Received: 29 July 2022 | Revised: 4 May 2023 | Accepted: 30 May 2023

DOI: 10.1002/wfs2.1496

ADVANCED REVIEW

WIREs FORENSIC SCIENCE WILEY

Digital forensics challenges and readiness for 6G Internet of Things (IoT) networks

Alex Olushola Akinbi

Department of Computing and Mathematics, Manchester Metropolitan University, Manchester, UK

Correspondence
Alex Olushola Akinbi, Department of Computing and Mathematics, Manchester Metropolitan University, Manchester, UK.
Email: a.akinbi@mmu.ac.uk

Edited by: Kim-Kwang Raymond Choo, Editor

Abstract

The development of sixth-generation (6G) wireless communication technology is expected to provide super high-speed data transmission, and advanced network performance than the current fifth-generation (5G) and be fully functional by the 2030s. This development will have a significant impact and add improvements to digital extended reality (XR), autonomous systems, vehicular ad hoc networks (VANETs), artificial intelligence (AI), underwater communications, blockchain technology, pervasive biomedical informatics and smart cities built on the digital infrastructure backbone of the Internet of Things (IoT). The ubiquitous nature of this large-scale 6G-enabled IoT that offers faster connectivity capabilities and integrates both terrestrial and non-terrestrial networks will not only create new data security and privacy issues but also provide a treasure trove of digital evidence useful for digital forensic examiners investigating security incidents and cybercrime. However, for digital forensic examiners, evidence collection, preservation and analysis will become a priority in the successful deployment of 6G IoT networks. In this study, we define key applications of 6G network technology to the Internet of Things and its existing architectures. The survey introduces potential digital forensic challenges and related issues affecting digital forensic investigations specific to 6G IoT networks. Finally, we highlight and discuss forensic readiness and future research directions for identified challenges within the 6G IoT network environments.

This article is categorized under:

Digital and Multimedia Science > IoT Forensics

KEYWORDS

6G, edge intelligence forensics, IoT forensics, optical wireless forensics, XR/VR forensics

1 | INTRODUCTION

Fifth-generation (5G) wireless communication technology has been a key enabler in the proliferation and growth of Internet of Things (IoT) applications (S. Li et al., 2018) which has seen billion of devices connected by wireless communication technologies. Compared to wireless technologies, such as 2G/3G/4G, Wi-Fi, Bluetooth, and so forth, 5G offers

improved latency, spectrum efficiency, reliability, and a transmission rate of between 10 and 20 Gps which is 100 times higher than 4G (Gai et al., 2021; Lu & Zheng, 2020). It has also taken communication previously limited to only humans to communication between humans and objects. However, the full potential of promising new IoT services from extended reality (XR), artificial intelligence (AI), autonomous systems, and telemedicine to underwater sea-based communication and intelligent vehicular ad hoc networks (VANETs) cannot be realized with 5G (Saad et al., 2020). These services are mostly based on ultra-high reliability, high data rates, unmanned mobility management, and long-distance communication (L. U. Khan et al., 2020), which exposes the limitations in the inherent properties of 5G.

These limitations have birthed the development of the sixth generation (6G) wireless network communication which aims to provide performance improvements required by these services. Another aspect of 6G is that it will create a large-scale heterogeneous network integrating terrestrial networks, space satellite networks, and marine networks. 6G will have a high peak rate of between 100 Gps and 1 Tbps, low latency, 0.1 ms on-time processing, spectrum efficiency of about 2–3 times better than 5G and overall network efficiency of 200 bits/J compared to 100 bits/J offered by the current 5G (Lu & Zheng, 2020).

These high-performance requirements are currently needed to unlock the mainstream adoption of augmented/virtual reality (AR/VR), 3D Holographic Display, real-time telemedicine, upscale the industry 4.0 revolution and meet the demands of autonomous transportation systems (Giordani et al., 2020; Meshram & Patil, 2020; Servetnyk & Servetnyk, 2021; Wollschlaeger et al., 2017; Z. Zhang et al., 2019). 6G will allow the proliferation and expansion of AI-powered IoT devices that will enhance end-user experience with increased human-to-object interactions. Statistics show that the global market of 6G is estimated to reach $1773.09 billion by 2035 (Global News Wire, 2021a) with the majority of smart and IoT devices operating on 6G networks or considered 6G "ready."

Existing security issues and privacy challenges in 5G networks such as authentication, access control, integrity, identity management, confidentiality and non-repudiation have also been identified in emerging 6G technologies (Sicari et al., 2020; M. Wang et al., 2020). Current 5G networks have not only increased the ubiquity of IoT devices but also the advent of IoT bot malware and botnets. Therefore, the ability to forensically analyze IoT malware-infected devices is very critical in 5G networks and beyond (X. Zhang, Upton, et al., 2020).

Moreover, newer forensic analysis challenges will also emerge in the state-of-the-art technologies enabled by 6G that include faster ubiquitous IoT services and applications, where various sensors and networks based on big data and deep learning are interconnected in real and virtual environments (Lu & Zheng, 2020). Hence this increase in IoT connectivity will not only expose the network communication surface area to exacerbate threats currently seen in 5G networks but also create a spike in prevalent and persistent security-related attacks and incidents that require different digital forensic investigation approaches in 6G networks.

As more connected objects and autonomous systems communicate seamlessly over an increasing system bandwidth and improved spectrum efficiency provided by 6G networks, the forensic investigation and incident response, as well as the attack or deficit attribution, would become more challenging in this vast network environment. Moreover, sifting through the sheer amount of data for valuable forensic artifacts to provide an end-to-end analysis of evidential data is not just difficult but will become increasingly challenging and close to impossible in fully distributed autonomous systems, underwater locations, and virtual and XR environments. Therefore, forensic examiners and incident responders will require specialized methods, procedures, and tools for identifying, collecting, preserving, and analyzing evidential data in large-scale heterogeneous 6G IoT network environments.

1.1 | Related studies

The rapid increase in IoT network connectivity has been enabled by the development of wireless communication technologies. However, to meet future promises of high-performance, autonomous, and heterogeneous networks that include reliable object-to-object communication, a much more efficient and reliable wireless communication has been proposed in the form of 6G. Recent research studies have focused specifically on the development of 6G and its enabling technologies (de Alwis et al., 2021; Giordani et al., 2020; W. Jiang, Han, et al., 2021; Nguyen et al., 2022; Xiaohu et al., 2020; Z. Zhang et al., 2019) including security and privacy challenges of 6G-enabled networks (Lu & Zheng, 2020; M. Wang et al., 2020). Moreover, researchers have also focused on the forensic challenges and opportunities in several IoT networks (Akinbi & Berry, 2020; Alenezi et al., 2019; Baggili et al., 2015; Choo, 2021; Conti et al., 2018; Dawson & Akinbi, 2021; Lutta et al., 2021; MacDermott et al., 2018; Oriwoh et al., 2013; Sandvik et al., 2023; Servida & Casey, 2019; Stoyanova et al., 2020).

The common theme of these previous studies is that the IoT networks are currently enabled by Wi-Fi, RF, 3G/4G/5G, Bluetooth and ZigBee network technologies. The methods and approaches used for forensic investigations in these studies can be generalized based on these underlying network technologies and infrastructure. Moreover, the existing studies do not highlight digital forensic challenges in future large-scale IoT heterogeneous networks that will integrate terrestrial networks, space satellite networks, and underwater/marine networks that are proposed to be enabled by key 6G wireless network technologies. Therefore, for future 6G networks, digital forensics and incident response will require different approaches specific to the key enabling technologies the network communication technology has been proposed to use. This article is the first of its kind to introduce digital forensic challenges and preparedness toward digital investigations for future 6G IoT network environments.

1.2 | Research contribution

In this article, a broad overview of the digital forensic challenges related to 6G IoT networks is first introduced. We discuss the key enabling technologies for 6G networks including an overview of 6G-enabled environments to help understand why conducting digital forensic investigations in these environments will require a different approach.

Hence, the key contributions of this survey can be summarized as follows:

1. The promising smart IoT network environments that 6G wireless communication technology will support are outlined.
2. The digital forensics issues and challenges in the key areas of the 6G IoT networks are identified and presented with a detailed discussion on specific digital forensic investigation challenges.
3. We highlight forensic readiness and future research directions toward conducting digital forensic investigations in these large-scale heterogeneous 6G-enabled IoT networks.

The rest of this article is organized as follows. A discussion of the methodology, results and related works is presented in Section 2. Section 3 provides a brief overview of 6G key technologies. In Section 4, we discuss the application of 6G wireless communication technology in IoT environments. In Section 5, we discuss the forensic challenges in 6G IoT networks. Forensic readiness and future research directions are presented in Section 6. Finally, Section 7 concludes the article.

2 | METHODOLOGY

In this article, we followed a fundamental procedure to select and filter the most relevant literature about 6G and IoT. The method used in this study follows the guideline and principles for conducting systematic surveys in software engineering as proposed by Petersen et al. (2008) and updated by Petersen et al. (2015). The aim is to obtain the most relevant studies related to 6G key enabling technologies (Section 3) and their application to the IoT (Section 4).

The search strategy was carried out across three databases and online libraries. The online libraries consulted include IEEE Explore, Google Scholar, and ScienceDirect, using keywords/strings, "*6G*" and "*IoT*," to obtain the most relevant studies related to the research study. These digital libraries are appropriate to conduct searches that cover the most relevant topics and selection of journals in computer networks, computer science and software engineering.

From the initial search conducted, a total of 157 articles (journal papers, conference proceedings, and early access articles) were generated. Specifically, we considered only publications from 1st January 2020 up to 30th April 2023 to obtain up-to-date papers relevant to the study. Specifically, there were 112 articles recovered from IEEE Explore, 61 articles from Google Scholar, and 40 articles from ScienceDirect. From the returned search results, we observed some publications were irrelevant or unqualified articles for selection based on our inclusion and exclusion criteria presented in the title, keywords and abstract. Publications that did not focus on 6G including its enabling technologies and application to IoT were removed. Secondly, papers not written in English or duplicates were deleted. Finally, 109 articles met the qualification which are IEEE Explore (71), Google Scholar (12), and ScienceDirect (26).

2.1 | Results

From the final 109 articles selected; the number of articles published since 2021 is the largest despite our search being conducted in March 2022. The results also show that IEEE Explore conferences and journals are the major sources for 6G development and research. From the selected articles, the percentage of the publications' theme could be split into concepts and opportunities accounting for 68%, key enabling technologies accounting for 96%, application of 6G accounting for 77%, and challenges accounting for 65%. It should be noted there is an overlap between the various themes in the 109 articles selected. In general, the selected publications show that the development of 6G wireless communication is in its nascent stages. However, research and interest in the academic community are growing at a very fast pace.

3 | 6G KEY ENABLING TECHNOLOGIES

To better understand the digital forensic challenges and approaches for evidence collection, preservation, and analysis in future 6G enabled IoT networks, we highlight several key enabling technologies that will be integrated to support the functionalities for future 6G network communications. The key enabling technologies briefly described in this section highlight network communication, data processing and storage in ecosystems of smart and highly heterogeneous 6G enabled IoT devices.

3.1 | Wireless network communication and performance technologies

To enable and integrate geo-wireless mobile communications, especially terrestrial, space, and underwater autonomous network communication, 6G will need to provide full wireless coverage and ultra-long-distance wireless connectivity with a delay of less than 1 ms (Chowdhury, Hossan, & Jang, 2018; H. Guo, Zhou, et al., 2021; Ji, Han, et al., 2021; Zhao et al., 2019). 6G will also need to support massive Ultra-reliable Low Latency Communications (mURLLC) in extreme or emergency events with spatially and temporally changing device densities, traffic patterns, spectrum, and infrastructure availability (Letaief et al., 2019). This includes promising solutions to the current communication spectrum which 6G will benefit from. The use of full-duplex (Terahertz) THz-based communications to ensure reliability and high spectral efficiency has been proposed (Bariah et al., 2020; Y. Yang, Yamagami, et al., 2020; Yu et al., 2020; S. Zhang, Liu, et al., 2020). This use of a wide spectrum bandwidth allows for wideband channels, low latency, ultra-high bandwidth, and support data transfer at very high speed (Allam & Jones, 2021; Alsharif et al., 2020; Yuan et al., 2020).

Other identified key enabling technologies include the use and application of channel coding, edge caching, non-orthogonal multiple access (NOMA) in the context of millimeter-wave (mmWave) communication (Lu & Zheng, 2020; Ziegler & Yrjola, 2020), and optical wireless communication (OWC) systems such as visible light communication (VLC) infrared radiation (IR), or ultraviolet (UV) spectra. OWC's excellent features make it a promising complementary option to radiofrequency (RF) based wireless communication systems (Chowdhury et al., 2020) and as such it has been identified as an enabling technology for future 6G network communications. One of the most promising OWC technologies includes optical camera communication (OCC), free-space optical (FSO) communication and VLC. VLC propagates data transfer via visible light beam, can offer high indoor speed, guarantees transmission privacy and security, and as such can be deployed in a wide range of the spectrum. VLCs possess the ability to provide illumination and wireless broadband communication simultaneously (Al-Kinani et al., 2018). Several research platforms such as OpenVLC have also been developed to accelerate the application and validation of VLC designs (Cui et al., 2020; Galisteo et al., 2019). Its successful deployment has already been achieved in the streaming of high-quality HD videos (X. Lin & Zhang, 2020; Ray, 2021) and implementation in light-fidelity (Li-Fi) (X. Wu, Zhou, & Yang, 2017). Li-Fi is strongly judged to be more suitable for underwater communication because radio waves cannot be used underwater as the waves are strongly absorbed by water within a few feet of transmission.

In addition, 6G will include the application of deep learning and machine learning (ML) enabled solutions to achieve maximum network optimization (Letaief et al., 2019; H. Yang, Alphones, et al., 2020; S. Zhang & Zhu, 2020; Zorzi et al., 2015). The use of deep learning and machine learning, edge intelligence (Deng et al., 2020; Z. Zhou et al., 2019) and reconfigurable intelligent surfaces (RISs) (C. Pan et al., 2021) will help in maintaining the increased efficiency as inherent problems in wireless networks. Current wireless network communication problems that are

solved by applying sets of rules derived from system analysis will no longer be applicable. The implementation of multiple-input and multiple-output (MIMO) channel estimation and detection (Y. Chen, Yan, et al., 2021; Huang et al., 2018; Ye et al., 2018), intelligent spectrum sharing (Matinmikko-Blue et al., 2020), modular recognition (West & O'Shea, 2017), channel decoding has been proposed to improve the state of network performance in 6G architectures.

3.2 | Transceiver and antenna technologies

To deliver reliable wireless network communication performance in proposed 6G networks, novel transmitters, transceivers, and antenna designs and developments for THz communication are crucial. Especially designing and developing large-scale antennas that will improve spectrum efficiency of wireless mobile communication systems (Lu & Zheng, 2020; Zong et al., 2019). The use of either-or combined electronics-based and photonics-based devices that can accommodate the transmission and delivery of high-rate data wirelessly needs to be designed and developed. Alternatively, integrated hybrid transceiver systems that can leverage and use multi-mode base stations across several frequencies including microwave, mmWave and THz spectra are needed (Saad et al., 2020; Xiao et al., 2017). In addition, the development of multi-modal micro-LED transmitters would be required to support high-speed VLC and OWC (Griffiths et al., 2020; Haas et al., 2020).

6G networks will also extend beyond the current 5G data access and storage from data centers to the edge through the use of both mobile base stations and fixed base stations for serving network operation centers (Ray, 2021) for terrestrial space-underwater networks. As a large amount of big data is being generated, transmitted, and shared in real-time, access to virtual networks in the cloud would be needed to extend the capabilities of content delivery networks (CDNs) to the use of underwater base stations, unmanned aerial vehicles (UAVs) and aerial satellites for 6G networks. Seamless integration of both mobile and fixed base stations which consists of satellite communication architectures, UAV/drone-based/balloons-assisted communication systems and underwater acoustic, optical and RF communication have already been identified (Alzidaneen et al., 2020; Dang et al., 2020; Ray, 2021). Due to their strong line-of-sight connection links (F. Guo, Yu, et al., 2021), mobility, flexibility, and ability to provide support in areas where cellular base stations are absent or not functioning, the use of UAV/drone-based/balloons systems have been considered crucial to future 6G architectures.

3.3 | Data processing and storage technologies

Current 5G IoT networks utilize cloud computing and centralized data storage infrastructures for processing and storing huge IoT data. With 6G, edge and distributed computing will become mainstream technologies to enable effective data mobility, scalability, access, and distribution (F. Guo, Yu, et al., 2021; Merluzzi et al., 2020). Low energy and secure data storage technologies have been proposed which apply the use of decentralized, serverless and trustworthy infrastructure solutions to process and store data in 6G IoT networks. The traditional client–server boundary will be eliminated, and each network node (including various terminals, base stations, gateways, routers, servers, etc.) will act not only as an information publisher but also as an information consumer (X. Qiao et al., 2020). Data storage will expand from traditional cloud infrastructures to edge networks and ubiquitous end devices to reduce latency and improve reliability by eliminating geographic distance (Cao et al., 2020; Huh & Seo, 2019). Edge computing servers will become a common infrastructure used to process data generated by 6G IoT network devices thus reducing data overload and latency. The use of off-chain databases that utilize the inherent properties of blockchain has also been proposed. In Gupta, Nair, et al. (2021), the use of UAVs that can communicate securely using blockchain among each other and with the ground station servers on the edge network was presented.

4 | 6G ENABLED IOT ENVIRONMENTS

Several identified IoT environments where 6G will be applied include intelligent VANETs and autonomous driving, UAVs, satellite IoT, smart healthcare IoT, industrial IoT, and extended, augmented and virtual reality IoT. For forensic investigators, these 6G enabled environments introduce new and extended environments of current IoT networks where forensic evidence collection, preservation and analysis will conduct for digital forensics and incident response.

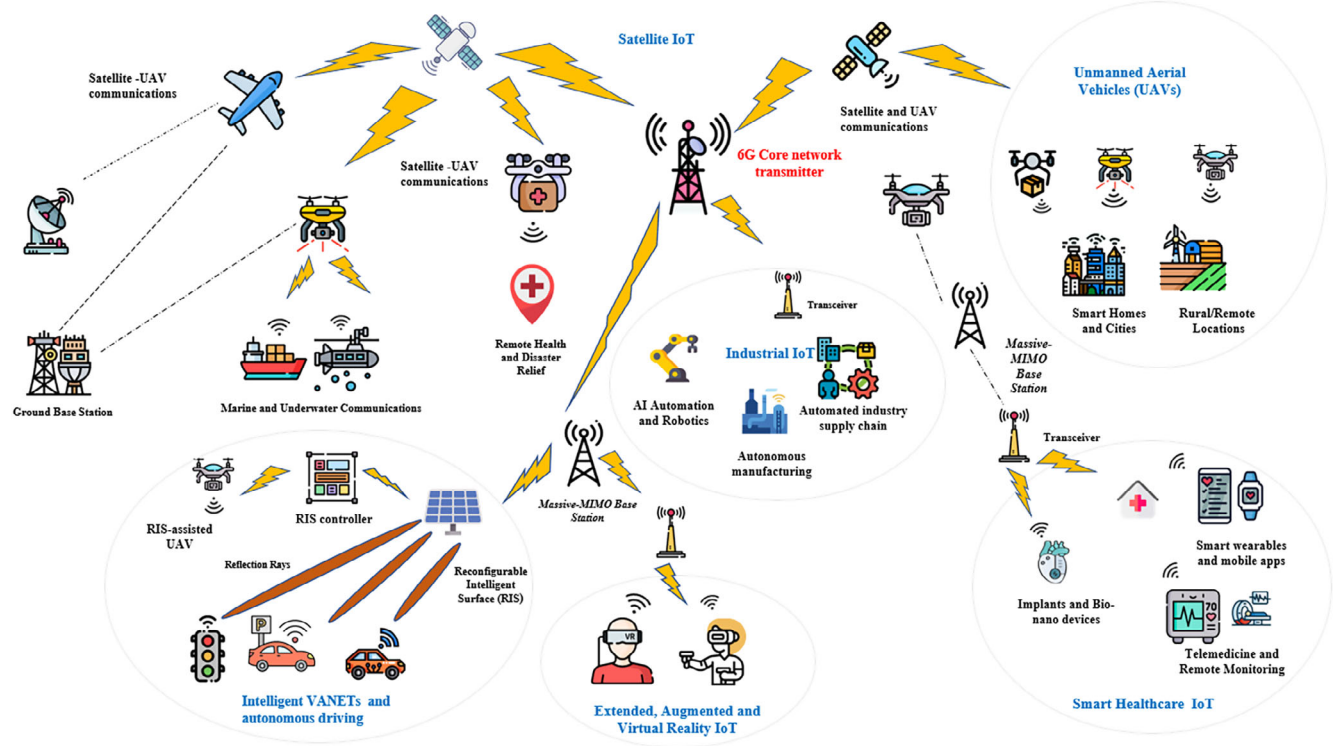

FIGURE 1 6G Internet of Things.

In this section, we review and summarize the state-of-the-art application of 6G IoT environments.

Figure 1 illustrates an overview of several applications of 6G wireless technology to several IoT environments including Intelligent VANETs and autonomous driving, UAVs, Satellite IoT, Smart healthcare IoT, Industrial IoT and Extended, Augmented and Virtual Reality IoT environments.

4.1 | Intelligent VANETs and autonomous driving

As global businesses, government representatives and organizations commit toward the rapid acceleration and transition to zero-carbon emission vehicles by 2035 (Committee on Climate Change, 2020), the goal of developing safe and fully autonomous vehicles has also been accelerated in tandem. Current terrestrial wireless networks are unable to meet the demands of future VANETs and will require both air and space satellite networks to compensate to achieve seamless communication of autonomous vehicles anywhere on the planet (H. Guo, Zhou, et al., 2021). Existing wireless networks including RF-based technology and 5G suffer communication and data packet loss due to deficiencies caused by the increase in the number of vehicles, high mobility and the large volume of network traffic generated and dispersed among vehicle-to-vehicle (V2V) communication (J. Hu et al., 2021; Kalalas & Alonso-Zarate, 2020; Lv et al., 2021; Mukhtaruzzaman & Atiquzzaman, 2020; Xu et al., 2021; Yao et al., 2013; Zhu et al., 2021). The resolve the issue, research developments have proposed a hybrid solution that includes RF and VLC technologies as a solution (Geng et al., 2022). However, the current 5G technology does not include VLC as an integrated technology for VANETs and 6G is envisioned to include and integrate VLC as an enabling technology for vehicular communications (Caputo et al., 2022).

Hence, to support intelligent VANETs and the safety of autonomous vehicles, an increase in reliability and low latency of V2V communication can only be met by the inherent properties and development infrastructure of 6G networks. 6G technology coupled with the application of deep learning (X. Chen, Leng, et al., 2021; F. Tang et al., 2020), AI-based clustering algorithms (Barbieri et al., 2021; Mukhtaruzzaman & Atiquzzaman, 2020; X. Zhou et al., 2021), edge intelligence, OWC, THz high-speed communication (He et al., 2021), and network-driven optimization using

machine learning algorithms (Sliwa et al., 2021) all provide a viable solution to resolving the current network communication inadequacies in VANETs.

4.2 | Unmanned aerial vehicles

Several recent studies have explored the application of 6G for UAVs. The studies (Dong et al., 2021; X. Jiang, Sheng, et al., 2021; R. Kumar & Agrawal, 2021; Qi et al., 2021; Sodhro, Pirbhulal, et al., 2021; S. Tang et al., 2021; H. Yang, Zhao, et al., 2021; Zhu et al., 2021) highlighted the role of UAVs in the delivery of ubiquitous network coverage of 6G wireless communication due to their low cost, deployment flexibility and low energy consumption. UAVs will act as edge network devices, and sensor devices and will be able to communicate seamlessly with other UAVs for real-time network updates across air-space geo locations especially in emergencies and transmit data between themselves and other base stations. This communication can only get achieved with better and more reliable connectivity provided by 6G technology. The study by Aggarwal et al. (2021) and Gupta, Nair, et al. (2021) describes how future UAVs utilizing 6G wireless communication could securely share and store data (captured high-quality videos and images) on distributed blockchain networks in real-time saving data storage space, processing and battery power which are inherently limited on UAVs such as drones. UAVs equipped with communication transceivers will be unrestricted to specific locations and obstacles, which allows them to provide wider cellular coverage in desirable locations and altitudes (J. Hu et al., 2021). Hence, UAVs will be very useful in assisting 6G IoT networks including intelligent VANETs and autonomous driving infrastructures.

4.3 | Satellite IoT

Extending terrestrial network communication coverage to non-terrestrial altitudes using low-orbit satellites will be feasible with 6G technology (C. Liu et al., 2021; Ziegler & Yrjola, 2020). This new 6G-enabled IoT network environment of non-terrestrial infrastructures includes the use of satellites and UAVs where conventional mobile/cellular technologies are difficult if not impossible to implement. The study by Chu et al. (2021) proposed models that address power consumption issues in future 6G satellite IoT networks using non-orthogonal multiple access (NOMA) schemes for low-orbit satellite internet communication. Hence, enabled by THz communication and low power consumption, a large number of low-orbit satellites can be deployed to extend internet coverage, deliver real-time internet access in remote locations, and also support marine/underwater networks. This new edge computing environment of satellites communicating in real-time using high-speed bandwidth will not only complement existing 4G and 5G terrestrial ecosystems but will be fully integrated to create a large-scale heterogeneous IoT network.

4.4 | Smart healthcare IoT

IoT is being applied in various areas to improve the provision and delivery of healthcare services. These include remote real-time health monitoring, telemedicine, home, and elderly healthcare and the detection and prevention of chronic diseases. Wearables, bio-integrated devices, and bio-nano intelligent systems are being developed with rapid speed to facilitate real-time healthcare services (Barakat et al., 2021; Bhat & Alqahtani, 2021; Hewa et al., 2020; Mardini et al., 2021; Mucchi et al., 2020; Nayak & Patgiri, 2020; Padhi & Charrua-Santos, 2021a). These IoT devices such as the ones described in Nasrollahzadeh et al. (2020) and Strobel and Mittnacht (2021) help to sense biological and chemical changes around a patient and send the collated data to edge or fog data center environments for further processing (Al-Turjman, 2020). However, its acceleration and progress are hindered by the reliability and latency of data communication by functioning sensors and nodes that transfer data to these data centers. These IoT devices currently use short-range communication standards like Bluetooth Low Energy (BLE) and ZigBee which incur significant delays. Although ZigBee is well suited for smart health applications, it poses a risk to the security of sensitive patient data that is being exchanged over the network and is not commonly implemented on smartphones compared to BLE (Baker et al., 2017). Similarly, long-range communications standards like Wi-Fi and NB-IoT operating on GSM, LTE, 4G and 5G networks do not offer reliable low-latency or high-speed communications compared to potential 6G technologies such as THz,

mURLLC or VLC. Studies conducted by Aggarwal et al. (2021), W. Guo (2020), Gupta et al. (2020), Hadi et al. (2020), Janjua et al. (2020), Kaiser et al. (2021) described the potential use of blockchain and AI-assisted UAVs in the future 6G-enabled smart health and telesurgery applications to better facilitate remote, reliable, and secure smart healthcare service delivery.

4.5 | Industrial IoT

The potential application of 6G wireless communication technology to Industrial IoT (IIoT) for optimizing better large-scale industrial operations and manufacturing processes has been identified and discussed in these studies (Ji, Wang, et al., 2021; Mukherjee et al., 2021; Padhi & Charrua-santos, 2021b; Peng et al., 2020; Sodhro, Zahid, et al., 2021). Specifically, the application of AI-enabled 6G technology can be used to achieve and accelerate smart automation and improve low carbon emissions and industry efficiency. Security and privacy considerations have also been the driving force behind the application of 6G-enabled technologies to IIOT. Certain network communication between industrial control systems and plants can be replaced using OWC such as VLC (Zakrzewski & Łaga, 2020). VLC is considered to be much more secure due to data being transmitted at a straight line of sight which maintains a high data density and fewer data distortion compared to current radio wave communication.

4.6 | Extended, augmented, and virtual reality IoT

One environment where the application of 6G technology will be significantly commercialized is with Extended, Augmented, and Virtual realities (XR, AR and VR). It is predicted that the market size for this technology will reach an estimated $393 billion by 2025 (Global News Wire, 2021b) and will spread into more diverse environments such as entertainment, AI, robotics (L. Qiao et al., 2021), and healthcare with extensive near-term growth potential. Newer IoT devices will be integrated with AI-enabled 6G-ready technology that allows the use of these devices to overlay objects into the real world. In healthcare, applied AR with high-speed 6G wireless communication will be used for telemedicine, telemonitoring and telesurgery practices (M. L. Jin et al., 2021). Major drawbacks have been identified in existing 5G telesurgery systems such as Virtual Interactive Presence and Augmented reality (VIPAR) (Davis et al., 2016), which include latency and poor data and network communication between remote and local stations. 6G technology has also been predicted to power next-generation consumer entertainment, especially in gaming and social media applications. Recent developments using VR to immerse a user into virtual worlds such as digital theme parks and first-person perspective or shooter (FPS) 3D games are becoming common features. Facebook's Metaverse (Sparkes, 2021) is one of such recent developments in social media VR/XR environments. Current 5G systems fall short of supporting these emerging applications. To enhance the commercial potential, it is envisioned that the current 5G URLLC will further evolve as enhanced-URLLC (e-URLLC) in 6G wireless communication networks (Nawaz et al., 2021). Studies Chakrabarti (2021) and Tripathi et al. (2021) highlight mobile AR driven by ultra-high bandwidth such as mmWave and THz spectrum provided by 6G. The application of AI and deep learning to effectively distribute and optimize user experience is being considered in prospective future 6G XR, AR, and VR IoT networks.

5 | FORENSICS CHALLENGES IN 6G IOT ENVIRONMENTS

6G wireless communication is promised to be a game-changer not just in extending wireless network technology from terrestrial to non-terrestrial architectures but will also provide superior user experience, service delivery and network optimization through fully autonomous and intelligent IoT networks and systems than current 5G technologies. This predicted high-speed, low latency, large-scale heterogeneous networks of devices transmitting, receiving, processing, and storing data in real-time will consist of valuable evidential data and forensic artifacts that could be relevant to digital forensics and incident response. However, the huge challenge for forensic examiners is the identification, collection, preservation, and reporting of digital evidence in these vast IoT environments. In this section, we introduce the main challenges of 6G IoT network environments.

5.1 | Forensic challenges in XR and VR environments

6G IoT network communication will make XR and VR much more mainstream, with autonomous and real-time communication between various network nodes in virtual worlds. This will create alternative realities where users can represent themselves as they wish, in just about any format they desire through their avatars (Freedom Fear Magazine, 2021). The application of 6G technology in the virtual world will undoubtedly not only improve user adoption and experience but will also increase the proliferation of virtual cybercrimes, cyber deviances, and cyber harms (Parti, 2010; Williams, 2006). Real-world crimes are perpetrated daily in virtual worlds, including money laundering, theft of digital assets such as non-fungible tokens (NFTs), sexual harassment and exploitation (virtual rape), intimidation or stalking, exchange of child abuse images and simulated sexual misconduct with an individual's avatar. In 2016, a gamer described being virtually groped by another avatar on *QuiVr* VR multi-player game (Jordan Belamire, 2016). Avatars are not autonomous but controlled by real people and can be susceptible to manipulation similar to real individuals (Papagiannidis et al., 2008). There are already reported cases of theft of virtual items that can be traded for virtual or actual cash and of sexual groping by one avatar by another (Schuyler Moore, 2017). Also, general issues of legal regulation regarding the application of VR technologies have emerged (Dremliuga et al., 2020). Real-world experiments have also been performed to demonstrate the feasibility of side-channel attacks in virtual environments (al Arafat et al., 2021; Ling et al., 2019). For these reasons, future virtual worlds present a unique set of challenges not just for the criminal justice system but also for digital forensic investigators in the collection, preservation, correlation, and analysis of forensic evidence.

Digital forensic investigation challenges have been previously identified for existing online platforms such as MMORPGs (Massive Multiplayer Online Role-Playing Games) (Taylor et al., 2019). However, the concept of conducting forensics investigations perpetrated in extended and virtual reality (XR/VR) environments is a new domain for most law enforcement agencies around the world. The lack of jurisdiction and geographical boundaries in these environments also makes forensic investigation significantly challenging. Therefore, making it difficult if not impossible to identify the scope of digital forensic investigations and the boundaries of a crime scene. Suggestions including surveillance actions by organizations that will play the same role as police, investigators and government in virtual worlds have been proposed (Park & Kim, 2022). However, at present, research focused on forensic methodologies, and techniques to collect evidential artifacts in virtual reality environments is still in its nascent stage (Yarramreddy et al., 2018). Moreover, there are not many digital forensic tools suitable for IoT and VR systems forensic investigations due to compatibility with the system that is being examined and also given the variety of existing firmware and operating systems (Castelo Gómez et al., 2021). Hence, forensic readiness and future research into frameworks and the development of tools to enable investigators to conduct sound forensic investigations in the near future are crucial.

5.2 | Forensic challenges of satellite IoT and UAVs

Digital forensic evidence identification, collection, preservation, correlation, and analysis of satellite IoT devices including UAVs will be very challenging considering the devices will be designed to work autonomously, in real-time and in non-terrestrial altitudes and underwater locations. Forensic analysis on a variety of UAVs including drones has been conducted in an attempt to extract, analyze, and process forensic artifacts (Al-Room et al., 2021; Hamdi et al., 2019; R. Kumar & Agrawal, 2021; Thornton & Bagheri Zadeh, 2022). The common theme in these studies is that in most cases, investigators require recovery of the physical devices and access to the OEM (Original Equipment Manufacturer) including flight logs and location data that can be found in the integrated memory of the drones.

However, the challenges in 6G-enabled IoT environments will include the physical recovery of damaged or compromised UAVs and satellite IoT devices deployed in non-terrestrial environments such as underwater locations and high altitudes as shown in Figure 1. The components of UAVs that constitute physical evidence can be potentially scattered across various locations (Bouafif et al., 2020; Horsman, 2016). Therefore, establishing a sound forensic link between a recovered UAV and the associated radio or ground controller to determine ownership can be challenging.

In some scenarios where investigators have been able to recover forensic evidence, it is often not possible to link the drone to a suspect based on data only extracted from the drone (Thornton & Bagheri Zadeh, 2022). Moreover, forensic artifacts are saved in a variety of file formats depending upon the OEM of the drone that cannot be analyzed using traditional digital forensic tools (R. Kumar & Agrawal, 2021). In most cases, investigators rely on a variety of open-source

tools that are not specifically designed for drone forensic analysis. Continuous and future research directions in UAV forensics with consideration for devices deployed in non-terrestrial altitudes are required to address these challenges.

5.3 | Forensic challenges in heterogeneous optical wireless networks

The convergence of heterogeneous networks consisting of both RF and optical wireless-based networks will play a leading role in the provision and delivery of high-quality of service (QoS) expected in 6G-enabled wireless communication networks (Chowdhury et al., 2020). This includes the hybrid approach of integrating two or more wireless technologies for reliability, increased uptime, efficiency, reduced interference, network load balancing and improvements, especially for remote and non-terrestrial environments. For example, a hybrid-dual approach could include RF/optical, Wi-Fi/Li-Fi, free-space optical (FSO)/VLC, Li-Fi/OCC, femtocell/VLC, power-line communication (PLC)/VLC, and so forth (Baig et al., 2018; Buyukcorak & Karabulut Kurt, 2017; Hu et al., 2016; Jin et al., 2015; Kashef et al., 2018; Khan et al., 2017; Li et al., 2016; Rahaim et al., 2017; Sharma et al., 2018; Vats et al., 2017; Wang et al., 2015, 2018; Wu & Haas, 2017).

However, the seamless integration of existing RF wireless networks with optical wireless networks requires dynamic network management technology such as software-defined networking (SDN), which is based on the principles of network virtualization and the establishment of separate control planes and data planes (Haas et al., 2020). A typical hybrid system as described in Chowdhury et al. (2020), G. Pan et al. (2017), Rahaim et al. (2011), Rakia et al. (2016), W. Wu, Safari, and Haas (2017), and Yan et al. (2016), consists of scenarios where a device/mobile terminal (receiver, transmitter, or transceiver) has access to both networks/access points (APs) simultaneously for uplink and downlink. Another scenario described in such a hybrid system is when one network/AP is used for uplink and another network exclusively for downlink. Access to a specific network can also vary based on the traffic type as different applications require different levels of QoS, supported by a variety of networks. Figure 2 shows a typical hybrid/heterogeneous network topology.

This type of hybrid/heterogeneous network topology in future 6G IoT networks creates difficulties for network forensics in identifying, capturing, and preserving all network packets from multiple networks and terminal nodes operating at a high-speed transmission rate. The difficulty also lies in the isolation, filtering and decoding of specific data packets considering a heterogeneous network will consist of various network protocols and metadata that are completely independent of one another but working together in tandem. If a network breach or an anomaly is detected on one network, it may be difficult to attribute the incident to that specific network alone. Moreover, ascertaining the integrity of data captured on a heterogeneous network is a critical and difficult task for network forensics. The scope, size and complexity of data make it challenging for investigators to maintain the integrity of the data.

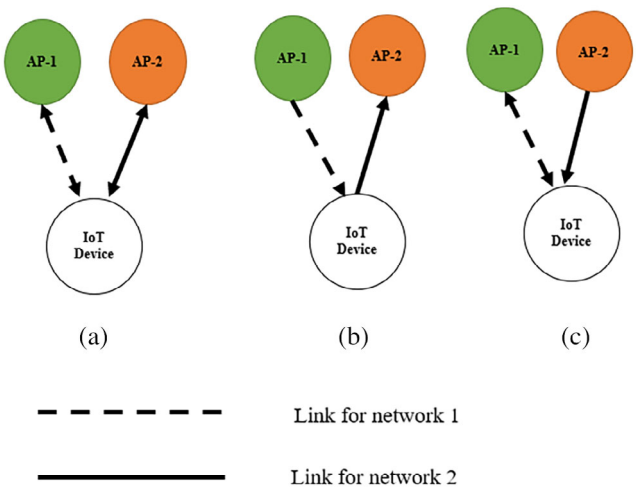

FIGURE 2 Hybrid/heterogeneous network topology: (a) both networks for uplink and downlink, (b) network-1 for downlink and network-2 for uplink, (c) network-1 for both uplink and downlink and network-2 for downlink. *Source*: Adapted from Chowdhury et al. (2020).

Each of the OWC technologies has unique architectures, that differ from one another in terms of modulation technique, transmitting system, receiving system and communication system (Chowdhury, Hossan, Islam, & Jang, 2018). The use of encryption and transmission of high-throughput OWC signals will be very challenging if not impossible.

Current studies for OWC especially the IEEE 802.15.7 standard of VLC have mainly focused on performance evaluation and optimization to improve the reliability and coverage of future IoT network communication in indoor and outdoor environments (Feng et al., 2019; Jani et al., 2019; Kashef et al., 2018; A. Kumar & Ghorai, 2020; M. Li & Lin, 2015; Ndjiongue et al., 2017; Sheng et al., 2022). However, no research studies focused on digital forensics and incident response approaches for OWC networks. Moreover, conducting sound network forensics will require a variety of specialized tools and techniques for deep packet inspection and analysis in 6G IoT heterogeneous networks.

5.4 | Forensic challenges in 6G edge computing environments

As discussed in Section 3, the key enabling technologies that will support heterogeneous 6G-enabled IoT networks will be housed in edge computing environments that constitute huge data centers and databases to the network's periphery, where it will be closer to devices and sensors (Iftikhar et al., 2023; Singh et al., 2021; Vu Khanh et al., 2023). Aggregated data stored on numerous edge computing servers from multiple IoT networks, could be difficult to identify and collect due to the sheer volume and complexity of the data. For example, some of the data may be stored in different formats or encrypted and could require real-time network monitoring which makes it more challenging for forensic investigators. Moreover, due to the limited computing and storage capacities of edge computing environments, edge nodes often offload computation tasks to the cloud if they lack the computation resources needed to meet performance requirements so that the end device can get a response within a reasonable latency (Chuang & Hung, 2023; R. Lin et al., 2023). Hence, relevant forensic artifacts may be volatile or non-persistent on edge servers and database locations. Evidential data may be spread across multiple cloud servers making collection and preservation challenging or impossible in certain scenarios. Therefore, novel digital forensic approaches and methods must be considered to enable coordinated and sound forensic investigations to be carried out on these heterogeneous 6G-enabled IoT networks.

6 | FORENSIC READINESS AND FUTURE RESEARCH DIRECTIONS

There is no doubt that the development and deployment of 6G wireless technology will have a profound impact on the future of wireless communication and enable the Internet of Everything. However, as we have identified from this survey, forensic investigators face many significant digital forensic challenges. In this section, we highlight several digital forensic approaches and research directions toward addressing these challenges. We also discuss forensic investigation opportunities and readiness for future 6G and beyond IoT networks.

6.1 | Edge intelligence forensics

Future 6G network communication will utilize wireless edge networks to provide not only low-latency content delivery and computation services but also localized data acquisition, aggregation, and processing (J. Zhang & Letaief, 2020). Recent studies have proposed the use of federated learning (FL) and machine learning (ML) approaches to optimize network performance, and low latency and improve user data privacy in IoT autonomous environments and envisioned 6G wireless networks (X. Chen, Leng, et al., 2021; Deng et al., 2020; Fadlullah & Kato, 2020; Gupta, Reebadiya, & Tanwar, 2021; Huh & Seo, 2019; Y. Liu et al., 2020; Qu et al., 2021; Samarakoon et al., 2018, 2020; Xianjia et al., 2021; Z. Yang, Chen, et al., 2021; X. Zhou et al., 2021). In digital forensics, machine learning (ML) approaches and methodologies have been proposed to address the ever-increasing volume, complexity, and diversity of data (Abraham et al., 2021; Lanagan & Choo, 2021; Rathore et al., 2021; Serhal & Le-Khac, 2021). These approaches when combined could enable the seamless identification and collection of forensic data from 6G IoT edge networks. Edge intelligence forensics offers intelligence at the edge to identify and collect evidential forensic artifacts from large 6G IoT network datasets for forensic analysis and examination using state-of-the-art federated and machine learning approaches.

For example, one viable approach to edge intelligence forensics will be the application of AI to identify and collect forensic evidence using self-learning ML models from vastly distributed 6G IoT network edge servers as shown in

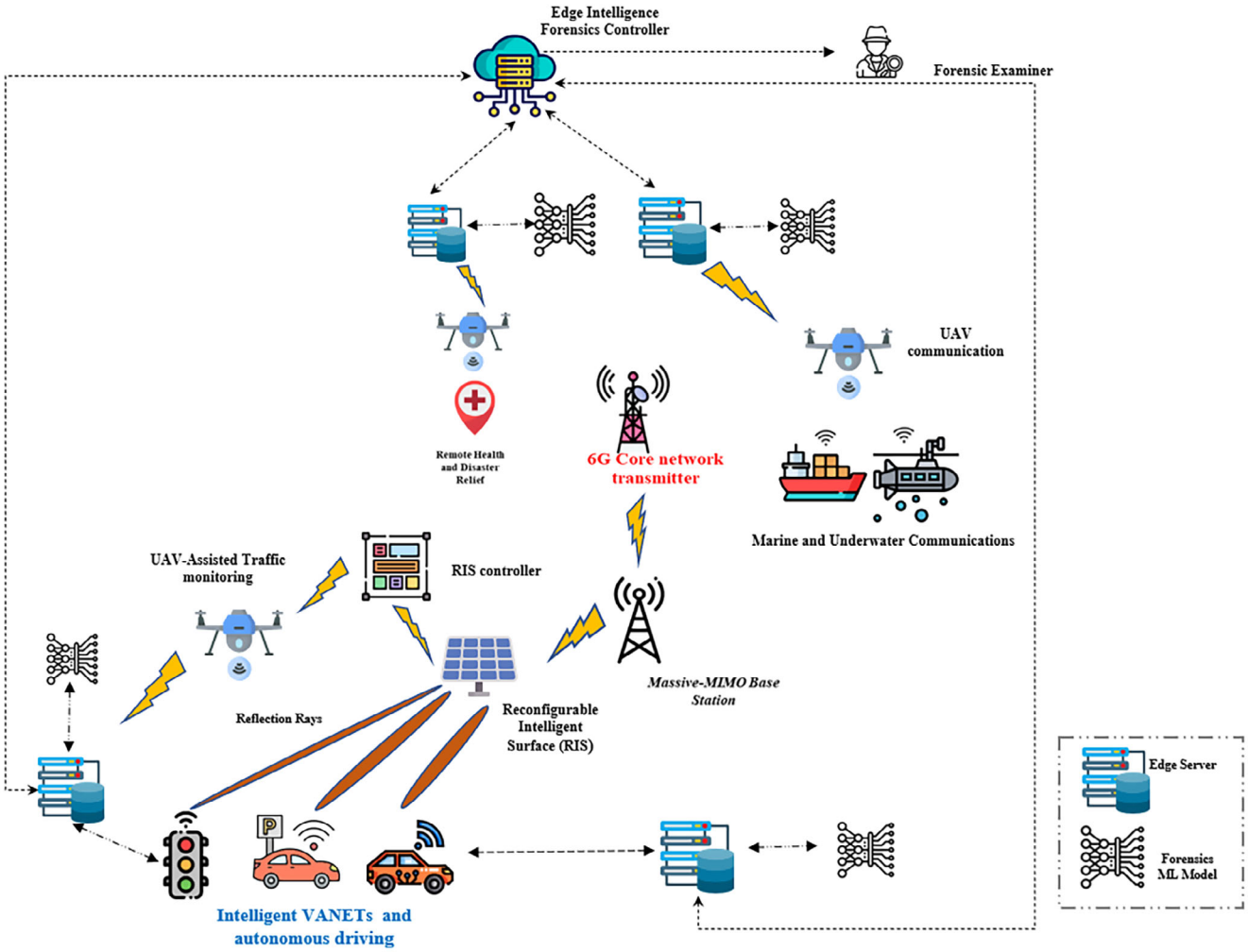

FIGURE 3 Edge intelligence forensics in 6G IoT networks.

Figure 3. In the given scenario, the UAVs as edge devices, provide an extension to the 6G wireless network communication. For intelligent VANETs and autonomous systems, UAVs are unable to provide path planning or make intelligent decisions due to high computation, data processing, and energy consumption. Due to these constraints, the UAVs forward data communication to the nearby edge servers (having higher capabilities) to perform these actions. Smart vehicles and intelligent traffic systems also forward data captured to nearby edge servers for autonomous driving decisions and real-time traffic management.

Similarly, in marine and underwater locations, UAVs forward data packets to nearby edge servers and caches for real-time data communication. In each scenario, the edge servers are deployed locally with adaptive forensic ML models based on FL anomaly detection which is governed by an edge intelligence controller. This approach allows the accurate identification and classification of attacks on the 6G IoT networks which can be monitored, collected, and analyzed by the forensic examiner through the controller. Due to the high volume and complexity of data, edge intelligence forensics can help investigators save time in big data analysis during forensic investigations, assist in real-time incident response to known attacks and facilitate the detection of network traffic anomalies. The ML models can be trained for specific 6G IoT network environments to identify network patterns and signatures for forensic analysis.

6.2 | XR/VR forensics

The development of 6G wireless communication technology will proliferate the use of XR/VR applications in contrast to the current 4G and 5G networks. Therefore, sound forensic methodologies and tools to recover evidential data and

reconstruct user activities in virtual environments are required. Current research studies have focused on how virtual reality could be used to support police investigations (Norman et al., 2020) or used to teach digital forensics concepts (Hassenfeldt et al., 2020). However, there is a lack of research studies that focus on digital forensic investigations in XR/VR environments. Moreover, there is a lack of forensic tools specifically for the identification, collection, preservation, and analysis of digital artifacts in XR/VR environments. In Yarramreddy et al. (2018), a forensic analysis of immersive virtual reality social applications was conducted. The authors recovered client-side and network-based artifacts generated using the HTC Vive and the Oculus Rift. The VR applications analyzed include Steam, Bigscreen, Rec Room, Altspacevr, and Facebook Spaces. Limited evidential data relating to users' activities were recovered from log files generated by the VR applications installed on a Windows PC workstation. Data remnants of forensic value were only successfully recovered from the network packet inspection of a single VR application in their experiments. Considering in the not-so-distant future, the development of XR/VR will move toward the full implementation of virtual experiences, assets and environments including "the metaverse," the study concludes that there is room for further research and development of tools in this nascent domain of digital forensics.

6.3 | Optical wireless network forensics

In scenarios that require digital forensics and incident response to cyber-attacks including injection and message replay attacks in OWC network topologies (Soderi et al., 2022), conducting network forensics using specialized tools will be required. Unlike traditional RF-based signals, sniffing, capturing, and decoding OWC signals require specialized hardware and software. In the study by Cui et al. (2020), a receiver coil, signal processing and frame decoding, spanning across multiple hardware and software were designed to successfully sniff and capture VLC signals based on Variable Pulse Position Modulation (VPPM) and On–Off Keying (OOK) modulation schemes. However, sniffing VLC signals based on other schemes including Color Shift Keying (CSK) and advanced modulation schemes such as DCO-OFDM (direct-current-biased optical OFDM) and ACO-OFDM (asymmetrically clipped optical OFDM) will require a different approach. A previous study by Marin-Garcia et al. (2016) described the complexity of sniffing VLC data for analysis. The study required the use of a sophisticated device setup that includes a telescope and a PIN photodiode followed by a trans-impedance amplifier at a distance of 30 m to sniff data in a VLC scenario. This further highlights the need for the development of simpler and less complicated tools for sniffing VLC network traffic for analysis. At the time of writing, there is a lack of development in tools for VLC data capture and analysis.

Since visible light cannot penetrate objects, VLC channels can be easily blocked during live traffic capture even with the application of MIMO techniques to mitigate atmospheric absorption, loss of sight (LOS) and the shadowing effect (Lian et al., 2019). This inevitably makes network sniffing problematic for forensic investigators.

Future research agendas will also need to focus on novel methods and tools required to capture and analyze network data in other OWC systems including underwater optical wireless communications (UOWCs) that transmit data using carriers such as acoustic waves, RF waves, and optical waves, especially in underwater locations that may be prone to signal interference or loss.

7 | CONCLUSION

6G wireless communication technology is expected to outperform current wireless network technologies by providing revolutionary support and application via the IoT. Its envisioned development and application create a variety of digital forensics challenges. In this article, we presented and discussed the major forensic challenges of 6G IoT networks along with potential forensic readiness approaches, opportunities, and future research directions. At the time of writing, there are no studies that have presented forensic challenges specific to future 6G IoT networks. This study highlights the need for more in-depth studies, and the development of scientifically validated forensic methodologies and tools to ensure successful digital investigations in future 6G IoT environments.

AUTHOR CONTRIBUTIONS

Alex Olushola Akinbi: Conceptualization (lead); data curation (lead); investigation (lead); methodology (lead); project administration (lead); writing – original draft (lead); writing – review and editing (lead).

ACKNOWLEDGMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST STATEMENT

The author declares no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Alex Olushola Akinbi https://orcid.org/0000-0001-6980-307X

RELATED WIREs ARTICLES

VANET security and forensics: Challenges and opportunities

FURTHER READING

Zhang, X., Wuwong, N., Li, H., & Zhang, X. (2010). Information security risk management framework for the cloud computing environments. In *10th IEEE international conference on computer and information technology* (pp. 1328–1334). IEEE. https://doi.org/10.1109/CIT.2010.501

REFERENCES

Abraham, J., Ng, R., Morelato, M., Tahtouh, M., & Roux, C. (2021). Automatically classifying crime scene images using machine learning methodologies. *Forensic Science International: Digital Investigation*, *39*, 301273. https://doi.org/10.1016/j.fsidi.2021.301273

Aggarwal, S., Kumar, N., & Tanwar, S. (2021). Blockchain-envisioned UAV communication using 6G networks: Open issues, use cases, and future directions. *IEEE Internet of Things Journal*, *8*(7), 5416–5441. https://doi.org/10.1109/JIOT.2020.3020819

Akinbi, A., & Berry, T. (2020). Forensic investigation of Google assistant. *SN Computer Science*, *1*(5), 272. https://doi.org/10.1007/s42979-020-00285-x

al Arafat, A., Guo, Z., & Awad, A. (2021). VR-Spy: A side-channel attack on virtual key-logging in VR headsets. In *Proceedings—2021 IEEE conference on virtual reality and 3D user interfaces, VR 2021*. IEEE. https://doi.org/10.1109/VR50410.2021.00081

Alenezi, A., Atlam, H., Alsagri, R., Alassafi, M., & Wills, G. (2019). IoT forensics: A state-of-the-art review, challenges and future directions. In *Proceedings of the 4th international conference on complexity, future information systems and risk* (pp. 106–115). SciTePress–Science and Technology Publications. https://doi.org/10.5220/0007905401060115

Al-Kinani, A., Wang, C. X., Zhou, L., & Zhang, W. (2018). Optical wireless communication channel measurements and models. *IEEE Communications Surveys and Tutorials*, *20*(3), 1939–1962. https://doi.org/10.1109/COMST.2018.2838096

Allam, Z., & Jones, D. S. (2021). Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies. *Land Use Policy*, *101*, 105201. https://doi.org/10.1016/j.landusepol.2020.105201

Al-Room, K., Iqbal, F., Baker, T., Shah, B., Yankson, B., MacDermott, A., & Hung, P. C. K. (2021). Drone forensics: A case study of digital forensic investigations conducted on common drone models. *International Journal of Digital Crime and Forensics*, *13*(1), 1–25. https://doi.org/10.4018/IJDCF.2021010101

Alsharif, M. H., Kelechi, A. H., Albreem, M. A., Chaudhry, S. A., Zia, M. S., & Kim, S. (2020). Sixth generation (6G) wireless networks: Vision, research activities, challenges and potential solutions. *Symmetry*, *12*(4), 676. https://doi.org/10.3390/sym12040676

Al-Turjman, F. (2020). A cognitive routing protocol for bio-inspired networking in the internet of nano-things (IoNT). *Mobile Networks and Applications*, *25*(5), 1929–1943. https://doi.org/10.1007/s11036-017-0940-8

Alzidaneen, A., Alsharoa, A., & Alouini, M. S. (2020). Resource and placement optimization for multiple UAVs using backhaul tethered balloons. *IEEE Wireless Communications Letters*, *9*(4), 543–547. https://doi.org/10.1109/LWC.2019.2961906

Baggili, I., Oduro, J., Anthony, K., Breitinger, F., & McGee, G. (2015). Watch what you wear: Preliminary forensic analysis of smart watches. In *Proceedings—10th international conference on availability, reliability and security, ARES 2015* (pp. 303–311). IEEE. https://doi.org/10.1109/ARES.2015.39

Baig, S., Muhammad Asif, H., Umer, T., Mumtaz, S., Shafiq, M., & Choi, J. G. (2018). High data rate discrete wavelet transform-based PLC-VLC design for 5G communication systems. *IEEE Access*, *6*, 52490–52499. https://doi.org/10.1109/ACCESS.2018.2870138

Baker, S. B., Xiang, W., & Atkinson, I. (2017). Internet of things for smart healthcare: Technologies, challenges, and opportunities. *IEEE Access*, *5*, 26521–26544. https://doi.org/10.1109/ACCESS.2017.2775180

Barakat, B., Taha, A., Samson, R., Steponenaite, A., Ansari, S., Langdon, P. M., Wassell, I. J., Abbasi, Q. H., Imran, M. A., & Keates, S. (2021). 6G opportunities arising from Internet of Things use cases: A review paper. *Future Internet*, *13*(6):159. https://doi.org/10.3390/fi13060159

Barbieri, L., Savazzi, S., Brambilla, M., & Nicoli, M. (2021). Decentralized federated learning for extended sensing in 6G connected vehicles. *Vehicular Communications*, *33*, 100396. https://doi.org/10.1016/j.vehcom.2021.100396

Bariah, L., Mohjazi, L., Muhaidat, S., Sofotasios, P. C., Kurt, G. K., Yanikomeroglu, H., & Dobre, O. A. (2020). A prospective look: Key enabling technologies, applications and open research topics in 6G networks. *IEEE Access*, *8*, 174792–174820. https://doi.org/10.1109/ACCESS.2020.3019590

Bhat, J. R., & Alqahtani, S. A. (2021). 6G ecosystem: Current status and future perspective. *IEEE Access*, *9*, 43134–43167. https://doi.org/10.1109/ACCESS.2021.3054833

Bouafif, H., Kamoun, F., & Iqbal, F. (2020). Towards a better understanding of drone forensics: A case study of parrot AR drone 2.0. *International Journal of Digital Crime and Forensics*, *12*(1), 35–57. https://doi.org/10.4018/IJDCF.2020010103

Buyukcorak, S., & Karabulut Kurt, G. (2017). A Bayesian perspective on RSS based localization for visible light communication with heterogeneous networks extension. *IEEE Access*, *5*, 17487–17500. https://doi.org/10.1109/ACCESS.2017.2746141

Cao, K., Liu, Y., Meng, G., & Sun, Q. (2020). An overview on edge computing research. *IEEE Access*, *8*, 85714–85728. https://doi.org/10.1109/ACCESS.2020.2991734

Caputo, S., Mucchi, L., Umair, M. A., Meucci, M., Seminara, M., & Catani, J. (2022). The role of bidirectional VLC systems in low-latency 6G vehicular networks and comparison with IEEE802.11p and LTE/5G C-V2X. *Sensors*, *22*(22), 8618. https://doi.org/10.3390/s22228618

Castelo Gómez, J. M., Carrillo Mondéjar, J., Roldán Gómez, J., & Martínez Martínez, J. (2021). Developing an IoT forensic methodology. A concept proposal. *Forensic Science International: Digital Investigation*, *36*, 301114. https://doi.org/10.1016/j.fsidi.2021.301114

Chakrabarti, K. (2021). Deep learning based offloading for mobile augmented reality application in 6G. *Computers and Electrical Engineering*, *95*, 107381. https://doi.org/10.1016/j.compeleceng.2021.107381

Chen, X., Leng, S., He, J., & Zhou, L. (2021). Deep-learning-based intelligent intervehicle distance control for 6G-enabled cooperative autonomous driving. *IEEE Internet of Things Journal*, *8*(20), 15180–15190. https://doi.org/10.1109/JIOT.2020.3048050

Chen, Y., Yan, L., Han, C., & Tao, M. (2021). Millidegree-level direction-of-arrival estimation and tracking for terahertz ultra-massive MIMO systems. *IEEE Transactions on Wireless Communications*, *21*, 869–883. https://doi.org/10.1109/TWC.2021.3100073

Choo, K.-K. R. (2021). Internet of things (IoT) security and forensics. In *Proceedings of the 2nd workshop on CPS&IoT security and privacy* (pp. 27–28). ACM Digital Library. https://doi.org/10.1145/3462633.3484691

Chowdhury, M. Z., Hasan, M. K., Shahjalal, M., Hossan, M. T., & Jang, Y. M. (2020). Optical wireless hybrid networks: Trends, opportunities, challenges, and research directions. *IEEE Communications Surveys & Tutorials*, *22*(2), 930–966. https://doi.org/10.1109/COMST.2020.2966855

Chowdhury, M. Z., Hossan, M. T., & Jang, Y. M. (2018). Interference management based on RT/nRT traffic classification for FFR-aided small cell/macrocell heterogeneous networks. *IEEE Access*, *6*, 31340–31358. https://doi.org/10.1109/ACCESS.2018.2844843

Chowdhury, M. Z., Hossan, M. T., Islam, A., & Jang, Y. M. (2018). A comparative survey of optical wireless technologies: Architectures and applications. *IEEE Access*, *6*, 9819–9840. https://doi.org/10.1109/ACCESS.2018.2792419

Chu, J., Chen, X., Zhong, C., & Zhang, Z. (2021). Robust design for NOMA-based multibeam LEO satellite internet of things. *IEEE Internet of Things Journal*, *8*(3), 1959–1970. https://doi.org/10.1109/JIOT.2020.3015995

Chuang, Y.-T., & Hung, Y.-T. (2023). A real-time and ACO-based offloading algorithm in edge computing. *Journal of Parallel and Distributed Computing*, *179*, 104703. https://doi.org/10.1016/j.jpdc.2023.04.004

Committee on Climate Change. (2020). *The sixth carbon budget: The UK's path to net zero*. The Carbon Budget.

Conti, M., Dehghantanha, A., Franke, K., & Watson, S. (2018). Internet of things security and forensics: Challenges and opportunities. *Future Generation Computer Systems*, *78*, 544–546. https://doi.org/10.1016/j.future.2017.07.060

Cui, M., Feng, Y., Wang, Q., & Xiong, J. (2020). *Sniffing visible light communication through walls*. ACM Digital Library. https://doi.org/10.1145/3372224.3419187

Dang, S., Amin, O., Shihada, B., & Alouini, M.-S. (2020). What should 6G be? *Nature Electronics*, *3*(1), 20–29. https://doi.org/10.1038/s41928-019-0355-6

Davis, M. C., Can, D. D., Pindrik, J., Rocque, B. G., & Johnston, J. M. (2016). Virtual interactive presence in global surgical education: International collaboration through augmented reality. *World Neurosurgery*, *86*, 103–111. https://doi.org/10.1016/j.wneu.2015.08.053

Dawson, L., & Akinbi, A. (2021). Challenges and opportunities for wearable IoT forensics: TomTom spark 3 as a case study. *Forensic Science International: Reports*, *3*, 100198. https://doi.org/10.1016/j.fsir.2021.100198

de Alwis, C., Kalla, A., Pham, Q.-V., Kumar, P., Dev, K., Hwang, W.-J., & Liyanage, M. (2021). Survey on 6G frontiers: Trends, applications, requirements, technologies and future research. *IEEE Open Journal of the Communications Society*, *2*, 836–886. https://doi.org/10.1109/ojcoms.2021.3071496

Deng, S., Zhao, H., Fang, W., Yin, J., Dustdar, S., & Zomaya, A. Y. (2020). Edge intelligence: The confluence of edge computing and artificial intelligence. *IEEE Internet of Things Journal*, *7*(8), 7457–7469. https://doi.org/10.1109/JIOT.2020.2984887

Dong, C., Shen, Y., Qu, Y., Wang, K., Zheng, J., Wu, Q., & Wu, F. (2021). UAVs as an intelligent service: Boosting edge intelligence for air-ground integrated networks. *IEEE Network*, *35*(4), 167–175. https://doi.org/10.1109/MNET.011.2000651

Dremliuga, R., Dremliuga, O., & Iakovenko, A. (2020). Virtual reality: General issues of legal regulation. *Journal of Politics and Law*, *13*(1), 75. https://doi.org/10.5539/jpl.v13n1p75

Fadlullah, Z. M., & Kato, N. (2020). HCP: Heterogeneous computing platform for federated learning based collaborative content caching towards 6G networks. *IEEE Transactions on Emerging Topics in Computing*, *10*, 112–123. https://doi.org/10.1109/TETC.2020.2986238

Feng, S., Bai, T., & Hanzo, L. (2019). Joint power allocation for the multi-user NOMA-downlink in a power-line-fed VLC network. *IEEE Transactions on Vehicular Technology*, *68*(5), 5185–5190. https://doi.org/10.1109/TVT.2019.2906095

Freedom Fear Magazine. (2021). *Crime and policing in virtual worlds*. http://f3magazine.unicri.it/?p=360

Gai, R., Du, X., Ma, S., Chen, N., & Gao, S. (2021). A summary of 5G applications and prospects of 5G in the internet of things. In *IEEE 2nd international conference on big data, artificial intelligence and internet of things engineering (ICBAIE)* (pp. 858–863). IEEE. https://doi.org/10.1109/ICBAIE52039.2021.9389985

Galisteo, A., Juara, D., & Giustiniano, D. (2019). Research in visible light communication systems with OpenVLC1.3. In *IEEE 5th world forum on Internet of Things, WF-IoT 2019—Conference proceedings*. IEEE. https://doi.org/10.1109/WF-IoT.2019.8767252

Geng, Z., Khan, F. N., Guan, X., & Dong, Y. (2022). Advances in visible light communication technologies and applications. *Photonics*, *9*(12), 893. https://doi.org/10.3390/photonics9120893

Giordani, M., Polese, M., Mezzavilla, M., Rangan, S., & Zorzi, M. (2020). Toward 6G networks: Use cases and technologies. *IEEE Communications Magazine*, *58*(3), 55–61. https://doi.org/10.1109/MCOM.001.1900411

Global News Wire. (2021a). *Global 6G market report 2021*. Global 6G Market Report 2021. https://www.globenewswire.com/en/news-release/2021/04/19/2212107/28124/en/Global-6G-Market-Report-2021-Market-to-Reach-1-773-09-Billion-by-2035.html

Global News Wire. (2021b). *Extended reality (XR) market size to reach USD 393 billion by 2025 at 69.4% CAGR—Report by market research future (MRFR)*. https://www.globenewswire.com/en/news-release/2021/08/09/2277296/0/en/Extended-Reality-XR-Market-Size-to-Reach-USD-393-Billion-by-2025-at-69-4-CAGR-Report-by-Market-Research-Future-MRFR.html

Griffiths, A. D., Herrnsdorf, J., McKendry, J. J. D., Strain, M. J., & Dawson, M. D. (2020). Gallium nitride micro-light-emitting diode structured light sources for multi-modal optical wireless communications systems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2169), 20190185. https://doi.org/10.1098/rsta.2019.0185

Guo, F., Yu, F. R., Zhang, H., Li, X., Ji, H., & Leung, V. C. M. (2021). Enabling massive IoT toward 6G: A comprehensive survey. *IEEE Internet of Things Journal*, *8*(15), 11891–11915. https://doi.org/10.1109/JIOT.2021.3063686

Guo, H., Zhou, X., Liu, J., & Zhang, Y. (2021). Vehicular intelligence in 6G: Networking, communications, and computing. *Vehicular Communications*, *33*, 100399. https://doi.org/10.1016/j.vehcom.2021.100399

Guo, W. (2020). Explainable artificial intelligence for 6G: Improving trust between human and machine. *IEEE Communications Magazine*, *58*(6), 39–45. https://doi.org/10.1109/MCOM.001.2000050

Gupta, R., Nair, A., Tanwar, S., & Kumar, N. (2021). Blockchain-assisted secure UAV communication in 6G environment: Architecture, opportunities, and challenges. *IET Communications*, *15*(10), 1352–1367. https://doi.org/10.1049/cmu2.12113

Gupta, R., Reebadiya, D., & Tanwar, S. (2021). 6G-enabled edge intelligence for ultra-reliable low latency applications: Vision and mission. *Computer Standards & Interfaces*, *77*, 103521. https://doi.org/10.1016/j.csi.2021.103521

Gupta, R., Shukla, A., & Tanwar, S. (2020). BATS: A blockchain and AI-empowered drone-assisted telesurgery system towards 6G. *IEEE Transactions on Network Science and Engineering*, *8*, 2958–2967. https://doi.org/10.1109/TNSE.2020.3043262

Haas, H., Elmirghani, J., & White, I. (2020). Optical wireless communication. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2169), 20200051. https://doi.org/10.1098/rsta.2020.0051

Hadi, M. S., Lawey, A. Q., El-Gorashi, T. E. H., & Elmirghani, J. M. H. (2020). Patient-centric HetNets powered by machine learning and big data analytics for 6G networks. *IEEE Access*, *8*, 85639–85655. https://doi.org/10.1109/ACCESS.2020.2992555

Hamdi, D. A., Iqbal, F., Alam, S., Kazim, A., & MacDermott, A. (2019). Drone forensics: A case study on DJI phantom 4. In *Proceedings of IEEE/ACS international conference on computer systems and applications*. AICCSA. https://doi.org/10.1109/AICCSA47632.2019.9035302

Hassenfeldt, C., Jacques, J., & Baggili, I. (2020). Exploring the learning efficacy of digital forensics concepts and bagging & tagging of digital devices in immersive virtual reality. *Forensic Science International: Digital Investigation*, *33*, 301011. https://doi.org/10.1016/j.fsidi.2020.301011

He, J., Yang, K., & Chen, H. H. (2021). 6G cellular networks and connected autonomous vehicles. *IEEE Network*, *35*(4), 255–261. https://doi.org/10.1109/MNET.011.2000541

Hewa, T., Gur, G., Kalla, A., Ylianttila, M., Bracken, A., & Liyanage, M. (2020). The role of blockchain in 6G: Challenges, opportunities and research directions. In *2nd 6G wireless summit (6G SUMMIT)* (pp. 1–5). IEEE. https://doi.org/10.1109/6GSUMMIT49458.2020.9083784

Horsman, G. (2016). Unmanned aerial vehicles: A preliminary analysis of forensic challenges. *Digital Investigation*, *16*, 1–11. https://doi.org/10.1016/j.diin.2015.11.002

Hu, J., Chen, C., Cai, L., Khosravi, M. R., Pei, Q., & Wan, S. (2021). UAV-assisted vehicular edge computing for the 6G internet of vehicles: Architecture, intelligence, and challenges. *IEEE Communications Standards Magazine*, *5*(2), 12–18. https://doi.org/10.1109/MCOMSTD.001.2000017

Hu, P., Pathak, P. H., Das, A. K., Yang, Z., & Mohapatra, P. (2016). PLiFi: Hybrid WiFi-VLC networking using power lines. In *Proceedings of the annual international conference on mobile computing and networking, MOBICOM*. ACM Digital Library. https://doi.org/10.1145/2981548.2981549

Huang, H., Yang, J., Huang, H., Song, Y., & Gui, G. (2018). Deep learning for super-resolution channel estimation and doa estimation based massive MIMO system. *IEEE Transactions on Vehicular Technology*, *67*, 8549–8560. https://doi.org/10.1109/TVT.2018.2851783

Huh, J.-H., & Seo, Y.-S. (2019). Understanding edge computing: Engineering evolution with artificial intelligence. *IEEE Access*, *7*, 164229–164245. https://doi.org/10.1109/ACCESS.2019.2945338

Iftikhar, S., Gill, S. S., Song, C., Xu, M., Aslanpour, M. S., Toosi, A. N., Du, J., Wu, H., Ghosh, S., Chowdhury, D., Golec, M., Kumar, M., Abdelmoniem, A. M., Cuadrado, F., Varghese, B., Rana, O., Dustdar, S., & Uhlig, S. (2023). AI-based fog and edge computing: A systematic review, taxonomy and future directions. *Internet of Things (Netherlands)*, *21*, 100674. https://doi.org/10.1016/j.iot.2022.100674

Jani, M., Garg, P., & Gupta, A. (2019). Performance analysis of a co-operative PLC/VLC system with multiple access points for indoor broadcasting. *AEU—International Journal of Electronics and Communications*, *103*, 64–73. https://doi.org/10.1016/j.aeue.2019.02.012

Janjua, M. B., Duranay, A. E., & Arslan, H. (2020). Role of wireless communication in healthcare system to cater disaster situations under 6G vision. *Frontiers in Communications and Networks*, *1*, 610879. https://doi.org/10.3389/frcmn.2020.610879

Ji, B., Han, Y., Liu, S., Tao, F., Zhang, G., Fu, Z., & Li, C. (2021). Several key technologies for 6G: Challenges and opportunities. *IEEE Communications Standards Magazine*, *5*, 44–51. https://doi.org/10.1109/MCOMSTD.001.2000038

Ji, B., Wang, Y., Song, K., Li, C., Wen, H., Menon, V. G., & Mumtaz, S. (2021). A survey of computational intelligence for 6G: Key technologies, applications and trends. *IEEE Transactions on Industrial Informatics*, *17*(10), 7145–7154. https://doi.org/10.1109/TII.2021.3052531

Jiang, W., Han, B., Habibi, M. A., & Schotten, H. D. (2021). The road towards 6G: A comprehensive survey. *IEEE Open Journal of the Communications Society*, *2*, 334–366. https://doi.org/10.1109/OJCOMS.2021.3057679

Jiang, X., Sheng, M., Zhao, N., Xing, C., Lu, W., & Wang, X. (2021). Green UAV communications for 6G: A survey. *Chinese Journal of Aeronautics*, *35*, 19–34. https://doi.org/10.1016/j.cja.2021.04.025

Jin, F., Zhang, R., & Hanzo, L. (2015). Resource allocation under delay-guarantee constraints for heterogeneous visible-light and RF femtocell. *IEEE Transactions on Wireless Communications*, *14*(2), 1020–1034. https://doi.org/10.1109/TWC.2014.2363451

Jin, M. L., Brown, M. M., Patwa, D., Nirmalan, A., & Edwards, P. A. (2021). Telemedicine, telementoring, and telesurgery for surgical practices. *Current Problems in Surgery*, *58*, 100986. https://doi.org/10.1016/j.cpsurg.2021.100987

Jordan Belamire. (2016). My first virtual reality groping. *Medium.Com*. https://medium.com/athena-talks/my-first-virtual-reality-sexual-assault-2330410b62ee

Kaiser, M. S., Zenia, N., Tabassum, F., Mamun, S. a., Rahman, M. A., Islam, M. S., & Mahmud, M. (2021). 6G access network for intelligent internet of healthcare things: Opportunity, challenges, and research directions. *Advances in Intelligent Systems and Computing*, *1309*, 317–328. https://doi.org/10.1007/978-981-33-4673-4_25

Kalalas, C., & Alonso-Zarate, J. (2020). Massive connectivity in 5G and beyond: Technical enablers for the energy and automotive verticals. In *2nd 6G wireless summit 2020: Gain edge for the 6G era, 6G SUMMIT 2020*. IEEE. https://doi.org/10.1109/6GSUMMIT49458.2020.9083809

Kashef, M., Abdallah, M., & Al-Dhahir, N. (2018). Transmit power optimization for a hybrid PLC/VLC/RF communication system. *IEEE Transactions on Green Communications and Networking*, *2*(1), 234–245. https://doi.org/10.1109/TGCN.2017.2774104

Khan, L. U., Yaqoob, I., Imran, M., Han, Z., & Hong, C. S. (2020). 6G wireless systems: A vision, architectural elements, and future directions. *IEEE Access*, *8*, 147029–147044. https://doi.org/10.1109/ACCESS.2020.3015289

Khan, M. N., Rafay, A., Gilani, S. O., & Jamil, M. (2017). Link adaptation for maximizing MI of hybrid optical/RF communication system. *Procedia Computer Science*, *110*, 282–289. https://doi.org/10.1016/j.procs.2017.06.096

Kumar, A., & Ghorai, S. K. (2020). BER performance analysis of OFDM-based integrated PLC and MIMO-VLC system. *IET Optoelectronics*, *14*(5), 242–251. https://doi.org/10.1049/iet-opt.2019.0132

Kumar, R., & Agrawal, A. K. (2021). Drone GPS data analysis for flight path reconstruction: A study on DJI, Parrot & Yuneec make drones. *Forensic Science International: Digital Investigation*, *38*, 301182. https://doi.org/10.1016/j.fsidi.2021.301182

Lanagan, S., & Choo, K. K. R. (2021). On the need for AI to triage encrypted data containers in U.S. law enforcement applications. *Forensic Science International: Digital Investigation*, *38*, 301217. https://doi.org/10.1016/j.fsidi.2021.301217

Letaief, K. B., Chen, W., Shi, Y., Zhang, J., & Zhang, Y.-J. A. (2019). The roadmap to 6G: AI empowered wireless networks. *IEEE Communications Magazine*, *57*(8), 84–90. https://doi.org/10.1109/MCOM.2019.1900271

Li, L., Zhang, Y., Fan, B., & Tian, H. (2016). Mobility-aware load balancing scheme in hybrid VLC-LTE networks. *IEEE Communications Letters*, *20*(11), 2276–2279. https://doi.org/10.1109/LCOMM.2016.2598559

Li, M., & Lin, H.-J. (2015). Design and implementation of smart home control systems based on wireless sensor networks and power line communications. *IEEE Transactions on Industrial Electronics*, *62*(7), 4430–4442. https://doi.org/10.1109/TIE.2014.2379586

Li, S., da Xu, L., & Zhao, S. (2018). 5G internet of things: A survey. *Journal of Industrial Information Integration*, *10*, 1–9. https://doi.org/10.1016/j.jii.2018.01.005

Lian, J., Vatansever, Z., Noshad, M., & Brandt-Pearce, M. (2019). Indoor visible light communications, networking, and applications. *Journal of Physics: Photonics*, *1*(1), 012001. https://doi.org/10.1088/2515-7647/aaf74a

Lin, R., Guo, X., Luo, S., Xiao, Y., Moran, B., & Zukerman, M. (2023). Application-aware computation offloading in edge computing networks. *SSRN Electronic Journal*, *146*, 86–97. https://doi.org/10.2139/ssrn.4333337

Lin, X., & Zhang, L. (2020). Intelligent and practical deep learning aided positioning design for visible light communication receivers. *IEEE Communications Letters*, *24*(3), 577–580. https://doi.org/10.1109/LCOMM.2019.2958629

Ling, Z., Li, Z., Chen, C., Luo, J., Yu, W., & Fu, X. (2019). I know what you enter on gear VR. In *IEEE conference on communications and network security, CNS 2019*. IEEE. https://doi.org/10.1109/CNS.2019.8802674

Liu, C., Feng, W., Tao, X., & Ge, N. (2021). MEC-empowered non-terrestrial network for 6G wide-area time-sensitive Internet of Things. *Engineering*, *8*, 96–107. https://doi.org/10.1016/j.eng.2021.11.002

Liu, Y., Yuan, X., Xiong, Z., Kang, J., Wang, X., & Niyato, D. (2020). Federated learning for 6G communications: Challenges, methods, and future directions. *China Communications*, *17*(9), 105–118. https://doi.org/10.23919/JCC.2020.09.009

Lu, Y., & Zheng, X. (2020). 6G: A survey on technologies, scenarios, challenges, and the related issues. *Journal of Industrial Information Integration*, *19*, 100158. https://doi.org/10.1016/j.jii.2020.100158

Lutta, P., Sedky, M., Hassan, M., Jayawickrama, U., & Bakhtiari Bastaki, B. (2021). The complexity of Internet of Things forensics: A state-of-the-art review. *Forensic Science International: Digital Investigation*, *38*, 301210. https://doi.org/10.1016/j.fsidi.2021.301210

Lv, Z., Qiao, L., & You, I. (2021). 6G-enabled network in box for internet of connected vehicles. *IEEE Transactions on Intelligent Transportation Systems*, *22*(8), 5275–5282. https://doi.org/10.1109/TITS.2020.3034817

MacDermott, A., Baker, T., & Shi, Q. (2018). Iot forensics: Challenges for the Ioa era. In *9th IFIP international conference on new technologies, mobility and security (NTMS)* (pp. 1–5). IEEE. https://doi.org/10.1109/NTMS.2018.8328748

Mardini, W., Aljawarneh, S., & Al-Abdi, A. (2021). Using multiple RPL instances to enhance the performance of new 6G and Internet of Everything (6G/IoE)-based healthcare monitoring systems. *Mobile Networks and Applications*, *26*(3), 952–968. https://doi.org/10.1007/s11036-020-01662-9

Marin-Garcia, I., Ramirez-Aguilera, A. M., Guerra, V., Rabadan, J., & Perez-Jimenez, R. (2016). Data sniffing over an open VLC channel. In *10th international symposium on communication systems, networks and digital signal processing (CSNDSP)* (pp. 1–6). IEEE. https://doi.org/10.1109/CSNDSP.2016.7573963

Matinmikko-Blue, M., Yrjola, S., & Ahokangas, P. (2020). Spectrum management in the 6G era: The role of regulation and spectrum sharing. In *2nd 6G wireless summit 2020: Gain edge for the 6G era, 6G SUMMIT 2020*. IEEE. https://doi.org/10.1109/6GSUMMIT49458.2020.9083851

Merluzzi, M., di Lorenzo, P., Barbarossa, S., & Frascolla, V. (2020). Dynamic computation offloading in multi-access edge computing via ultra-reliable and low-latency communications. *IEEE Transactions on Signal and Information Processing over Networks*, *6*, 342–356. https://doi.org/10.1109/TSIPN.2020.2981266

Meshram, D. A., & Patil, D. D. (2020). 5G enabled tactile internet for tele-robotic surgery. *Procedia Computer Science*, *171*, 2618–2625. https://doi.org/10.1016/j.procs.2020.04.284

Mucchi, L., Jayousi, S., Caputo, S., Paoletti, E., Zoppi, P., Geli, S., & Dioniso, P. (2020). How 6G technology Can change the future wireless healthcare. In *2nd 6G wireless summit (6G SUMMIT)* (pp. 1–6). IEEE. https://doi.org/10.1109/6GSUMMIT49458.2020.9083916

Mukherjee, A., Goswami, P., Khan, M. A., Manman, L., Yang, L., & Pillai, P. (2021). Energy-efficient resource allocation strategy in massive iot for industrial 6G applications. *IEEE Internet of Things Journal*, *8*(7), 5194–5201. https://doi.org/10.1109/JIOT.2020.3035608

Mukhtaruzzaman, M., & Atiquzzaman, M. (2020). Clustering in vehicular ad hoc network: Algorithms and challenges. *Computers and Electrical Engineering*, *88*, 106851. https://doi.org/10.1016/j.compeleceng.2020.106851

Nasrollahzadeh, M., Sajjadi, M., Soufi, G. J., Iravani, S., & Varma, R. S. (2020). Nanomaterials and nanotechnology-associated innovations against viral infections with a focus on coronaviruses. *Nanomaterials*, *10*(6), 1072. https://doi.org/10.3390/nano10061072

Nawaz, S. J., Sharma, S. K., Patwary, M. N., & Asaduzzaman, M. (2021). Next-generation consumer electronics for 6G wireless era. *IEEE Access*, *9*, 143198–143211. https://doi.org/10.1109/access.2021.3121037

Nayak, S., Patgiri, R. (2021). 6G Communication Technology: A Vision on Intelligent Healthcare. In R. Patgiri, A. Biswas, & P. Roy (Eds.), *Health Informatics: A Computational Perspective in Healthcare*. Studies in Computational Intelligence, vol 932. Springer. https://doi.org/10.1007/978-981-15-9735-0_1

Ndjiongue, A. R., Ferreira, H. C., Song, J., Yang, F., & Cheng, L. (2017). Hybrid PLC-VLC channel model and spectral estimation using a nonparametric approach. *Transactions on Emerging Telecommunications Technologies*, *28*(12), e3224. https://doi.org/10.1002/ett.3224

Nguyen, D. C., Ding, M., Pathirana, P. N., Seneviratne, A., Li, J., Niyato, D., Dobre, O., & Poor, H. V. (2022). 6G internet of things: A comprehensive survey. *IEEE Internet of Things Journal*, *9*(1), 359–383. https://doi.org/10.1109/JIOT.2021.3103320

Norman, D. G., Wade, K. A., Williams, M. A., & Watson, D. G. (2020). Caught virtually lying—Crime scenes in virtual reality help to expose Suspects' concealed recognition. *Journal of Applied Research in Memory and Cognition*, *9*(1), 118–127. https://doi.org/10.1016/j.jarmac.2019.12.008

Oriwoh, E., Jazani, D., Epiphaniou, G., & Sant, P. (2013). *Internet of Things forensics: Challenges and approaches*. IEEE. https://doi.org/10.4108/icst.collaboratecom.2013.254159

Padhi, P. K., & Charrua-santos, F. (2021a). 6G enabled industrial Internet of Everything: Towards a theoretical framework. *Applied System Innovations*, *4*(1), 11. https://doi.org/10.3390/ASI4010011

Padhi, P. K., & Charrua-Santos, F. (2021b). 6G enabled tactile internet and cognitive internet of healthcare everything: Towards a theoretical framework. *Applied System Innovations*, *4*(3), 66. https://doi.org/10.3390/asi4030066

Pan, C., Ren, H., Wang, K., Kolb, J. F., Elkashlan, M., Chen, M., di Renzo, M., Hao, Y., Wang, J., Swindlehurst, A. L., You, X., & Hanzo, L. (2021). Reconfigurable intelligent surfaces for 6G systems: Principles, applications, and research directions. *IEEE Communications Magazine*, *59*, 14–20. https://doi.org/10.1109/MCOM.001.2001076

Pan, G., Lei, H., Ding, Z., & Ni, Q. (2017). On 3-D hybrid VLC-RF systems with light energy harvesting and OMA scheme over RF links. *2017 IEEE global communications conference, GLOBECOM 2017—Proceedings*, 1–6. https://doi.org/10.1109/GLOCOM.2017.8254799

Papagiannidis, S., Bourlakis, M., & Li, F. (2008). Making real money in virtual worlds: MMORPGs and emerging business opportunities, challenges and ethical implications in metaverses. *Technological Forecasting and Social Change*, *75*(5), 610–622. https://doi.org/10.1016/j.techfore.2007.04.007

Park, S.-M., & Kim, Y.-G. (2022). A metaverse: Taxonomy, components, applications, and open challenges. *IEEE Access*, *10*, 4209–4251. https://doi.org/10.1109/ACCESS.2021.3140175

Parti, K. (2010). Actual policing in virtual reality—A cause of moral panic or a justified need? *Virtual Reality*, 1–28. https://doi.org/10.5772/13224

Peng, M., Garg, S., Wang, X., Bradai, A., Lin, H., & Hossain, M. S. (2020). Learning-based IoT data aggregation for disaster scenarios. *IEEE Access*, *8*, 128490–128497. https://doi.org/10.1109/ACCESS.2020.3008289

Petersen, K., Feldt, R., Mujtaba, S., & Mattsson, M. (2008). Systematic mapping studies in software engineering. In *12th international conference on evaluation and assessment in software engineering, EASE 2008*. Publisher is ACM Digital. https://doi.org/10.14236/ewic/ease2008.8

Petersen, K., Vakkalanka, S., & Kuzniarz, L. (2015). Guidelines for conducting systematic mapping studies in software engineering: An update. *Information and Software Technology*, *64*, 1–18. https://doi.org/10.1016/j.infsof.2015.03.007

Qi, F., Li, W., Yu, P., Feng, L., & Zhou, F. (2021). Deep learning-based BackCom multiple beamforming for 6G UAV IoT networks. *EURASIP Journal on Wireless Communications and Networking*, *2021*(1), 50. https://doi.org/10.1186/s13638-021-01932-4

Qiao, L., Li, Y., Chen, D., Serikawa, S., Guizani, M., & Lv, Z. (2021). A survey on 5G/6G, AI, and robotics. *Computers & Electrical Engineering*, *95*, 107372. https://doi.org/10.1016/j.compeleceng.2021.107372

Qiao, X., Huang, Y., Dustdar, S., & Chen, J. (2020). 6G vision: An AI-driven decentralized network and service architecture. *IEEE Internet Computing*, *24*(4), 33–40. https://doi.org/10.1109/MIC.2020.2987738

Qu, Y., Dong, C., Zheng, J., Dai, H., Wu, F., Guo, S., & Anpalagan, A. (2021). Empowering edge intelligence by air-ground integrated federated learning. *IEEE Network*, *35*(5), 34–41. https://doi.org/10.1109/MNET.111.2100044

Rahaim, M. B., Morrison, J., & Little, T. D. C. (2017). Beam control for indoor FSO and dynamic dual-use VLC lighting systems. *Journal of Communications and Information Networks*, *2*(4), 11–27. https://doi.org/10.1007/s41650-017-0041-7

Rahaim, M. B., Vegni, A. M., & Little, T. D. C. (2011). A hybrid radio frequency and broadcast visible light communication system. In *IEEE GLOBECOM workshops, GC Wkshps 2011*. IEEE. https://doi.org/10.1109/GLOCOMW.2011.6162563

Rakia, T., Yang, H. C., Gebali, F., & Alouini, M. S. (2016). Optimal design of dual-hop VLC/RF communication system with energy harvesting. *IEEE Communications Letters*, *20*(10), 1979–1982. https://doi.org/10.1109/LCOMM.2016.2595561

Rathore, H., Samavedhi, A., Sahay, S. K., & Sewak, M. (2021). Robust malware detection models: Learning from adversarial attacks and defenses. *Forensic Science International: Digital Investigation*, *37*, 301183. https://doi.org/10.1016/j.fsidi.2021.301183

Ray, P. P. (2021). A perspective on 6G: Requirement, technology, enablers, challenges and future road map. *Journal of Systems Architecture*, *118*, 102180. https://doi.org/10.1016/j.sysarc.2021.102180

Saad, W., Bennis, M., & Chen, M. (2020). A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. *IEEE Network*, *34*(3), 134–142. https://doi.org/10.1109/MNET.001.1900287

Samarakoon, S., Bennis, M., Saad, W., & Debbah, M. (2018). Federated learning for ultra-reliable low-latency V2V communications. In *IEEE Global Communications Conference, GLOBECOM 2018—Proceedings*. IEEE. https://doi.org/10.1109/GLOCOM.2018.8647927

Samarakoon, S., Bennis, M., Saad, W., & Debbah, M. (2020). Distributed federated learning for ultra-reliable low-latency vehicular communications. *IEEE Transactions on Communications*, *68*(2), 1146–1159. https://doi.org/10.1109/TCOMM.2019.2956472

Sandvik, J.-P., Franke, K., Abie, H., & Årnes, A. (2023). Evidence in the fog—Triage in fog computing systems. *Forensic Science International: Digital Investigation*, *44*, 301506. https://doi.org/10.1016/j.fsidi.2023.301506

Schuyler Moore. (2017). *The legal reality of virtual reality*. Forbes. https://www.forbes.com/sites/schuylermoore/2017/03/10/the-legal-reality-of-virtual-reality/?sh=6b0eb3eb2049

Serhal, C., & Le-Khac, N.-A. (2021). Machine learning based approach to analyze file meta data for smart phone file triage. *Forensic Science International: Digital Investigation*, *37*, 301194. https://doi.org/10.1016/j.fsidi.2021.301194

Servetnyk, M., & Servetnyk, R. (2021). Emerging applications, technologies, and services in wireless communications: 5G to 6G evolution. *Journal of Scientific Papers "Social Development and Security"*, *11*(2), 3–10. https://doi.org/10.33445/sds.2021.11.2.1

Servida, F., & Casey, E. (2019). IoT forensic challenges and opportunities for digital traces. *Digital Investigation*, *28*, S22–S29. https://doi.org/10.1016/j.diin.2019.01.012

Sharma, P. K., Jeong, Y. S., & Park, J. H. (2018). EH-HL: Effective communication model by integrated EH-WSN and hybrid LiFi/WiFi for IoT. *IEEE Internet of Things Journal*, *5*(3), 1719–1726. https://doi.org/10.1109/JIOT.2018.2791999

Sheng, H., Zhang, H. Y., Yang, F., Li, C. H., & Wang, J. (2022). A CSMA/CA based MAC protocol for hybrid power-line/visible-light communication networks: Design and analysis. *Digital Communications and Networks*. https://doi.org/10.1016/j.dcan.2022.09.019

Sicari, S., Rizzardi, A., & Coen-Porisini, A. (2020). 5G in the Internet of Things era: An overview on security and privacy challenges. *Computer Networks*, *179*, 107345. https://doi.org/10.1016/j.comnet.2020.107345

Singh, J., Singh, P., & Gill, S. S. (2021). Fog computing: A taxonomy, systematic review, current trends and research challenges. *Journal of Parallel and Distributed Computing*, *157*, 56–85. https://doi.org/10.1016/j.jpdc.2021.06.005

Sliwa, B., Adam, R., & Wietfeld, C. (2021). Client-based intelligence for resource efficient vehicular big data transfer in future 6G networks. *IEEE Transactions on Vehicular Technology*, *70*(6), 5332–5346. https://doi.org/10.1109/TVT.2021.3060459

Soderi, S., Brighente, A., Turrin, F., & Conti, M. (2022). VLC physical layer security through RIS-aided jamming receiver for 6G wireless networks. In *19th annual IEEE international conference on sensing, communication, and networking (SECON)* (pp. 370–378). IEEE. https://doi.org/10.1109/SECON55815.2022.9918547

Sodhro, A. H., Pirbhulal, S., Luo, Z., Muhammad, K., & Zahid, N. Z. (2021). Toward 6G architecture for energy-efficient communication in iot-enabled smart automation systems. *IEEE Internet of Things Journal*, *8*(7), 5141–5148. https://doi.org/10.1109/JIOT.2020.3024715

Sodhro, A. H., Zahid, N., Wang, L., Pirbhulal, S., Ouzrout, Y., Sekhari Seklouli, A., Lira Neto, A. V., MacEdo, A. R. L. D., & Albuquerque, V. H. C. D. (2021). Toward ML-based energy-efficient mechanism for 6G enabled industrial network in box systems. *IEEE Transactions on Industrial Informatics*, *17*(10), 7185–7192. https://doi.org/10.1109/TII.2020.3026663

Sparkes, M. (2021). What is a metaverse. *New Scientist*, *251*(3348), 18. https://doi.org/10.1016/s0262-4079(21)01450-0

Stoyanova, M., Nikoloudakis, Y., Panagiotakis, S., Pallis, E., & Markakis, E. K. (2020). A survey on the internet of things (IoT) forensics: Challenges, approaches, and open issues. *IEEE Communications Surveys & Tutorials*, *22*(2), 1191–1221. https://doi.org/10.1109/COMST.2019.2962586

Strobel, G., & Mittnacht, J. (2021). Richard, are we there yet? An internet of nano things information system architecture. In *Proceedings of the annual Hawaii international conference on system sciences*. IEEE. https://doi.org/10.24251/hicss.2021.555

Tang, F., Kawamoto, Y., Kato, N., & Liu, J. (2020). Future intelligent and secure vehicular network toward 6G: Machine-learning approaches. *Proceedings of the IEEE*, *108*(2), 292–307. https://doi.org/10.1109/JPROC.2019.2954595

Tang, S., Zhou, W., Chen, L., Lai, L., Xia, J., & Fan, L. (2021). Battery-constrained federated edge learning in UAV-enabled IoT for B5G/6G networks. *Physical Communication*, *47*, 101381. https://doi.org/10.1016/j.phycom.2021.101381

Taylor, D. C. P. J., Mwiki, H., Dehghantanha, A., Akibini, A., Choo, K. K. R., Hammoudeh, M., & Parizi, R. (2019). Forensic investigation of cross platform massively multiplayer online games: Minecraft as a case study. *Science & Justice*, *59*(3), 337–348. https://doi.org/10.1016/j.scijus.2019.01.005

Thornton, G., & Bagheri Zadeh, P. (2022). An investigation into unmanned aerial system (UAS) forensics: Data extraction & analysis. *Forensic Science International: Digital Investigation*, *41*, 301379. https://doi.org/10.1016/j.fsidi.2022.301379

Tripathi, S., Sabu, N. V., Gupta, A. K., & Dhillon, H. S. (2021). *Millimeter-wave and terahertz spectrum for 6G wireless* (pp. 83–121). Springer Link. https://doi.org/10.1007/978-3-030-72777-2_6

Vats, A., Aggarwal, M., & Ahuja, S. (2017). Modeling and outage analysis of multiple relayed hybrid VLC-RF system. In *International conference on computer, communications and electronics, COMPTELIX 2017*. IEEE. https://doi.org/10.1109/COMPTELIX.2017.8003974

Vu Khanh, Q., Nguyen, V.-H., Minh, Q. N., Dang Van, A., Le Anh, N., & Chehri, A. (2023). An efficient edge computing management mechanism for sustainable smart cities. *Sustainable Computing: Informatics and Systems*, *38*, 100867. https://doi.org/10.1016/j.suscom.2023.100867

Wang, F., Wang, Z., Qian, C., Dai, L., & Yang, Z. (2015). MDP-based vertical handover scheme for indoor VLC-WiFi systems. In *Optoelectronics and communications conference, OECC 2015*. IEEE. https://doi.org/10.1109/OECC.2015.7340272

Wang, J., Jiang, C., Zhang, H., Zhang, X., Leung, V. C. M., & Hanzo, L. (2018). Learning-aided network association for hybrid indoor LiFi-WiFi systems. *IEEE Transactions on Vehicular Technology*, *67*(4), 3561–3574. https://doi.org/10.1109/TVT.2017.2778345

Wang, M., Zhu, T., Zhang, T., Zhang, J., Yu, S., & Zhou, W. (2020). Security and privacy in 6G networks: New areas and new challenges. *Digital Communications and Networks*, *6*(3), 281–291. https://doi.org/10.1016/j.dcan.2020.07.003

West, N. E., & O'Shea, T. (2017). Deep architectures for modulation recognition. In *IEEE international symposium on dynamic spectrum access networks, DySPAN 2017*. IEEE. https://doi.org/10.1109/DySPAN.2017.7920754

Williams, M. (2006). *Virtually criminal: Crime, deviance and regulation online*. Taylor & Francis. https://doi.org/10.4324/9780203015223

Wollschlaeger, M., Sauter, T., & Jasperneite, J. (2017). The future of industrial communication: Automation networks in the era of the Internet of Things and industry 4.0. *IEEE Industrial Electronics Magazine*, *11*, 17–27. https://doi.org/10.1109/MIE.2017.2649104

Wu, W., Zhou, F., & Yang, Q. (2017). Dynamic network resource optimization in hybrid VLC and radio frequency networks. In *International conference on selected topics in mobile and wireless networking, MoWNeT 2017*. IEEE. https://doi.org/10.1109/MoWNet.2017.8045951

Wu, X., & Haas, H. (2017). Access point assignment in hybrid LiFi and WiFi networks in consideration of LiFi channel blockage. In *IEEE workshop on signal processing advances in wireless communications, SPAWC*. IEEE. https://doi.org/10.1109/SPAWC.2017.8227704

Wu, X., Safari, M., & Haas, H. (2017). Access point selection for hybrid Li-Fi and Wi-Fi networks. *IEEE Transactions on Communications*, *65*(12), 5375–5385. https://doi.org/10.1109/TCOMM.2017.2740211

Xianjia, Y., Queralta, J. P., Heikkonen, J., & Westerlund, T. (2021). Federated learning in robotic and autonomous systems. *Procedia Computer Science*, *191*, 135–142. https://doi.org/10.1016/j.procs.2021.07.041

Xiao, M., Mumtaz, S., Huang, Y., Dai, L., Li, Y., Matthaiou, M., Karagiannidis, G. K., Bjornson, E., Yang, K., Chih-Lin, I., & Ghosh, A. (2017). Millimeter wave communications for future mobile networks. *IEEE Journal on Selected Areas in Communications*, *35*(9), 1909–1935. https://doi.org/10.1109/JSAC.2017.2719924

Xiaohu, Y., Cheng-xiang, W., Jie, H., Xiqi, G., Michael, W., Yongming, H., Chuan, Z., Yanxiang, J., Min, Z., Dongming, W., Zhiwen, P., Pengcheng, Z., Yang, Y., Zening, L. I. U., Ping, Z., Xiaofeng, T., Shaoqian, L., Xinying, M., Shuangfeng, H., ... Zhang, P. (2020). Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts. *Science China Information Sciences*, *64*, 110301.

Xu, X., Yao, L., Bilal, M., Wan, S., Dai, F., & Choo, K. K. R. (2021). Service migration across edge devices in 6G-enabled internet of vehicles networks. *IEEE Internet of Things Journal.*, *9*, 1930–1937. https://doi.org/10.1109/JIOT.2021.3089204

Yan, C., Xu, Y., Shen, J., & Chen, J. (2016). A combination of VLC and WiFi based indoor wireless access network and its handover strategy. In *IEEE international conference on ubiquitous wireless broadband, ICUWB 2016*. IEEE. https://doi.org/10.1109/ICUWB.2016.7790528

Yang, H., Alphones, A., Xiong, Z., Niyato, D., Zhao, J., & Wu, K. (2020). Artificial-intelligence-enabled intelligent 6G networks. *IEEE Network*, *34*, 272–280. https://doi.org/10.1109/MNET.011.2000195

Yang, H., Zhao, J., Nie, J., Kumar, N., Lam, K. Y., & Xiong, Z. (2021). UAV-assisted 5G/6G networks: Joint scheduling and resource allocation based on asynchronous reinforcement learning. *IEEE INFOCOM 2021—IEEE conference on computer communications workshops, INFOCOM WKSHPS 2021*. https://doi.org/10.1109/INFOCOMWKSHPS51825.2021.9484604

Yang, Y., Yamagami, Y., Yu, X., Pitchappa, P., Webber, J., Zhang, B., Fujita, M., Nagatsuma, T., & Singh, R. (2020). Terahertz topological photonics for on-chip communication. *Nature Photonics*, *14*(7), 446–451. https://doi.org/10.1038/s41566-020-0618-9

Yang, Z., Chen, M., Wong, K.-K., Poor, H. V., & Cui, S. (2021). Federated learning for 6G: Applications, challenges, and opportunities. *Engineering*, *8*, 33–41. https://doi.org/10.1016/j.eng.2021.12.002

Yao, Y., Rao, L., Liu, X., & Zhou, X. (2013). Delay analysis and study of IEEE 802.11p based DSRC safety communication in a highway environment. In *Proceedings IEEE INFOCOM* (pp. 1591–1599). IEEE. https://doi.org/10.1109/INFCOM.2013.6566955

Yarramreddy, A., Gromkowski, P., & Baggili, I. (2018). Forensic analysis of immersive virtual reality social applications: A primary account. *IEEE Security and Privacy Workshops (SPW)*, *2018*, 186–196. https://doi.org/10.1109/SPW.2018.00034

Ye, H., Li, G. Y., & Juang, B. H. (2018). Power of deep learning for channel estimation and signal detection in OFDM systems. *IEEE Wireless Communications Letters*, *7*, 114–117. https://doi.org/10.1109/LWC.2017.2757490

Yu, M., Tang, A., Wang, X., & Han, C. (2020). Joint scheduling and power allocation for 6G terahertz mesh networks. In *International conference on computing, networking and communications, ICNC 2020*. IEEE. https://doi.org/10.1109/ICNC47757.2020.9049790

Yuan, Y., Zhao, Y., Zong, B., & Parolari, S. (2020). Potential key technologies for 6G mobile communications. *Science China Information Sciences*, *63*(8), 183301. https://doi.org/10.1007/s11432-019-2789-y

Zakrzewski, Z., & Łaga, B. (2020). *Potential use of fiber-optic and Li-Fi systems in private 5G/6G networks dedicated to the industrial IoT*. SPIE Press. https://doi.org/10.1117/12.2566060

Zhang, J., & Letaief, K. B. (2020). Mobile edge intelligence and computing for the internet of vehicles. *Proceedings of the IEEE*, *108*(2), 246–261. https://doi.org/10.1109/JPROC.2019.2947490

Zhang, S., Liu, J., Guo, H., Qi, M., & Kato, N. (2020). Envisioning device-to-device communications in 6G. *IEEE Network*, *34*, 86–91. https://doi.org/10.1109/MNET.001.1900652

Zhang, S., & Zhu, D. (2020). Towards artificial intelligence enabled 6G: State of the art, challenges, and opportunities. *Computer Networks*, *183*, 107556. https://doi.org/10.1016/j.comnet.2020.107556

Zhang, X., Upton, O., Beebe, N. L., & Choo, K. K. R. (2020). IoT botnet forensics: A comprehensive digital forensic case study on Mirai botnet servers. *Forensic Science International: Digital Investigation*, *32*, 300926. https://doi.org/10.1016/j.fsidi.2020.300926

Zhang, Z., Xiao, Y., Ma, Z., Xiao, M., Ding, Z., Lei, X., Karagiannidis, G. K., & Fan, P. (2019). 6G wireless networks: Vision, requirements, architecture, and key technologies. *IEEE Vehicular Technology Magazine*, *14*(3), 28–41. https://doi.org/10.1109/MVT.2019.2921208

Zhao, Y., Yu, G., & Xu, H. (2019). 6G mobile communication networks: Vision, challenges, and key technologies. *Scientia Sinica Information*, *49*, 963–987. https://doi.org/10.1360/n112019-00033

Zhou, X., Liang, W., She, J., Yan, Z., & Wang, K. (2021). Two-layer federated learning with heterogeneous model aggregation for 6G supported internet of vehicles. *IEEE Transactions on Vehicular Technology*, *70*(6), 5308–5317. https://doi.org/10.1109/TVT.2021.3077893

Zhou, Z., Chen, X., Li, E., Zeng, L., Luo, K., & Zhang, J. (2019). Edge intelligence: Paving the last mile of artificial intelligence with edge computing. *Proceedings of the IEEE*, *107*(8), 1738–1762. https://doi.org/10.1109/JPROC.2019.2918951

Zhu, D., Bilal, M., & Xu, X. (2021). Edge task migration with 6G-enabled network in box for Cybertwin based internet of vehicles. *IEEE Transactions on Industrial Informatics*, *18*, 4893–4901. https://doi.org/10.1109/TII.2021.3113879

Ziegler, V., & Yrjola, S. (2020). 6G indicators of value and performance. In *2nd 6G wireless summit (6G SUMMIT)* (pp. 1–5). IEEE. https://doi.org/10.1109/6GSUMMIT49458.2020.9083885

Zong, B., Fan, C., Wang, X., Duan, X., Wang, B., & Wang, J. (2019). 6G technologies: Key drivers, Core requirements, system architectures, and enabling technologies. *IEEE Vehicular Technology Magazine*, *14*(3), 18–27. https://doi.org/10.1109/MVT.2019.2921398

Zorzi, M., Zanella, A., Testolin, A., De Filippo De Grazia, M., & Zorzi, M. (2015). Cognition-based networks: A new perspective on network optimization using learning and distributed intelligence. *IEEE Access*, *3*, 1512–1530. https://doi.org/10.1109/ACCESS.2015.2471178

How to cite this article: Akinbi, A. O. (2023). Digital forensics challenges and readiness for 6G Internet of Things (IoT) networks. *WIREs Forensic Science*, e1496. https://doi.org/10.1002/wfs2.1496