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A Survey on Future Millimeter-Wave Communication Applications

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ABSTRACT Millimeter-wave communications (mmWave) are gaining significant attention for their diverse applications across various domains, being key for the development of ultra-fast, low-latency wireless systems. This paper surveys the main application use cases where mmWave technologies can be adopted, focusing not only on scenarios where they are used for communication purposes, but also on other applications such as imaging and sensing. Each use case is described and characterized in order to provide a general overview of the foreseen mmWave application scenarios. The document also surveys existing standardization activities regarding mmWave frequencies across several application areas and discusses recent works regarding mmWave propagation, including both channel modeling as well as electromagnetic field exposure assessment and dosimetry, in different application domains. The document serves as a reference for a quick overview of all use cases where mmWave will have a practical impact.

INDEX TERMS millimeter-wave communications, vehicular networks, 5G, B5G, 6G, uav, immersive communications

I. INTRODUCTION

The ever-increasing demand for high-speed and reliable wireless communication has driven researchers and industry professionals to explore new frontiers in communication technologies. Among these frontiers, millimeter-wave (mmWave) communication has emerged as a promising solution.

MmWave communication utilizes electromagnetic waves with frequencies ranging from 30 to 300 gigahertz (GHz) within the millimeter-wave frequency band. The unique characteristics of mmWave signals offer several advantages for communication applications. Firstly, mmWave frequencies provide significantly larger available bandwidths compared to traditional communication bands. This abundance of bandwidth allows for unprecedented data transfer rates, enabling the transmission of large volumes of information in a short span of time. Additionally, mmWave signals exhibit high directionality, which means they can be focused and concentrated into narrow beams. This characteristic enables the implementation of highly efficient and targeted communication links. By using beamforming techniques and advanced antenna arrays, mmWave systems can establish robust connections with enhanced throughput and reduced interference.

The integration of mmWave technology in communication systems holds immense potential across various domains. As an example, in the realm of cellular networks, mmWave communications are expected to play a crucial role in the development of fifth-generation (5G), beyond 5G (B5G) and sixth-generation (6G) networks. These networks leverage mmWave frequencies to deliver ultra-high data rates, low latency, and support massive device connectivity. By harnessing the vast bandwidth available in the mmWave spectrum, these networks offer enhanced mobile broadband services, facilitate reliable machine-to-machine communications, and unlock transformative applications such as virtual reality (VR) and augmented reality (AR).

While mmWave technology offers numerous advantages, it also presents unique challenges. The propagation characteristics of mmWave signals are highly sensitive to blockages and atmospheric conditions, resulting in limited coverage and reduced signal penetration. Overcoming these challenges requires the development of advanced beamforming techniques, sophisticated antenna arrays, and adaptive signal processing algorithms to mitigate the limitations associated with mmWave communication.

This document aims to identify the main use cases of mmWave communication, providing an extensive description and characterization of each one. First, the document focuses on application scenarios where mmWave technologies are used for communication purposes and information transfer. In this area the following broad application use cases will be analyzed:

- Vehicular networks (Section III)
- 5G/B5G/6G cellular networks (Section IV)
- UAV-assisted networks (Section VI)
- Wireless Data centers (Section VII)
- Satellite communications (Section VI)
- Immersive communications (Section XX)

Furthermore and for completeness, this document focuses on other applications of mmWave technology, not directly related to communication. In particular applications such as object detection, localization and tracking as well as integrated sensing and communication using THz bands will be analysed in Section IX. As additional contributions, Section X discusses standardization activities related to mmWave systems, while Section XI reports on channel models and propagation-related issues, including exposure considerations generally adopted in the study and analysis of mmWave systems.

II. MMWAVE COMMUNICATION BASICS

In order to understand the potential of mmWave technology in communication applications, it is essential to grasp the fundamental principles of mmWave communication. This section provides a quick overview of mmWave communication basics, including its frequency range, characteristics, advantages, and challenges. A more detailed survey of the physical layer characteristics of mmWave communication can be found in [1], [2].

A. FREQUENCY RANGE AND CHARACTERISTICS OF MMWAVE SYSTEMS

MmWave communication operates within the frequency range of 30 to 300 gigahertz (GHz). This range is significantly higher than the frequencies traditionally used in communication systems, such as microwave and radio frequencies. MmWave systems possess distinct characteristics that differentiate them from lower frequency bands communications:

- Large Available Bandwidth: The mmWave spectrum offers vast amounts of available bandwidth, enabling the transmission of large volumes of data. This abundance of bandwidth is essential for meeting the ever-increasing demands for high-speed communication.
- Short Wavelength: MmWave signals have short wavelengths, typically ranging from 1 to 10 millimeters. The shorter wavelength allows for the implementation of compact and highly directive antenna arrays, facilitating efficient beamforming techniques.
- High Directionality: mmWave systems work by concentrating signals into narrow beams, which can be steered in any direction thanks to specific beamforming algorithms. This characteristic enables the efficient use of available resources, reducing interference and improving overall system performance.

B. ADVANTAGES AND CHALLENGES OF MMWAVE COMMUNICATION

MmWave communication offers several advantages that make it an attractive choice for various applications:

- High Data Rates: The large available bandwidth in mmWave frequencies allows for the transmission of data at significantly higher rates compared to lower frequency bands. This makes mmWave communication suitable for applications with demanding data transfer requirements, such as high-definition video streaming and virtual reality.
- Low Interference: By focusing signal energy in specific directions, mmWave systems help minimize interference from other sources, improving signal quality and enhancing overall network capacity.
- Small Form Factor: Due to the short wavelength of mmWave signals, antennas and other components can be designed to be compact and can fit into smaller form factors, making them suitable for integration into devices with size constraints, such as smartphones and Internet of Things (IoT) devices.

While mmWave communication offers significant advantages, it also presents unique challenges:

- Limited Coverage and Signal Penetration: MmWave signals are more susceptible to blockages and atmospheric conditions, resulting in reduced coverage compared to lower frequency bands. They have limited ability to penetrate obstacles, such as buildings or foliage, which can affect their usability in certain scenarios.
- Higher Path Loss: MmWave signals experience higher path loss compared to lower frequency bands. This means that they attenuate more rapidly over distance, requiring the use of advanced antenna arrays, beamforming, and signal processing techniques to compensate for the higher losses.
- Sensitivity to Reflections and Diffraction: MmWave signals are also highly sensitive to reflections and diffraction, which can lead to multipath fading and signal degradation. Again, sophisticated signal processing algorithms and beamforming techniques are necessary to mitigate these effects and maintain reliable communication links.

C. MASSIVE MIMO SYSTEMS AND ANTENNAS

Massive MIMO (Multiple-Input Multiple-Output) is a key technology that plays a crucial role in enhancing the performance and capacity of mmWave systems [3], [4]. By utilizing a large number of antenna elements configured in multiple arrays, such systems offers several advantages and have unique characteristics:

- Angular resolution: it refers to the system's ability to differentiate between signals arriving from different directions. With a dense antenna array, the system can pinpoint the direction of arrival for each user's signal more precisely and decode it more efficiently.
- Delay resolution: represents the ability to distinguish between signals arriving with slight time delays. This is important because radio signals can bounce off objects or travel through different paths, introducing delays. Massive MIMO can differentiate between these delayed versions of the same signal, ensuring better reception.
- Antenna selection: traditional MIMO systems employ all available antennas for transmission and reception. However, this approach can be impractical for cost or hardware limitations, as there might be constraints on the number of RF chain to be used simultaneously. Antenna selection algorithms address these limitations by strategically choosing a subset of antennas for each transmission or reception cycle. This allows the system to achieve good performance with fewer active antennas [5]–[8]

Understanding the basics of mmWave communication sets the foundation for exploring its applications and addressing the associated challenges. The next sections of this paper will delve into the specific applications of mmWave technology and the advancements made in overcoming the limitations of mmWave communication in various communication systems

III. VEHICULAR NETWORKS

V2X (Vehicle-to-Everything) communication [9] is revolutionizing the automotive industry by enabling vehicles to exchange information with other vehicles, infrastructure, pedestrians, and networks (Figure 1). It improves road safety, optimizes traffic flow, and enhances the driving experience. V2X facilitates early collision warnings, optimized traffic management, and active participation of pedestrians and cyclists. It also supports autonomous driving and enables a wide range of applications such as traffic management, emergency services, and energy efficiency. The high bandwidth provided by mmWave and THz communications may be extremely beneficial for V2X applications [10]. Indeed, predictions for future autonomous vehicles foresee up to 1 TB of generated data per driving hour, with rates achieving more than 750 Mbps. In the following we focus on three main use cases, namely Vehicle-to-Sensor on-board (V2S), Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I).

A. VEHICLE-TO-SENSOR ON-BOARD (V2S)

Vehicle-to-Sensors on-board (V2S) or Intra-Vehicle communication technology refers to the integration of sensors and sensing capabilities within vehicles to enable data collection, analysis, and decision-making processes. V2S technology empowers vehicles to interact with a variety of on-board sensors, transforming them into intelligent entities capable of perceiving and understanding their surroundings. This technology plays a vital role in enhancing the capabilities of autonomous vehicles, advanced driver assistance systems (ADAS), and smart transportation systems.

FIGURE 1. Vehicular network scenario highlighting V2S, V2V and V2I applications

A plethora of sensors is installed in modern cars, ranging from simple scalar sensors (temperature, pressure, speed, etc.) to more sophisticated multi-dimensional sensor systems such as cameras and LIDARs. As an example, automotive cameras are used to detect speed limit signs, enhance night vision using infrared sensors, check blind spots and lane departure or help prevent driver fatigue. The data generated by automotive cameras is substantial. Data rates range from 100 Mb/s for low-resolution to 700 Mb/s for high-resolution raw images at a frame frequency of 15 Hz. This makes automotive cameras one of the highest data rate sources of sensor data in vehicles. LIDAR (Light Detection and Ranging) systems utilize narrow laser beams to create high-resolution three-dimensional (3D) digital images, providing depth information and a 360-degree field of view. LIDAR is capable of generating detailed 3D maps and detecting cars, bicycles, and pedestrians. LIDAR data rates are comparable to those of automotive cameras, typically ranging from 10 to 100 Mb/s, depending on the number of laser beams and update rate [11].

The main communication technologies used for interconnecting sensors in a vehicle are generally based on wired networking standards such as local area networks (LAN) or bus-based communication protocols (e.g., Controller Area Network (CAN)). These communication technologies facilitate data exchange and coordination between various sensors within the vehicle, support high-speed data transfer and enable real-time communication between sensors and electronic control units (ECU). Main applications include engine control, transmission control, and chassis control [12]. However, average modern cars relying on such technologies contain wiring reaching up to 4 km in length and 50 kg in mass [13].

Wireless communications may be used instead of wires, helping in reducing design complexity, manufacturing costs and total weight of vehicles. Among the various wireless technologies that could be used, mmWave may be preferred due to the large available bandwidth, high nominal gains with directional antennas and low interference (very high attenuation through the car). These characteristics satisfy the high bandwidth, reliability, security and low latency requirements of vehicle control applications.

A specific case which might benefit extremely from the use of mmWave communication is the one of brain-controlled vehicles (BCV) [14]. In a BCV, the vehicle is operated by the human mind instead of physical interaction. BCV has the potential to enhance independence for people with disabilities by offering an alternative interface for vehicle control. It can also improve manual driving by predicting actions and detecting discomfort. Human adaptability is crucial in managing uncertainties and complexities of autonomous driving, even with the vision of fully automated vehicles. BCV can mitigate limitations of autonomous driving in challenging environments. However, current wireless communication and computation technologies are inadequate for brain-machine interactions. For instance, a rough estimate of brain recording rate is approximately 100 Gb/s, which surpasses the capabilities of current wireless technologies, but may be supported by MmWave communications [15].

B. VEHICLE-TO-VEHICLE (V2V)

Vehicle-to-Vehicle (V2V) communication enables vehicles to exchange information with one another in real-time. V2V technology holds immense promise in enhancing road safety, improving traffic efficiency, and enabling new intelligent transportation systems. V2V communication allows vehicles in close proximity to share critical information, such as speed, acceleration, position, and heading, with one another. This exchange of real-time data enables vehicles to gain a comprehensive understanding of their surrounding environment, thereby enabling advanced driver assistance systems (ADAS) and cooperative driving applications. By leveraging V2V technology, vehicles can enhance situational awareness, detect potential hazards, and make informed decisions to improve safety and efficiency on the roads.

Among the various communication technologies that enable V2V capabilities, millimeter-wave (mmWave) communication has emerged as a key enabler for reliable and high-bandwidth data exchange between vehicles [16]. This high-bandwidth capability is crucial for V2V applications that require the exchange of rich sensor data, video streams, and real-time traffic information. The ability of mmWave communication to handle such data-intensive applications paves the way for enhanced cooperative perception, platooning, and cooperative maneuvering among vehicles. Moreover, mmWave communication enables the use of highly directional beamforming, which allows for precise and efficient communication links between vehicles. Beamforming techniques can focus the mmWave signals into narrow beams, facilitating reliable communication even in the presence of obstacles or interference. This characteristic of mmWave technology enhances the reliability and robustness of V2V communication, enabling vehicles to maintain communication links over longer distances and in challenging environments.

However, the use of mmWave technology in V2V communication also presents challenges. MmWave signals are susceptible to blockage and attenuation by physical objects such as buildings and vehicles. The limited propagation range of mmWave signals requires the deployment of a dense network of base stations or roadside infrastructure to ensure continuous coverage and connectivity. Furthermore, the design of efficient and robust beamforming algorithms [17], [18], as well as the mitigation of interference in dense vehicular environments [19], are areas of active research and development in mmWave-based V2V communication systems.

C. VEHICLE-TO-INFRASTRUCTURE (V2I)

Alongside the development of Vehicle-to-Vehicle (V2V) and Vehicle-to-Sensors on-board (V2S) communication technologies, Vehicle-to-Infrastructure (V2I) communication holds great potential in enabling safer, more efficient, and smarter transportation systems [20]. V2I communication provides vehicles with access to real-time information from the surrounding infrastructure, enabling them to make informed decisions and optimize their operations. By exchanging data with infrastructure elements, vehicles can receive information about traffic conditions, road hazards, traffic signal timings, and parking availability, among other critical details. This enables enhanced situational awareness, improves traffic flow, and facilitates the deployment of advanced driver assistance systems (ADAS) and autonomous driving functionalities. In this context, millimeter-wave (mmWave) communication has emerged as a promising technology for facilitating reliable and high-bandwidth communication between vehicles and infrastructure elements [21]. Its abundant available bandwidth enables the transmission of large volumes of data, supporting high-resolution video streams, sensor data, and real-time traffic information. This high-bandwidth capability of mmWave technology is crucial for enabling data-intensive V2I applications that require rapid and reliable communication between vehicles and infrastructure. Nevertheless, the deployment of mmWave-based V2I communication presents certain challenges. The propagation characteristics of mmWave signals, including susceptibility to blockage and attenuation by physical objects, necessitate the installation of a dense network of infrastructure units for continuous coverage and reliable connectivity, or the development of sophisticated beam alignment algorithms [22]. Moreover, the coordination and synchronization of communication among multiple vehicles and infrastructure elements in a dense vehicular environment require efficient protocols and algorithms to mitigate interference and optimize resource allocation [23].

IV. 5G/B5G/6G CELLULAR NETWORKS

A. ACCESS

Millimeter-wave (mmWave) cellular access is a cutting-edge technology that utilizes high-frequency radio waves in the millimeter-wave frequency band, to provide wireless connectivity between mobile devices and the cellular network

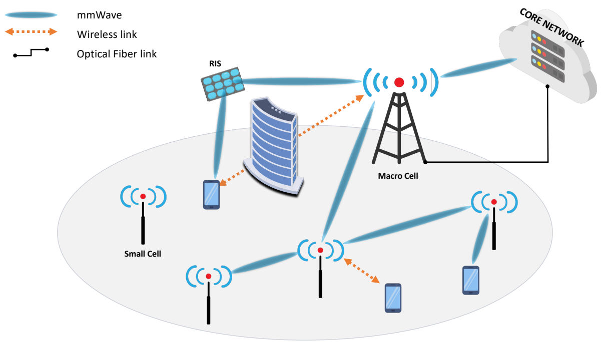

FIGURE 2. mmWave cellular network comprising access and backhauling links

(Figure 2). It is a key component of 5G and beyond, aiming to deliver ultra-fast data rates (in the order of Gbps) and low latency (below 10 ms). MmWave cellular access leverages the abundant available spectrum in the millimeter-wave frequency range over 10 GHz, which enables the transmission of large amounts of data at extremely high speeds. These high-frequency signals offer significant bandwidth advantages over lower-frequency bands used in previous cellular technologies, allowing for faster downloads, seamless streaming of high-definition content, and support for emerging applications such as virtual reality and augmented reality. To support mmWave cellular access, mobile devices require specialized antennas and transceivers capable of transmitting and receiving signals in the millimeter-wave frequency range. These devices employ advanced Multiple Input Multiple Output (MIMO) and beamforming techniques, such as phased array antennas, to create highly focused beams that can be directed toward the nearest base station. Beamforming enhances signal strength and reception, compensating for the higher propagation losses associated with mmWave frequencies. Since mmWave signals are more susceptible to blockage and attenuation by physical obstacles like buildings, trees, and even rainfall, the deployment of a dense network of small cells or base stations to ensure continuous coverage and reliable connectivity is necessary [24], [25]. A technology envisioned to solve the coverage issues inherent with mmWave technologies is the one provided by Reconfigurable Intelligent Surfaces (RIS) [26] [27], planar surfaces typically composed of a large number of low-cost nearly-passive scattering elements, having the ability to shape the amplitude and phase shift of the impinging signals and therefore reconfigure the propagation environment. Due to their low production and operational costs (orders-of-magnitude lower compared to technologies based on active antenna arrays), RIS are envisioned to be deployed in a wide range of scenarios (walls, ceilings, billboards, lampposts, and even on the surface of vehicles) to support communication applications [28].

B. BACKHAUL

Cellular backhaul refers to the infrastructure and network connections that connect individual cell sites, typically base stations, to the core network of a cellular network operator. It serves as the link between the base stations at the edge of the network and the central network infrastructure, enabling the transport of voice, data, and other communication services to and from the end users.

In cellular networks, such as 4G LTE and 5G, base stations are strategically placed to provide coverage and capacity for mobile devices within a specific geographic area, known as a cell. These base stations collect and transmit data from user devices within their coverage area. However, the base stations themselves need to be connected to the core network, where services are processed and routed to their intended destinations.

Traditionally, cellular backhaul was implemented using wired connections such as fiber-optic cables, copper lines, or microwave links. Fiber-optic cables offer high bandwidth and low latency, making them a popular choice for high-capacity backhaul. Copper lines, such as Ethernet or T1/E1 lines, are also used in some scenarios.

With the advent of 5G and its requirements for higher data rates, ultra-low latency, and increased network capacity, cellular backhaul faces new challenges. In addition to traditional wired connections, wireless technologies such as millimeter-wave and microwave bands are being explored to meet the growing demands of 5G networks, especially considering the ultra-dense deployments of micro cells and base stations envisioned in such scenarios. These wireless backhaul solutions can provide flexibility, rapid deployment, and cost-effectiveness in scenarios where wired connections may be impractical or costly.

Several challenges associated to wireless backhauling based on mmWave technologies can be identified, including generic resource allocation (both in terms of spectrum and power) [29]–[31], optimized deployment for integrated access and backhaul [32], security [33], as well as performance evaluation.

V. UAV-ASSISTED NETWORKS

UAV-assisted networking refers to the integration of Unmanned Aerial Vehicles (UAVs) into existing communication networks to enhance their performance, coverage, and capabilities (Figure 3). In this context, UAVs are utilized as mobile communication nodes that can extend network coverage, provide temporary connectivity in remote or disaster-stricken areas, and support various communication services. The integration of UAVs into networking infrastructure requires efficient communication protocols, routing algorithms, and coordination mechanisms, as UAVs need to establish and maintain reliable connections with ground-based stations or other UAVs, ensure seamless handovers between different network nodes, and optimize resource allocation for efficient operation [34].

A. ACCESS

UAVs present an opportunity for aerial connectivity between sky-based access points and ground User Equipments (UEs)

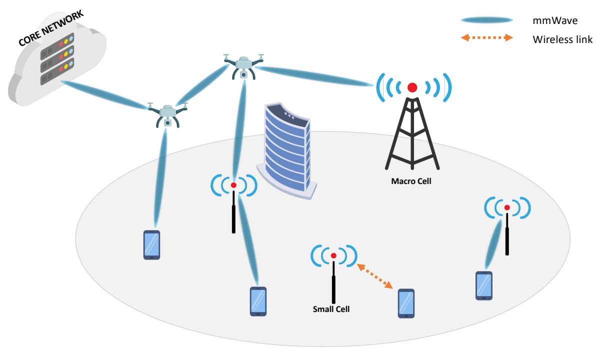

FIGURE 3. UAV assisted network with access, relay and backhauling links based on mmWave technology

within specific areas of interest and in situations like disaster monitoring, border patrol, and emergency response. This technology also has the potential to be useful for providing internet coverage during events with unexpected spikes in demand, where UAVs carrying a radio access node could be promptly dispatched, cheaply maintained, and easily manoeuvred. [35]. UAVs can function in various roles such as aerial base stations, roadside units, data collectors, and even as mobile edge computing servers or caching mechanisms, enabling dynamic wireless access. To address the escalating demand for data capacity, integrating aerial access in UAV-supported wireless networks with mmWave communications is a promising strategy. Specifically, bidirectional mmWave links can be effectively designed for aerial access applications within our considered scenario. These bidirectional links, comprising downlink air to ground (A2G) as well as uplink ground to air (G2A) connections, cater to diverse applications such as downlink transmission for simultaneous ground UEs, employing cache-enabled remote radio heads (RRHs) atop flying platforms, deploying aerial BSs equipped with multiple transmit antennas to serve legitimate ground receivers, and more [36].

At the same time, the use of UAV for aerial access presents several technical challenges: [34]

- Limited Range and Beamforming: As discussed, millimeter wave (mmWave) signals used by UAVs have a shorter range and are highly susceptible to blockages compared to traditional cellular frequencies. This restricts the coverage area of a UAV and requires precise beamforming techniques to maintain a strong signal with users on the ground, especially considering the constant movement of the UAV [37]–[39].
- Backhaul Connectivity: traditional cellular networks are designed with down-tilted antennas for ground coverage, making them incompatible with a flying UAV. Establishing a reliable backhaul connection for the UAV's mmWave signal becomes crucial. Options include deploying a dedicated high-bandwidth network, utilizing satellite connections (which may introduce latency issues), or relying on future advancements in Non-Line-of-Sight (NLoS) mmWave communication techniques [40]–[42].
- Power Consumption and Flight Time: Operating mmWave communication systems on UAVs requires significant power. This translates to shorter flight times for UAVs, requiring frequent battery changes or alternative power solutions to maintain extended deployments [43], [44].
- Regulations and Security: Integrating UAVs into cellular networks demands addressing regulations concerning airspace management and potential interference with existing systems. Additionally, security considerations are paramount, as UAVs acting as base stations become potential targets for cyberattacks [45], [46].

B. RELAY

Expanding their role, UAVs can act as aerial relays, facilitating wireless connectivity to ground UEs without direct transmission links. In this scenario, data packets initially transmitted from source UEs reach an initial UAV through aerial access and are subsequently forwarded between multiple UAVs in a multi-hop manner. Alternatively, these packets can be relayed directly to the destination UE using a load-carry-and-deliver forwarding mechanism. To sustain the growing transmission capacity and data traffic, leveraging higher mmWave frequencies instead of lower microwave frequencies is more feasible when designing aerial to aerial (A2A) communication links for both aerial relay and multi-hop interconnections. Additionally, inter-UAV information exchange can occur through multi-hop drone interconnection based on A2A mmWave links, achieved by using multiple antenna arrays to establish directional mmWave links among neighboring UAVs in a mesh architecture [47].

C. BACKHAUL

In 5G wireless systems with ultra-dense small cell deployments, traditional wired backhauls connecting base stations (BS) to the core network via optical fiber or coax in terrestrial networks may lack flexibility, ease of deployment, and cost-effectiveness for widespread small cell deployment. A number of works have therefore analyzed the possibility of using aerial base stations to provided backhauling services [35], [48]–[51]. These works generally demonstrate the feasibility of utilizing mmwave wireless backhaul to provide a compelling alternative by enabling rapid network expansion without the need for extensive fiber optic installations.

Integrating UAVs and mmWave communications for ultra-high-speed wireless backhaul not only enhances flexibility but also potentially reduces costs associated with wired backhauls in terrestrial networks. For instance, the mmWave mesh concept has been proposed to deliver ultra-high-speed wireless backhaul between mmWave flyMesh and relay BS [52].

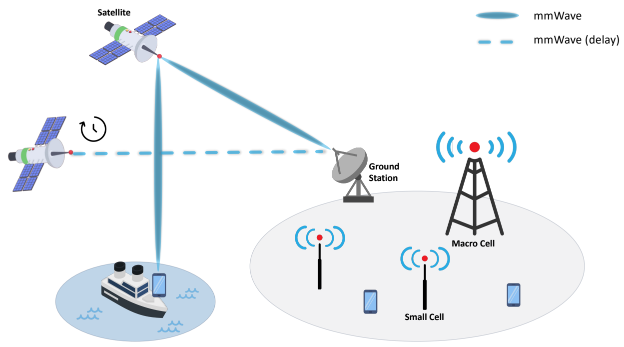

FIGURE 4. Satellite network based on mmWave links

While the applications presented in the literature are promising, some technical challenges arise due to the characteristics of both UAVs and mmWave signals. As previously mentioned, mmWave signals suffer from high propagation loss, which is exacerbated by blockage from buildings and obstacles, particularly in urban areas. The high altitude of UAVs, particularly in the cited areas, may intensify these limitations. However, solutions such as directional antennas and antenna arrays can significantly mitigate these challenges by acquiring high beam gains and improving transmission range through flexible beamforming and massive MIMO techniques. Additionally, the agile and adjustable mobility of UAVs is a key feature for their capability and flexibility in establishing robust connection links. [36]

VI. SATELLITE COMMUNICATIONS

Modern satellite communications play a vital role in enabling global connectivity, providing communication services to remote areas, supporting disaster response, and facilitating various applications such as broadcasting and internet access, especially for mobile terminals in transit, such as airplanes or vessels. Satellite communication systems involve the transmission and reception of signals between ground-based stations and satellites in orbit. Ground stations, equipped with antennas and other equipment to establish communication links with satellites, serve as the interface between the terrestrial networks and the satellite network. Satellites are the backbone of the communication infrastructure and are equipped with transponders, which receive signals from ground stations, amplify them, and retransmit them back to Earth (Figure 4). Satellites can be positioned in various orbits, such as geostationary orbit (GEO), medium Earth orbit (MEO), or low Earth orbit (LEO), depending on the application and coverage requirements.

Satellite networks traditionally operate with frequency bands below 6 GHz, such as the L band (1-2 GHz), the S band (2-4 GHz) and the C band (4-6 GHz). MmWave technology and the use of higher bands such as Ku (12-14Ghz), Ka (20-30Ghz), V (40-50Ghz) and E (60-90 Ghz) can provide significantly higher bandwidth compared to traditional satellite communication frequency bands. By utilizing such frequencies, satellite systems can establish high-capacity links, enabling faster data rates and supporting bandwidth-intensive applications like ultra-high-definition video streaming or data-intensive scientific research [53], [54]. At the same time, several challenges related to the use of mmWave technology for satellites need to be tackled [55]:

- Propagation Delay: Satellite altitude causes additional delays in communication links, particularly for geostationary satellites, resulting in round trip latencies greater than 250 ms. This delay might hinder services requiring ultra-low latency. Furthermore, longer delays impact protocol layers, potentially leading to outdated channel quality measurements.
- Path-loss: Compared to lower frequencies, mmWaves experience much greater signal weakening as they travel through space. This translates to needing (i) stronger transmitters to compensate for path loss and ensure a usable signal reaches Earth and (ii) larger antennas on both the satellite and ground stations to focus and capture the weaker mmWave signals [56], [57].
- Doppler Effect: Movement of satellites introduces Doppler effects, especially pronounced in low orbit (LEO) satellites. For instance, a LEO satellite at 600 km altitude and 2 GHz carrier frequency can reach Doppler shifts of up to 48 kHz, significantly higher than those experienced by a user inside a high-speed train.
- Deployment: Satellites typically require longer setup times compared to other technologies such as, e.g., UAV-based networks. However, while aerial platforms complement existing infrastructure quickly, satellites offer wide area coverage once deployed.
- Density of constellations: Satellite constellations are growing in size, with a clear trend towards higher densities to enhance global coverage, improve connectivity, and increase service capacity. Specifically, massive constellations of low-Earth orbit (LEO) satellites, such as CubeSat [58] and Starlink [59] are seen as crucial facilitators for pervasive, high-speed communication around the world. This increase raises synchronization issues, requiring precise coordination to avoid collisions and manage cross-link interference, especially critical for mmWave frequencies [60]. Higher densities also intensify challenges like signal interference, collision avoidance, and orbital debris, necessitating advanced operational strategies to ensure service continuity and safety [61].

VII. WIRELESS DATA CENTERS

Modern data centers play a crucial role in supporting the growing demands of digital services and applications. They are highly complex and efficient facilities designed to store, process, and transmit massive amounts of data. Communication is a critical aspect of data centers, enabling seamless connectivity between various components and facilitating efficient data transfer.

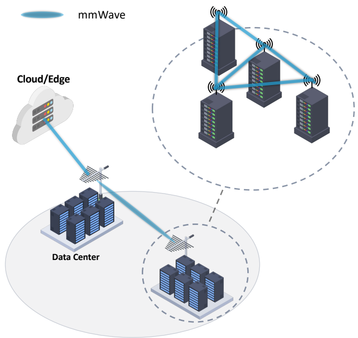

FIGURE 5. mmWave Wireless Data Center

In terms of communication, most data center communication occurs through wired technologies to establish high-speed, reliable, and low-latency connections. Examples include Ethernet, fiber optics or InfiniBand.

Despite the dominance of wired technologies, MmWave communication technology (Figure 5) holds potential for various applications within modern data centers [62]–[64]:

- Inter-Data Center Communication: MmWave can enable high-capacity, low-latency wireless links between geographically distributed data centers. These links can serve as a backup or alternative to traditional wired connections, enhancing the resilience and redundancy of data center networks.
- Point-to-Point Connectivity: MmWave can be used to establish point-to-point wireless links within data centers for specific applications that require high bandwidth and low latency. For instance, it can facilitate connections between high-performance computing clusters or storage systems, reducing the need for lengthy and complex wired cabling.
- Edge Computing: With the rise of edge computing, where data processing occurs closer to the source of data, mmWave can provide wireless connectivity between edge devices and the core data center infrastructure. This allows for faster data transfer and real-time analytics, enhancing the overall performance of edge computing deployments.

While wired technologies like Ethernet and fiber optics dominate data center communication, emerging wireless technologies like mmWave offer new possibilities for high-capacity, low-latency wireless connections within and between data centers. The use of mmWave in data centers can enhance their performance, flexibility, and adaptability to meet the increasing demands of data-intensive applications.

VIII. IMMERSIVE COMMUNICATIONS

Immersive communications encompass methods or technologies that create deeply engaging and interactive experiences, often by leveraging advanced multimedia elements. These technologies aim to transport individuals into an environment that feels realistic and engaging, blurring the lines between the physical and virtual worlds. Examples of immersive communications include Extended Reality (XR), as well as Holographic communications, haptic communications and immersive telepresence. Use cases include immersive gaming and learning, telesurgery, holographic teleconferecing and the metaverse. Immersive communications technologies often relies on the exchange of high-definition video, audio, and other sensory inputs, which require massive amount of bandwidth. Moreover, due to the nature of their usage, such technologies generally require very low delays in order to provide an optimal interactive experience. For these reasons, mmWave technologies play a crucial role in such applications [65].

A. EXTENDED REALITY

XR, or Extended Reality, encompasses Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR), as well as related technologies that merge physical and virtual worlds through video processing. Users interact with virtual avatars and content using XR devices. AR overlays artificial objects in the real world, while VR creates entirely virtual environments. MR combines aspects of both. Rendering high-quality VR content demands significant computing power, prompting research into wireless VR. Future XR aims for multi-sensory integration, combining human senses with XR content, necessitating interdisciplinary collaboration across fields like AI, computer vision, and networking to create truly immersive experience. XR demands low latency for smooth content playback based on user motions. In VR, motion-to-photon (MTP) delay—measuring the time between user movement and its display in the headset—must be under 20 ms to prevent VR sickness. The industry aims for delays below 15 ms for optimal experiences. For VR gaming, a response latency of up to 50 ms is noticeable but acceptable. To achieve low content delivery latency, ultra-high data transmission rates are necessary, especially for VR where high-resolution videos are essential. Even with data reduction techniques like tile-based transmission, VR video delivery may require over 2.35 Gbps, significantly higher than current high-definition video streaming rates [66], [67].

B. HOLOGRAPHIC COMMUNICATION

Holographic communication relies on holography technology, evolving through optical, digital, and computer-generated holography. Digital methods involve numerical calculation for image reproduction. Generating dynamic 3D holograms in real-time remains challenging, leading to alternative approaches like "false holography," using illusions or volumetric displays for 3D imaging. Volumetric displays create 3D images within confined spaces, like cubes or cones, while false holography methods use glass panes or projectors to simulate 3D effects. Holographic communication involves transferring data representing dynamic 3D images over networks, enabling the display of objects in 3D at the receiver.

Holographic communication is expected to enable new services in 6G, encompassing various forms of 3D data transfer and rendering. There's no consensus on its scope, with some considering AR/VR 3D data transfer as a form of holographic communication. Here, it refers to autostereoscopic 3D display, viewable without special glasses, achieved through real or false holography or other techniques. Similar to traditional multimedia communications, holographic communication can involve real-time or recorded content and various communication modes such as unicast, multicast, or broadcast.

The bandwidth and delay requirements associated with holographic communications are impressive and call for novel technologies such as mmWave and Thz communications.

Holograms are categorized as volumetric-based or image-based, each requiring different data rates. Volumetric holograms represent physical objects using 3D pixels or voxels (e.g., point clouds), demanding data rates from hundreds of Mbps to several Gbps, depending on resolution. For instance, transmitting a human-sized point cloud at 30 frames per second ranges from 300 Mbps to 3 Gbps.

Image-based holograms like light-field video (LFV) are more precise, capturing objects from various angles and positions. Transmitting LFV-based holograms for human-sized objects may require data rates between 100 Gbps and 2 Tbps due to the volume of images needed.

For real-time holographic communication, delays (capturing, processing, transmission, and rendering) should be under 100 ms. Synchronization among multiple sensors capturing holographic data is crucial, especially in holographic teleconferencing involving participants from different locations to ensure a consistent quality of experience (QoE).

Multi-sensory information (haptic, audio, and video) in holographic communication requires synchronization in transmission to avoid immersive experience degradation due to out-of-sync issues. For satisfactory QoE, the tolerable delay difference between audiovisual and haptic data should be lower than 80 ms. [68]

IX. OTHER APPLICATIONS

Millimeter-wave (mmWave) technology extends beyond its conventional application in communication systems and finds diverse utility in non-communication domains, notably in object detection and sensing applications. The unique characteristics of mmWave frequencies make them well-suited for various non-communication purposes, primarily in the realm of object detection and sensing [69].

A. MMWAVE SENSING

In recent years, mmWave frequencies have gained significant traction in fields like automotive radar systems, security screening, industrial automation, healthcare, and environmental sensing. The inherent properties of mmWave signals, such as their short wavelengths and wide bandwidth, allow for the ability to create high-resolution images, enable precise object detection, localization, and identification. In details, short wavelengths allow to detect smaller objects and differentiate between objects that are closer together, while the available wide bandwidth allows for better sensing performance in range, angular and doppler resolutions, i.e., the ability to more accurately sense an increased number of objects or to map a comple3x environment. [70]–[72]

In automotive industries, mmWave radar systems operating around 77 GHz play a pivotal role in advanced driver-assistance systems (ADAS) and autonomous vehicles [73]. These radar systems utilize mmWave frequencies to detect and track objects, pedestrians, and other vehicles with high accuracy, providing crucial data for collision avoidance, adaptive cruise control, and autonomous driving functionalities.

Furthermore, in security screening applications, mmWave imaging systems are employed for security checks in airports and other high-security areas. These systems utilize mmWave frequencies to create detailed images that can penetrate clothing and materials, revealing concealed objects or weapons without compromising individual privacy [74].

In industrial and manufacturing settings, mmWave sensors are utilized for level sensing, material inspection, and process monitoring due to their ability to penetrate certain materials and provide accurate measurements in challenging environments. Additionally, in healthcare, mmWave imaging holds promise for applications such as medical imaging and diagnostics. Researchers are exploring the use of mmWave technology for non-invasive imaging techniques that could offer detailed and high-resolution images for various medical purposes. [75].

Overall, the unique characteristics of mmWave frequencies make them valuable for object detection and sensing applications in various industries, offering high-resolution, accurate detection capabilities in scenarios where precision, reliability, and resolution are critical factors. These applications highlight the diverse potential of mmWave technology beyond traditional communication systems, paving the way for innovative solutions in object detection, imaging, and sensing domains.

B. INTEGRATED SENSING AND COMMUNICATION AT THZ BAND

Beyond mmWaves, the THz band (0.1-10 THz) is expected to play an essential role in future communication systems. In addition, an unprecedented paradigm shift is envisioned on the integration of ultra-reliable communications with high resolution sensing. Indeed, THz Integrated Sensing and Communications (ISAC) has been recently suggested to jointly make use of the key benefits of THz-band, e.g., ultra-wide bandwidth and enhanced beamforming [76]. THz signals can penetrate biological tissues, clothing and other materials and therefore could be employed in medical diagnostics or in non-invasive security screening at airports or public venues, detecting concealed weapons or explosives. Similarly, THz-ISAC can be used for non-destructive testing in industrial applications, such as inspecting the quality of materials, detecting defects in manufacturing processes, and ensuring product quality. Moreover, THz waves interact with molecular vibrations, enabling the identification and analysis of specific substances. THz-ISAC can be used for molecular spectroscopy applications, including identifying chemical compounds and biomolecules. Still, several technological challenges need to be solved in order to create working THz-ISAC solutions. Certain characteristics of mm-Wave become more aggravated at THz frequencies, such as high path loss and shorter transmission range. Current antenna solutions, such as phased arrays and MIMO systems, provide a foundation but are not sufficient to overcome these challenges. To cope with this, innovative antenna designs and dispositions should be further explored: examples include tunable graphene-based plasmonic nano-antennas, leaky-wave antennas, extremely dense antenna arrays, and intelligent reflective surfaces, which need to be developed to enhance performance and efficiency [77]–[80].

Hybrid beamforming could provide solutions in facing the path loss and complex channel characteristics in the THz frequency range, along with challenges like beam split and misalignment. At the same time, challenges such as wideband processing and waveform design, especially in IRS-assisted scenarios, require novel solutions for effective communication and sensing. Furthermore, THz-ISAC systems must consider environmental factors such as atmospheric conditions, which can impact the performance of sensing and communication, as well as ensuring space-efficient integration of sensing and communication components, which poses a challenge in general [81].

X. STANDARDIZATION ACTIVITIES

Standardization activities for mmWave communications play a pivotal role in defining the protocols, specifications, and frameworks necessary to harness the potential of these high-frequency bands in wireless communication technologies. These standardization efforts, undertaken by organizations such as the Institute of Electrical and Electronics Engineers (IEEE), International Telecommunication Union (ITU), and 3rd Generation Partnership Project (3GPP), among others, are essential in establishing interoperability, reliability, and performance benchmarks for mmWave-based communication systems. The standards set by these bodies define the technical specifications, radio interface designs, modulation schemes, beamforming techniques, and protocol stacks crucial for efficient mmWave communication. They address challenges associated with signal propagation, path loss, interference, and beam steering inherent to these high-frequency bands, aiming to overcome limitations in range and penetration through obstacles. The overarching goal of these standardization endeavors is to unlock the full potential of mmWave frequencies, harnessing their substantial bandwidth to deliver ultra-fast, low-latency wireless connectivity, enabling a new era of high-speed innovative applications while ensuring seamless interoperability and reliability across diverse devices and networks.

A. VEHICULAR NETWORKS

1) IEEE 802.11bd

The IEEE 802.11bd standard is an evolution of the IEEE 802.11p standard, which was developed to support vehicular communication for safety and traffic management purposes. The objectives of IEEE 802.11bd include achieving higher throughput, extended communication range, and vehicle positioning capabilities. To enhance the performance of 802.11p, advanced techniques from standards like 802.11n, 802.11ac, and 802.11ax are being leveraged. Main features of IEEE 802.11bd physical layer are the use of mmWave frequencies, Dual Carrier Modulation (DCM) to improve reliability and range, LDPC coding, and multiple transmit/receive antennas [82]. The MAC layer of IEEE 802.11bd adopts contention parameters from 802.11p to ensure fair channel access. A 20 MHz channel access mechanism similar to 802.11n/ac is used, where a primary channel and a secondary channel are utilized. The primary channel is used for transmission, while the secondary channel is sensed for a shorter duration. Vehicle positioning capabilities are likely to be based on the IEEE 802.11ax Next Generation Positioning (NGP) scheme. Overall, IEEE 802.11bd aims to enhance the performance and capabilities of IEEE 802.11p for vehicular communication by incorporating advanced techniques and addressing specific requirements such as higher throughput, extended range, and vehicle positioning [83].

2) 3GPP NR V2X

The 3GPP NR V2X standard enables communication between vehicles and their surrounding environment [84]. It supports V2V, V2I, V2P, and V2N interactions, enhancing road safety, traffic efficiency, and connected vehicle services. Built upon 5G NR specifications, the V2X standard optimizes communication for vehicles. It ensures reliable and low-latency connections, enabling intelligent transportation systems. Key features of the 3GPP NR V2X standard include:

- URLLC: Provides ultra-reliable and low-latency communication for time-critical applications like collision avoidance.
- Direct Communication: Enables vehicles to exchange real-time information directly, improving safety and awareness.
- Network-Assisted Communication: Supports information exchange with infrastructure and network elements for services like traffic coordination and remote monitoring.
- Scalability and Flexibility: Accommodates various deployment scenarios and communication ranges, enabling diverse use cases.
- Security and Privacy: Incorporates authentication, encryption, and privacy protection mechanisms for secure communication.

Standardizing V2X within 3GPP promotes interoperability, allowing widespread adoption and innovative applications such as adaptive cruise control and traffic management, advancing transportation systems.

B. CELLULAR NETWORKS

The main activities regarding mmWave cellular technologies are managed by the 3rd Generation Partnership Project (3GPP), which is responsible of all activities concerning cellular communication standardization. The 3GPP 5G NR (New Radio) FR2 standard refers to the specifications and standards developed for the operation of 5G cellular networks in the frequency range known as FR2, or the millimeter-wave (mmWave) frequency range [85]. The FR2 frequency range, introduced from realease 17 of the 3GPP standard, spans from approximately 24.25 GHz to 52.6 GHz, and it is a key component of 5G networks. The FR2 standard specifies the technical details, protocols, and procedures necessary for deploying and operating 5G networks in these high-frequency bands.

Some key aspects of the 3GPP 5G NR FR2 standard include:

- Frequency Bands: The FR2 standard defines the specific frequency bands within the mmWave range that can be used for 5G deployment. These frequency bands may vary across different regions and regulatory domains.
- Channel Access and Modulation: The FR2 standard specifies the channel access methods and modulation schemes suitable for mmWave frequencies. It includes the use of wide bandwidths and advanced modulation techniques to achieve high data rates and support massive connectivity.
- Beamforming and Beam Management: Given the unique propagation characteristics of mmWave signals, the FR2 standard incorporates beamforming and beam management techniques to enhance signal transmission and reception. Beamforming allows the network to focus the signal towards specific user equipment, compensating for the higher path loss and interference challenges in the mmWave bands.
- Mobility Management: The FR2 standard addresses mobility management in mmWave frequency bands, which can present challenges due to signal blockage and higher susceptibility to environmental conditions. It includes mechanisms for seamless handovers, beam tracking, and beam switching to maintain connectivity while the user equipment moves between different base stations.
- Interference Management: Interference is a critical consideration in the mmWave frequency range due to the high density of cells and potential interference from various sources. The FR2 standard defines interference mitigation techniques and strategies to minimize the impact of interference and ensure optimal network performance.
- MIMO (Multiple-Input Multiple-Output) and Massive MIMO: The FR2 standard supports advanced MIMO techniques, including massive MIMO, which utilizes a large number of antennas at the base station to enhance spectral efficiency and capacity in the mmWave bands.

By standardizing the operation of 5G networks in the mmWave frequency range, the 3GPP 5G NR FR2 standard enables the deployment of high-capacity, ultra-fast, and low-latency 5G networks. It provides the foundation for various 5G use cases and applications that require the increased bandwidth and capacity offered by the mmWave bands, such as high-definition video streaming, augmented reality, virtual reality, and industrial IoT applications.

C. WIRELESS PERSONAL AREA NETWORKS (WPAN)

WPAN standards are intended to short range, high data rate communications, and are therefore intended to be used in a variety of scenarios characterized by limited ranges including personal devices (e.g., VR/AR headsets, docking stations etc.), wireless data centers as well as inter-vehicular communication.

1) IEEE 802.11ad/ay

IEEE 802.11ad [86] and IEEE 802.11ay [87] are wireless standards operating in the 60 GHz band, part of the IEEE 802.11 family of Wi-Fi standards.

IEEE 802.11ad, known as WiGig, functions in the 60 GHz frequency band, offering very high data rates, reaching multi-gigabit-per-second speeds. It is tailored for short-range communication, typically within a room or confined space. This standard is suitable for high-speed data transfer applications like high-definition video streaming and rapid file transfers at limited range, due to the nature of the carrier frequency.

IEEE 802.11ay is an extension of 802.11ad, aiming to enhance its capabilities. It operates in the 60 GHz band, providing even higher throughput compared to 802.11ad, potentially doubling or quadrupling its data rates. 802.11ay seeks to maintain high-speed communication within short distances while extending coverage range beyond 802.11ad. This standard is designed for various applications, including high-speed data transfer, augmented reality (AR), virtual reality (VR), and wireless docking.

Both standards incorporate beamforming techniques to enhance signal directionality and improve communication reliability in the 60 GHz frequency band. At the same time, these standards can also provide interoperability with other Wi-Fi standards operating in lower frequency bands, allowing for backward compatibility.

2) IEEE 802.15.3c/f

IEEE 802.15.3c stands as a wireless communication standard, specifically operating in the 60 GHz frequency band [88] (while the 802.15.3f standard extends the operation of the protocol up to 71GHz). It's engineered to facilitate the transmission of data at very high rates, capable of reaching multi-gigabit-per-second speeds. This standard is particularly well-suited for applications that demand substantial bandwidth, such as streaming high-definition multimedia content or swiftly transferring large files. One of its notable attributes is its proficiency in providing efficient communication over relatively short distances. While it offers impressive data rates, this technology typically functions optimally within limited ranges, making it ideal for scenarios where devices are in proximity to each other, like within a room or an enclosed space. In terms of application, IEEE 802.15.3c caters to various connectivity needs. It supports both point-to-point connections, allowing devices to communicate directly, as well as multi-point connections, enabling multiple devices to form a network for shared communication.

XI. MMWAVE PROPAGATION: CHANNEL MODELING AND EXPOSURE

Understanding mmwave propagation is key for two activities: (i) channel modeling and (ii) assessment of electromagnetic field (EMF) exposure. The former involves studying the behavior of the communication channel through which mmwave signals propagate, in order to improve the design, performance, and optimization of communication systems based on the transmission of such frequencies. The latter focuses on evaluating the EMF exposure levels, to the last objective of ensuring that such exposure complies with safety limits established by national and international standards and guidelines [89], [90].

As aforementioned, mmWave transmissions have unique propagation characteristics that make them very different from traditional communication systems. Due to their shorter wavelengths, mmWave signals encounter increased path loss, higher susceptibility to blockages from obstacles like buildings or foliage, and are more sensitive to atmospheric absorption. These factors result in a highly directional and spatially varying channel, making accurate propagation analysis a complex task. Similarly, conventional metrics and techniques used to evaluate human exposure levels at sub-mm wave frequencies are inadequate for the complexities of forthcoming exposure scenarios.On one hand, the inherent variability in mmWave scenarios poses challenges in characterizing human exposure with a realistic number of measurements or simulations. On the other hand, the short wavelength and significant reduction in power penetration depth necessitate a shift in the biological target of interest and the electromagnetic field (EMF) quantities to be assessed. In the following discussion, we first review recent studies pertaining to channel modeling in various mmWave application scenarios and the methodologies employed to assess EMF human exposure at these frequencies. Subsequently, we short reviewed works specifically addressing mmWave EMF exposure.

A. CHANNEL MODELING

In recent years a number of research groups have developed different mmWave channel models, depending on the application scenario under consideration. Considering its direct implication on everyday communications, channel model estimation for cellular networks have received considerable attention both from standardization entities such as the 3GPP [91] as well as from independent research groups [92], [93]. For what concern vehicular networks, examples can be found for V2S, V2V and V2I cases. As an example, the works in [94] and [95] derived channel model for in-vehicle (V2S) applications, focusing on 3-11GHz and 55-65GHz band, respectively. This studies analysed the impact of the position of the receiver and transmitter inside a vehicle, moving them in the engine, passenger or chassis compartments. Other works have explored the V2V inter vehicle scenario, from 56-64GHz [96], [97], to 76 GHz [98]. However, such works generally consider simplistic scenarios, without considering the inherent dynamism and presence of obstructions typical of real-world vehicular settings. Moreover, just few of them study the impact of antenna position and directionality on the channel models. In general, more measurements campaign regarding vehicular scenarios in the mm-wave bands are essential for providing accurate channel models [99]. Some works also considered the V2I scenario. As an example, the work in [100] provides a comprehensive study on on the channel characteristics of the V2I link in mmWave band (22.1-23.1 GHz) for various road environments and deployment configurations (urban/highway scenarios, different vehicle types, different height of the base station, etc.).

Channel modeling for mmWave-based UAV networks also received attention in the last few years. In aerial scenarios, millimeter waves (mmWaves) can impact communication quality differently than in ground deployments due to various factors. Firstly, certain frequencies in the mmWave spectrum, such as the 60 GHz band, are affected by oxygen absorption, and atmospheric conditions at high altitudes may vary, influencing aerial scenarios differently than ground deployments. Secondly, the inherent inaccuracy of UAV (Unmanned Aerial Vehicle) on-board sensors, even when GPS-locked, can cause slight horizontal and vertical fluctuations in the drone's position. Moreover, drone movements in harsh wind conditions, including pitch and roll, can affect the orientation of the mmWave radio. Since mmWaves rely on highly directional communications, these fluctuations can significantly degrade channel quality. Due to these challenges, evaluating mmWave UAV-to-UAV communications requires dedicated air-to-air (A2A) propagation and fading models, distinct from ground-tailored studies [101] [102] [103]. Similarly to the UAV case, attention has been given also to modeling satellite mmWave channels [56] [104]. Channel modeling has been performed also for very specific application scenarios and unique environments such as mmWave wireless data centers [105], as well as for in-on-and-around human body devices [106] typical of immersive communications. Finally, some effort has been given very recently to characterize channels at THz frequencies (0.1-10THz): however, channel modeling at this frequencies is sill in its infancy and require further studies for proper characteriziation as well as for preparing THz band standardization [107].

B. EMF EXPOSURE ASSESSMENT AND DOSIMETRY

As new RF technologies have been introduced and new frequency bands assigned, they have also become controversial due to safety concerns. Therefore, studies on assessing human EMF exposure and modeling the interaction between the human body and the EMF generated by these new technologies represent the initial steps to be addressed. In the following, with the term ''exposure assessment'' we refer to the evaluation of levels of RF energy incident on the body, and the term ''dosimetry'' refers to determining the absorption of RF energy within the body. As mentioned above, the International Commission on Non-Ionizing Radiation Protection and the IEEE International Committee on Electromagnetic Safety (ICES) provide exposure reference level (IEEE) and reference level and basic restrictions (ICNIRP) to protect humans against harmful health effect due to the EMF exposure. At radiofrequencies (RFs), EMFs interact with the human body by means of an extended or localized tissue heating. Consequently, exposure guidelines for RFs and microwaves are set to prevent health effects caused by whole-body or localized heating and compliance with the guidelines will ensure that heating effects are sufficiently small not to be harmful. Limits on whole-body exposure are designed to consider the total heat load on the human body from EMF exposure and they are expressed, conservatively, in terms of incident power density:

$$S_{\text{inc}} = \frac{P}{A} = |\mathbf{E} \times \mathbf{H}^*| \quad (1)$$

where P is the incident power, A is the exposed surface area, and $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field vectors, respectively and their product is the Poynting Vector. To consider the physical properties of the exposed subject and to better correlate the EMF exposure level to the sustained biological effect (i.e. body core temperature increases higher than + 1°C), standards specify as a relevant dosimetric quantity (i.e. ''Basic restriction''), the Specific Absorption Rate (SAR), which is the quantitative measure of EM power absorbed per unit mass (in W/kg):

$$\text{SAR} = \frac{P}{m} = \frac{\sigma E^2}{\rho} = C\frac{dT}{dt} \quad (2)$$

where m is the tissue mass, σ is its conductivity, ρ its mass density, C is the heat capacity, and T is the temperature. In case of whole-body exposure this quantity is averaged over the whole body (wbSAR). As for local exposure, at frequencies below 6 GHz, SAR is still the metric used to assess the exposure because its average over a 10 g of contiguous tissue well correlates to local heating. As EMF frequency increases, exposure of the body and the resultant heating becomes more superficial, and above about 6 GHz this heating occurs predominantly within the skin. For instance, 86% of the power at 6 and 300 GHz is absorbed within 8 and 0.2 mm of the surface respectively [108]. With the development of 5G and its projected use of higher mmWave frequencies, guidelines were accordingly updated, and new metrics to protect against excessive heating have been introduced. The ICNIRP-2020 guidelines/IEEE standard C95.1 introduced absorbed/epithelial power density (S_{ab}), averaged over a surface of 1 cm^2, as the basic restriction to prevent excessive surface heating for local exposures above 30 GHz.

$$S_{ab} = \frac{1}{A}\int_S \text{Re}\,|\mathbf{E} \times \mathbf{H}^*| dS \quad (3)$$

where A is the surface area, dS is the surface element and $\text{Re}\,|\mathbf{E} \times \mathbf{H}^*|$ is the real part of the Poynting vector.

With the introduction of new wireless communication technologies, characterized by a great variability in terms of propagation conditions, frequency bands, communication protocols, and the increasing number of EMF sources to which humans are simultaneously exposed, the accurate estimation of whole body (wbSAR) and local (S_{ab}) dosimetric quantities becomes particularly challenging. The main issues encountered in mmWave computational exposure assessment and dosimetry studies concern then the characterization of the exposure conditions variability and the modeling of the main biological target of mmWave-body interaction, i.e. the skin.

As to the former, we refer to the modeling of all conditions which reflect the complexity of realistic scenarios, consisting of many antennas (MIMO), with 3D-beamforming capabilities, surrounded by physical objects, both fixed and moving, and eventually placed at different heights. In this scenario, traditional techniques, based on classical deterministic dosimetry, in which a single simulation models a single exposure condition, should be merged to innovative approaches and integrated solutions able to reduce time and computing resources.

To this aim, hybrid approaches combining deterministic and probabilistic techniques have been recently proposed with particular focus on complex vehicular and cellular networks scenarios. They include Finite difference Time Domain (FDTD)/method of moments [109], ray-tracing [110], [111], stochastic or machine learning and deterministic dosimetry [112], [113], near-field transformation/FDTD [114]. In most of these studies the EMF source is placed far from the body, thus assuring that, even in the worst-case conditions, such as when multiple antennas are transmitting and are in Line of sight with the exposed subject, and focal beam occurs in the body, limits are unlikely to be exceeded. Therefore, dosimetric studies over EMF exposure assessment studies can serve as input for optimizing the deployment of antennas and networks following the concept of a human-centric approach.

Conversely, the absorption of RF energy from sources close to the body at mmWave frequencies, such as in the forthcoming body-centric communication systems could, in principle, induce high hotspot on superficial body layers, estimating this absorption solely based on incident power density at the skin surface might yield overly conservative results. Hence, the primary efforts in characterizing the interaction between mmwaves and the human body have focused and will continue to focus on providing accurate and reliable models of the skin. Skin is not only the largest, but also, functionally, the most versatile organ of the human body. From the EM point of view, the skin can be considered as an anisotropic multilayer dispersive structure made of three different layers, namely, epidermis, dermis, and subcutaneous fat layer [115]. Each layer can be distinguished from another one by dielectric properties, namely electric conductivity and permittivity, and this difference produces an interface impacting on the incident wave propagation; this concept is crucial in the skin modeling because it has an inner structure in which it is possible to detect more than one layer and these strata differ between each other for their dielectric properties [116] . Because of this inner complex structure, many studies have analyzed its impact on the estimated absorbed power to understand if, and eventually to which extent, the presence of multiple layers could affect the exposure assessment results. This issue has been faced by the comparison between the dosimetric-related quantities of interest obtained in the homogeneous model of the skin (i.e. dermis) and in the layered models, made of stratum corneum and viable epidermis and dermis. The impact of the use in computational dosimetric studies of a layered model of the skin rather than the homogeneous one has been investigated in terms of SAR [108], [117], [118], temperature increase [119], [120], reflection and transmission coefficients [120], [121] and absorbed power density [122], [123]. The majority of these studies have concluded that modeling the skin as a single homogeneous layer characterized as dermis leads to underestimation of dosimetric quantities compared to the layered model comprising the stratum corneum, viable epidermis, and dermis. Nevertheless, there is currently no consensus on the optimal approach to modeling the skin in computational dosimetry studies.

XII. CONCLUSION

This paper presented a survey of the future application scenarios envisioned for mmWave technologies. We highlight that mmWave technologies will find applications in several domains, ranging from terrestrial developments (cellular, vehicular, data centers, immersive communications) to aerial/non-terrestrial installations (UAV, satellites), as well as for applications beyond communications such as imaging and sensing. We presented each use case focusing on its characteristics and describing the main challenges associated to it. Furthermore, the paper presented a survey of the main standardization activities regarding mmWave frequencies as well as channel modeling and EMF exposure considerations in different application scenarios. The document is intended to serve as reference for researchers and practitioners willing to explore practical applications of mmWave technologies.

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