Future BANs - DTN Applications and Requirements

Rami Khaldi*, Armin Lehmann*, Bogdan Ghita†, Ulrich Trick*
*Research Group for Telecommunication Networks, Frankfurt University of Applied Sciences, Frankfurt am Main, Germany
†School of Engineering, Computing and Mathematics, University of Plymouth, Plymouth, United Kingdom
{khaldi, lehmann, trick}@e-technik.org, bogdan.ghita@plymouth.ac.uk

***Abstract*—With the anticipated development of 6G technology, the scope of Body Area Network (BAN) applications is undergoing significant expansion, enhancing capabilities for a wider range of sophisticated scenarios, including augmented/virtual reality, holographic-type communication, and in particular integrated sensing and communication. This evolution introduces more stringent requirements, such as high data rates, low latency, precise synchronization, and advanced sensing capabilities. Given these advancements, traditional simulators, constrained by their inability to provide a real-time bidirectional connection with the actual network, fall short of addressing these complexities. A Digital Twin Network (DTN), serving as a real-time virtual replica of the physical network, can bridge this gap by simulating and testing BANs in order to troubleshoot, predict, and optimize their functionality and performance. This paper aims to present advanced BAN use cases with a special focus on sensing along with their stringent demands and demonstrates how DTN plays a crucial role in addressing these requirements through tailored DTN applications. Additionally, it will elaborate on the specific requirements for the digital twin that emerge from these applications. This work also involves identifying potential models that need to be considered to construct a comprehensive BAN digital twin framework.**

***Index Terms*—Digital Twin Network, 5G, 6G, Body Area Network, Integrated Sensing and Communication, Sub-THz**

I. Introduction

Body Area Networks (BANs) consist of a collection of devices, including sensors and actuators, situated on or around the body, designed to monitor and respond to various physiological and environmental parameters. They are typically connected to a Gateway, such as a personal device like a smartphone, which is characterized by greater computing capabilities compared to individual small sensors or actuators. This Gateway is then connected to Wide Area Networks [1, 2]. BANs were initially used in the healthcare sector for straightforward monitoring and support use cases. However, with the anticipated development of 6G technology, the scope of BAN applications is expanding significantly, as 6G networks are set to enhance BANs by enabling more sophisticated applications such as Holographic-type communication (HTC), AR/VR, and advanced sensing. Future BANs are expected to evolve into complex networks featuring a range of advanced applications, from healthcare to entertainment realms like gaming, training environments including disaster simulation exercises for humanitarian aid workers, and Integrated Sensing and Communication (ISAC). While 5G networks marked a significant advancement, they fall short of meeting the more stringent requirements for advanced BAN applications, including high data rate, ultra-low latency, high mobility, synchronization, reliability, efficient traffic management, and especially sensing. 6G networks are expected to provide the necessary infrastructure to support these applications and also to generate new use cases based on sensing capabilities, such as utilizing the Sub-terahertz (Sub-THz) interface for environmental exploration [3].

In the context of BANs, digital twins can provide valuable insights into network performance, user behavior, environmental interactions, and sensing capabilities. The concept of a digital twin in Product Lifecycle Management (PLM) enables the creation of a virtual replica of a physical entity. This replication is achieved by collecting state information about the physical entity, thereby allowing its adaptation and improvement based on simulations. Inspired by this, a Digital Twin Network (DTN) acts as a virtual counterpart of a physical network and can offer advantages for network operation, administration, and management, including network simulation, testing, troubleshooting, prediction, and optimization to improve network Key Performance Indicators (KPIs) [4, 8, 16, 17].

This paper presents challenging use cases of BANs across multiple sectors, with a particular emphasis on sensing capabilities. It will illustrate how the BAN digital twin, applied through customized DTN applications, plays an essential role in fulfilling these needs. Moreover, the paper will detail the specific requirements of the DTNs emerging from these applications. Furthermore, this work includes the exploration of potential models essential for developing an extensive framework for a BAN digital twin. The paper is structured as follows: It begins by examining the state of the art and limitations of BANs, then explores the anticipated advancements in BANs enhanced by 6G technology, focusing on advanced sensing capabilities. It proceeds to present a DTN architecture as proposed by ITU-T Y.3090, then defines BAN DTN use cases, requirements, and models, followed by the introduction of a basic architecture for BAN DTN. Finally, the paper concludes with a summary and proposes directions for future research.

II. BAN State of the Art and Limitations

BANs primarily consist of sensors and actuators located near the body. Sensors are primarily designed to gather biometric data, such as blood values, glucose levels, or temperature. They can also include non-medical body area devices, such as tracking and gaming devices. Actuators can perform tasks under human or machine control. Wireless BAN technology typically includes multiple devices forwarding data to external servers in different networks via a Gateway [1, 2]. Fig. 1 shows the state-of-the-art architecture of wireless BAN.

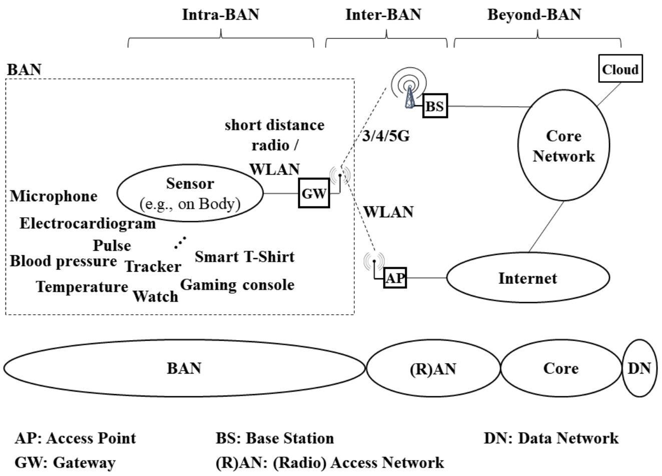

Fig. 1. Wireless Body Area Network (BAN): State of The Art

The Wireless BAN architecture is typically divided into three tiers: intra-WBAN, inter-WBAN, and beyond-WBAN. The intra-WBAN tier encompasses the communication between the devices and a Gateway located near the body. Data transmission might occur via a multi-hop WBAN, where data is relayed through intermediate nodes to reach the Gateway, or through a single-hop WBAN, where devices directly communicate with a Gateway. The latter configuration offers the advantage of reduced delay. Wireless technologies used include Short Distance Radio (such as Bluetooth, and Zigbee), and Wireless Local Area Networks (WLANs). The inter-WBAN tier extends the network's reach by linking the Gateway to an Access Point (AP) or a Base Station (BS), utilizing various wireless communication methods. These methods include cellular technologies such as 3G, 4G, and 5G, as well as WLAN technologies [3]. The beyond-WBAN tier connects an AP or a BS to external networks, which may include servers dedicated to functions such as monitoring or providing instructions [1, 5, 6, 18, 19].

Current BAN use cases include health monitoring, elderly care, humanitarian helpers and athletes' performance monitoring, disaster management, and surveillance [1, 18, 20, 21]. Although sufficient for existing applications, current approaches struggle to meet scenarios with more complex or strict sensing, data, latency, mobility, synchronization, and reliability/resiliency requirements. These limitations constrain both existing and potential future use cases, rendering some applications impractical. The remainder of this section will present several such use cases.

Brain-Computer Interfaces (BCIs) capture brain activity or environmental stimuli, converting them into actions, thereby bypassing or enhancing neural pathways [10, 22]. HTC facilitates remote interventions, projecting 3D holograms for real-time interaction by professionals through BAN-connected sensors and actuators [3, 11, 12, 23]. Gamers equipped with wearable devices including haptic feedback and VR glasses achieve an enhanced experience, which is further augmented by "digital lollipops" that simulate taste sensations [3, 12, 13]. For humanitarian training, AR/VR and smart wearables simulate disaster environments, providing lifelike visualizations for effective training, supported by real-time physiological monitoring with BANs.

To support these applications, particularly those that demand robust sensing capabilities, there is a need for advanced BAN solutions. The following chapter will introduce the prospects of future BANs, the adoption of Sub-terahertz technology in 6G, and a convergent use case: Integrated Sensing.

III. Future BANs

Future BANs are anticipated to integrate multiple wireless technologies including 6G to optimize data transmission and processing. The KPIs for 6G are promising, featuring a high data rate (more than 1 Tbps), low latency (less than 1 ms), robust mobility support, high reliability, and advanced sensing capabilities [3]. The forthcoming 6G enables more sophisticated applications, such as HTC and AR/VR, benefiting from features like network slicing, Network Function Virtualization (NFV), Service Based Architecture (SBA), and Artificial Intelligence as a Service (AIaaS). Fig. 2 summarizes future network architecture and highlights various network scopes and boundaries, including the BAN, Radio Access Network (RAN), Core Network (CN), and Data Network (DN) [3].

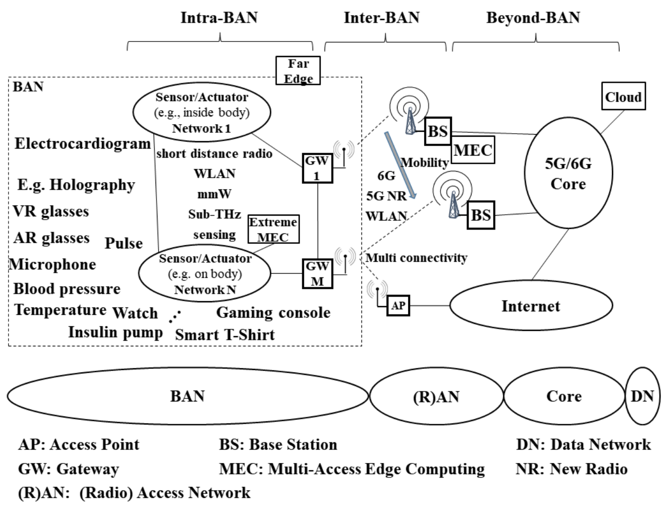

Fig. 2. Network Architecture of Future Body Area Network

Multi-Access Edge Computing (MEC) servers are deployed within the BAN (extreme edge), near the BAN (far edge), as well as within or in proximity to the BS, supporting AIaaS and Compute as a Service (CaaS). These services, which can be provided by third-party providers, deliver context-aware services directly at the network edge, aiding in reducing network latency according to the specific requirements of the application [7]. These BANs support multi-connectivity scenarios, allowing a Gateway to simultaneously leverage both one or multiple BSs and a WiFi AP for connections to other networks, such as the Internet. Such capability is crucial for failover scenarios, ensuring network resilience, or managing different traffic types based on their criticality. The 5G/6G CN maintains connectivity with the central cloud and other DNs with applications [3].

The adoption of Sub-THz technology (frequency range 100-300 GHz) as a feature of 6G systems contributes not only to higher data rates and lower latency but also offers significant sensing capabilities by leveraging the specific propagation characteristics of the signals. Integrated Sensing and Communication (ISAC) technology enables cellular networks to serve as "perceptive networks". Joint sensing and communication integrate the functions of sensing and communication, where each supports the other. For example, communication signals can be used for sensing, and accurate sensing improves communication performance through precise beamforming. This integration reduces costs, power consumption, latency, and device density. The integration of Sub-THz technology within BANs and at BSs enables large-scale environmental sensing, such as measuring coverage to determine the range and field of view for object detection; assessing accuracy to gauge the difference between sensing values and real object; evaluating resolution for object separation; calculating detection/false alarm probabilities; determining the availability of the system for providing required sensing service; and monitoring the refresh rate for updating data. Sensing enables applications such as high-resolution radio frequency imaging, effective even under challenging conditions like darkness or severe weather, and applications such as chemical analysis, explosive detection, and pollution monitoring [26]. Furthermore, it facilitates high-fidelity holographic telepresence, 3-D mapping, and enhancements in security and safety, traditionally handled by separate, specialized devices. Hence, it helps in reducing dependence on "legacy" sensing devices, supplementing or even replacing conventional devices like cameras or gas detectors while being less intrusive [3, 14, 15, 17, 25–28]. The following section builds on the use cases outlined in Chapter II by proposing an integrating scenario, referred to as a convergent use case.

Convergent Use Case: Integrated Sensing: Various domains, including gaming, sports, healthcare, humanitarian aid, and training, can benefit from advanced sensors and devices. For gaming, sensors like accelerometers, gyroscopes, and muscle movement sensors, along with AR/VR glasses, can create deeply immersive experiences, where the virtual world is not just seen but felt through tactile feedback systems, with real-time interactions. In sports and training, heart rate monitors, cortisol level sensors, and respiration sensors provide critical data for performance optimization and health monitoring. Devices for measuring sleep quality and environmental factors, such as temperature sensors and humidity sensors, support overall well-being. A specific subset of these devices may be equipped with a Sub-THz interface providing high data rates and low latency, and offering sensing features such as mapping, localization, and enhanced security and safety measures. Each device possesses one or more capabilities, with some devices sharing overlapping functions. For example, both cameras and devices with a Sub-THz interface can detect obstacles, showcasing an intersection of capabilities. The intercommunication of devices ensures that, in a given scenario, devices can support and enhance each other's functionalities. For instance, in environments where traditional cameras are ineffective, switching to Sub-THz sensors can maintain visibility. In humanitarian aid, the ability of the advanced BAN can help rescue teams in fire incidents or earthquake scenarios, providing them with clear images and facilitating communication in environments where traditional devices might fail. Therefore, careful planning regarding the type and number of devices is essential, taking into account resource constraints and the specific requirements of each scenario. This strategic device planning ensures the optimal deployment of technologies, enabling a broad spectrum of use cases by leveraging both traditional and Sub-THz interface-equipped devices to overcome limitations and enhance functionality in diverse environments [29–31].

To meet crucial requirements in the BAN, there is a need for an advanced approach that surpasses traditional simulations. Creating a Digital Twin of the BAN involves constructing a real-time virtual replica of the BAN, which allows for comprehensive analysis, diagnosis, control, and optimization of the network. The following chapter will introduce a DTN architecture, and highlight some DTN applications, requirements, and modeling approaches, tailored to the convergent use case.

IV. DTN Architecture, Applications, Requirements, and Models

A. DTN Architecture

Fig. 3 shows a DTN reference architecture as proposed by ITU-T Y.3090. The DTN can be conceptualized as a "Three-layer, three-domain, and double closed-loop" architecture. This includes [8]:

- **Physical Network Layer:** Comprising all network elements and facilitating the exchange of data and control with the digital twin entity via southbound interfaces. This layer can encompass various network types and domains.
- **Network Digital Twin Layer:** The core of the DTN system, consisting of three key subsystems:
  - Unified Data Repository: Collects real-time operational data to form a single source of truth, supporting various network applications with data collection, storage, services, and management.

– Unified Data Models: Develops data-based models for typical application scenarios, offering model instances for network applications and ensuring network service agility and programmability. It includes both basic models (network element and topology models) and functional models (for network analysis, emulation, diagnosis, prediction, etc.).
– Digital Twin Entity Management: Manages a DTN, including topology, model management, and security management.

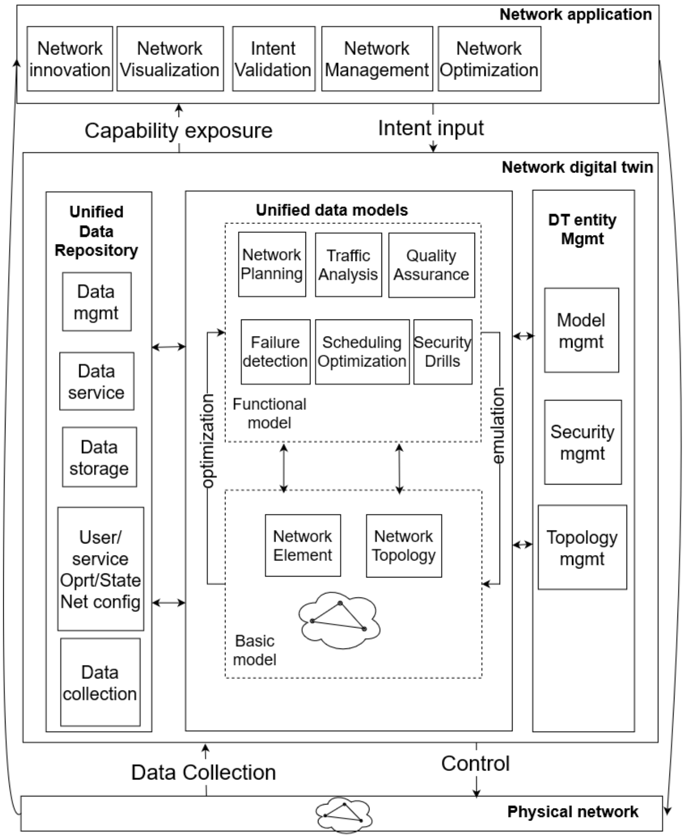

Fig. 3. Reference architecture of a digital twin network [8]

- **Network Application Layer:** Where network applications interact with the digital twin layer, deploying services through modeling instances. After verification, control updates are sent to the physical network. This layer supports rapid deployment of applications like network operation, maintenance, optimization, and innovation, reducing cost and impact on network operations.

B. Specific BAN DTN Use Cases

A DTN facilitates a variety of use cases to enhance the network. The following list highlights key DTN applications tailored to the BANs, focussing on sensors, and actuators. These serve as examples of the network applications depicted in Fig. 3:

- **Sensor Optimization and Orchestration:** Utilizing predictive analytics, the system proactively determines the necessity and optimal positioning of sensors, ensuring their deployment is precisely aligned with evolving demands. This dynamic approach allows for the activation of additional sensors as required, optimization of sensor locations, and the strategic combination or substitution of sensors to adapt to changing conditions or objectives. Decisions on sensor deployment are taken by a comprehensive analysis of KPIs including energy efficiency, performance, resiliency against disruptions, latency minimization, and adaptability to environmental variables. Each decision is customized to meet the unique requirements of the current scenario.
- **Integrated Sensing and Communication Optimization:** Optimization of network resources for simultaneous sensing and communication tasks, ensuring that both functions are performed efficiently without negatively influencing each other's performance.
- **Environmental Modeling:** Creating digital twins of the physical environment to predict and analyze the impact of environmental changes on the communication network and its sensing capabilities.
- **Energy Consumption Optimization:** Analyzing and optimizing energy usage across the sensor network to extend battery life and reduce operational costs.
- **Sensor Twinning:** This involves creating and managing twins of the physical sensor network within the digital twin environment. It allows for real-time monitoring and simulation of sensor network operations, enabling the identification of potential issues and the testing of changes without impacting the environment.
- **Failover Strategies:** Implementing robust failover mechanisms within the DTN to ensure continuous operation of the BAN, even when individual components fail. This includes using redundant sensors and switching between primary and e.g. devices with Sub-THz interface.
- **Data Reduction:** Utilizing techniques to reduce the volume of data transmitted and stored by filtering out redundant or irrelevant data at the source. For example, camera data may become redundant when a device with a Sub-THz interface is already providing mapping data. This minimizes network load and storage requirements while ensuring that critical data is not affected negatively.
- **Predictive Maintenance:** Leveraging machine learning algorithms to predict the failure or maintenance needs of sensors before they occur.

C. BAN DTN Requirements

In order to enable seamless BAN DTN use cases as outlined earlier, several DTN requirements emerge. These requirements are derived from both the practical needs of the specific applications and those common across general DTNs, as proposed by ITU-T Y.3090 [8]. The following list highlights the main requirements to be fulfilled for an efficient and operational BAN DTN:

- **Real-Time Data Acquisition and Integration:** Capability to continuously gather and integrate data from various sources, including network components, sensors, and user interactions, to maintain an up-to-date digital replica.

- **Synchronization Between Sensing and Communication:** Ensuring real-time synchronization between sensing data acquisition and communication tasks.
- **High-Resolution Sensing Data Integration:** Capability to integrate and process high-resolution sensing data from various sources, including the Sub-THz sensors.
- **Scalable Computational Infrastructure:** A robust and scalable computational framework to process and analyze large datasets, and simulate complex scenarios.
- **High-Fidelity Modeling:** Precision in modeling the physical characteristics and behaviors of network components and user interactions to ensure the digital twin accurately reflects the real world.
- **Advanced Analytics and Machine Learning:** Tools for deep analysis, including pattern recognition, predictive modeling, and machine learning algorithms to forecast future states and optimize performance.
- **Secure and Compliant Data Handling:** Strong security and compliance measures to protect sensitive data.
- **User-Friendly Interface and Visualization Tools:** Intuitive interfaces and visualization capabilities for users to interact with and understand the digital twin's data and insights.

D. BAN DTN Models

The BAN DTN requires orchestrated models that are tailored to support the robust and accurate replication of the physical BAN and fulfill the presented BAN DTN use cases. Below are the most relevant:

- **Predictive Analytics Model:** Analyzing historical and real-time data to forecast the need for specific types of sensors and their optimal quantities.
- **Spatial Optimization Model:** Evaluating the physical environment to identify the most effective sensor locations, ensuring maximum coverage and data accuracy while considering environmental constraints.
- **Dynamic Orchestration Model:** Enabling the system to dynamically adjust sensor configurations (such as activating, repositioning, or substituting sensors) to respond to changing KPI such as user need, energy efficiency, performance, resiliency, latency, and environmental adaptability.
- **Network Model:** Representing the communication pathways within the BAN.
- **Communication Model:** Defining efficient data transmission protocols, especially for low-latency requirements.
- **Stochastic Demand Model:** Predicting variations in sensor data demand and network load.
- **Environmental Impact Model:** Simulating the impact of the physical environment on the performance of sensing and communication tasks, enabling predictive adjustments to network operations to mitigate negative impacts.
- **Computing Model:** Managing the computational demands of processing data and running optimization algorithms.
- **Energy Management Model:** Simulating energy consumption patterns and identifying potential areas for efficiency improvements across the network and devices.
- **Resilience and Failover Model:** Simulating network failover scenarios to assess and enhance network resilience. For example, a malfunctioning camera could be replaced by a device equipped with Sub-THz technology, which can maintain visibility under conditions where traditional cameras fail.
- **Data Fusion and Processing Model:** Integrating and processing data from diverse sources, ensuring cohesive and comprehensive environmental understanding.
- **Security and Privacy Model:** Ensuring the integrity and confidentiality of data, incorporating encryption, access controls, and compliance with standards.
- **Network Performance and Optimization Model:** Modeling network behavior, data flow, and performance metrics to optimize the network.

Fig. 4 depicts a basic architecture of BAN DTN, illustrating how specific BAN DTN use cases activate DTN services, which then use underlying models to achieve objectives such as optimization and prediction, while the DTN Layer issues control or update directives to the BAN.

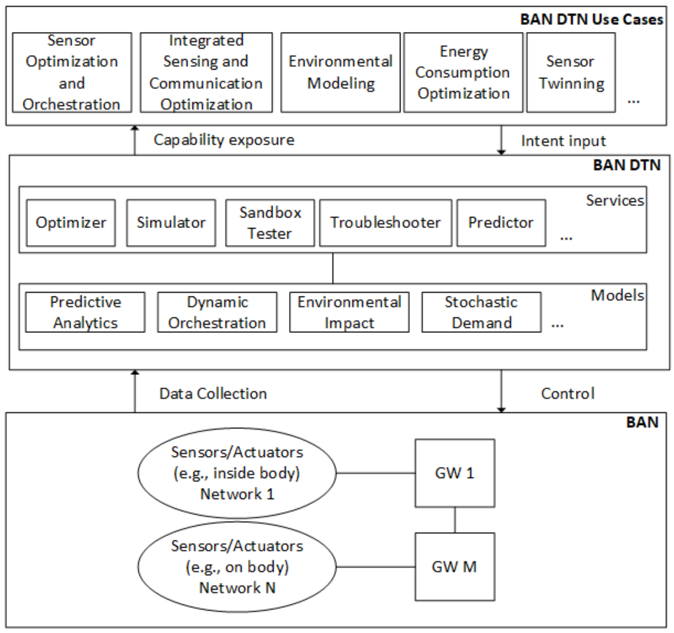

Fig. 4. A Basic Architecture of BAN DTN

V. Summary and Outlook

This paper has outlined the necessity for an advanced approach to the testing, validation, analysis, and optimization of future BANs. Unlike conventional static simulators, a DTN creates a bidirectional, real-time virtual counterpart, enabling dynamic adjustments to evolving conditions and substantially improving decision-making processes. Initially, the current BANs state of the art was examined, highlighting their limitations and identifying use cases that are currently not feasible. Subsequently, the potential of future BANs was explored, including a "Convergent Use Case" that integrates emerging technologies such as AR/VR and HTC, with a particular emphasis on the advanced sensing capabilities afforded by 6G technology. Based on it, potential applications of DTN, along with their requirements and the necessary models, have been listed. This work serves as a basis for defining or refining detailed architectures and use cases for BAN DTN, including requirements for DTN, followed by the development and orchestration of DTN models, and can be a cornerstone for the development of a comprehensive Body Area DTN framework.

References

[1] Taleb, H., Nasser, A., Andrieux, G. et al. "Wireless technologies, medical applications and future challenges in WBAN: a survey. Wireless Netw 27, 5271-5295 (2021), doi: 10.1007/s11276-021-02780-2

[2] P. Kulakowski, K. Turbic and L. M. Correia, "From Nano-Communications to Body Area Networks: A Perspective on Truly Personal Communications," in IEEE Access, vol. 8, pp. 159839-159853, 2020, doi: https://doi.org/10.1109/ACCESS.2020.3015825

[3] Trick, Ulrich. "5G: The 5th Generation Mobile Networks," Berlin, Boston: De Gruyter Oldenbourg, 2024, doi: https://doi.org/10.1515/9783111186610

[4] Grieves, Michael. (2002). "Completing the Cycle: Using PLM Information in the Sales and Service Functions," SME Management Forum, Troy, Michigan, USA

[5] M. Hämäläinen et al., "Recent Progress in ETSI TC SmartBAN Standardization," 2023 IEEE 17th International Symposium on Medical Information and Communication Technology (ISMICT), Lincoln, NE, USA, 2023, pp. 1-6, doi: https://doi.org/10.1109/ISMICT58261.2023.10152168

[6] M. Maman, B. Denis and R. D'Errico, "Research trends in wireless body area networks: From On-Body to Body-to-Body cooperation," 2014 8th International Symposium on Medical Information and Communication Technology (ISMICT), Firenze, Italy, 2014, pp. 1-5, doi: https://doi.org/10.1109/ISMICT.2014.6825240

[7] A. Ahmed and E. Ahmed, "A survey on mobile edge computing," 2016 10th International Conference on Intelligent Systems and Control (ISCO), Coimbatore, India, 2016, pp. 1-8, doi: https://doi.org/10.1109/ISCO.2016.7727082

[8] International Telecommunication Union, "Digital twin network: Requirements and architecture - Recommendation ITU-T Y.3090," 2022. https://handle.itu.int/11.1002/1000/14852

[9] Bagaa M, Dutra DLC, Taleb T, Flinck H. "Toward Enabling Network Slice Mobility to Support 6G System," IEEE Transactions on Wireless Communications. 2022 Dec 1;21(12):10130-10144. Epub 2022. doi: https://doi.org/10.1109/TWC.2022.3182591

[10] Jerry J. Shih, Dean J. Krusienski, Jonathan R. Wolpaw, "Brain-Computer Interfaces in Medicine," Mayo Clinic Proceedings, Volume 87, Issue 3, 2012, Pages 268-279, ISSN 0025-6196, doi: https://doi.org/10.1016/j.mayocp.2011.12.008

[11] I. Akyildiz and H. Guo, "Holographic-type communication: A new challenge for the next decade," 2022, vol. 3, pp. 421-442. doi: https://doi.org/10.52953/YRLL3571

[12] R. Li et al., "Network 2030 - A Blueprint of Technology, Applications, and Market Drivers towards the Year 2030 and Beyond. Whitepaper. ITU-T FG-NET2030," May 2019. [Online]. Available: https://www.itu.int/en/ITU-T/focusgroups/net2030/Documents/White_Paper.pdf

[13] H. Abed et al., "A Wire-Free and Fiber-Based Smart T-Shirt for Real-Time Breathing Rate Monitoring," in IEEE Sensors Journal, vol. 22, no. 5, pp. 4463-4471, 2022, doi: https://doi.org/10.1109/JSEN.2021.3139032

[14] A. Zhang, M. L. Rahman, X. Huang, Y. J. Guo, S. Chen and R. W. Heath, "Perceptive Mobile Networks: Cellular Networks With Radio Vision via Joint Communication and Radar Sensing," in IEEE Vehicular Technology Magazine, vol. 16, no. 2, pp. 20-30, June 2021, doi: https://doi.org/10.1109/MVT.2020.3037430

[15] Y. Cui, X. Jing and J. Mu, "Integrated Sensing and Communications Via 5G NR Waveform: Performance Analysis," ICASSP 2022 - 2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Singapore, Singapore, 2022, pp. 8747-8751, doi: https://doi.org/10.1109/ICASSP43922.2022.9746355

[16] Almasan P, Ferriol-Galmés M, Paillisse J, Suárez-Varela J, Perino D, López D, Perales AA, Harvey P, Ciavaglia L, Wong L, Ram V. "Digital twin network: Opportunities and challenges," arXiv preprint arXiv:2201.01144. 2022 Jan 4

[17] D. K. Pin Tan et al., "Integrated Sensing and Communication in 6G: Motivations, Use Cases, Requirements, Challenges and Future Directions," 2021 1st IEEE International Online Symposium on Joint Communications & Sensing (JC&S), Dresden, Germany, 2021, pp. 1-6, doi: https://doi.org/10.1109/JCS52304.2021.9376324

[18] Liu, Q., Mkongwa, K.G. & Zhang, C. "Performance issues in wireless body area networks for the healthcare application: a survey and future prospects," SN Appl. Sci. 3, 155 (2021), https://doi.org/doi:10.1007/s42452-020-04058-2

[19] Keikhosrokiani, P., Zakaria, N., Mustaffa, N., Wan, TC., Sarwar, M.I., Azimi, K. (2015). "Wireless Networks in Mobile Healthcare," In: Adibi, S. (eds) Mobile Health. Springer Series in Bio-/Neuroinformatics, vol 5. Springer, Cham, doi: https://doi.org/10.1007/978-3-319-12817-7_30

[20] Crosby, G.V., Chin, C.A., Ghosh, T., Murimi, R. (2015). "Wireless Body Area Networks in mHealth," In: Adibi, S. (eds) Mobile Health. Springer Series in Bio-/Neuroinformatics, vol 5. Springer, Cham, doi: https://doi.org/10.1007/978-3-319-12817-7_37

[21] E. Jovanov, A. O'Donnell Lords, D. Raskovic, P. G. Cox, R. Adhami and F. Andrasik, "Stress monitoring using a distributed wireless intelligent sensor system," in IEEE Engineering in Medicine and Biology Magazine, vol. 22, no. 3, pp. 49-55, May-June 2003, doi: https://doi.org/10.1109/MEMB.2003.1213626

[22] Moioli, R.C., Nardelli, P.H., Barros, M.T., Saad, W., Hekmatmanesh, A., Silva, P.E., Sena, A.S., Dzaferagic, M., Šiljak, H., Leekwijck, W.V., Carrillo, D., & Latr'e, S. (2020). "Neurosciences and 6G: Lessons from and Needs of Communicative Brains," ArXiv, abs/2004.01834

[23] Ian F. Akyildiz, Hongzhi Guo, "Holographic-type communication: A new challenge for the next decade," in ITU Journal on Future and Evolving Technologies, Volume 3 (2022), Issue 2, Pages 421-44, doi: https://doi.org/10.52953/YRLL3571

[24] M. Gundall, J. Stegmann, C. Huber and H. D. Schotten, "Towards Organic 6G Networks: Virtualization and Live Migration of Core Network Functions," Mobile Communication - Technologies and Applications; 25th ITG-Symposium, Osnabrueck, Germany, 2021, pp. 1-6

[25] Liu, F., Masouros, C., & Eldar, Y. C. (Eds.) (2023). "Integrated Sensing and Communications," Springer Verlag, doi: https://doi.org/10.1007/978-981-99-2501-8

[26] one6G Association, "6G Technology Overview," 2023. [Online]. Available: https://one6g.org/resources/publications/

[27] Ericsson, "Sub-terahertz communication in 6G," 2024. [Online]. Available: https://www.ericsson.com/en/6g/spectrum/sub-thz

[28] Huawei, "Integrated Sensing and Communication," 2022. [Online]. Available: https://www-file.huawei.com/-/media/corp2020/pdf/publications/huawei-research/issue2/isac-en.pdf?la=en

[29] A. Tarniceriu et al., "Towards 24/7 continuous heart rate monitoring," 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Orlando, FL, USA, 2016, pp. 186-189, doi: https://doi.org/10.1109/EMBC.2016.7590671

[30] B. Zhang, "Application of Smart Wearing Real-time Heart Rate Monitoring in Sports Training," 2021 International Conference on Health Big Data and Smart Sports (HBDSS), Guilin, China, 2021, pp. 177-180, doi: https://doi.org/10.1109/HBDSS54392.2021.00041

[31] Cay M, Ucar C, Senol D, Cevirgen F, Ozbag D, Altay Z, Yildiz S. "Effect of increase in cortisol level due to stress in healthy young individuals on dynamic and static balance scores," North Clin Istanb. 2018 May 29;5(4):295-301. doi: https://doi.org/10.14744/nci.2017.42103. PMID: 30859159; PMCID: PMC6371989