6G with the target year as 2030 [98]. Researchers argue that B5G will affect all sectors of the economy. This section, however, is targeted at the health sector only with an emphasis on wearable devices. For instance, Kazim *et al* [93] opined that 'unobtrusive and noninvasive measurements using RF sensing, monitoring, and the control of wearable medical devices are the areas that would potentially benefit from B5G'. Thus, B5G is seen as an enabler for future p-health use-cases such as wearable device technologies.

Moreover, the 5G regime has been reviewed by researchers as not capable of meeting the future use-cases by the year 2030 [98]; thus, working towards the B5G regime such as the 6Genesis Flagship program in Finland [61], [99] will amount to being proactive in research and development of innovative wearable healthcare device. The identified KPIs (smartness, speed, and smallness) discussed previously are further decomposed into latency, mobility, connection density, energy efficiency, peak data rate, spectrum efficiency, user experience data rate, and area traffic capacity [98]. This is to spotlight specific differences in 5G and B5G in addressing the inherent challenges in the existing wearable device. In the following subsections, the review examines some of the distinct characteristics envisaged to support future wearable device technology.

### A. BEYOND MM-WAVE COMMUNICATION IMPACT ON WEARABLE DEVICE TECHNOLOGY

Existing 5G technology operates at extremely high frequency such as the mmWave [100]. However, B5G or 6G is expected to leverage the higher spectrum technologies such as terahertz and optical communication [61], [101]. mmWave signals have been shown to be susceptible to challenges such as severe path loss, directivity, narrow beamwidth, and sensitivity to blockage [102]. Moreover, the IEEE 802.15.6-body area networks (BANS) protocol designed for on-body communication limits the usage of wearable devices as they suffer signal connectivity degradation due to energy constraints. Recent works suggest the integration of ''intelligent walls'' [93] to aid the collection of weak signals from wearable devices and interlink with another wearable device in the vicinity. This will further encourage the integration of communication for machine learning schemes into smart wearable device [103] to improve its responsiveness and derivable utility.

### B. SUPPORT FOR THE INTERNET OF NANO-THINGS AND INTERNET OF BODIES VIA SMART WEARABLE DEVICE TECHNOLOGY

Support the Internet of Nano-Things and Internet of Bodies through smart wearable devices and intra-body communications achieved by implantable nanodevices and nanosensors with extremely low power consumption (on the order of picowatts, nanowatts, and microwatts) [100]. Network generation trends from 4G to 5G and beyond, indicate a shift toward the comprehensive realization of the internet of things, nanothings, bodies, and wearables [100]. Consequently, future wearable networks will need to transfer a much higher amount of data at a much higher speed [101]. This has given rise to a new paradigm known as the Internet of Medical Things (IoMT) [93] in a bid to achieve innovative p-healthcare delivery by leveraging the potential of B5G technology.

### C. NETWORK EFFICIENCY IMPACT ON WEARABLE DEVICE TECHNOLOGY

In addition, unlike the 5G network with 99.999% reliability and 1ms latency, the B5G networks such as 6G are expected to guarantee continuous availability (99.99999% reliability at ultra-low latency ($100\mu$s) [101]. Future wearable devices will require more stringent end-to-end latency as well as tighter reliability boundaries [104]. To become ubiquitous beyond 5G, wearable device designers and manufacturers should consider creating a balance between open innovation and seamless connectivity of their products [35]. This will enhance end-users trust and reliability of the information relayed and results from these devices.

### D. DIVERSE MOBILITY MANAGEMENT IMPACT ON WEARABLE DEVICE TECHNOLOGY

The mobile Internet and Internet of Everything (IoE) are two drivers for 6G that will support holographic and high-precision communications for tactile and haptic applications (e.g., the tactile Internet) [105] to provide a full sensory (i.e., vision, hearing, smell, taste, and touch) experience. This requires processing a very high volume of data in near real-time, with extremely high throughput (approximately Tb/s), and low latency [100] which undoubtedly is guaranteed by B5G and essential for a future wearable device in handling, processing, and transmitting large chunks of data with velocity, volatility, and variability.

### E. MULTIPLE DATA ACCESS TECHNOLOGY IMPACT ON WEARABLE DEVICE TECHNOLOGY

Wearables are generally seen as a subcategory of IoT. They can connect to other devices to collect or share data [36]. In addition to real-time display of information allowing users on-the-spot access to information, wearables could offload data to the cloud or other devices that can handle more computationally intensive analysis [68]. Beyond 5G, wearable devices will leverage more on multiple access to data such as the cloud, and other large storage compliant servers [106]. Hence, future wearable device is expected to participate in the integration of ''things connectivity'' to enhance its performance and derivable utility by its end-users rather than an isolated physical and physiological changes determinants which is the current practice.

## VIII. CONCLUSION

In this work, an introspective review of wearable device technologies KPIs is presented in relation to its transition into the B5G network in a bid to deliver innovative healthcare. The overall performance, perceptibility, and people's acceptability of these devices are based on the level of transformative integration of these KPIs in their design in response to social demands. Though significant improvements have been achieved in the design and development of these devices in response to social and economic dynamics, there is a need for improved practical implementation and incorporation of more innovative and eco-friendly solutions into these devices to boost their performance for a seamless transition into the emerging generation network, the B5G. These identified E-DISC wearable devices' KPIs namely energy efficiency, discretization, robust intelligence, secured network, and customizable standards are interwoven in their operations with AI at the hub in delivering smart, speedy, and reliable information that are assets for personal and medical purposes.

Currently, the wearable market is experiencing a global technological boom due to an increase in demand for contactless p-health and other socio-economic factors. However, there are numerous technical issues and challenges confronting the performance of the wearable device that requires urgent attention. These challenges cut across wearable reliability issues such as smartness (usability safety), dependability (trust in relayed information), availability (cost-effective real-time connectivity), maintainability (error control), and real-time issues such as security (standardized interoperability), and speed (wider coverage and responsiveness). In addressing these challenges, intensive research and development effort should be channeled towards B5G-AI trustworthiness in engineering designs, formulation of universal standards for clinical data collection and integration procedures, and secured cloud-based storage paradigms, as it will result in a seamless functioning of wearable device technologies from 5G to B5G.

With the unique characterization that the B5G network is expected to offer, the emerging transient technology paradigm of wearable devices for healthcare delivery will crystallize to smooth operation in an eco-friendly environment where the increase in speed of secured information transmission in a smart manner is guaranteed to meet and exceed end-users expectation. This is only possible as the gap between research and innovation in wearable technologies and communication networks align through the practical implementation of ideas that will translate wearable devices into irresistible assets for innovative p-healthcare delivery.

## REFERENCES

[1] R. Dangi, P. Lalwani, G. Choudhary, I. You, and G. Pau, "Study and investigation on 5G technology: A systematic review," *Sensors*, vol. 22, no. 1, p. 26, Dec. 2021. [Online]. Available: https://www.mdpi.com/1424-8220/22/1/26

[2] T. Norp, "5G requirements and key performance indicators," *J. ICT* vol. 6.1, pp. 15–30, May 2018.

[3] Y.-L. Zheng, X.-R. Ding, C. C. Y. Poon, B. P. L. Lo, H. Zhang, X.-L. Zhou, G.-Z. Yang, N. Zhao, and Y.-T. Zhang, "Unobtrusive sensing and wearable devices for health informatics," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 5, pp. 1538–1554, May 2014.

[4] T. Loncar-Turukalo, E. Zdravevski, J. M. da Silva, I. Chouvarda, and V. Trajkovik, "Literature on wearable technology for connected health: Scoping review of research trends, advances, and barriers," *J. Med. Internet Res.*, vol. 21, no. 9, Sep. 2019, Art. no. e14017.

[5] C. Garcia-Perez, A. Diaz-Zayas, A. Rios, P. Merino, K. Katsalis, C.-Y. Chang, S. Shariat, N. Nikaein, P. Rodriguez, and D. Morris, "Improving the efficiency and reliability of wearable based mobile eHealth applications," *Pervas. Mobile Comput.*, vol. 40, pp. 674–691, Sep. 2017.

[6] S. Chun, D. W. Kim, J. Kim, and C. Pang, "A transparent, glue-free, skin-attachable graphene pressure sensor with micropillars for skin-elasticity measurement," *Nanotechnology*, vol. 30, no. 33, pp. 335–501, May 2019.

[7] A. Ometov, V. Shubina, L. Klus, J. Skibinska, S. Saafi, P. Pascacio, L. Flueratoru, D. Q. Gaibor, N. Chukhno, O. Chukhno, and A. Ali, "A survey on wearable technology: History, state-of-the-art and current challenges," *Comput. Netw.*, vol. 193, Jul. 2021, Art. no. 108074.

[8] C. Y. Poon, Y. Wong, and Y.-T. Zhang, "M-health: The development of cuff-less and wearable blood pressure meters for use in body sensor networks," in *Proc. IEEE/NLM Life Sci. Syst. Appl. Workshop*, Jul. 2006, pp. 1–2.

[9] J. U. R. Kazim, T. J. Cui, A. Zoha, L. Li, S. A. Shah, A. Alomainy, M. A. Imran, and Q. H. Abbasi, "Wireless on walls: Revolutionizing the future of health care," *IEEE Antennas Propag. Mag.*, vol. 63, no. 6, pp. 87–93, Dec. 2021.

[10] G. Dimauro, V. Bevilacqua, and L. Pecchia, "Bioelectronic technologies and artificial intelligence for medical diagnosis and healthcare," *Electronics*, vol. 10, no. 11, p. 1242, May 2021.

[11] A. Sharifi, A. R. Khavarian-Garmsir, and R. K. R. Kummitha, "Contributions of smart city solutions and technologies to resilience against the COVID-19 pandemic: A literature review," *Sustainability*, vol. 13, no. 14, p. 8018, Jul. 2021.

[12] J. I. Mechanick and Z. Shan, *Wearable Technologies in Lifestyle Medicine*. Cham: Springer, 2020, pp. 133–143.

[13] S. Lee and D. Lee, "Healthcare wearable devices: An analysis of key factors for continuous use intention," *Service Bus.*, vol. 14, pp. 1–29, Dec. 2020.

[14] S. O. Ajakwe, R. Arkter, L. A. C. Ahakonye, D.-S. Kim, and J.-M. Lee, "Real-time monitoring of COVID-19 vaccination compliance: A ubiquitous IT convergence approach," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2021, pp. 440–445.

[15] Z. Lou, L. Wang, K. Jiang, Z. Wei, and G. Shen, "Reviews of wearable healthcare systems: Materials, devices and system integration," *Mater. Sci. Eng., R, Rep.*, vol. 140, Apr. 2020, Art. no. 100523.

[16] M. Mardonova and Y. Choi, "Review of wearable device technology and its applications to the mining industry," *Energies*, vol. 11, no. 3, p. 547, Mar. 2018.

[17] W. Wu and H. Haick, "Materials and wearable devices for autonomous monitoring of physiological markers," *Adv. Mater.*, vol. 30, no. 41, Oct. 2018, Art. no. 1705024.

[18] T. Huynh and H. Haick, "Autonomous flexible sensors for health monitoring," *Adv. Mater.*, vol. 30, no. 50, Dec. 2018, Art. no. 1802337.

[19] D. R. Seshadri, J. R. Rowbottom, C. Drummond, J. E. Voos, and J. Craker, "A review of wearable technology: Moving beyond the hype: From need through sensor implementation," in *Proc. 8th Cairo Int. Biomed. Eng. Conf. (CIBEC)*, Dec. 2016, pp. 52–55.

[20] F. A. Kraemer, A. E. Braten, N. Tamkittikhun, and D. Palma, "Fog computing in healthcare—A review and discussion," *IEEE Access*, vol. 5, pp. 9206–9222, 2017.

[21] A. Shah, S. Ahirrao, S. Phansalkar, and K. Kotecha, "Survey on: Applications of smart wearable technology in health insurance," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 1042, no. 1, Jan. 2021, Art. no. 012025.

[22] V. Vijayan, J. P. Connolly, J. Condell, N. McKelvey, and P. Gardiner, "Review of wearable devices and data collection considerations for connected health," *Sensors*, vol. 21, no. 16, p. 5589, Aug. 2021.

[23] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement," *PLoS Med.*, vol. 6, no. 7, Jul. 2009, Art. no. e1000097. [Online]. Available: https://www.bmj.com/content/339/bmj.b2535, doi: 10.1371/journal.pmed.1000097.

[24] H. Sun, Z. Zhang, R. Q. Hu, and Y. Qian, "Wearable communications in 5G: Challenges and enabling technologies," *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 100–109, Sep. 2018.

[25] L. Lu, J. Zhang, Y. Xie, F. Gao, S. Xu, X. Wu, and Z. Ye, "Wearable health devices in health care: Narrative systematic review," *JMIR mHealth uHealth*, vol. 8, no. 11, Nov. 2020, Art. no. e18907.

[26] S. Said, S. A. Kork, and A. Nait-Ali, *Wearable Technologies in Biomedical and Biometric Applications*. Singapore: Springer, 2019, pp. 211–227.

[27] O. Peltola, *Introduction to Wearable Healthcare Technology*. Jyväskylä, Finland: Univ. Jyväskylä, Dec. 2017, doi: 10.13140/RG.2.2.28570.90564.

[28] L. V. Sujay. (May 2021). *Number of Connected Wearable Devices Worldwide From 2016 to 2022*. [Online]. Available: statista.com/statistics/487291

[29] IHS. (Sep. 2013). *Wearable Technology Market Assessment an IHS Whitepaper*. [Online]. Available: https://rb.gy/igk5f6

[30] G. V. Research. (Jun. 2020). *Wearable Technology Market Size, Share and Trends Analysis Report by Product (Wrist-Wear, Eye-Wear and Head-Wear, Foot-Wear, Neck-Wear, Body-Wear), by Application, By Region, and Segment Forecasts, 2020–2027*. [Online]. Available: https://rb.gy/giukgw

[31] K. Vijayalakshmi, S. Uma, R. Bhuvanya, and A. Suresh, "A demand for wearable devices in health care," *Int. J. Eng. Technol.*, vol. 7, no. 1, pp. 1–4, 2018.

[32] B. Jean-M, *Emerging Trends in Wearable Technology Across Several Markets*. Saint-Prex, Switzerland: Fischer Connectors, Oct. 2020. [Online]. Available: https://www.engineeringwhitepapers.com/white-papers/emerging-trends-in-wearable-technology-across-markets/?

[33] K. D. Wyatt, L. R. Poole, A. F. Mullan, S. L. Kopecky, and H. A. Heaton, "Clinical evaluation and diagnostic yield following evaluation of abnormal pulse detected using apple watch," *J. Amer. Med. Inform. Assoc.*, vol. 27, no. 9, pp. 1359–1363, Sep. 2020.

[34] N. Al-Falahy and O. Y. Alani, "Technologies for 5G networks: Challenges and opportunities," *IT Prof.*, vol. 19, no. 1, pp. 12–20, Jan./Feb. 2017.

[35] J. Wei, "How wearables intersect with the cloud and the Internet of Things: Considerations for the developers of wearables," *IEEE Consum. Electron. Mag.*, vol. 3, no. 3, pp. 53–56, Jul. 2014.

[36] J. S. Talboom and M. J. Huentelman, "Big data collision: The Internet of Things, wearable devices and genomics in the study of neurological traits and disease," *Human Mol. Genet.*, vol. 27, no. R1, pp. R35–R39, May 2018.

[37] D.-H. Kim, N. Lu, R. Ma, Y. S. Kim, R. H. Kim, S. Wang, J. Wu, S. M. Won, H. Tao, A. Islam, and K. J. Yu, "Epidermal electronics," *Science*, vol. 333, pp. 838–843, Sep. 2011.

[38] H. J. Baek, G. S. Chung, K. K. Kim, and K. S. Park, "A smart health monitoring chair for nonintrusive measurement of biological signals," *IEEE Trans. Inf. Technol. Biomed.*, vol. 16, no. 1, pp. 150–158, Jan. 2012.

[39] M. Walter, B. Eilebrecht, T. Wartzek, and S. Leonhardt, "The smart car seat: Personalized monitoring of vital signs in automotive applications," *Pers. Ubiquitous Comput.*, vol. 15, no. 7, pp. 707–715, Oct. 2011.

[40] M.-Z. Poh, D. McDuff, and R. Picard, "A medical mirror for non-contact health monitoring," in *Proc. ACM SIGGRAPH Emerg. Technol. (SIGGRAPH)*, 2011, p. 1.

[41] J. Gömez-Clapers and R. Casanella, "A fast and easy-to-use ECG acquisition and heart rate monitoring system using a wireless steering wheel," *IEEE Sensors J.*, vol. 12, no. 3, pp. 610–616, Mar. 2012.

[42] Y. Lin, "A natural contact sensor paradigm for nonintrusive and real-time sensing of biosignals in human-machine interactions," *IEEE Sensors J.*, vol. 11, no. 3, pp. 522–529, Mar. 2011.

[43] O. T. Inan, D. Park, L. Giovangrandi, and G. T. A. Kovacs, "Noninvasive measurement of physiological signals on a modified home bathroom scale," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 8, pp. 2137–2143, Aug. 2012.

[44] Y. M. Chi, S. R. Deiss, and G. Cauwenberghs, "Non-contact low power EEG/ECG electrode for high density wearable biopotential sensor networks," in *Proc. 6th Int. Workshop Wearable Implant. Body Sensor Netw.*, Jun. 2009, pp. 250–2246.

[45] G. Peng and M. F. Bocko, "Non-contact ECG sensing employing gradiometer electrodes," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 1, pp. 179–183, Jan. 2013.

[46] Y.-C. Wu, C.-S. Chang, Y. Sawaguchi, W.-C. Yu, M.-J. Chen, J.-Y. Lin, S.-M. Liu, C.-C. Han, W.-L. Huang, and C.-Y. Su, *A Mobile-Phone-Based Health Management System*. Rijeka, Croatia: InTech, Dec. 2011.

[47] J. Andreu-Perez, D. R. Leff, H. M. Ip, and G. Z. Yang, "From wearable sensors to smart implants–toward pervasive and personalized healthcare," *IEEE Trans. Biomed. Eng.*, vol. 62, no. 12, pp. 2750–2762, Dec. 2015.

[48] S. L. Koay, T. H. Kwon, and W. Y. Chung, "National nosocomial infections surveillance (NNIS) system report, data summary from January 1992 through June 2004, issued October 2004," *Sensor Lett.*, vol. 9, no. 1, pp. 399–403, 2011.

[49] C. M. N. Brigante, N. Abbate, A. Basile, A. C. Faulisi, and S. Sessa, "Towards miniaturization of a MEMS-based wearable motion capture system," *IEEE Trans. Ind. Electron.*, vol. 58, no. 8, pp. 3234–3241, Aug. 2011.

[50] C. C. Poon and Y. T. Zhang, "Perspectives on high technologies for low-cost healthcare," *IEEE Eng. Med. Biol. Mag.*, vol. 27, no. 5, pp. 42–47, Oct. 2008.

[51] N. S. Shenck and J. A. Paradiso, "Energy scavenging with shoe-mounted piezoelectrics," *IEEE Micro*, vol. 21, no. 3, pp. 30–42, May/Jun. 2001.

[52] S. Mandal, L. Turicchia, and R. Sarpeshkar, "A low-power, battery-free tag for body sensor networks," *IEEE Pervasive Comput.*, vol. 9, no. 1, pp. 71–77, Mar. 2010.

[53] B. Liu, X. Wang, B. Liu, Q. Wang, D. Tan, W. Song, X. Hou, D. Chen, and G. Shen, "Advanced rechargeable lithium-ion batteries based on bendable $ZnCo_2O_4$-urchins-on-carbon-fibers electrodes," *Nano Res.*, vol. 6, no. 7, pp. 525–534, Jul. 2013.

[54] K. Q. Fan and Z. H. Liu, "Capturing energy through a shoe-mounted piezoelectric energy harvester," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2018, pp. 768–773.

[55] Y. Fu, X. Cai, H. Wu, Z. Lv, S. Hou, M. Peng, X. Yu, and D. Zou, "Fiber supercapacitors utilizing pen ink for flexible/wearable energy storage," *Adv. Mater.*, vol. 24, no. 42, pp. 5713–5718, Nov. 2012.

[56] V. Leonov, "Thermoelectric energy harvesting of human body heat for wearable sensors," *IEEE Sensors J.*, vol. 13, no. 6, pp. 2284–2291, Jun. 2013.

[57] H. K. Saini, J. Grover, and M. Khajanchi, "Future visions of eco-friendly 5G communication: Exposing the drivers," in *Advances in Power Generation from Renewable Energy Sources (APGRES)*, Feb. 2019, pp. 1–5. [Online]. Available: https://ssrn.com/abstract=3442585, doi: 10.2139/ssrn.3442585.

[58] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, and R. Schober, "An overview of sustainable green 5G networks," *IEEE Wireless Commun.*, vol. 24, no. 4, pp. 72–80, Aug. 2014.

[59] S. O. Ajakwe and B. C. Asiegbu, "Comparative analysis of off-shore and inshore software development cost," *J. Res. Nat. Develop., JORIND*, vol. 13, no. 2, pp. 221–236, 2015. [Online]. Available: https://www.ajol.info/index.php/jorind/issue/view/12587

[60] S. Kim, J. S. Ho, and A. S. Y. Poon, "Midfield wireless powering of subwavelength autonomous devices," *Phys. Rev. Lett.*, vol. 110, no. 20, pp. 203905–203910, May 2013.

[61] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," *IEEE Netw.*, vol. 34, no. 3, pp. 134–142, May/Jun. 2020.

[62] K. Kang, J. Ryu, J. Hur, and L. Sha, "Design and QoS of a wireless system for real-time remote electrocardiography," *IEEE J. Biomed. Health Informat.*, vol. 17, no. 3, pp. 745–755, May 2013.

[63] K. Donald. (2022). *Wearable Industry Disruptions, Growth and Potentials*. Accessed: Jan. 27, 2022. [Online]. Available: https://tinyurl.com/3mdaj6j9

[64] S. K. Ameri, R. Ho, H. Jang, L. Tao, Y. Wang, L. Wang, D. M. Schnyer, D. Akinwande, and N. Lu, "Graphene electronic tattoo sensors," *ACS Nano*, vol. 11, no. 8, pp. 7634–7641, Aug. 2017.

[65] S. O. Ajakwe, V. U. Ihekoronye, D.-S. Kim, and J. M. Lee, "DRONET: Multi-tasking framework for real-time industrial facility aerial surveillance and safety," *Drones*, vol. 6, no. 2, p. 46, Feb. 2022.

[66] A. S. Alvarado, C. Lakshminarayan, and J. C. Príncipe, "Time-based compression and classification of heartbeats," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 6, pp. 1641–1648, Jun. 2012.

[67] S.-L. Koay, T.-H. Kwon, and W.-Y. Chung, "Motion artifacts cancellation by adaptive neuro-fuzzy inference system for wearable health shirts," *Sensor Lett.*, vol. 9, no. 1, pp. 399–403, Feb. 2011.

[68] Y. Gao, H. Li, and Y. Luo, "An empirical study of wearable technology acceptance in healthcare," *Ind. Manage. Data Syst.*, vol. 115, no. 9, pp. 1704–1723, 2015.

[69] D. Kutscher, "It's the network: Towards better security and transport performance in 5G," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2016, pp. 656–661.

[70] S. Ji, Z. Gui, T. Zhou, H. Yan, and J. Shen, "An efficient and certificateless conditional privacy-preserving authentication scheme for wireless body area networks big data services," *IEEE Access*, vol. 6, pp. 69603–69611, 2018.

[71] C. C. Tan, H. Wang, S. Zhong, and Q. Li, "Body sensor network security: An identity-based cryptography approach," in *Proc. 1st ACM Conf. Wireless Netw. Secur. (WiSec)*, 2008, pp. 239–244.

[72] S. P. Bendale and J. R. Prasad, ''Security threats and challenges in future mobile wireless networks,'' in *Proc. IEEE Global Conf. Wireless Comput. Netw. (GCWCN)*, Nov. 2018, pp. 146–150.

[73] C. C. Y. Poon, Y.-T. Zhang, and S.-D. Bao, ''A novel biometrics method to secure wireless body area sensor networks for telemedicine and m-health,'' *IEEE Commun. Mag.*, vol. 44, no. 4, pp. 73–81, Apr. 2006.

[74] C. I. Nwakanma, A. P. Anantha, F. B. Islam, J.-M. Lee, and D.-S. Kim, ''3GPP release-16 for industrial Internet of Things and mission critical communications,'' in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2020, pp. 403–406.

[75] C. Heneghan, B. Goldacre, and K. R. Mahtani, ''Why clinical trial outcomes fail to translate into benefits for patients,'' *Trials*, vol. 18, no. 1, pp. 1359–1363, Dec. 2017.

[76] M. Z. Noohani and K. U. Magsi, ''A review of 5G technology: Architecture, security and wide applications,'' *Int. Res. J. Eng. Technol. (IRJET)*, vol. 7, pp. 3440–3471, Dec. 2020.

[77] J. Chakareski, S. Naqvi, N. Mastronarde, J. Xu, F. Afghah, and A. Razi, ''An energy efficient framework for UAV-assisted millimeter wave 5G heterogeneous cellular networks,'' *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 1, pp. 37–44, Mar. 2019.

[78] M. Agiwal, N. Saxena, and A. Roy, ''Ten commandments of emerging 5G networks,'' *Wireless Pers. Commun.*, vol. 98, no. 3, pp. 2591–2621, Feb. 2018.

[79] A. M. Lacy, R. Bravo, A. M. Otero-Piñeiro, R. Pena, F. B. D. Lacy, R. Menchaca, and J. M. Balibrea, ''5G-assisted telementored surgery,'' *Brit. J. Surg.*, vol. 106, no. 12, pp. 1576–1579, Oct. 2019.

[80] M. Zhu and Z. Zhang, ''Photonic based RF self-interference cancellation for 5G mobile communication systems,'' in *Proc. SPIE, Fiber Optic Sens. Opt. Commun., Int. Symp. Optoelectronic Technol. Appl.*, vol. 10849, Beijing, China, Dec. 2018, Art. no. 1084906, doi: 10.1117/12.2502677.

[81] G. E. Athanasiadou, P. Fytampanis, D. A. Zarbouti, G. V. Tsoulos, P. K. Gkonis, and D. I. Kaklamani, ''Radio network planning towards 5G mmWave standalone small-cell architectures,'' *Electronics*, vol. 9, no. 2, p. 339, Feb. 2020.

[82] S. Buzzi, I. Chih-Lin, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, ''A survey of energy-efficient techniques for 5G networks and challenges ahead,'' *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 697–709, Apr. 2016.

[83] R. Jinia, A. Tahsin, and S. E. Ullaho, ''Performance analysis of a 5G compatible windowing and overlapping scheme implemented hybrid precoded mmWave massive MIMO NC- OFDM system,'' *Amer. J. Electr. Comput. Eng.*, vol. 2, no. 2, pp. 5–15, 2018.

[84] M. S. A. Muthanna, A. M. O. Musaeed, A. Muthanna, M. Filimonova, and Y. A. H. Esmail, ''Analysis of the advantages of millimeter waves for video traffic transmission in 5G networks,'' in *Proc. IEEE Conf. Russian Young Researchers Electr. Electron. Eng. (EIConRus)*, Jan. 2020, pp. 51–53.

[85] G. C. Amaizu, C. I. Nwakanma, S. Bhardwaj, J. M. Lee, and D. S. Kim, ''Composite and Efficient DDoS Attack Detection Framework for B5G Networks,'' *Comput. Netw.*, vol. 188, Apr. 2021, Art. no. 107871. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1389128621000438, doi: 10.1016/j.comnet.2021.107871.

[86] L. A. C. Ahakonye, C. I. Nwakanma, S. O. Ajakwe, J. M. Lee, and D.-S. Kim, ''Countering DNS vulnerability to attacks using ensemble learning,'' in *Proc. Int. Conf. Artif. Intell. Inf. Commun. (ICAIIC)*, Feb. 2022, pp. 7–10, doi: 10.1109/ICAIIC54071.2022.9722641.

[87] R. Singh, W. Lehr, D. Sicker, and K. M. S. Huq, ''Beyond 5G: The Role of THz Spectrum,'' *Proc. 47th Res. Conf. Commun., Inf. Internet Policy*, Jul. 2019, [Online]. Available: https://ssrn.com/abstract=3426810, doi: 10.2139/ssrn.3426810.

[88] L. He, Z. Yan, and M. Atiquzzaman, ''LTE/LTE—A network security data collection and analysis for security measurement: A survey,'' *IEEE Access*, vol. 6, pp. 4220–4242, 2018.

[89] R. Gopal and V. Parthasarathy, ''HBSIDS: Human body sensor based intrusion detection system in a cooperative network,'' in *Proc. Int. Conf. Sci. Eng. Manage. Res. (ICSEMR)*, Nov. 2014, pp. 1–4.

[90] M. Chen, Y. Qian, J. Chen, K. Hwang, S. Mao, and L. Hu, ''Privacy protection and intrusion avoidance for cloudlet-based medical data sharing,'' *IEEE Trans. Cloud Comput.*, vol. 8, no. 4, pp. 1274–1283, Oct. 2020.

[91] C. Smyth, G. Wang, R. Panicker, A. Nag, B. Cardiff, and D. John, ''Continuous user authentication using IoT wearable sensors,'' in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS)*, May 2021, pp. 1–5.

[92] M. Kavitha, P. V. V. S. Srinivas, P. S. L. Kalyampudi, and S. Srinivasulu, ''Machine learning techniques for anomaly detection in smart healthcare,'' in *Proc. 3rd Int. Conf. Inventive Res. Comput. Appl. (ICIRCA)*, Sep. 2021, pp. 1350–1356.

[93] J. U. R. Kazim, T. J. Cui, A. Zoha, L. Li, S. A. Shah, A. Alomainy, M. A. Imran, and Q. H. Abbasi, ''Wireless on walls: Revolutionizing the future of health care,'' *IEEE Antennas Propag. Mag.*, vol. 63, no. 6, pp. 87–93, Dec. 2021.

[94] G. Minopoulos and K. E. Psannis, ''Opportunities and challenges of tangible XR applications for 5G networks and beyond,'' *IEEE Consum. Electron. Mag.*, early access, Mar. 7, 2022, doi: 10.1109/MCE.2022.3156305.

[95] A. Ghosh, A. Maeder, M. Baker, and D. Chandramouli, ''5G evolution: A view on 5G cellular technology beyond 3GPP release 15,'' *IEEE Access*, vol. 7, pp. 127639–127651, 2019.

[96] J. Santos, T. Wauters, B. Volckaert, and F. De Turck, ''Towards low-latency service delivery in a continuum of virtual resources: State-of-the-art and research directions,'' *IEEE Commun. Surveys Tuts.*, vol. 23, no. 4, pp. 2557–2589, 4th Quart., 2021.

[97] E. Dahlman, S. Parkvall, and J. Sköld, *5G NR: The Next Generation' Wireless Access Technology*. Amsterdam, The Netherlands: Elsevier, 2018, doi: 10.1016/C2017-0-01347-2.

[98] Y. Choongil, D. J. Gweon, J. K. young, and K. C. Hyun, ''Perspectives on 6G wireless communications,'' *ICT Exp.*, pp. 1–10, Jan. 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S240595952100182X, doi: 10.1016/j.icte.2021.12.017.

[99] M. Katz, M. Matinmikko-Blue, and M. Latva-Aho, ''6Genesis flagship program: Building the bridges towards 6G-enabled wireless smart society and ecosystem,'' in *Proc. IEEE 10th Latin-American Conf. Commun. (LATINCOM)*, Nov. 2018, pp. 1–9.

[100] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, ''6G wireless networks: Vision, requirements, architecture, and key technologies,'' *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, Sep. 2019.

[101] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, ''Toward 6G networks: Use cases and technologies,'' *IEEE Commun. Mag.*, vol. 58, no. 3, pp. 55–61, Dec. 2020.

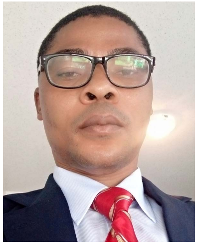
[102] A. N. Uwaechia and N. M. Mahyuddin, ''A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges,'' *IEEE Access*, vol. 8, pp. 62367–62414, 2020.

[103] I. Tomkos, D. Klonidis, E. Pikasis, and S. Theodoridis, ''Toward the 6G network era: Opportunities and challenges,'' *IT Prof.*, vol. 22, no. 1, pp. 34–38, Jan. 2020.

[104] Nokia. (2016). *5G for Mission Critical Communications: Nokia White Paper*. Global Mobile Suppliers Association (GSA). [Online]. Available: https://gsacom.com/paper/5g-mission-critical-communication-nokia-white-%paper/

[105] R. Li, ''Network 2030: Market Drivers and Prospects,'' in *Proc. 1st Int. Telecommun. Union Workshop Netw.*, vol. 1, New York, NY, USA, 2018, pp. 1–21. [Online]. Available: https://www.itu.int/en/ITU-T/Workshops-and-Seminars/201810/Documents/Richard_Li_Presentation.pdf

[106] A. Deore. (Jun. 2020). *Fitting Like a Glove: The Impact of 5G on Wearable Technologies*. [Online]. Available: https://vsplc.com/2020/06/29/



**SIMEON OKECHUKWU AJAKWE** (Member, IEEE) received the Diploma degree in computer science from the Institute of Management Technology, Enugu, in 2004, the Bachelor of Science degree in computer science from Imo State University, Owerri, in 2009, and the Master of Science (M.Sc.) degree (Hons.) in information technology from the Federal University of Technology, Owerri, Imo, Nigeria, in 2016. He is currently a Ph.D. Scholar and a full-time Researcher with the Networked System Laboratory, IT-Convergence Engineering, Kumoh National Institute of Technology, Gumi, South Korea. He is also a Chartered Information Technology Professional with many years of IT-related industrial and academic experience. He is a member of Computer Professionals of Nigeria (CPN) and Nigeria Computer Society (NCS). His research interests include artificial intelligence, deep learning, software engineering, information systems, and security.

**COSMAS IFEANYI NWAKANMA** (Member, IEEE) received the Diploma degree (Hons.) in electrical/electronics engineering from Federal Polytechnic Nekede Imo State Nigeria, in 1999, the Bachelor of Engineering degree in communication engineering, the master's degree in information technology, and the Master of Business Administration (M.B.A.) degree in project management technology from the Federal University of Technology, Owerri, in 2004, 2012, and 2016, respectively, and the Ph.D. degree in IT-convergence engineering from the Networked System Laboratory, IT-Convergence Engineering, Kumoh National Institute of Technology, Gumi, South Korea, in 2022. Since 2009, he has been lecturing and doing research with the Federal University of Technology. He was an Intern with Asea Brown Boveri (ABB), Nigeria, in 2003. He also a Postdoctoral Researcher with the ICT Convergence Research Center (ICTCRC), Kumoh National Institute of Technology. He is a member of Computer Professionals Council of Nigeria (CPN), Nigeria Society of Engineers (NSE), and registered by the Council for the Regulation of Engineering in Nigeria (COREN). His research interests include reliability of artificial intelligence (AI) application to Internet of Things (IoT) for smart factories, homes and vehicles, and metaverse.

**DONG-SEONG KIM** (Senior Member, IEEE) received the Ph.D. degree in electrical and computer engineering from Seoul National University, Seoul, South Korea, in 2003. From 1994 to 2003, he worked as a full-time Researcher in ERC-ACI at Seoul National University. From March 2003 to February 2005, he worked as a Postdoctoral Researcher with the Wireless Network Laboratory, School of Electrical and Computer Engineering, Cornell University, NY, USA. From 2007 to 2009, he was a Visiting Professor with the Department of Computer Science, University of California at Davis, Davis, CA, USA. He is currently the Director of the KIT Convergence Research Institute and the ICT Convergence Research Center (ITRC and NRF Advanced Research Center Program) supported by Korean Government with the Kumoh National Institute of Technology. He is a Senior Member of ACM. His current research interests include real-time IoT and smart platform, industrial wireless control networks, networked embedded systems, and fieldbus.

**JAE-MIN LEE** (Member, IEEE) received the Ph.D. degree in electrical and computer engineering from Seoul National University, Seoul, South Korea, in 2005. From 2005 to 2014, he was a Senior Engineer with Samsung Electronics, Suwon, South Korea. From 2015 to 2016, he was a Principle Engineer at Samsung Electronics, Suwon. Since 2017, he has been an Assistant Professor with the School of Electronic Engineering and the Department of IT-Convergence Engineering, Kumoh National Institute of Technology, Gyeongbuk, South Korea. His current research interests include industrial wireless control networks, performance analysis of wireless networks, and TRIZ.

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