IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 28, 2019, accepted December 31, 2019, date of publication January 7, 2020, date of current version January 17, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2964673

The Potential Short- and Long-Term Disruptions and Transformative Impacts of 5G and Beyond Wireless Networks: Lessons Learnt From the Development of a 5G Testbed Environment

MOHMAMMAD N. PATWARY[1], (Senior Member, IEEE),
SYED JUNAID NAWAZ[2], (Senior Member, IEEE),
MD. ABDUR RAHMAN[3], (Senior Member, IEEE),
SHREE KRISHNA SHARMA[4], (Senior Member, IEEE),
MD. MAMUNUR RASHID[5], AND STUART J. BARNES[5]
[1]School of Computing and Digital Technology, Birmingham City University, Birmingham B5 5JU, U.K.
[2]Department of Electrical and Computer Engineering, COMSATS University Islamabad (CUI), Islamabad 45550, Pakistan
[3]Department of Cyber Security and Forensic Computing, University of Prince Mugrin, Medina 42241, Saudi Arabia
[4]Interdisciplinary Center for Security, Reliability and Trust (SnT), University of Luxembourg, L-1855 Luxembourg City, Luxembourg
[5]Consumer and Organizational Data Analytics (CODA) Research Centre, King's College London, London WC2B 4BG, U.K.

Corresponding author: Syed Junaid Nawaz (junaidnawaz@ieee.org)

ABSTRACT The capacity and coverage requirements for 5th generation (5G) and beyond wireless connectivity will be significantly different from the predecessor networks. To meet these requirements, the anticipated deployment cost in the United Kingdom (UK) is predicted to be between £30bn and £50bn, whereas the current annual capital expenditure (CapEX) of the mobile network operators (MNOs) is £2.5bn. This prospect has vastly impacted and has become one of the major delaying factors for building the 5G physical infrastructure, whereas other areas of 5G are progressing at their speed. Due to the expensive and complicated nature of the network infrastructure and spectrum, the second-tier operators, widely known as mobile virtual network operators (MVNO), are entirely dependent on the MNOs. In this paper, an extensive study is conducted to explore the possibilities of reducing the 5G deployment cost and developing viable business models. In this regard, the potential of infrastructure, data, and spectrum sharing is thoroughly investigated. It is established that the use of existing public infrastructure (e.g., streetlights, telephone poles, etc.) has a potential to reduce the anticipated cost by about 40% to 60%. This paper also reviews the recent Ofcom initiatives to release location-based licenses of the 5G-compatible radio spectrum. Our study suggests that simplification of infrastructure and spectrum will encourage the exponential growth of scenario-specific cellular networks (e.g., private networks, community networks, micro-operators) and will potentially disrupt the current business models of telecommunication business stakeholders – specifically MNOs and TowerCos. Furthermore, the anticipated dense device connectivity in 5G will increase the resolution of traditional and non-traditional data availability significantly. This will encourage extensive data harvesting as a business opportunity and function within small and medium-sized enterprises (SMEs) as well as large social networks. Consequently, the rise of new infrastructures and spectrum stakeholders is anticipated. This will fuel the development of a 5G data exchange ecosystem where data transactions are deemed to be high-value business commodities. The privacy and security of such data, as well as definitions of the associated revenue models and ownership, are challenging areas – and these have yet to emerge and mature fully. In this direction, this paper proposes the development of a unified data hub with layered structured privacy and security along with blockchain and encrypted off-chain based ownership/royalty tracking. Also, a data economy-oriented business model is proposed. The study found that with the potential commodification of data and data transactions along with the low-cost physical infrastructure and spectrum, the 5G network will introduce significant disruption in the Telco business ecosystem.

INDEX TERMS 5G, beyond 5G, deployment, infrastructure, testbed, security, teleco business.

I. INTRODUCTION

The rollout of 5th generation (5G) of communication networks has commenced with Release-15 of 3rd Generation

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

Partnership Project (3GPP) [1]. This release of 5G new radio (5G NR) has extended the provisions for both standalone and non-standalone operations. Based on the ongoing field trials and non-commercial (test) deployment based investigations, the standardization of 5G is expected to mature with Release-16 of 3GPP by the year 2020. The 5G networks are expected to bring a transformative impact in the role that mobile communication technologies play in the society [2]. The 5G has taken a huge leap forward in the offered services, which are introduced through the advent of various new innovative technologies. The notable target 5G services can be named as enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLCs), massive machine-type communications (mMTCs), and Tactile Internet (TI) [3]–[5]. To solely benefit from the services offered by 5G technologies, the substantiation of 5G affordability and business case is a vital necessity.

A. MOTIVATION FOR 5G BUSINESS CASE

Despite the revolutionary technologies and innovative services being offered by 5G networks, the difficulties associated with their deployment along with other technological shortcomings have already started to appear in the literature, see e.g., [6]–[9]. The registered critical limitations and challenges for 5G networks can be summarized as: i) the enormous deployment cost, ii) the explosion of connected devices caused by the advent of mMTCs may very rapidly lead towards reaching the network capacity limit, iii) the rate and volume of the data generated in hyper massively connected 5G networks may need new data analytic innovations, and iv) the privacy and security provisions in massively connected networks – to name a few. The telecommunication engineers, industries, and researchers from around the globe have also already initiated the speculative propositions for network requirements and candidate technologies for beyond 5G (B5G) networks, see e.g., [10]–[14].

With a drastic increase in mobile internet users, the subscribers are likely to reach 5.0bn over the next 15 years [15]. Moreover, the sole mobile subscribers are expected to rise to 5.8bn between the years 2018 to 2025. A contribution of $ 2.2 trillion from 5G technologies to the global economy in the next 15 years is projected [15]. To facilitate this generation shift, a capital expenditure (CapEx) of $ 480bn is anticipated from the MNOs between the years 2018 and 2020. Moreover, with most of the 5G services happening after 2020, the CapEx will significantly exceed the CapEx anticipated by 2020. Admittedly, a huge investment for the network infrastructure deployment is a prerequisite to fully reap the benefits offered by the 5G networks. This necessitates the development of a comprehensive business model for 5G rollout to convince the investors, mobile operators, and other stake-holders to invest the requisite revenue. To this end, very recently, only a few articles discussing the 5G rollout cost, business cases, and other associated implications have appeared in the literature. Nevertheless, there is a strong need to thoroughly research the 5G rollout implications and to develop the sustainable business models addressing the complete scope of all 5G services (e.g., eMBB, mMTC, TI, etc) and all network scenarios (e.g., urban, rural, etc).

B. POTENTIAL SOLUTIONS FOR 5G AFFORDABILITY

The affordability of delivering the eMBB services offered by 5G is regarded as a vital issue by International Telecommunication Union (ITU) broadband commission [16]. The potential domains that can be explored to meet the challenge of making the ultra-fast mobile broadband as affordable to further enable the smooth provision of different societal and other interesting services can be identified as: i) infrastructure sharing, ii) Neutral hosting, iii) unlicensed spectrum utilization, iv) location-based spectrum licensing, v) energy-efficient networking, vi) wireless backhauling, vii) infrastructure cost reduction through softwarization and virtualization of the network functions, and viii) data sharing. Furthermore, in [17], a comparison of different potential technologies for the provision of network backhaul has been conducted. The fixed wireless backhaul is suggested as the most cost-effective solution for high cost fibers, while the utilization of low cost fibers has been suggested to result in direct-fiber technology as the most cost-effective solution. In [18], the 5G infrastructure strategies for capacity, coverage, and cost of 5G eMBB have been discussed for the Netherlands. The analysis for both supply-driven and demand-driven investment has been conducted. Also, the potential for traffic capacity enhancement in the existing Dutch macrocell network with the integration of the new 5G spectrum (only) has been studied. It has been determined that the average per-user capacity enhancement of 40%, as compared to the existing 4th generation (4G) networks, can be achieved by solely integrating the new 5G spectrum (i.e., without deploying the small-cells). The further improvement required beyond this determined threshold will necessitate the densification of the network with small-cells. The development of a framework to study the affordability of all 5G services, beyond eMBB, is a vital need at the current context. Moreover, the establishment of worldwide prospective on the affordability of 5G rollout is another important open challenge.

C. 5G ROLLOUT IN THE UNITED KINGDOM

In this section, we discuss about various aspects of 5G rollout in the United Kingdom (UK) including the recent developments. The ambitions of the UK government to be a global leader in 5G communication network technology needs the resolution of barriers and challenges in the commercial deployment of 5G. In this direction, the article [19] provided a review of critical problems related to the market factors for 5G rollout in the UK. In [20], a framework for the techno-economic market analysis of network backhaul has been proposed. The proposed framework can be used to study the total cost of ownership (TCO) of a network backhaul and business feasibility of the 5G network deployment aspects. The module takes the consideration of both the network CapEx and OpEx. A case study has also been conducted to demonstrate the usability of the proposed framework. A thorough analysis of techno-economic aspects of deploying eMBB in a typical dense urban area, realized by a 1km^2 grid of central London in the UK, has been conducted in [7]. Various aspects such as CapEx/OpEx, maximum user rate, and capacity have been studied for macro, micro, and hot-spot cellular network settings at 700MHz, 3.5GHz, and 24–27.5GHz operating frequencies, respectively. The headline rate of 64 to 100 Mbps, across all the coverage area, is expected to be achieved through several different technology prospects. However, the use of mmWave and 802.11ac are advised as necessary for achieving capacity in the orders of 100Gbps/km^2 for outdoor and indoor settings, respectively. It has been speculated that a 100-fold increased capacity and 100Mbps headline rate everywhere may be attained with an escalation of 4 to 5 times in the deployment cost as compared to that of 4G Long Term Evolution (LTE) networks.

Furthermore, in [6], a business model to study the cost and revenue flow of 5G has been proposed by conducting the case studies for three different boroughs of central London, UK. The eMBB services of 5G are considered important for the business case between the years 2020 to 2030. Some business risks that may emerge in the later years are also indicated. The network share has been highlighted as a significantly helpful aspect in improving the business case. Moreover, it is encouraged to conduct further research for different regions to obtain a nationwide understanding of the business case. In [21], the 5G rollout implications in UK have been discussed. The history of implications faced in the 4G rollout has been extrapolated to forecast the characteristics between the years 2020 and 2030. It has been concluded that the 5G eMBB may reach out to 90% of Britain's population by 2027. The challenges associated with capital intensity fluctuations may affect the pace of 5G rollout to the rural areas. Some infrastructure sharing suggestions for deploying small-cells can be considered to reduce the 5G deployment cost. The Ofcom has recently initiated the location-based licensing of 5G compatible radio spectrum [22], which will significantly help in making 5G affordable in the UK. Moreover, authors in [21] thoroughly discussed the policy matters and potential directions to drive the 5G rollout. Furthermore, the need for incorporating more spectrum for serving ultra-high-speed broadband to rural area users has also been suggested. In summary, the development of a comprehensive understanding of the disruptive impacts of 5G and beyond wireless networks in the UK is of vital importance in promoting a sustainable and ambitious digital economy in the long-term.

D. CONTRIBUTIONS AND ORGANIZATION

The main contribution of this paper is the investigation of potential long- and short-term transformative and disruptive impacts of 5G rollout. Potential solutions for reducing the 5G deployment cost and developing long-term sustainable business model for 5G through network infrastructure sharing, public infrastructure sharing, radio spectrum sharing, and data sharing are proposed. The interplay between 5G technology enablers, spectrum regulation, and business models is also thoroughly reviewed and an integrative prospective is presented. A typical UK city is considered for conducting the case study in this paper. Different to the approach of extrapolating the historic prospective adopted in [21], our work intends to provide the prospective learnt from a 5G testbed environment. The notable contributions of this paper are highlighted as follows,

- Starting with a review of the main 5G new technologies and target services, existing open challenges in the deployment of 5G networks and the research challenges that may go beyond 5G networks are thoroughly reviewed along with the potential future enabling technologies.
- The requirements, challenges, and solutions associated with 5G rollout are thoroughly reviewed. In this regard, a comprehensive study on the potential sharing of network infrastructure, public infrastructure, radio spectrum, and generated-data for reducing the 5G deployment cost and developing a sustainable 5G business is conducted.
- Along with a discussion on the potential barriers in sharing of data in 5G and beyond networks, the state-of-the-art of data privacy and security techniques and their importance in data-sharing based business models is thoroughly reviewed. Open issues and challenges pertaining to security are also discussed.
- State-of-the-art of spectrum trading and management techniques is reviewed, and the analysis is further extended to motivate the location-based shared licensing of the radio spectrum.
- A framework for passive infrastructure sharing (e.g., public infrastructure, site sharing, mast sharing, power cabling sharing, etc) and neutral hosting is proposed to reduce the deployment cost and provide an opportunity to the local authorities to become direct or indirect partners in the 5G business model.
- A case study, based on a 5G testbed environment, is conducted for a typical city of UK. The infrastructure sharing potential in reducing the 5G deployment cost in the UK as compared to its anticipated cost is studied. Moreover, the data-sharing and location-based licensing are motivated to bring a significant further reduction in the deployment cost as well as to provide a long-term sustainable business model.
- Finally, based on the proposed case study and conducted analysis, a data economy based long-term 5G business model is proposed and a list of related recommendations is provided.

The rest of the paper is organized as follows. Section II provides an overview of the 5G networks by thoroughly reviewing the technology enablers, target services, and related open research challenges. Section III discusses the radio spectrum regulation and management aspects of 5G and beyond communication networks. Section IV presents the 5G business opportunities and its deployment requirements. Section V presents the lessons learnt from the development of a 5G testbed environment for a typical UK city along with a thorough analysis and list of recommendations. Moreover, an integrative prospective on technology, spectrum, and business model is also proposed. Finally, the paper is concluded in Section VI.

II. 5G NETWORKS: TECHNOLOGIES AND SERVICES

The 5G wireless communication networks have introduced various new revolutionary technologies along with the evolution in the existing networks. The 5G networks are envisaged to offer various new services of new types to everything at all-time with ultra-reliable, ultra-fast, and ultra-low-latency communication links. The standardization of 5G networks as the standalone and non-standalone operating network has appeared with Release 15 [1] of 3GPP named as 5G New Radio (NR). This initial standardization effort is expected to advance with the Release 16 of 3GPP by the year 2020. The test and commercial deployment of 5G NR has now started in some cities of the world. Studying the perspective of both technology and economics is essential in establishing an integrative view on 5G to make it a success. This section provides an overview of the key 5G technologies and services. The challenges associated with the deployment of 5G networks and various other open research challenges (that may go beyond 5G (B5G) networks) are highlighted in this section.

A. 5G TARGET SERVICES

This section provides an overview of the prime 5G target services, i.e., eMBB, mMTC, and URLLC. Moreover, their enabling technologies and application scenarios are also briefly discussed.

1) ENHANCED MOBILE BROADBAND (eMBB)

The enhanced mobile broadband (eMBB) in 5G networks targets to provide an increase of 1000× and 10× in aggregate and individual-link throughput [23], respectively, compared to the 4G wireless networks. The downlink and uplink data rate targets of 5G networks are up to 20Gbps and 10Gbps, respectively. This high data rate is envisioned to support high throughput demanding services, e.g., tactile internet (TI), augmented reality and HD video streaming. TI is a new 5G service that aims at providing a real-time interface for humans and machines interaction [5]. The interface may support real-time audiovisual and haptic inputs based controlling of machines, e.g., remote humanly controlled robots for industrial and other operations, etc [24]. The notable new technologies enabling such high throughput in 5G networks can be named as massive multiple-input multiple-output (mMIMO) and mmWave band.

2) ULTRA RELIABLE LOW LATENCY COMMUNICATIONS (URLLC)

The 5G wireless networks target at achieving packet error rate and end-to-end latency of $\leq 10^{-5}$ and 1ms, respectively. Such ultra reliable low latency communications (URLLC) will help in realizing the dreams of various new types of network services, e.g., auto-driving cars, remote health services (ambulance aid, robotic surgeries etc), logistics automation, to name a few [25]–[27]. The critical technology innovations enabling URLLC in 5G networks are network slicing (NS), network softwarization, network function virtualization (NFV), and mobile edge computing (MEC).

3) MASSIVE MACHINE TYPE COMMUNICATIONS (mMTC)

The target of mMTC in 5G networks is the provision of internet access to a massive number of low data-rate and low power devices, e.g., the requisite connectivity to IoT devices. The IoT technology is believed to revolutionize the way we live and work today through various new innovative services. The communication in such typical applications is usually only occasionally required, e.g., in remote environmental sensing and utility metering applications, etc. The key technology enablers for mMTC in 5G networks providing minimal operational cost, grant-free, and time alignment-free connectivity to a massive number of devices can be listed as non-orthogonal multiple access (NOMA), end-to-end (E2E) NS, collaborative edge and cloud computing framework, and NFV [28], [29]. With the availability of required technology for IoT in 5G, the prospects of business paradigm shift for operators and vendors in providing IoT services in 5G are discussed in [30].

B. 5G NEW RADIO TECHNOLOGIES

5G NR is a new radio interface released by 3GPP to satisfy the growing needs of radio access in future wireless networks. The 5G-NR provides a number of significant new technologies and advantages compared to the 4G networks. In the following, we highlight the key features of different evolved and new revolutionary technologies in the 5G NR.

1) mmWave

The scarcity of conventional microwave band has led to the exploration of mmWave realm. The multi-gigahertz bandwidth available in mmWave range has a strong potential in addressing the capacity demands of 5G and beyond wireless networks [31]. The initial standardization of mmWave technology for short-range communications initially appeared in IEEE 802.11ad [32]. The Release 15 of 3GPP has specified 24.25GHz – 52.6GHz band associated with the band numbers from 257 to 511 as one of the major 5G frequency ranges [33]. The propagation behavior of mmWave spectrum in terms of high pathloss and the dominant phenomenon of specular reflections (instead of scattering, as in microwave band) has confined its applications to short-range and line-of-sight (LoS) communications [34].

Establishing a better understanding of propagation behavior of mmWave and beyond bands (e.g., sub-teraHz and teraHz bands) may lead to the availability of more usable bandwidth for B5G networks in the future.

One of the primary reasons behind the high licensing cost of radio spectrum is the scarcity of usable radio resources. Technological advancements for extending the usable radio spectrum beyond microwave bands (i.e., mmWave, sub-TeraHz, and TeraHz) may also lead to reduction in the radio spectrum cost. Moreover, the location-based licensing is another potential direction in reducing the deployment cost of 5G, which is thoroughly discussed in the sequel.

2) MASSIVE-MIMO

Massive multiple-input multiple-output (mMIMO) [35] is defined by a large-scale multi-antenna system in which massive amount of antennas are employed at the base station (BS), i.e., significantly larger than the users being served. The use of large-scale multiple antennas allows the aggressive manipulation of angular/spatial domain. The manipulation of angular domain parameters helps in countering the time and/or frequency selective behaviour of the propagation channels [36], [37]. This additional degree-of-freedom (DoF) offered by mMIMO systems can be exploited for diversity, multiplexing, and/or beamforming gains. The 5G NR with mMIMO can exploit 3D beamforming with up to 256 antenna elements at the BS to increase the coverage and capacity of the network [38]. In a frequency division duplex (FDD) mMIMO system, the pilot resources required for estimating the channels is proportional to both the number of BS antennas and the number of users being served. Moreover, it requires high computational power at both the ends of the link for estimating the corresponding channels which also elevates the system cost. However, in time division duplex (TDD) mMIMO systems, the channel reciprocity property is exploited, which relieves the user-end from the burden of channel estimation. Whereas, TDD mMIMO systems have a performance limitation of increased interference due to pilot contamination.

The cost of communication services is steadily increasing, which has emerged from the increasing cost of hardware, energy and spectral resources, and mobile tariffs. These aspects have led to the exploration of cost-effective system architectures and designs. In this context, a low-cost and high-efficiency design for the mMIMO system is proposed in citetan2018low. Imposing constraints on the transmit power and the amount of RF chains, while relaxing the hardware-perfections (inexpensive) and hybrid architecture designs can help mMIMO in achieving the overall low cost of the system. The successful rollout of mMIMO has a direct relation with the cost-effective implementation of RF chains.

3) FULL-DUPLEX

Full-duplex is a key 5G technology, which theoretically has the potential of doubling the channel capacity through the concurrent transmission and reception of information in a single channel resource. The performance of full-duplex method relies on the performance of self-interference-cancellation methods, which may practically be performed through active analog/digital cancellation or passive cancellation methods [39]. The cost effectiveness of the full-duplex solution depends on the tradeoff between the offered spectral efficiency and requisite interference cancellation capability.

4) NOMA

The provision of wireless medium's access to multiple users was conventionally achieved through the allocation of (sliced) distinct channel resources (time, frequency, or code, etc.) among the users and spatial re-utilization of the resources. The massive growth in the number of network users and the limited availability of usable frequency spectrum has led towards the evolution of multiple-access methods from orthogonal to non-orthogonal resource allocation based methods. The NOMA scheme allocates non-orthogonal channel resources to the users while exploiting an additional dimension/domain of power. Signal processing methods for channel estimation and interference suppression are the prime operations required in NOMA transceivers. Practically, the hybrid of conventional orthogonal multiple access schemes (e.g., CDMA, SDMA, etc.) and power domain multiple access is also referred to as hybrid NOMA. The chipset hardware support for the user side to perform successive interference cancellation (SIC) is also released [40]. Along with many other new technologies, NOMA is also one of the technology revolutions being introduced for the first time in 5G [41]. The spectrum efficiency and grant-free access provision advantages offered by NOMA makes it one of the core mMTC enablers in 5G wireless networks. On one hand, the spectrum sharing feature makes the NOMA a cost effective solution, while on the other hand, the multiple access interference requires costly computational capabilities for its successive cancellation. Overall, the advantages offered by NOMA compared to the conventional methods are at the cost of increased decoders complexity.

5) SMALL-CELLS

The ultra-dense network (UDN) planning enables the deployment of multiple small cells within the coverage region of a macro-cell [42]. These low-power short-elevation BSs based small cells employ a more aggressive spatial reuse of the resources and efficient users to BS association based on promising propagation channel conditions. The ultra-dense deployment of cells is a crucial enabler of eMBB in 5G networks [43], which has a strong potential in boosting the cell coverage and network capacity. The MNOs are required to densify the network several times more in 5G as compared to the 4G deployment. The high CapEx and OpEx requirements for deployment and maintenance of such a dense network is believed to be a potential delaying factor in 5G rollout.

A further densification of the network from small-cells to tiny-cells may impose severe infrastructural deployment challenges and related economics challenges. Moreover, a further aggressive reuses of the spectral resources is also expected to drastically increase the network interference. In the light of these concerns, the concepts of cell-free communications as distributed mMIMO systems and unmanned aerial vehicles (UAV) assisted cellular communication concepts are emerging as prominent solutions.

6) NETWORK SLICING, NETWORK SOFTWARIZATION, AND MOBILE EDGE COMPUTING

The new novel concepts of network slicing (NS) and NFV constitute an important part of the list of revolutionary technologies of 5G. In NFV, various network service features are designed as implemented in software that runs on off-the-shelf hardware [44]. The examples of these service feature include caching, network address translation, and domain name services. The NS allows the operations on an infrastructure shared among multiple network slices to create an end-to-end (E2E) true virtual network [45]. Mobile Edge Computing (MEC) is another exciting technology which offloads the network traffic by serving the users demands directly from the network edge, e.g., this can be achieved through caching of the popular (users specific) contents on the network edge (e.g., BS, access points, etc) [46]. These technologies hold the key role in achieving URLLC in 5G networks.

With the advancements in mobile network generations, the MNOs are required to spend a huge amount of revenue to upgrade their network. On the other hand, the average revenue generation opportunities for the MNOs per network user are on the decline [47]. One of the prominent solutions to reduce the CapEx and OpEx of the networks is in the exploration of softwarization, virtualization, and intelligentization of the mobile network operations.

C. 5G AND BEYOND OPEN RESEARCH CHALLENGES

Despite that 5G networks have introduced various revolutionary technologies and promising services; the huge cost of deployment associated to 5G networks and further growing demands of rigorous network performance requirements necessitate the initiation of dedicated efforts to indicate and resolve the challenges. This section highlights the challenges in the deployment of 5G and some open research challenges and technologies for B5G wireless networks.

1) ENERGY EFFICIENCY

The energy efficiency of communication networks has a direct relationship with the operational, environmental, and economic factors. The 5G technology innovations, such as mMIMO and ultra-dense networks, provide a manifold increase in energy efficiency. A further improvement in network operational energy efficiency in densely connected networks of the future will only help in reducing the network operational cost but also in realizing the dream of a green world. With the advent of mMTCs and small-cells in 5G networks, a huge number of BSs, sensing nodes, and user devices will constitute the network. In this massive connectivity context, the energy-efficient design of the network devices will be a highly compelling aspect [48]. The realization of joint energy, spectral, and spatially efficient green communication systems of the future will be in the optimization of b/s/J/m^3.

2) NETWORK CAPACITY

With the advent of mMTC in 5G networks, a massive proliferation in the number of network nodes is expected in the coming years. The densification of cells may eventually meet its practical limit, as a further decrease in cell size (towards very tiny cells) may have some unmanageable associated physical deployment constraints, deployment costs, and intercell interference. Further evolution and revolution in network technologies and extension in usable frequency spectrum may be required. A promising future enhancement can be seen in the idea of employing vehicular BSs, i.e., cell-free networks served through Unmanned Aerial Vehicles (UAVs). The future networks may be 3-D natured with volumetric quantification of coverage specifications and spectral efficiency [10] (i.e., b/s/Hz/m^3).

3) THROUGHPUT

The throughput offerings of 5G wireless networks are expected to attract various high data rate demanding applications, e.g., virtual reality applications. Such applications and massive connectivity may result in 5G reaching its limit in a decade or so [13]. For meeting the exceptionally high throughput demands of future networks, one venue can be the exploration of mmWave, sub-teraHz, and teraHz bands. Moreover, communication in the optical spectrum (visible light) may also attract various LoS and indoor communication applications [14].

4) INTER-PORTABILITY AND CONGESTION IN HETEROGENEOUS NETWORKS

The 5G networks will operate in the coexistence of its predecessors (1G to 4G). Achieving harmonization of operations across different network architectures with different conditions for real-time communication applications is another challenging issue for operations in 1G-5G hybrid heterogeneous networks. The MNOs may deploy a core 5G radio access network (RAN) infrastructure to coordinate the network heterogeneity [2]. The application of machine Learning (ML) methods for achieving the harmonization and learning of the network state is a potential enabler [10].

The MEC technology of 5G wireless networks is expected to provide a substantial improvement in the performance of not only to 5G users/devices but also to users operating on previous generations [10], [46]. The intelligent caching at the network edge will help in offloading the data traffic from the network backhaul. The congestion in access networks in ultra-dense connectivity scenarios (e.g., mMTC, etc.) is another challenging issue. Grant-free access to IoT devices may help in resolving the congestion in ultra-dense access networks imposed due to the heavy burden of signaling for enabling communication of a large number of short-data-packets.

5) ETHICS FOR BIG DATA ANALYTICS

The recent advances in communication network technologies, proliferation in the number of connected devices, and growing multimedia applications are leading towards a flourishing expansion in the data generation [49]. The radio communication networks are not only the carriers but also a leading source of generation of data. Appropriate exploitation of big data analytics has a strong potential in facilitating the improvement in the performance of the communication systems as well as in maximizing the revenue generation opportunities for the stakeholders [50]. In [29], the data-aware intelligence for extracting useful information from the data and enhancing the network performance for IoT applications have been discussed. Also, a collaborative processing framework while combining the benefits of edge and cloud computing for live data anaytics in IoT networks has been proposed. Along with the benefits offered by big data analytics, there are also various critical concerns being raised regarding the ethics of the analytics [51]. The essential factors for devising comprehensive data sharing policies need to be explored to interpret the broader context of data choice, collection circumstances, ownership rights, substantiation and usage permissions. There is a need to conduct thorough investigations to understand the implications related to data analytics technology in B5G communication networks concerning the individuals and organizational interests.

6) SECURITY AND PRIVACY

The provision of security and privacy of data is among the most important concerns in 5G rollout. In densely connected networks, provided the provisions of data security and privacy, the enormous amount of generated data can be potentially used to enhance the network performance [52] as well as revolutionize the existing business models. Ensuring a balance in the policies for enabling necessary data sharing with high data security may emerge as a main policing challenge in the future.

5G offers new and disruptive business cases [53]. While rolling out 5G networks in the next-generation smart cities due to many new features of 5G networks and the fact that 5G will envelop almost all dimensions of human life, business, and government affairs with ultra-high-speed access to services, anywhere, anytime and any type, 5G security requirements have to be thoroughly researched [54]. 5G rollout will also bring a wide range of threats and a greatly expanded attack surface [55]. For example, 5G physical layer security at the RAN [54] is susceptible to new types of attacks and performance bottlenecks such as eavesdropping, contaminating, spoofing, and jamming. Since 5G rollout will leverage existing telecom infrastructure and other computing and networking paradigms [54], 5G will operate within heterogeneous networks (HetNets) [56].

The HetNet architecture, compared to a single-tier architecture, can potentially lead to the user devices to be more vulnerable to eavesdropping [57] and hence privacy and location leakage may arise due to frequent handover caused by the high density of small cells in the HetNets [56]. As a result, a new generation of security services is a vital need [57]. Novel 5G authentication and key agreement (AKA), subscriber identification module (USIM), and elliptic curve cryptography (ECC) based design of handoff authentication for 5G wireless local area network (WLAN) HetNets will be needed that can extend the provisions of secure and seamless internet connectivity [58]. Many of these additional requirements come from the technology shift to software defined network (SDN) [54] and NFV [44], network slicing, mMIMO [35], NOMA [59], ultra-dense small cell network [42], D2D and M2M communications, and the cloud, and they lead to the need of increased security on the network side. 5G NOMA, mmWave, mMIMO, and beamforming can improve physical layer security of 5G networks through co-operative jamming [57], [60], which will allow secret and high-quality channel with the legitimate UEs while frustrating eavesdroppers with noisy, random, and poor channel conditions. The directional property of mmWave can be leveraged to establish and share secret keys that are unconditionally secure from the passive eavesdroppers [31], [61]. A thorough review on the security considerations for 5G deployment is conducted in the sequel.

7) DEPLOYMENT COST

The huge CapEx and operational expenditure (OpEx) requirements and lack of clear business model are among the major challenges in fully benefiting from the revolutionary 5G technologies. In this context, it is important to jointly investigate the perspective of technology and economics. The potential directions to reduce the deployment costs can be indicated as the sharing of infrastructure (passive and active), neutral hosting, and location-based spectrum licensing – to name a few. The deployment cost analysis is one of the primary subjects addressed in this paper.

III. SPECTRUM MANAGEMENT AND REGULATION

Regulation and management of the radio spectrum is another vital task in formulating a viable 5G business solution to fully benefit from the provisions of technological innovations. The demand for new radio spectrum and efficient utilization of the available spectrum, towards supporting the ever-increasing volume of data traffic caused due to the massive number of devices as well as bandwidth-hungry services, is rapidly increasing. To this end, the introduction of new spectrum such as millimeter wave frequency band, dynamic spectrum sharing, location-based licensing of spectrum and spectrum trading are among the promising solutions. Regarding the spectrum regulation, the mostly widely-discussed approaches include Citizens Broadband Radio Service (CBRS) (mostly in the US), LSA (mostly in the Europe), and TV White Space (TVWS) in the global level [62]. In the following, we discuss spectrum sharing models and techniques as well as regulatory aspects of spectrum sharing.

A. SPECTRUM SHARING MODELS AND TECHNIQUES

Dynamic spectrum sharing techniques can enable the sharing of the radio spectrum among two or more wireless systems and can effectively utilize the available radio frequencies [63]. The existing dynamic spectrum sharing models can be broadly categorized into the following three types: (i) Commons Model, (ii) Shared-use model, and (iii) exclusive-use model [64]. In the spectrum commons model, radio spectrum is not owned by any provider and all the secondary users or unlicensed users can access the spectrum with equal rights. This sharing model suitable for spectrum sharing operation in the unlicensed bands such as Unlicensed National Information Infrastructure (U-NII), i.e., 5GHz, and Industrial, Scientific and Medical (ISM), i.e., 2.4 GHz. The main problem with this open access approach is that unlicensed users may suffer from the inter-user interference, and this may result in the network congestion.

In the shared-use model, the secondary users utilize the vacant spectrum or underutilized spectrum in an opportunistic way or an interference-avoidance manner without harming the normal operation of the primary users by using various Cognitive Radio (CR) techniques. The CR technology is considered as one promising technology to address the issue of spectrum scarcity, which can enable the coexistence of two or more wireless systems either in an opportunistic mode, i.e., interweave paradigm or with the interference avoidance mode, i.e., underlay paradigm [65]. The interweave paradigm mainly deals with the spectrum sharing or database assisted techniques, while the underlay techniques enable the spectrum sharing techniques of wireless systems by means of suitable interference mitigation techniques such as beamforming and power control.

Besides the aforementioned interweave and underlay paradigms, several advanced spectrum sharing mechanisms including Carrier Aggregation (CA) and Channel Bonding (CB) [66], Spectrum Access System (SAS), Licensed Shared Access (LSA) and Licensed Assisted Access (LAA) [67] have been investigated in the literature. Furthermore, various other spectrum sharing techniques such as spectrum leasing, spectrum trading, spectrum harvesting and spectrum mobility have been discussed in the literature towards improving the spectrum efficiency and energy efficiency of wireless networks [68].

On the other hand, the secondary users can acquire the exclusive spectrum usages right for the required bandwidth and duration in the exclusive-use model. These exclusive rights can be obtained from the primary system either by purchasing the spectrum from the primary service providers or spectrum licensees or by providing a cooperation reward, for instance the relaying of the primary data. As compared to the shared-used model, this approach has several advantages for the secondary users as they do not need to sense the primary channel and do not need to switch from one channel to another channel. This mode of spectrum sharing in the exclusive-mode is also called as spectrum trading [64], which can be implemented either directly between the secondary and primary service providers or can be managed by a spectrum manager/broker or a spectrum exchange market.

An auction operation may be needed or not depending on the required duration for spectrum trading, i.e., long duration of spectrum trading needs an auction while a short duration may not need an auction. Auctioning process becomes more suitable in the scenarios with a high demand and limited supply since a seller can attract more benefits by involving multiple bidders. However, this method depends on various factors such as low number of bidders or a single bidder, all bidders asking below the required price, time dependency, and the need of multiple iterations to obtain a suitable solution, thus resulting to the need of a real-time multi-seller and multi-channel model while considering the dynamicity of the channel and traffic conditions [64]. On the other hand, non-auction based models can be designed based on game-theoretical models and may be categorized into monetary [69] and non-monetary types [70].

Considering the increasing demand for Ultra-Reliable and Low-Latency Communications (URLLC) applications such as industrial automation, there arises the need of meeting reliability requirements with the available spectrum. The existing factory automation generally utilizes unlicensed Industrial, Scientific and Medical (ISM) bands and benefits from their wider bandwidths in handling large traffic volumes. However, the reliability targets of below 10 ms can not meet with the existing solutions [71], and also the unlicensed mode of operation requires the careful design of minimizing or avoiding interference being subject to strict regulatory constraints. Considering these drawbacks of utilizing unlicensed bands or factory automation applications, the authors in [72] demonstrated the possibility of utilizing 5G cellular licensed band as an alternative option for factory automation applications, and also showed the significance of utilizing integrated unlicensed and licensed bands in terms of economic viability. However, several challenges in terms of synchronized operation in the unlicensed and licensed bands and over-the-air inter-system coordination needs to be addressed to realize this integrated spectrum utilization approach in practice.

The authors in [73] discussed the use of 24 GHz as the Gigabit wireless networking spectrum based on the forecast methodology for 5G spectrum by K-ICT for IMT 2020 Korea [74], where three different forecast methodologies for 5G spectrum needs, namely, traffic forecast-based approach, technical performance-based approach, and application-based approach have been identified. From the analysis presented in [73] regarding the use of 24 GHz, there arises the requirement of over 370 MHz spectrum for mobile broadband services for 1 Gbps speed and this requirement is expected to increase by 10% till 2024. Also, the analysis pointed out the need of about 233,282 base stations in the analyzed regions consisting of dense urban, urban and sub-urban areas to support the increasing number of 5G users.

Moreover, understanding the spectrum usage pattern with the help of suitable spectrum monitoring techniques/platforms is a vital task towards enhancing the radio spectrum utilization efficiency of Beyond 5G dynamic sharing systems. In this direction, Machine Learning (ML) techniques are of significant importance to predict the future spectrum usage and to address the inefficiency issues in spectrum management and utilization. The existing ML techniques can be broadly categorized into supervised, unsupervised and reinforcement learning [75]. Authors in [76] carried out the analysis of spectrum occupancy in CR networks by utilizing different supervised and unsupervised ML techniques. Under the supervised learning approach, various techniques including Naive Bayesian Classifier (NBC), Support Vector Machine (SVM), Decision Trees (DT), and Linear Regression (LR) were considered while under the unsupervised learning, Hidden Markov Model (HMM) approach was investigated along with their numerical comparisons in terms of computational time and classification accuracy.

Furthermore, a conceptual framework of end-to-end learning for spectrum monitoring applications has been presented in [77] along with a generic methodology to design and implement wireless signal classifiers followed by two case-studies related to modulation recognition and wireless technology interference detection. The end-to-end learning concept investigated in [77] refers to a learning procedure in which the features of a wireless signal are extracted, and a wireless signal classifier is utilized to classify the received signals. Moreover, it may not be reliable in practice to learn the radio spectrum usage by an individual node due to several issues such as multi-path fading and hidden node problem, leading to the need of collaborative learning and spectrum sharing strategy [78]. Also, a non-collaborative way of spectrum usage learning in mmWave bands may result in challenging issues due to the involved directional antenna beams, and this can be improved by enabling collaboration among the secondary users to predict or estimate the spectrum occupancy distribution of the radio channels [79].

B. SPECTRUM REGULATION

As highlighted earlier, the most widely-accepted spectrum sharing approaches from the regulatory perspective include CBRS (mostly in the US), LSA (mostly in the Europe), and he TVWS in the global level [62]. For the TVWSs, licensed and database-based sharing models have been considered under regulatory discussion after several standardization trials by the OFCOM in the UK [80] and by the FCC in the USA. Authors in [62] have analyzed and compared the attractiveness and viability of these spectrum sharing methods by utilizing main economy business indicators towards developing a scalable sharing method since designing a scalable model for all the involved stakeholders is essential towards to make a spectrum sharing concept adoptable in practice. Furthermore, sharing of infrastructure and frequency assets as compared to the conventional way of controlling these assets at the resource-level, and the openness of the business models are of significant importance from the business perspective.

Although the TVWS method provides the advantages of low entry barrier and practically free spectrum, its market acceptance has been quite low due to non-guaranteed QoS and uncertainties related to predictability and available frequency assets. On the other hand, the LSA approach provides the advantages of higher certainty and predictability for both the LSA licensees and incumbent users. And the CBRS approach provides benefits of low entry barrier to new operators and facilitates the scaling of ecosystem with new roles and innovations as compared to other approaches. For all these three sharing models, authors in [62] showed the positive effect of various economy factors including leverage of underutilized assets, value orientation, adaptability to underlying policies, reduced need for the ownership and the sharing platform. The recent contributions in [81], [82] analyzed the issues faced by today's industries in acquiring frequency resources to support the Industrial IoT applications along with their key requirements. Also, the authors in [81] introduced a CBRS based spectrum sharing model to address the industrial IoT needs and requirements by considering four different practical use-cases. It has been demonstrated that CBRS is suitable for various industrial IoT use-cases with the minimal overhead on the leasing rules defined to enable the spectrum lease to the neighboring enterprises.

As compared to the exclusive licensing of the spectrum, spectrum sharing (license-exempt) mechanisms facilitate new Mobile Network Operators (MNOs) to enter into the market with lower barrier and fosters the competition among the MNOs to introduce new services. In this direction, LSA approach is considered as an important spectrum sharing method by European regulatory and standardization bodies, which allows an MNO to share the spectrum with the incumbent users under certain conditions and rules which can guarantee the QoS to both the LSA licensees and incumbent users [83], [84]. To enable the implementation of the LSA approach in practical heterogeneous networks consisting multiple frequency bands and radio access technologies, novel coordination protocols need to be investigated towards facilitating the integration of shared bands into the cellular infrastructure and the cooperation between MNOs and incumbents. The LSA-based spectrum sharing can be realized across several dimensions including time, frequency and geographical location, and relies on a sharing framework under the responsibility of national regulatory authority/administration [85].

IV. BUSINESS OPPORTUNITIES AND DEPLOYMENT REQUIREMENTS

This section mainly discusses the 5G deployment requirements, the economic constraints associated with the 5G rollout, and their potential solutions. The principal factors that may affect the speed of adoption of 5G and its generation of value can be listed as the cost of 5G rollout, availability of opportunities for different 5G service classes, need for a supportive policy framework, availability of 5G devices, compelling business model and value perception [15]. We propose that smart management and sharing of infrastructure (network and public), generated data, and radio spectrum between different users/operators are the potential directions to reduce the 5G deployment cost as well as develop long-term 5G business models. To this end, this section first thoroughly investigates the potential in sharing of network and public infrastructure for reducing the 5G rollout cost. Furthermore, the potential of smart management and sharing of the radio spectrum in reducing the 5G rollout cost is reviewed. The sharing of data to generate value as well as improve network performance requires comprehensive data privacy and security model. Therefore, security and privacy concerns and other barriers in sharing of data are also thoroughly studied in this section.

A. INFRASTRUCTURE REQUIREMENTS

Over the past few decades, the land-mobile radio cellular networks have evolved from 1G to 4G. The infrastructure for these mobile generations has been established with a massive investment. In the existing infrastructure, there may exist over several hundred thousands of wireless communication sites worldwide. The sites may include wireless setups for emergency services, broadcast services, cellular communication services, and other national communication services. The reduction in a typical cell-size has been witnessed along with the progression in generations of wireless networks. The cell coverage radius of a standard cell from 2G to 4G has evolved from approximately 10s of km to a single km. To fully harvest the benefits from 5G technologies, an extension in the spectrum and densification of the network is obliged. The inclusion of radically high mmWave radio spectrum in 5G requires beamforming and beam-management equipment at the small-cell BSs. Furthermore, the ultra-dense deployment of cells, i.e., small-cells with cell-radius of only a few meters, necessitates massive infrastructural provisions. Consequently, to meet the vast infrastructural requirements for deploying small-cells and mmWave communication facilities at the ultra-densified BSs in 5G networks, an enormous revenue investment is needed.

In the provision of true 5G services, an ultra-densification is inevitable, and meeting the challenges in providing essential infrastructural requirements needs the conduction of thorough investigations. In such an ultra-dense BSs deployment context, the conventional BSs deployment-related challenges may also get amplified. These challenges include: abidance of BSs antenna tilts and power radiation standards for health/safety, lease disputes with landlords, planning permissions and lack of suitable sites. The safe user to BSs distance can be calculated by exercising the recommendations for electric field intensity by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [86]. For radiations at different frequency bands, Table 1 presents the electric field intensity (using ICNIRP recommendations), equivalent isotropically radiated power (EIRP), and safe-user-distance in volts per meter (V/m), Watts (W), and centimeter (cm), respectively. The basic deployment principle being followed by the operators is to ensure 1/10th of the ICNIRP voltage density, for the exposure of RF for a long time (i.e., more than six minutes). Thus, considering the radiation power, the safe-user-distance in the table represents the shortest permissible distance between the transmitter and human-head. The enforcement of maximum power radiation standards and safe-user-distance assurance for health/safety may be another critical challenge in ultra-dense deployment context. The details of different classes of BSs defined by 3GPP that can be manifested as small-cells for ultra-network-densification, as provided by [87], are presented in Table 2. The typical BS bands, transmit power, gain, EIRP range, and installation classes configurations are classified into medium range, local area, and home BSs. The details provided in Table 1 and 2 may assist in devising a comprehensive strategy for infrastructure sharing and value generation opportunities to support a swift 5G rollout.

TABLE 1. Safe work distance recommended by ICNIRP from the typical transmit power of the respective frequency [86].

Frequency (MHz)	ICNIRP EMF Limit (V/m)	EIRP (W)	Distance (cm)
800	39	100	140.44
900	41	100	133.59
1800	58	50	66.78
2100	61	50	63.49
2600	61	10	28.39
3500	61	2	12.7

TABLE 2. Typical mapping of installation classes for typical small cell deployments [87].

3GPP BS Class	Configuration	Typical Total Tx Power	Typical Gain	EIRP Range	Installation Class
Medium Range BS	2 bands	20 W	7 - 13 dBi	100 - 400 W	E+
	1 band	10 W	7 - 13 dBi	50 - 200 W	E100 or E+
Local Area BS	5 bands	2.5 W	2 - 5 dBi	4 - 8 W	E10
	1 band	0.5 W	2 - 5 dBi	0.8 - 1.6 W	E0 or E2
Home BS	5 bands	100 mW	0 - 3 dBi	0.1 - 0.2 W	E0 or E2
	1 band	20 mW	0 - 3 dBi	0.02 - 0.04 W	E0

B. INFRASTRUCTURE SHARING POTENTIAL

Sharing of existing telecommunication and public infrastructure for small-cell deployment is an attractive solution to substantially reduce the 5G deployment cost and to encourage revenue generation opportunities for Mobile Network Operators (MNOs). The hesitance of MNOs in implementing

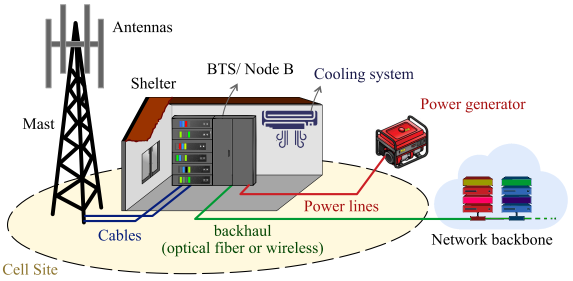


FIGURE 1. **Schematic diagram of a cell site illustrating the components in the context of possible infrastructure sharing.**

the standalone 5G solution is understandable. Fig. 1 illustrates the schematic diagram of network infrastructure by highlighting the important candidate components for possible infrastructure sharing. To this end, the solution may be in the optimization of technology and passive infrastructure along with the development of the revenue generation models for supporting the sharing of active infrastructure. To make the cost-optimization more effective and quick, devising a robust pathway is vital. In this regard, the promotion of competition among different partakers from infrastructure domain may help. Moreover, the thorough policying for sharing infrastructural services between different MNOs is another potential step. More importantly, the induction of non-MNO assets for 5G deployment into the infrastructure sharing business model will help in further stimulating the rollout. The Neutral Hosting model can be mainly signified as an effective form of infrastructure sharing.

Active sharing requires the MNOs to share elements of the active network layer. The active sharing components include RF antennas, MSC, HLR, OMC, SGSN/GGSN, core transmission ring, core network logical entities, billing platform and value-added services (VAS). Despite the cost optimization advantages associated with active sharing approach, it is becoming unpopular due to various dynamic reasons linked to network infrastructure domain. The forms of *passive sharing* are site and mast sharing. The passive sharing agreements are associated with multi-tenancy within sites (physical location), power cabling, cabinet/shelter, generator, cooling system, and mast and backhaul (fiber).

The following is the potential list of sharing components.

1) Mast Sharing
2) Site Sharing
3) Full RAN Sharing
4) Network Roaming
5) Core Transmission Ring Sharing
6) Shared Core Network Elements and Platforms

Moreover, the public infrastructure from local governments potentially available for sharing/reuse can be listed as:

1) Streetlamps
2) Road/street signs
3) Rooftops
4) Tall building with suitable projections surfaces – considering proximity
5) Traffic signals
6) Cabinets
7) CCTV installations

For sharing the indicated public infrastructure, there are various other factors which may need careful consideration. The capability of street furniture (e.g., streetlamps) for bearing the extra weight required to hold antennas and other equipment needs to be assessed. Moreover, the height requirements of the street furniture to facilitate different BS installation classes to meet the safe-user-distance recommendations (as discussed in the previous subsection) also needs to be investigated. Furthermore, various other factors like weather aspects (e.g., aerodynamics etc.) are also critical in adopting a passive infrastructure sharing option. In light of these critical factors, streetlamps are recommended as the most suitable choice for passive infrastructure sharing in this work. The iWS recommended design [88] for a typical small-cell mast is illustrated in Fig. 2 along with the height recommendations for different BS installation classes. This solution is for 4G cells, which can be revisited in the context of required ultra-densification in 5G networks.

C. DATA SHARING POTENTIAL AND ASSOCIATED BARRIERS

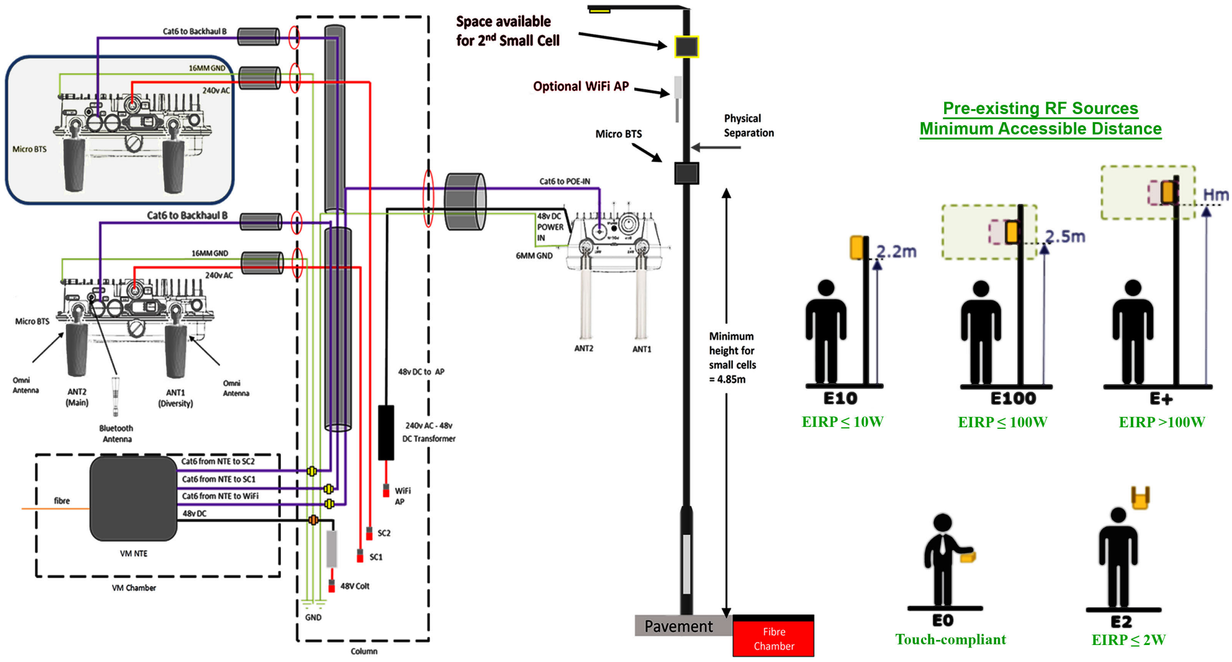
A significant increase in the generation of data from different network services is expected in the coming years [10]. An annual growth of 55% in data-traffic is forecasted from the year 2020 to 2030 [89], which will include a significant contribution from the subscriptions of new services introduced by 5G such as mMTC. As a result, the data generated per month is expected to reach 5.016 ZetaBytes (ZB) by the year 2030. Appropriate exploitation of this huge amount of generated data can assist in not only improving the user experience but also in creating the new revenue generation opportunities. A balanced policy for sharing of data with different stakeholders, while also maintaining the necessary privacy and security provisions, can help in directly translating the data value into performance enhancement and revenue generation opportunities. To this end, this section highlights the barriers in data sharing and motivates the opportunities for their resolution.

1) LACK OF USE CASES

There are no explicit motivational use cases available; which is because of the data value conception being a recently emerged perspective. This data-value based core business has developed with a drastic increase in the amount of data generation arose with the growing network services. Development of explicit examples/models for facilitating successful selling and buying of valuable data in the mutual benefit of all stakeholders is necessarily required.

2) IMMATURE MARKET

The current business strategy is not exclusively based on the data value. The immaturity of the market in this context is one of the critical barriers in the initiation of dedicated efforts for defining the required policies of data sharing.



(a) Example: iWS recommended solution for small cell mast (Source: iWireless Solutions)

(b) Installation classes for simplified deployment of small cells.

FIGURE 2. iWS recommended solution for small cell mast [88] and installation classes for simplified deployment of small cells.

The commissioning of data sharing has a strong potential in generating new data value based business models in the long-term.

3) FRAGMENTED DATA LANDSCAPE

The data in the current model is often not in the entangled form, which is a primary requirement to identify the data value. The lack of availability of concatenated/de-fragmented data to define a meaningful business model is a crucial barrier.

4) RELUCTANCE OF DATA SHARING

The data privacy, security of data privacy, and the absence of any comprehensive business model are among the primitive reasons causing hesitation in the sharing of data. The lack of a distinct definition of direct or indirect financial benefits associated with data sharing for core business is another leading cause.

5) SKILLS AND COMPETENCE

The lack of skill sets for the collection and processing of data into suitable compositions for enabling data sharing is another critical barrier. The shortage of available data scientists and the high cost of associated equipment are vital causes. Moreover, the absence of a unified technical-platform for data processing and serving is also a prime contributor to the barrier.

D. CONCEPTUALIZATIONS FROM INNOVATION AND ECONOMICS

The economics and engineering design are the two prime perspectives that drive the market of new technologies such as 5G networks. The engineering design perspective focuses on technological innovations and evolution of the products/designs to achieve performance revolutions. However, the economic outlook fundamentally deals with the exploration of prospects for the marketing of engineering designs/products for transactions across different consumer groups (both sides of the market). In [90], an integrative framework to bridge the gap between economics and engineering design prospects is proposed. Various useful opportunities associated with both the aspects are thoroughly reviewed, and the proposed framework is further utilized to derive a model indicating the patterns of interaction between innovation and competition. The transformative impacts of digital platforms bring sociotechnical and distributive in nature on different related industries are discussed in [91]. A list of questions for advancing the research on digital platforms in the business domain in the context of emerging data-driven approaches is provided along with a thorough discussion. Through an appropriate conception of business models and ecosystems, dynamic capabilities can be established for enabling the firms to generate value opportunities in platform-centric ecosystems [92]. For the generation of value from innovation in digital platform-based ecosystems by exploiting dynamic and integrative capabilities are discussed in [93]. Based on the conducted theoretical analysis, a way forward for the creation and capturing of value by platform leaders through dynamic capabilities is proposed. Moreover, three types of dynamic capabilities are indicated, which, at a minimum, are critical for the platform leaders. The indicated types of dynamic capabilities for ecosystem orchestration are named as innovation, environmental scanning/sensing, and integrative capabilities.

The private 5G networks can be described as 5G technology based networks operated privately for extending the services to a dedicated confined (local) area. The concept of micro-operators in 5G aims at enhancing the local service delivery in high-demand regions on behalf of the MNO as neutral hosts with open 5G networks by targeting specific customers in different vertical sectors in closed 5G networks. The micro-operators concept may adopt various diverse types of platform business models for service delivery to different mix kind of customers. In the context of emerging 5G wireless networks, the transformations in the mobile communication business ecosystem are discussed in [94], [95]. Three business model choices and value ecosystems for local 5G micro operators are studied, viz: horizontal, and oblique business model and ecosystem. Moreover, the essential related aspects, such as scalability, adaptability, and sustainability of the business models and ecosystems, are also thoroughly investigated. In [96], the need for a transparent 5G business model to fully benefit from the novel use cases and innovative technologies of 5G networks. In [97], a new business model is identified for exploiting cooperation between users, heterogeneous network structure, and mobile operators. The emphasis of the study is on the business models for reducing power consumption in mobile communication networks. The unfolding of 5G business is discussed, and a framework for analyzing 5G business models is constructed with a particular emphasis on value creation and value capture. In the context of the industrial internet, business ecosystems are studied in [98]. The study emphasizes the importance of understanding the context of the integrated and co-dependent processes of value creation and value capturing. The standing of firms within the ecosystem in terms of stages of production or service of the life cycle and other aspects is essential.

Value creation for the consumers is the central element in the demand-side strategy and various business models. In [99], the potential of jointly researching the business models and demand-side strategy is motivated. It is indicated that the natural cross-fertilization in both the domains can mutually benefit in promoting a suitable strategy-making. In [100], analysis on the appropriate choice of the business model; from Proprietary, Open-source, and Mixed-source models; for the firms selling software and related complementary services is conducted. Among various other useful conclusions drawn from the analysis, it is also established that there may exist no trade-off between value creation and value capture while comparing business models of different openness nature. The transformative impacts of a business model based approach/thinking on the strategic management in an organization are discussed in [101]. Given that the environment in every organization in an industry is not the same; therefore, establishing of the choice of model is essential in devising the management strategy. Moreover, the interaction with stakeholders selected through the choice of business model also influences the ability to implement the model. Furthermore, it is also emphasized that as the realistic environments and scenarios are time-variant therefore, the business models and ecosystems may be devised as adaptive and progressive in order to encourage new opportunities for the business models. The potential causes that make the market places difficult and may lead to failure of business models are essential to be thoroughly investigated. Startups with highly efficient technologies can also likely fail. In [102], a comparative perspective of Pipes and Platforms in the context of potential reasons for failures of business models is highlighted. The distinction between these two types of business models is motivated as necessary for avoiding the failures.

We have now established that there is undisputable business attention in commercializing the current infrastructure of the 5G for greater business opportunities. This opportunity also comes with a great challenge of price due to the volume of the devices required for the 5G and infrastructural CapEx costs. The business investor communities certainly need a new 5G specific licensing and insurance mechanism in place to secure their investments. This business fear is not just related to the risk they see by putting a huge investment in this advanced 5G infrastructure, they are also in a concern of the longevity of the solution. There are telco companies who are already deployed and launched their 5G network for the community to experience the advantage of 5G to generate enough interest and momentum from the public to create the investor's interest in infrastructure investments. While this is certainly magnetizing interest from the investors, but big national investors are still concern about their long-term business assurance to make the investment viable for them. This is already accepted that the new infrastructure will bring a large commercial benefit and will also open numerous new business opportunities, but the lack of policy level assurance of their business investment is still a key challenge here. The current financial business model is struggling to succeed as there is no long-term investment assurance by the government or the telco associations. This also linked to another business model challenges on the policy side too as this is a very innovative technology and the infrastructure requirements are rapidly changing in different phases of 5G development. These dimensions of the problem also make their policy lead business model very challenging to set a fix future standard. Another major business question for the infrastructural investors remains open if the technology makes a shift from 5G to more advance network not following the gradual standard migration path allowing infrastructure to devalue its investments and made enough profit throughout its lifetime. While all these circular interdependencies make the new infrastructure very complex business model to invest in the proposed in hand infrastructure model looks like a way forward for the success of the 5G.

V. CASE STUDY: A TYPICAL UK CITY

This section presents a case study conducted to represent a typical UK city. For this purpose, the local authority rendered typical West Midlands city layout is adopted. In the UK, there are four major MNOs. In Table 5, the details of current major infrastructure consumers in the UK are provided, which are classified into MNOs, MVNOs, private networks, and semi-private networks classes. This study is broadly focused on exploring the interrelationship between technology, spectrum, and business prospects for 5G networks. There exist enormous potential to reuse the available physical resources on a shared basis in order to avoid the development of new infrastructure. Mainly, this study aims at demonstrating the potential of available infrastructure sharing (e.g., street furniture and public building, etc.), data sharing (with necessary security provisions), and spectrum sharing (e.g., location-based licensing) opportunities. These aspects provide the basic framework of this case study. We begin with the introduction of the 5G testbed environment and experimental setup, then further proceed with conducting a comprehensive analysis on our findings.

TABLE 3. Summary of 5G networks target KPIs.

Service Platform	**Device Density ($/km^2$)**	**Mobility (km/h)**	**User Data Rate.**	**Cell Edge Rate**	**Latency**	**Availability (Reliability)**
eMBB	Up to 10k	0 to 360	50 - 100 Mbps	50 Mbps DL, 25 Mbps UL	10 - 50ms	99%
mMTC	Up to 1m		Up to 100kbps	100 kbps DL and UL	>50ms	99%
URLLC	Up to 10k		Up to 100 Mbps	10 Mbps DL and UL	1 - 50ms	99.9% - 99.999%

A. 5G TESTBED ENVIRONMENT AND EXPERIMENTAL SETUP

West-Midland 5G (WM5G) is the UK's largest 5G testbed, which is available at the 5G business & innovation center (5GBIC) in Birmingham City University (BCU) UK. The WM5G is a public-private partnership initiative with an investment of up to £150m. This partnership aims at providing innovation to attain enhanced digital productivity and economy. The WM5G at 5GBIC is utilized for the conduction of this case study. The key performance indicators (KPIs) of the 5G testbed environment are summarized in Table 3. The derived coverage range estimate for different 5G target services (i.e., eMBB, URLLC, and mMTC) is provided in Table 4. The table exhibits a more ubiquitous view of the scale of infrastructural provisions required for 5G services. The characterization of coverage range into different cellular conditions/environments (i.e., rural, sub-urban, and urban) and various frequency bands (i.e., 700MHz, 3.5GHz, and 26GHz) is also presented.

The Case study is conducted for a 5 km^2 area representing a typical UK city. The configuration of existing telecom and local authorities owned infrastructure in the considered region is plotted in Fig. 3. In Fig. 3(a), (b), (c), and (d), the location of existing 4G macro-cells, with added public buildings, with added street furniture, and superimposed all available infrastructure are plotted. There is a requirement to provide good quality outdoor services for at least 140,000 premises to which the obligation holder does not currently provide the good coverage. Moreover, there is a requirement to deploy at least 500 new wide area mobile sites in rural areas, to be co-located at least at 1 km distance from existing sites. This concludes that each of the new 500 sites shall have a minimum EIRP of 43 dBm. We suggest that, in such dense deployment contest, conducting a comprehensive study on ICNIRP requirements and environmental sustainability of the structures is a vital need. It is observed that the potential of public buildings and street furniture to facilitate the necessary infrastructure for 5G deployment also provides a significant opportunity for the Local Authority to directly or indirectly participate in the business model along with the MNOs [103].

TABLE 4. Coverage range approximation for favourable channel conditions.

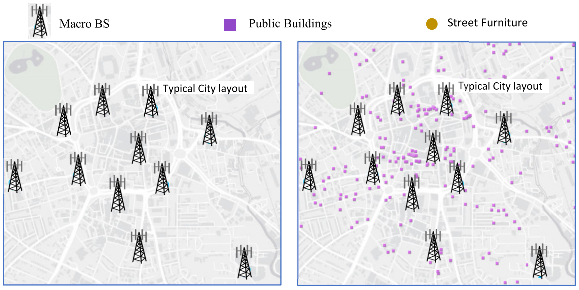
Frequency Band	**Environment**	**Coverage range (kms)**		
		eMBB	**URLLC**	**mMTC**
700MHz	Rural	2.62	2.69	12.5
	Sub-Urban	0.8	0.82	7
	Urban	0.59	0.65	4.3
3.5GHz	Rural	0.62	0.65	5.65
	Sub-Urban	0.17	0.17	2.09
	Urban	0.09	0.09	0.47
26GHz	Rural	0.16	0.17	1.52
	Sub-Urban	0.13	0.13	0.97
	Urban	0.08	0.08	0.48

TABLE 5. Details of the infrastructure consumers.

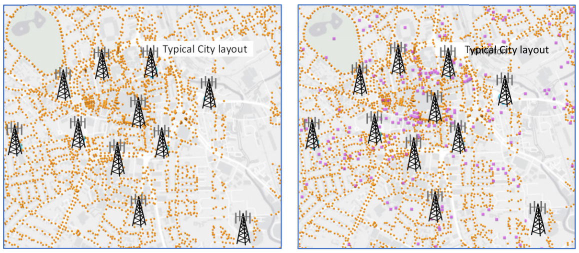
MNO	**MVNO**	**Private & semi-private network**
EE	Virgin Mobile; ASDA Mobile; BT Mobile	• National Roads Telecommunications Services (NRTS) and Traffic Scotland • Network Rail Telecom
Three	iDmobile; FreedomPop; The People's Operator	• Airwave/ESN
O2	Tesco Mobile; Lycamobile; Giffgaff	• Power Utilities
Vodafone	Lebara Mobile; TalkTalk Mobile; TalkMobile	• Sigfox/Arqiva

B. SPECTRUM FLEXIBILITY

The radio frequency spectrum being a core enabler of wireless communications has a high significance in shaping



(a) Existing 4G Macrocell. (b) Existing 4G Macro cell and public buildings.



(c) Existing 4G Macro cell and street furniture. (d) Superposition of existing 4G Macro cell, public buildings and street furniture.

FIGURE 3. Case study– A 5 km^2 area of a typical city.

a country's economy and society. The huge deployment and radio spectrum costs are regarded as the potential delaying causes in the provision of 5G technology innovations. Enabling opportunities for innovation with spectrum sharing has a strong potential in reducing the overall cost. In the light of growing interest in the use of communication applications and services introduced by 5G, there is a need to develop viable solutions for licensing the radio spectrum for meeting the local connectivity needs. In this regard, the location-based licensing of the radio spectrum can significantly help the MNOs in utilizing the 5G radio spectrum in the suitable local regions. The UK, in this regard, has become the first country in location-based spectrum licensing. The Ofcom has become the leader by releasing the location-based licensing of 5G compatible bands [22]. This new way of spectrum licensing also mainly opens the possibilities for location wise re-licensing of the radio spectrum which is allocated to the MNOs but it is not being utilized in the locations. The nature of 5G-compatible radio, e.g., millimeter-wave (mmWave) signal propagation, and small-sized cells suit the adoption of such location-based licenses due to their shorter coverage distance from a base station. The offering of location-based spectrum licensing will also open opportunities for small drivers (businesses, organizations, enterprises, industries, etc) to set up their own customized local wireless network at a cheaper cost with higher reliability and security provisions. The extended application scenarios of this arrangement may include private wireless networks for machine-to-machine communications in industrial, agricultural, others for various useful services. Moreover, the deployment of setup for wireless broadband connectivity in rural areas using fixed wireless access (FWA) may also benefit from it.

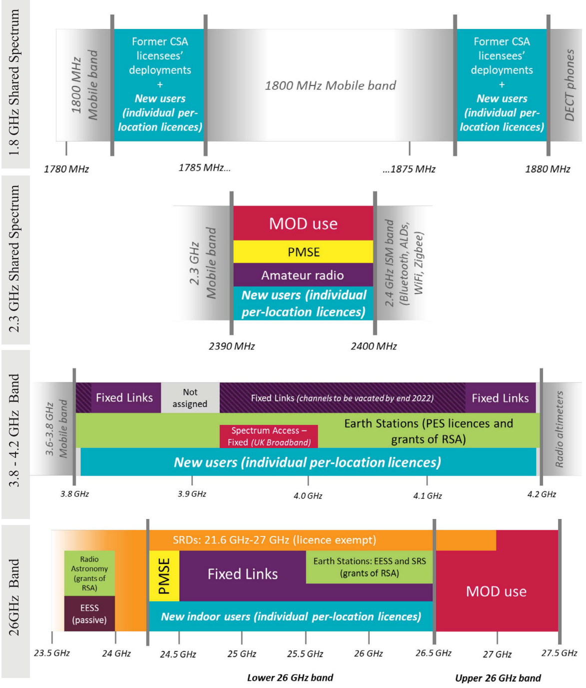


FIGURE 4. Ofcom 5G Spectrum sharing framework UK; i.e., for 1.8GHz, 2.3GHz, 3.8-4.2GHz, Lower-26GHz, and Upper-26GHz bands [104].

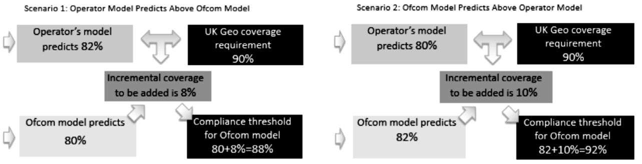


FIGURE 5. Scenarios for Ofcom and operator model prediction using UK's geo coverage model and requirements [22], [104].

The framework of four prime 5G bands for location-based shared licensing released by Ofcom UK [104] are shown in Fig. 4, i.e., 1.8GHz, 2.3GHz, 3.8 - 4.2 GHz, and 26GHz. The configuration of existing users in the corresponding bands are also indicated. The provision of a new regulatory framework for new users to access the spectrum is provided under *Mobile Trading Regulations* [105]. The radio spectrum landscape indicating the new users with individual per-location licences, fixed links licences, concurrent spectrum access (CSA) licences, and former CSA licences are also indicated in the Fig. 4. The scenarios for Ofcom and operator model prediction using UK's geo coverage model and requirements are illustrated in Fig. 5. The compliance threshold for Ofcom model is 88% and 92% for the scenario of operator-model predicting above Ofcome-model and Ofcome-model predicting above operator-model, respectively. The summary of prices of channels of different sizes in the UK by Ofcom [104] is provided in Table 6. The average size of channel is considered as 40 MHz, where the cost for channel sizes higher and lower than 40 MHz are decided in proportionate to that. Complete details of tariffs by Ofcom for the year 2019/2020 can be found in [106].

TABLE 6. Channel size and price in the UK [104].

Channel size (MHz)	Price per channel (£)
2×3.3	80
10	80
20	160
30	240
40	320
50	400
60	480
80	640
100	800

C. SECURITY CONSIDERATIONS

The provision of security and privacy in massively connected 5G and B5G communication networks is one of the prime challenges. A variety of emerging new use-cases and networking paradigms demand new security requirements and considerations [57]. For example, 5G networks need to employ adaptive intrusion detection system, which can perform the following tasks: (i) detect bandwidth spoofing attack on 5G relay, small cell access point, and base station, (ii) employ UEs initial authentication at the access points, and 5G RAN by a highly secured authentication and handover mechanism with the minimal handover latency and no loss of user privacy. The SDN controller handles DDoS attack and a secure VNF in the cloud filters out malicious packets from legitimate packets [107]. 5G device-to-device (D2D) and machine-to-machine (M2M) communication security needs, vulnerabilities, and potential solutions have to be investigated. To this end, the important contexts include the following: (i) direct radio communications, (ii) large-scale D2D deployments, (iii) cooperative communications for securing D2D communications, (iv) power control and channel access in securing D2D communications,(v) continuous authenticity with legitimacy patterns, (vi) key exchange protocols involved with the D2D users and gNB, (vii) design of D2D links to use as friendly jammers, and (viii) helping authorized cellular users against malicious wiretapping [57], [108].

Furthermore, C-RAN security has to be ensured in service plane, control plane, and physical plane [109]. 5G NR vulnerability has to be addressed in terms of jamming and spoofing by investigating the physical downlink and uplink control channels/signals and through designing proper mitigation strategies for proceeding towards the design of 5G NR chipsets and BSs [110]. New 5G paradigms will have to be handled by the UK MNO businesses. For example, security challenges related to network slicing; such as on-demand security isolation of network slices, the security of inter-slice communications, impersonation attack, security policy mismatch, DoS attack, side-channel attacks, privacy attacks, resource harmonization between inter-domain slice segments and hypervisor attacks have to be considered [55], [60]. New types of 5G-based verticals, e.g., IoT, need to establish secure 5G-based network slicing technique with secure key establishment among IoT devices, MEC, and IoT cloud server [111]. UK businesses will need innovative 5G Network Slice brokering mechanism using blockchain for reducing service creation time and for enabling the manufacturing equipment to autonomously and dynamically acquire the slice required for more efficient operations [112].

Moreover, SDN and NFVs are vulnerable to various types of attacks including the following: (i) DoS, hijacking, and saturation attack on SDN controller, switches, and hypervisor, (ii) network slice theft from hypervisor and shared cloud resources and SDN (virtual) switches, (iii) routers configuration attacks, (iv) SDN configuration attacks, (v) penetration attack on SDN virtual resources, (vi) TCP-level attack on SDN controller-switch communication, and (vii) man-in-the-middle attack on the SDN controller-communication [55], [57], [60], [113].

The advent in security mechanisms is highly required to meet the overall 5G advanced features such as ultra-low latency and ultra-high energy efficiency [57]. Different to the conventional radio cellular networks, the emerging 5G wireless networks will be service-oriented, which necessitates a particular emphasis on security and privacy requirements from the perspective of service-based architecture (SBA) [57]. Hence, UK MNOs have to ensure data exchange security for network function (NF) service registration and de-registration, NF service discovery, NF service authorization and authentication in the presence of different attack vectors that may cause loss of NF availability, loss of data integrity, and attack from the insiders [114]. 5G advocates the use of MEC, which offers heterogeneous network nodes interoperating in an open ecosystem where distributed computing and virtualization may be exploited by service providers to extend the provisions of different applications to the end-users [55]. Hence, at the time of rolling out 5G networks, MEC threats have to be considered at the frontend (UE/IoT to MEC network), backend (MEC network to cloud), and 5G MEC core network [55], [111].

New dimensions of 5G UE Security, trust, authentication, policy, compliance, and privacy for ultra-mobility will be required. Since 5G networks are expected to extend the provisions of everything as a service, where the users data/information will be stored and shared online, maintaining users/data privacy during 5G rollout in HetNets will be highly challenging [55]. Due to the reduced cell size in 5G networks, there may often appear the scenarios in which a mobile user may move through multiple small sized cells within a single communication session. Therefore, the privacy assurance is more challenging in 5G networks due to the possible involvement of untrusted or compromised APs involved during the handover [56]. Hence, hybrid and flexible authentication of UEs should be devised that will allow authentication by the network only, authentication by the service provider only, and authentication by both the network and service providers [57]. 5G rollout cost model in terms of financial protection against secrecy outage and service outage can be considered by introducing a cyber-insurance framework for 5G cellular networks [115]. Pre-5G or legacy privacy vulnerabilities should be carefully addressed while rolling out 5G network [113]. Pre-5G legacy authentication, privacy, and protocol exploits in the context of 5G have to be addressed such as implicit trust in pre-authentication messages and legacy symmetric key security architecture [116]. Furthermore, identify security, location security, IMSI security, and mobile terminal security have to be considered [55].

While rolling out 5G in the UK, the threats originated from devices or UEs, the air interface at RAN threats [117], edge network threats, backhaul threats, 5G core network threats, and external network threats have to be considered [55], [60]. Because failing to handle the security and privacy of user data and application would have the repercussion of 5G rollout costs. For example, the 5G network has to proactively handle UE threats such as bots, DDos, man-in-the-middle attacks, firmware hacks, device tampering, and malware. The 5G RAN air interface threats include physical layer security to handle jamming, man-in-the-middle attacks, and eavesdropping. The threats at the MEC layer have to handle MEC server vulnerability, rogue nodes, weak authentication issues, side-channel attacks, and improper access control. The backhaul threats include DDoS attacks, control and user plane sniffing, MEC backhaul sniffing, and flow modification attacks. The 5G core network threats that need to be mitigated and handled are software and SDN issues, API vulnerabilities, network slicing issues, DoS and DDoS attacks, improper access control, and virtualization issues. Finally, the external network threats include application server vulnerabilities, cloud services vulnerabilities, bots, and other IP based attacks, application vulnerabilities, API vulnerabilities, and roaming partner vulnerabilities [60].

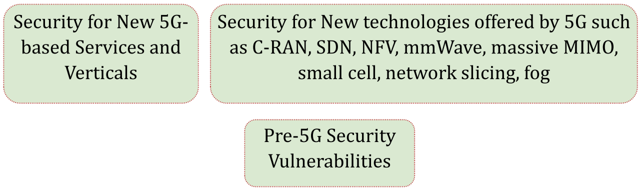


FIGURE 6. 5G and beyond rollout security consideration scope.

Different stakeholders related to 5G rollout are recommended to consider the following B5G security considerations to minimize the costs related to security breaches and safety and privacy of data flowing through 5G networks [113]. Fig. 6 shows a high-level requirement of 5G security considerations, and Fig. 7 shows the salient areas of 5G security that needs to be considered while rolling out 5G. In this section, we will illustrate the state-of-the-art 5G rollout security dimensions that need to be considered by the concerned entities.

1) BLOCKCHAIN USAGE FOR B5G APPLICATIONS

The section reviews the blockchain, smartcontract, and other related aspects from 5G roullout prospective.

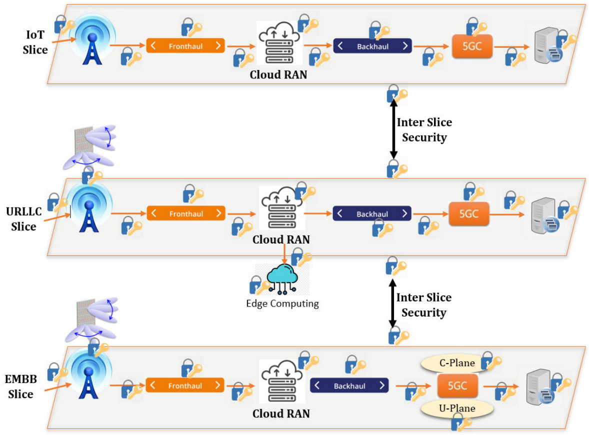


FIGURE 7. Proposed Security endpoints to be considered while rolling out 5G infrastructure in UK.

a: BLOCKCHAIN FUNDAMENTALS

Blockchain's immutable, auditable and traceable features would convince 5G and beyond stakeholders to embrace the decentralization in the 5G applications. Using blockchain technology, it's possible to build a 5G vertical in which the history of transactions can be verified. Thanks to the Blockchain's support of secure authentication, different 5G vertical applications can perform different real-time applications legitimately without needing third-party verification [118].

Blockchain can be used for uniquely identifying any entity involved within 5G-based system with a unique digital hash, which is written on the blockchain network for security, verification and most importantly, end user validation [118]. Blockchain platform also allows uploading metadata about documents to the blockchain network where authorized entities of a particular 5G vertical application can co-sign documents and miners or authorized users can verify to commit it to the Blockchain. Thus, Blockchain can recognize any entity within 5G application eco-system and prevent from personification [119].

An interesting feature of Blockchain is that the Data on Blockchain can be made private, public or it can follow a hybrid pattern. In a hybrid Blockchain solution, information is first recorded in a private Blockchain that creates hashes which is then posted on a public Blockchain. This solution is believed to guarantee the privacy of user data and effectively leverage the immutable nature of public Blockchain. For example, in the case of a 5G-based land registry vertical, the details of a real estate transactions are placed on a private blockchain network run by known computers, and then, in order for citizens to verify the authenticity of certificates, that data can be turned into a cryptographic "hash" that are made public on the blockchain, which is run by thousands of computers worldwide. This would allow enabling people interested in a specific Blockchain registries to see and verify the date of past transactions on their distribute Applications [120].

Secrecy of block data can be maintained through secure wallet within UEs, especially, when the users are mobile and hence have to move among inter-5G area network coverages. The will allow secure communication with one's cyber profile. While transactions and smart contracts are stored in the Blockchain, 5G vertical applications' raw or multimedia big data also needs to be stored in decentralized off-chain storage. The hash values for each chunk of big data returned from the off-chain are saved within the Blockchain, which is typically accessed via distributed applications (DApps) [121].

b: BLOCKCHAIN AND SMART CONTRACT

A Blockchain smart contract allows programming logic to be embedded within a block. The smart contract exposes functionality in the form of an endpoint API, which can be invoked by making a blockchain transaction [122]. Smart contracts are executed based on the terms of the agreement among a number of parties being directly written into lines of code that are deployed within Blockchain [123].

For example, a 5G vertical such as land registry's smart contract can be designed to verify that the land location, size and owner is genuine and the land owner and buyer and Govt. entities involved are genuine and that all the conditions of contract has been met over time. Blockchain smart contracts can be designed to embed the underlying contractual terms and conditions with respect to the time, location and the types of documents to be verified and the types of stakeholders to be involved and co-signed. The smart contract logic are then automatically executed spatio-temporally based on the terms and conditions. Thus, the Blockchain stores the updated ownership and transactions corresponding to each in a historical manner [124].

In the case of a 5G-based health vertical in which a patient undergoes a treatment plan, smart contract can be designed to store the public key of the patient and the stakeholders who have access to his/her health data such as doctor, hospital, and family caregiver [125]. The smart contract can also be programmed to allow amount and the type of data to be shared, the frequency of the sharing, the location and scope of data sharing and the storage duration [126].

c: SALIENT FEATURES OF BLOCKCHAIN FOR 5G ROLLOUT

Proof of Location (PoL) allows an entity's physical location coordinates to be broadcasted to the blockchain in a way that its stakeholders can rely on the location data without having to trust the broadcasting entity. GPS, the de-factor standard of PoL, signal can be jammed, hacked, and spoofed. GPS does not work indoors, and shows poor performance near high-rise buildings. The GPS data is not end-to-end encrypted. Blockchain-based PoL protocols show promising results to provide an encrypted and guaranteed spatial certificate for 5G vertical applications [127].

GPS signals are unidirectional and un-encrypted, which makes it problematic for Blockchain smart contracts that need to execute when spatial geo-fencing conditions are met. Blockchain-based PoL empowers a permission-less and decentralized way of secure location verification services. By building such service on top of blockchain technology, the 5G verticals will be able to execute smart contracts and provide a traceable confirmed timeline of Blockchain's location based transactions [128]. Reliably mapping transactions to their location and time allows an entity within a 5G ecosystem to obtain its spatio-temporal certificate. Among several techniques suggested by researchers, a localized trusted set of entities serving as miners that have a proven location, and that can only be accessed within a spatio-temporal geofence is gaining popularity [129]. For UEs, it can be a 5G cellular tower, a wireless access point, or an optical access point (5G front or backhaul network), etc.

Blockchain-based 5G verticals that use Location-Based Service (LBS) can certify that the geographic location of the transaction claimed by an entity must have been authenticated and genuine [130]. Blockchain can store PoLs into a Blockchain as cryptographically secure location. For example, Crypto-Spatial Coordinates (CSC) for 5G-based Blockchain Application is "an open and interoperable standard for location" service that permits any smart contract to make an immutable claim to an address on the blockchain as well as a corresponding physical location on the map that can be verified on- or off-chain. Blockchain can generate PoL as digital certificate of presence in CSC format during a blockchain transaction verification. This will answer the queries within a 5G vertical such as "where did the transaction occur?" or "where was the transaction performed?" In addition, spatial blockchain with CSC metadata allows 5G verticals to geo-locate a digital asset such as 5G UE, drone, unmanned vehicle, etc. anywhere in real time. 5G-based spatial blockchain applications can program smart contracts that can automatically trigger a location-based transaction from the customer's wallet. Unlike centralized LBS providers that have a monopoly on location information, Blockchain-based PoL will allow 5G verticals over their geospatial data by making such data cryptographically immutable and thus untamperable by external parties, as well as by enabling private location witnessing without requiring the need to reveal personal information [129].

UK businesses can use blockchain for a 5G-based decentralized business model such as commerce, context, content, and connection [53], [113]. For example, blockchain smart contract can be used for secure 5G network slice brokering and maintaining immutable service level agreement (SLA) ledgers to bind 5G business actors such as manufacturing equipment owner, IoT manufacturing equipment, infrastructure providers (InP), MNOs, micro-operators (μO), virtual mobile network operators (MVNO), over-the-top service providers (OTT) and verticals.

Blockchain can be used for secure 5G network sharing scenarios [131], e.g., multiple 5G network operators can extend and collaborate among roaming end-users and incentivizes local businesses and other actors to densify and extend the 5G coverage. Blockchain ledger can be used to store the proof of bandwidth and other types of 5G network resource usage, traffic flow and accounting. MNOs can employ blockchain to provide secure authentication scheme for 5G Ultra Dense Access Point Network [132]. Also, blockchain is envisioned to provide security and privacy of IoT data in 5G HetNets [133]. In the literature, researchers have proposed blockchain to offer efficient privacy-preserving and data sharing schemes for 5G verticals [134].

UK businesses can leverage blockchain for secure registration of a new cellular user and UE, authentication and authorization of users and different services, usage of networks, distributed mobility management (DMM), authenticate the priorities and 5G network services usage and propose algorithm of allocating communication and computation resources to minimize the delay of data transmission and computation, billing and payment and manage roaming bills context of 5G HetNets [135]. Blockchain can handle robust and universal seamless handover authentication for 5G HetNets by leveraging the trapdoor collision property and the tamper-resistant property. More specifically, blockchain will allow 5G network slice providers to securely perform brokering process and allow leasing resources from different providers securely and privately [136]. Furthermore, blockchain will allow UK's businesses to enable industry 4.0 automation processes and manufacturing IoT equipment to autonomously and dynamically acquire the 5G-based slices with QoS needed for most efficient operations [137]. Blockchain-based AKA protocol can be employed, which will allow UEs to move smoothly in a trusted APs group without frequent authentication within an ultra-dense small cell network [132].

2) ARTIFICIAL INTELLIGENCE, DEEP LEARNING AND MACHINE LEARNING FOR 5G SECURITY THREAT INTELLIGENCE

Since the UK is one of the leaders in artificial intelligence research, 5G security can leverage this strength. Various use case scenarios of AI-based security for 5G and beyond applications can be found at [113]. Blockchain and AI methods can together form a strong platform to support secure and intelligent resource management, flexible networking, and reliable orchestration in 5G and beyond scenarios such as spectrum sharing, D2D caching, V2V energy optimization, and computation off-loading [138]. The novel machine learning algorithm can be trained to teach security threats faced by 5G network-interfaced intrusion detection and prevention system, cyber threat and anomaly identification system, and help to secure threats on UK's 5G network [139]. UK's 5G MNOs or service brokers can use AI to allow self-adaptation of security needs according to live 5G traffic flowing through VNF. The AI-based VNF can employ auto-scaling and deploy more 5G network resources, employ appropriate deep learning framework, or even the detection model, with a more suitable one to the given cyber-defense context [140].

3) QUANTUM SAFETY AND NEXT GENERATION CIPHERS FOR B5G APPLICATIONS

In order to face the challenge of cryptographic vulnerability threats due to advancements in computing capabilities of adversaries, UK 5G rollout should consider quantum-resistant authentication and data distribution scheme, and lattice-based homomorphic encryption technology, which greatly reduces the network burden at the same time achieves strong security including privacy protection and anti-quantum attacks [141]. 5G MNOs can leverage the visible spectrum as a noise source for designing next-generation random cryptographic seeds and key generation system suitable for 5G networks [142]. To support real-time data secrecy over 5G intra-slice security applications and protect the private information and hide the communication signals in the frequency, spectrum stream cipher can be a viable option [143]. To lower the authentication delay in an ultra-dense small cell network, certificate authority (CA)-based approach can be availed [144]. Different 5G network slicing may deploy different public-key cryptosystems, and hence, the 5G network should allow diversified types of cryptosystems that will allow heterogeneous sign-cryption schemes such as public key infrastructure and the certificate-less public key cryptography environment [145].

4) 5G VERTICALS' SECURITY CONSIDERATIONS

In general, an integrated effort has to be given to secure the UK's business verticals. In the following, we focus security considerations of rolling out 5G-based V2X and Industry 4.0 verticals.

Security vulnerabilities in the areas of mutual authentication and authorization, confidentiality and integrity protection, replay protection, Secure provisioning and storage, privacy ID, personal data, and tracking in the vehicular context are of significant importance [146]. Especially, the security analysis of V2X verticals in the areas of the termination of user plane security at gNB, authentication and authorization of UE at the 5G RAN, 5G RAN security, UE Security, and network Slicing security have to be ensured [146]. V2X security can be obtained by securing 5G network slicing through permissioned consortium blockchain. Using dedicated networking slicing and blockchain ledgers, vehicles can share information via 5G networks with outside world entities or D2D entities [147].

A 5G enabled vehicular network can facilitate a reliable, secure and privacy-aware real-time video reporting service by using novel block cipher with 1.2 Gbps speed of secure video data sharing. This is to enable the participating vehicles to instantly report the high-definition videos/photos of any events (e.g., traffic accidents, etc) to ensure a timely response from concerned departments (e.g., sending ambulance vehicles to the accident scene, etc) [148]. Using blockchain, SDN-enabled 5G-V2X can detect malicious vehicular nodes or messages while keeping the overhead and impact on the network performance in an acceptable range [120]. Leveraging 5G SDN [60] with resilient V2X security design, different types of attacks such as DDoS targeting either the controllers or the vehicles in the network can be mitigated, and at the same time, it allows tracing back the source of the attack [149]. By leveraging the directional beamforming, secure 5G V2X applications such as vehicle platooning will allow platoons to establish shared secret keys 166 Mbps, which is four-times higher than that of Diffie-Hellman and assumed to allow One Time Pad (OTP) encryption [61].

Due to the vulnerabilities of IoT devices, the IoT verticals need to establish a secure MEC framework for cloud-assisted IoT environments and the secure APIs through which developers serve contents to such IoT applications of MEC [55]. Extensive security surveys based on 5G properties in the areas of short-range IoT applications, delay-tolerant IoT applications, critical IoT application, and massive IoT applications are needed before 5G rollout [60]. For example, 5G vertical security requirements of IoT-based electricity services within a smart city is needed before 5G rollout in UK [150]. Attack vectors on SDN-based identity and access management, authentication, non-repudiation, audit, trust and assurance, compliance, confidentiality, integrity, availability, and privacy issues are to be considered, and proper safeguards and security risk mitigation techniques to support security at 5G access network, application layer, UE, management, core network, and infrastructure and virtualization components have to be deployed. The utilization of innovative security measures for IoT networks, such as two-factor AKA schemes, can help in resisting various different types of attacks to ensure user privacy through both anonymity and unlinkability [151]. Since botnet is a major threat for IoT verticals [152], 5G rollout design should be able to dynamically detect botnet traffic pattern and mitigate the attack in 5G network environment by leveraging the combination of SDN and NFV techniques to adapt botnet detection and reaction functions in 5G networks.

D. MARKET INTERESTS AND COST ANALYSIS

The overall 5G rollout cost in the UK is estimated as £30bn - £50bn, while the UK mobile operator annual CapEx is estimated as £2.5bn. Such a high cost of the rollout in the UK is highly unlikely to be solely supported by the MNOs. This section discusses the economic constraints related with to rollout of 5G and B5G network in the UK. Moreover, the consumer market saturated and flat revenue prospects are also discussed.

There will be 518,345 sites required to be deployed in the UK [153]. These sites are classified as:(i) 7,616 sites for dense urban areas, (ii) 186,732 sites for urban areas, (iii) 309,014 sites for sub-urban areas, and (iv) 15,000 sites for rural areas. Typical infrastructure capability for different site deployment options and cell types are indicated in Table 7. The following subsections thoroughly discuss the CapEx and OpEx associated with new standalone and shared-infrastructure based macro-cell and small-cells.

TABLE 7. Typical infrastructure capability for different network architecture site types.

Site Deployment Option:	Macro Cell	Microcell	Picocell	Femtocell	Small Cell
Greenfield	✓	✗	✗	✗	✗
Rooftop	✓	✓	✗	✗	✗
Streetworks	✗	✓	✓	✗	✓
Indoor	✗	✗	✓	✓	✓

TABLE 8. Typical CapEx requirement to upgrade existing macro-cells with 5G capabilities. The sharing and non-sharing based costs comparison is presented. The cost heads shared between two MNOs are shaded in Gray color.

Macro Item costs	Not Shared	Cost shared between two MNOs	
	Urban/Rural Sites (Rooftop/ greenfield) (£)	MNO 1 (£)	MNO 2 (£)
Survey and Design	1,700.00	850.00	850.00
Site Acquisition and planning	4,000.00	2,000.00	2,000.00
Civils works - Urban (mainly RT)	60,000.00	30,000.00	30,000.00
Power Supply Unit (PSU)	2,400.00	1,200.00	1,200.00
Heating, ventilation, and air conditioning (HVAC)	6,600.00	3,300.00	3,300.00
Rigging	6,000.00	6,000.00	6,000.00
Antenna's (x6)	6,000.00	3,000.00	3,000.00
Antenna MIMO X3 (Based on £15k per 64x mMIMO)	45,000.00	45,000.00	45,000.00
Radio Hardware	5,000	5,000.00	5,000.00
DICI	4,000.00	4,000.00	4,000.00
Transfer to Operations	1,000.00	1,000.00	1,000.00
Project Management	4,000.00	4,000.00	4,000.00
Total without mMIMO	**100,700.00**	**60,350.00**	**60,350.00**
Total With mMIMO	**145,700.00**	**105,350.00**	**105,350.00**
Total without mMimo - including Risk and Margin	**120,840.00**	**72,420.00**	**72,420.00**

1) MACRO-CELLS

Out of the total number of required sites, about 40,000 existing cell sites can be reused for macro-cells. The CapEx requirements to upgrade the existing macro-cells with 5G capability, without sharing the costs, for urban and rural areas are indicated in Table 8. Moreover, for the case of shared costs between different MNOs, the CapEx required for upgrading the existing macro-cells with 5G capabilities are also indicated in the Table. From different heads of CapEx, a few can be identified as shareable among multiple MNOs. In this context, the equal cost sharing map between two different MNOs (i.e., MNO1 and MNO2) is shown in the table where the rows shaded in grey color represent the heads

TABLE 9. Generic CapEx requirements for different deployment options for small-cells.

Small-Cell items	Single Operator		Shared between two operators		Sharing (%)
	Deploying new pole. Cost (£)	**Using existing street furniture. Cost (£)**	**Deploying new pole. Cost for each operator (£)**	**Using existing street furniture. Cost for each operator (£)**	
Design development of street-side pole (new)	5000	0	2500	0	50%
Design & Engineering (existing)	2000	2000	1200	1200	60%
Civil Work	1000	1000	800	800	80%
Power	1000	1000	500	500	50%
New Fibre (could be reduced if fibre already present)	2660	2660	1330	1330	50%
RF equipment (non-shared)	7500	7500	7500	7500	
			(4500, if dual band transceiver is used of £9000)	(4500, if dual band transceiver is used of £9000)	
Total:	**19,160**	**14,160**	**13,830**	**11,330**	Single band antenna
			Exiting pole + antenna sharing - 9000)	Exiting pole + antenna sharing - 9000)	
			10,830	**8,330**	With dual band antenna

whose costs are shared (the costs of remaining heads can not be shared). For upgrading an existing macocell site with 5G capabilities for a single MNO without any sharing of costs, the costs of the heads survey and design; site acquisition and planning; civil works (urban); power supply unit (PSU); Heating, ventilation, and air conditioning (HVAC); and antennas are estimated to be £1, 700.00; 4, 000.00; 60, 000.00; 2, 400.00; 6, 600.00; 6, 000.00, respectively. When the costs of these heads are shared between two MNOs, an overall reduction in the cost from £100, 700.00 to £60, 350.00 and £145, 700.00 to £105, 350.00 can be achieved for the cases of without and with mMIMO capability, respectively. This cost reduction of 27.70% and 40.07% per MNO per macocell site upgradation for the cases of with and without mMIMO capabilities, respectively, with the scheme of sharing the costs between two MNOs can further be significantly increased by increasing the number of involved MNOs in the sharing scheme. Moreover, by including the risk and margin costs, the cost of without mMIMO capability scenario can be reduced from £120, 840.00 to £72, 420.00 (i.e., a reduction of 40.07%) through sharing of the indicated heads equally between two MNOs.

2) SMALL-CELLS

The CapEx requirements for small-cells deployment with and without sharing options are presented in Table 9. For the case of the sole operator, the costs of deploying a small-cell with a new pole compared to the cost for utilizing the existing street-furniture are presented. Moreover, for the case of sharing the small-cell poles between two operators, the cost comparison for new pole and street-furniture based deployment cases is also presented. For all four cases, the costs of design development of street-side pole, design and engineering aspects, civil work, power, new fibers, and RF-equipment items are discussed. Moreover, the anticipated sharing percentage of different items are also indicated.

For the case of sole operator BSs (no active sharing), the CapEx requirements for 5G small-cell deployment is calculated to be £19,160 and £14,160 for the cases of new-pole and street-furniture utilization based implementations, respectively. For the model of cost-sharing between two operators, the CapEx requirements for 5G small-cell deployment is calculated to be £13,830 and £11,330 for the case of new-pole and street-furniture utilization based deployments, respectively. These costs are for single-band antenna BSs, whereas, the dual-band antenna based BSs deployment costs are also indicated. Moreover, the considered sharing percentage of each head is also indicated in the table. The conducted analysis establishes that a reduction of 27.82% and 19.99% in the small-cells deployment cost can be achieved through the sharing of cost between two MNOs for the cases of deploying a new-pole and utilizing the existing street furniture, respectively. The utilization of existing street furniture for small-cell deployment can potential provide a decrease of about 18.07% compared to the case of development of new-pole.

To achieve the cost reduction potential offered by the discussed sharing models, the assessment of characteristics of available street furniture and public infrastructure in the UK for their capacity to hold extra weight, requisite height compliance, wind sustainability, neighborhood infrastructure

TABLE 10. Characteristics of public infrastructure in the UK related to small cell deployment.

Parameter to consider	Target	Available range
Height	4 meter	6 - 10m
Weight bearing capacity	7.5kg	5 - 15kg
Wind sustainability	20km/h	22km/h for continuous 10 minutes
Neighbourhood (infrastructure distance)	50 - 80m	40 - 100m
Opex	unknown	£700 - 800 per pole per year

availability, and suitability in terms of OpEx is essential. In Table 10, the target range for small-cell deployment compared to the available range of the public infrastructure in the UK in terms of discussed critical parameters are presented.

E. REVENUE AND DATA FLOW MODEL

A shift in the attitude of the mobile service providers from transaction to relationship, marketing push to consumer pull, customer acquisition to customer retention, average revenue per user to average profit per user, intelligence in platform to intelligence in user equipment, investment infrastructure to leveraging key assets, and technology to content/data is presumed to arise.

The drive for revenue generation from 5G technologies can be achieved by devising separate short- and long-term strategies. In the short-term, the existing practices can be potentially evolved to offer the necessary infrastructure for attractive 5G business models; e.g., Neutral Hosting for small-cell sites, etc. To this end, the active and passive infrastructure sharing may be vital to facilitate the initial rollout. There is also a need to thoroughly study the available avenues for further reducing both capital expenditures (CapEx) and operational expenditures (OpEx). However, with the advent of 5G features, the existing backbone revenue-generating services (e.g., voice and text messaging) may not stay as an attractive proposition for long. In the long-term, big data analytics and innovative new services based entirely new platforms for value extraction may be strongly be required to build prevailing business models.

The notable items for consideration under the CapEx head can be listed as RF design and planning, site engineering, cabinet/antenna, baseband radios, installation and swap, project management, software (SW) license, cell-site gateway, antennas, site acquisition, power, backhaul, network implementation, and system integration. The primary items under OpEx head can be arranged as site rentals, power supply, backhaul, annual fees (SW etc.), network optimizations, central operations, hardware (HW) maintenance, SW Maintenance, and support setup. To attain the optimized CapEx and OpEx for the 5G network rollout, the following multi-step way forward is suggested,

- Split the intended coverage area into small cells – although the appropriate coverage can be attained with macro cell infrastructure.
- Use street furniture as possible infrastructure for small cells as the first option, followed by public and private buildings or rooftops and then telegraph poles if available.
- If possible, share antennas of the neighbouring spectrum at the same small cell site.
- Share fibre, power and other maintenance CapEx and OpEx.

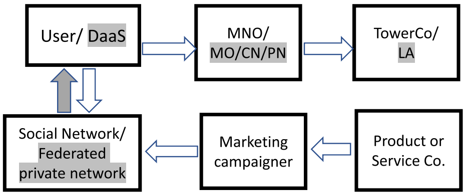


FIGURE 8. A simplified new revenue flow landscape with consumer, connectivity and service provider 5G will promote.

TABLE 11. The new-look; stakeholders and revenue-flow.

Nature of business	Stakeholder	New Entrant
Infrastructure provider	TowerCo (4 in the UK, one of them dominates the market)	Local Authority (LA) as neutral host with public infrastructure offer to MNO
Connectivity provider	MNOs (4 in the UK)	Private network, community networks, micro operator with cheap infrastructure and spectrum
Connectivity dependent service provider	Social networks (Facebook, Google, Uber etc)	Federated private networks/ SME's providing data as a services decision as a service.
Service consumer with Mobility and Connectivity	User	Independent user/ SME's consuming data as a services decision as a service.

There exist various strong synergies between infrastructure designs, business models, and revenue generation methods. Fig. 8 shows the primary landscape of revenue flow; where the consumer, network connectivity, and service providers act as the central elements of the ecosystem. The new market entrant are highlighted in gray color. The notable stakeholders and revenue-flow aspect are indicated in Table 11. The landscape of business is inscribed as infrastructure provider, connectivity provider, connectivity dependent services provider, and service consumers with mobility and connectivity. Examples of essential stakeholders, along with the crucial new entrants, are also quoted. There exist a substantial potential for the local authorities to become stakeholders in the business model by offering the public infrastructure as utilizable in the telecommunication setup deployments. The business model may adapt direct revenue sharing or utility-based incentives for inducing the local authorities into the future telecom ecosystem. The understanding of the potential benefits that the infrastructure sharing agreements can bring to the local authorities is also of critical importance for achieving long-term sustainability.

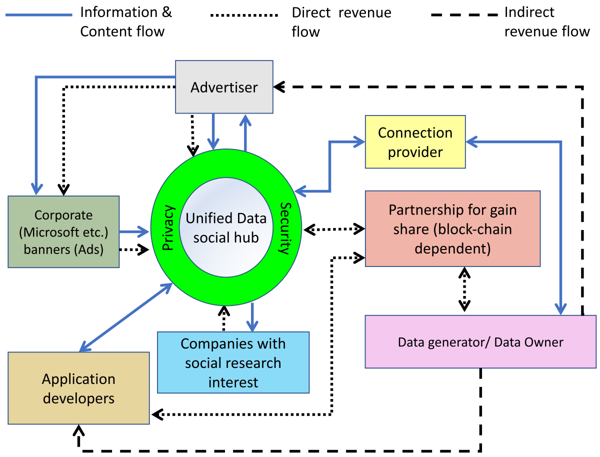


FIGURE 9. **Proposed system model for data and revenue flow.**

The proposed system model for data and revenue flow between different stakeholders is illustrated in Fig. 9. A *unified data special hub* may have two-way information and context flow with connection providers, advertisers, and companies with social research interests. The data-sharing may be protected with privacy and security suits. A controlled interface of applications developers to the data hub is critical in facilitating the development of advanced applications and indirect revenue flow, while also protecting the sanctity of the data. The application developers also require a two-way direct and in-direct revenue flow model with the partnership for gain share and data owners/generators, respectively. The partnership for gain share may be implemented as blockchain dependant facilitated through the direct revenue flow with application developers. The modeling and designing of the information-sharing platform between connection providers and data owners is another necessity to sanction the essential availability of data to the *unified data social hub*. Information flow from advertisers to the data hub can run through corporate (Microsoft etc.) banners/advertisements while modeling a direct revenue flow mechanism between the two is also crucial. The companies with social research interest along with information sharing also need a revenue flow model to benefit from and to the unified data social hub.

The proposed data economy-oriented business model indicates the potential commodification of data and data transactions along with low-cost physical infrastructure and spectrum. It can be foreseen that the 5G network will introduce significant disruption within the Telco business ecosystem. Although there are large investment saving, we also understand, and considerations need to be made that not owning the physical infrastructure by telecom service providers there are potential legal complexities to acquire the positions and installations of the equipment on these proposed locations. This is due to heterogeneous public or private ownership of these infrastructures, and it is challenging to make a standard legal framework and financial model to acquire these resources. However, if we make a cost-benefit analysis, this is still a viable route for success without making this 5G infrastructure building a huge question for public-private investors.

F. FUTURE RECOMMENDATIONS

In the following, we provide some recommendations towards accelerating the 5G deployment process and reducing its cost.

1) The local authority-owned street furniture and other associated public infrastructure assets form the strongest possible set of candidate infrastructure assets for 5G deployment. This provides Local Authorities with potential opportunities for creating new direct or indirect streams of revenue generation.
2) Considering the currently available radio technology and existing roadside infrastructure, it is possible to continue with the current models of active and passive infrastructure sharing.
3) Neutral Hosting may potentially disrupt the current models of TowerCo business oligopoly.
4) Data as a service and decision as a service is to be one of the prime revenue generating services to corporate and retail consumers for the 5G's success.
5) MNOs are required to adopt a harmonised co-existence with micro-operators, community network, and other private networks.
6) The success of federated private networks will introduce the potential of distributed web, a way forward to redefine the internet.

VI. CONCLUSION

A thorough analysis of the potential long- and short-term transformative impacts anticipated from the 5G rollout has been conducted in this paper. The huge anticipated cost of 5G deployment is one of the major barriers in fully receiving the benefits from the innovative 5G communication technologies. Moreover, the lack of confidence of the MNOs on the revenue generation opportunities and existing business models is a primary determinant restraining them from investing the requisite deployment cost. To this end, the sharing of network infrastructure, public infrastructure, radio spectrum, and data are recommended as potential measures to reduce the deployment, operational, and maintenance costs as well as to develop a marketable 5G business model. The local authorities can potentially avail this opportunity to become direct or indirect partners in the telecommunication business model by offering the provisions of sharing the public infrastructure (street furniture, public buildings, etc.) for 5G deployment. A data sharing based value generation model as a long-term 5G business solution has also been proposed in this manuscript. The barriers in the sharing of data have been highlighted.

Moreover, the concerns associated with data privacy and security, along with their potential solutions, have also been studied. Based on the proposed resolutions, a 5G testbed environment-based case study for a typical UK city has been conducted. It has been established that a reduction of up to 28% and 40% in the cost of small-cells deployment and existing macrocells upgradation, respectively, can be achieved through the sharing of costs of different heads between two MNOs. Moreover, the utilization of existing street furniture compared to the development of a new-pole for the deployment of a small-cell has the potential to achieve a reduction of about 18% in the cost. Furthermore, it has been concluded that public infrastructure sharing can potentially contribute to an overall reduction of 40-60% in the deployment cost compared to the anticipated cost. In addition, the location-based shared spectrum licensing and proposed data value generation based long-term sustainable business model have been shown to help in further reducing the CapEx and OpEx significantly.

Based on the conducted case study and analysis, a list of recommendations has been proposed to reduce the 5G deployment cost and encourage the business. We envisage, due to the potential accessibility of low-cost infrastructure and spectrum as well as end-user revenue generation potential from data, the data and connectivity dependent service providers will disrupt traditional MNO business models by deploying large number of private networks. Subsequently, user may access to 5G mobile broadband with significantly low-cost as a trade-off with potential data sharing incentive within an agreed framework.

REFERENCES

[1] *System Architecture for the 5G System; Stage 2, Releases 15*, document 3GPP TS 23.501, V15.2.0, Technical Specification Group Services and Systems Aspects, 3GPP, 2018.

[2] E. Obiodu and M. Giles, "The 5G era: Age of boundless connectivity and intelligent automation," GSMA Intell., London, U.K., Tech. Rep., Feb. 2017. [Online]. Available: https://www.gsmaintelligence.com/research/2017/02/the-5g-era-age-of-boundlessconnectivity-and-intelligent-automation/614/

[3] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[4] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5G: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017.

[5] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, "5G-enabled tactile Internet," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 3, pp. 460–473, Mar. 2016.

[6] J. Rendon Schneir, A. Ajibulu, K. Konstantinou, J. Bradford, G. Zimmermann, H. Droste, and R. Canto, "A business case for 5G mobile broadband in a dense urban area," *Telecommun. Policy*, vol. 43, no. 7, Aug. 2019, Art. no. 101813.

[7] D. Wisely, N. Wang, and R. Tafazolli, "Capacity and costs for 5G networks in dense urban areas," *IET Commun.*, vol. 12, no. 19, pp. 2502–2510, Dec. 2018.

[8] K. David and H. Berndt, "6G vision and requirements: Is there any need for beyond 5G?" *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 72–80, Sep. 2018.

[9] M. Chiani, E. Paolini, and F. Callegati, "Open issues and beyond 5G," in *Proc. 5G Italy White eBook: From Research to Market*. Rome, Italy: CNIT, 2018. [Online]. Available: https://www.5gitaly.eu/en/white-ebook-2/

[10] S. J. Nawaz, S. K. Sharma, S. Wyne, M. N. Patwary, and M. Asaduzzaman, "Quantum machine learning for 6G communication networks: State-of-the-art and vision for the future," *IEEE Access*, vol. 7, pp. 46317–46350, 2019.

[11] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," Feb. 2019, *arXiv:1902.10265*. [Online]. Available: https://arxiv.org/abs/1902.10265

[12] F. Tariq, M. R. A. Khandaker, K.-K. Wong, M. Imran, M. Bennis, and M. Debbah, "A speculative study on 6G," Feb. 2019, *arXiv:1902.06700v1*. [Online]. Available: https://arxiv.org/abs/1902.06700v1

[13] B. Zong, C. Fan, X. Wang, X. Duan, B. Wang, and J. Wang, "6G technologies: Key drivers, core requirements, system architectures, and enabling technologies," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 18–27, Sep. 2019.

[14] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G wireless communications: Vision and potential techniques," *IEEE Netw.*, vol. 33, no. 4, pp. 70–75, Jul. 2019.

[15] "The mobile economy," GSMA Intell., London, U.K., Tech. Rep., 2019. [Online]. Available: https://www.gsmaintelligence.com/research/?file=b9a6e6202ee1d5f787cfebb95d3639c5&download

[16] F. Mekuria and L. Mfupe, "Spectrum sharing & affordable broadband in 5G," in *Proc. Global Wireless Summit (GWS)*, Oct. 2017, pp. 114–118.

[17] W. Xie, N.-T. Mao, and K. Rundberget, "Cost comparisons of backhaul transport technologies for 5G fixed wireless access," in *Proc. IEEE 5G World Forum (5GWF)*, Jul. 2018, pp. 159–163.

[18] E. J. Oughton, Z. Frias, S. Van Der Gaast, and R. Van Der Berg, "Assessing the capacity, coverage and cost of 5G infrastructure strategies: Analysis of the Netherlands," *Telematics Inform.*, vol. 37, pp. 50–69, Apr. 2019.

[19] P. Jones and D. Comfort, "A commentary on the rollout of 5G mobile in the UK," *J. Public Affairs*, 2019, Art. no. e1993. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/pa.1993, doi: 10.1002/pa.1993.

[20] F. Yaghoubi, M. Mahloo, L. Wosinska, P. Monti, F. S. Farias, J. C. W. A. Costa, and J. Chen, "Techno-economic and business feasibility analysis of 5G transport networks," in *Optical and Wireless Convergence for 5G Networks*. Hoboken, NJ, USA: Wiley, 2019, ch. 13, pp. 273–295.

[21] E. J. Oughton and Z. Frias, "The cost, coverage and rollout implications of 5G infrastructure in Britain," *Telecommun. Policy*, vol. 42, no. 8, pp. 636–652, Sep. 2018.

[22] Ofcom. *Enabling Wireless Innovation Through Local Licensing*. Accessed: Jul. 2019. [Online]. Available: https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation?showall=1

[23] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[24] C. Li, C.-P. Li, K. Hosseini, S. B. Lee, J. Jiang, W. Chen, G. Horn, T. Ji, J. E. Smee, and J. Li, "5G-based systems design for tactile Internet," *Proc. IEEE*, vol. 107, no. 2, pp. 307–324, Feb. 2019.

[25] S. F. Abedin, M. G. R. Alam, S. M. A. Kazmi, N. H. Tran, D. Niyato, and C. S. Hong, "Resource allocation for ultra-reliable and enhanced mobile broadband IoT applications in fog network," *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 489–502, Jan. 2019.

[26] *IMT Vision—'Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond'*, document M.2083, IMT, International Telecommunication Union, Sep. 2015.

[27] H. Ji, S. Park, J. Yeo, Y. Kim, J. Lee, and B. Shim, "Ultra-reliable and low-latency communications in 5G downlink: Physical layer aspects," *IEEE Wireless Commun.*, vol. 25, no. 3, pp. 124–130, Jun. 2018.

[28] C. Bockelmann, N. K. Pratas, G. Wunder, S. Saur, M. Navarro, D. Gregoratti, G. Vivier, E. De Carvalho, Y. Ji, C. Stefanovic, P. Popovski, Q. Wang, M. Schellmann, E. Kosmatos, P. Demestichas, M. Raceala-Motoc, P. Jung, S. Stanczak, and A. Dekorsy, "Towards massive connectivity support for scalable mMTC communications in 5G networks," *IEEE Access*, vol. 6, pp. 28969–28992, 2018.

[29] S. K. Sharma and X. Wang, "Live data analytics with collaborative edge and cloud processing in wireless IoT networks," *IEEE Access*, vol. 5, pp. 4621–4635, 2017.

[30] M. R. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel, and L. Ladid, "Internet of Things in the 5G era: Enablers, architecture, and business models," *IEEE J. Select. Areas Commun.*, vol. 34, no. 3, pp. 510–527, Mar. 2016.

[31] F. Jameel, S. Wyne, S. J. Nawaz, and Z. Chang, "Propagation channels for mmWave vehicular communications: State-of-the-art and future research directions," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 144–150, Feb. 2019.

[32] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.

[33] G. Sanfilippo, O. Galinina, S. Andreev, S. Pizzi, and G. Araniti, "A concise review of 5G new radio capabilities for directional access at mmWave frequencies," in *Internet of Things, Smart Spaces, and Next Generation Networks and Systems*. Cham, Switzerland: Springer, 2018, pp. 340–354.

[34] S. Gulfam, S. Nawaz, K. Baltzis, A. Ahmed, and N. Khan, "Characterization of fading statistics of mmWave (28 GHz and 38 GHz) outdoor and indoor radio propagation channels," *Technologies*, vol. 7, no. 1, p. 9, Jan. 2019.

[35] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[36] S. J. Nawaz, B. H. Qureshi, and N. M. Khan, "A generalized 3-D scattering model for a macrocell environment with a directional antenna at the BS," *IEEE Trans. Veh. Technol.*, vol. 59, no. 7, pp. 3193–3204, Sep. 2010.

[37] B. Mansoor, S. Nawaz, and S. Gulfam, "Massive-MIMO sparse uplink channel estimation using implicit training and compressed sensing," *Appl. Sci.*, vol. 7, no. 1, p. 63, Jan. 2017.

[38] E. Dahlman, S. Parkvall, and J. Skold, *5G NR: The Next Generation Wireless Access Technology*. New York, NY, USA: Academic, 2018.

[39] X. Xia, K. Xu, Y. Wang, and Y. Xu, "A 5G-enabling technology: benefits, feasibility, and limitations of in-band full-duplex mMIMO," *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 81–90, Sep. 2018.

[40] L. Dai, B. Wang, Z. Ding, Z. Wang, S. Chen, and L. Hanzo, "A survey of non-orthogonal multiple access for 5G," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2294–2323, 3rd Quart., 2018.

[41] L. Dai, B. Wang, Y. Yuan, S. Han, C.-L. I, and Z. Wang, "Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2015.

[42] J. F. Valenzuela-Valdes, A. Palomares, J. C. Gonzalez-Macias, A. Valenzuela-Valdes, P. Padilla, and F. Luna-Valero, "On the ultra-dense small cell deployment for 5G networks," in *Proc. IEEE 5G World Forum (5GWF)*, Jul. 2018, pp. 369–372.

[43] X. Ge, S. Tu, G. Mao, C. Wang, and T. Han, "5G ultra-dense cellular networks," *IEEE Wireless Commun.*, vol. 23, no. 1, pp. 72–79, Feb. 2016.

[44] A. Basta, A. Blenk, K. Hoffmann, H. J. Morper, M. Hoffmann, and W. Kellerer, "Towards a cost optimal design for a 5G mobile core network based on SDN and NFV," *IEEE Trans. Netw. Service Manag.*, vol. 14, no. 4, pp. 1061–1075, Dec. 2017.

[45] I. Afolabi, T. Taleb, K. Samdanis, A. Ksentini, and H. Flinck, "Network slicing and softwarization: A survey on principles, enabling technologies, and solutions," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2429–2453, 3rd Quart., 2018.

[46] N. Abbas, Y. Zhang, A. Taherkordi, and T. Skeie, "Mobile edge computing: A survey," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 450–465, Feb. 2018.

[47] B. Naudts, M. Kind, F.-J. Westphal, S. Verbrugge, D. Colle, and M. Pickavet, "Techno-economic analysis of software defined networking as architecture for the virtualization of a mobile network," in *Proc. Eur. Workshop Softw. Defined Netw.*, Oct. 2012, pp. 1–6.

[48] S. Buzzi, C.-L. I, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, "A survey of energy-efficient techniques for 5G networks and challenges ahead," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 697–709, Apr. 2016.

[49] N. Zhang, P. Yang, J. Ren, D. Chen, L. Yu, and X. Shen, "Synergy of big data and 5G wireless networks: Opportunities, approaches, and challenges," *IEEE Wireless Commun.*, vol. 25, no. 1, pp. 12–18, Feb. 2018.

[50] Y. He, F. R. Yu, N. Zhao, H. Yin, H. Yao, and R. C. Qiu, "Big data analytics in mobile cellular networks," *IEEE Access*, vol. 4, pp. 1985–1996, 2016.

[51] D. E. O'Leary, "Ethics for big data and analytics," *IEEE Intell. Syst.*, vol. 31, no. 4, pp. 81–84, Jul. 2016.

[52] X. Jing, Z. Yan, and W. Pedrycz, "Security data collection and data analytics in the Internet: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1, pp. 586–618, 1st Quart., 2019.

[53] K. Valtanen, J. Backman, and S. Yrjola, "Blockchain-powered value creation in the 5G and smart grid use cases," *IEEE Access*, vol. 7, pp. 25690–25707, 2019.

[54] P. Schneider and G. Horn, "Towards 5G security," in *Proc. IEEE Trustcom/BigDataSE/ISPA*, Aug. 2015, pp. 1165–1170.

[55] I. Ahmad, T. Kumar, M. Liyanage, J. Okwuibe, M. Ylianttila, and A. Gurtov, "Overview of 5G security challenges and solutions," *IEEE Commun. Standards Mag.*, vol. 2, no. 1, pp. 36–43, Mar. 2018.

[56] X. Duan and X. Wang, "Authentication handover and privacy protection in 5G hetnets using software-defined networking," *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 28–35, Apr. 2015.

[57] D. Fang, Y. Qian, and R. Q. Hu, "Security for 5G mobile wireless networks," *IEEE Access*, vol. 6, pp. 4850–4874, 2018.

[58] A. Braeken, M. Liyanage, P. Kumar, and J. Murphy, "Novel 5G authentication protocol to improve the resistance against active attacks and malicious serving networks," *IEEE Access*, vol. 7, pp. 64040–64052, 2019.

[59] Z. Ding, Y. Liu, J. Choi, Q. Sun, M. Elkashlan, C.-L. I, and H. V. Poor, "Application of non-orthogonal multiple access in LTE and 5G networks," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 185–191, Feb. 2017.

[60] R. Khan, P. Kumar, D. N. K. Jayakody, and M. Liyanage, "A survey on security and privacy of 5G technologies: Potential solutions, recent advancements and future directions," *IEEE Commun. Surveys Tuts.*, to be published.

[61] M. Karmoose, C. Fragouli, S. Diggavi, R. Misoczki, L. L. Yang, and Z. Zhang, "Using mm-waves for secret key establishment," *IEEE Commun. Lett.*, vol. 23, no. 6, pp. 1077–1080, Jun. 2019.

[62] S. Yrjölä, M. Matinmikko, M. Mustonen, and P. Ahokangas, "Spectrum sharing transforms mobile broadband networks towards markets," *Int. J. Adv. Intell. Syst.*, vol. 10, nos. 3–4, pp. 410–422, 2017.

[63] S. K. Sharma, T. E. Bogale, L. B. Le, S. Chatzinotas, X. Wang, and B. Ottersten, "Dynamic spectrum sharing in 5G wireless networks with full-duplex technology: Recent advances and research challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 674–707, Feb. 2018.

[64] M. R. Hassan, G. C. Karmakar, J. Kamruzzaman, and B. Srinivasan, "Exclusive use spectrum access trading models in cognitive radio networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2192–2231, 4th Quart., 2017.

[65] S. K. Sharma, T. E. Bogale, S. Chatzinotas, B. Ottersten, L. B. Le, and X. Wang, "Cognitive radio techniques under practical imperfections: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 1858–1884, 4th Quart., 2015.

[66] Z. Khan, H. Ahmadi, E. Hossain, M. Coupechoux, L. A. Dasilva, and J. J. Lehtomäki, "Carrier aggregation/channel bonding in next generation cellular networks: Methods and challenges," *IEEE Netw.*, vol. 28, no. 6, pp. 34–40, Nov. 2014.

[67] A. Mukherjee, J.-F. Cheng, S. Falahati, H. Koorapaty, D. H. Kang, R. Karaki, L. Falconetti, and D. Larsson, "Licensed-assisted access LTE: Coexistence with IEEE 802.11 and the evolution toward 5G," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 50–57, Jun. 2016.

[68] C. Yang, J. Li, M. Guizani, A. Anpalagan, and M. Elkashlan, "Advanced spectrum sharing in 5G cognitive heterogeneous networks," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 94–101, Apr. 2016.

[69] I. Bajaj, Y. H. Lee, and Y. Gong, "A spectrum trading scheme for licensed user incentives," *IEEE Trans. Commun.*, vol. 63, no. 11, pp. 4026–4036, Nov. 2015.

[70] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 203–213, Jan. 2008.

[71] B. Holfeld, D. Wieruch, T. Wirth, L. Thiele, S. A. Ashraf, J. Huschke, I. Aktas, and J. Ansari, "Wireless communication for factory automation: An opportunity for LTE and 5G systems," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 36–43, Jun. 2016.

[72] G. Hampel, C. Li, and J. Li, "5G ultra-reliable low-latency communications in factory automation leveraging licensed and unlicensed bands," *IEEE Commun. Mag.*, vol. 57, no. 5, pp. 117–123, May 2019.

[73] I. Ridwany and Iskandar, "Forecast of spectrum requirement for mobile broadband," in *Proc. 12th Int. Conf. Telecommun. Syst., Services, Appl. (TSSA)*, Oct. 2018, pp. 1–5.

[74] E.-K. Hong, "Spectrum needs estimate and K-ICT plan for IMT2020," in *Proc. 5G Forum*, May 2017.

[75] S. K. Sharma and X. Wang, "Towards massive machine type communications in ultra-dense cellular IoT networks: Current issues and machine learning-assisted solutions," *IEEE Commun. Surveys Tuts.*, to be published.

[76] F. Azmat, Y. Chen, and N. Stocks, "Analysis of spectrum occupancy using machine learning algorithms," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 6853–6860, Sep. 2016.

[77] M. Kulin, T. Kazaz, I. Moerman, and E. De Poorter, "End-to-end learning from spectrum data: A deep learning approach for wireless signal identification in spectrum monitoring applications," *IEEE Access*, vol. 6, pp. 18484–18501, 2018.

[78] S. K. Sharma and X. Wang, "Cooperative sensing delay minimization in cloud-assisted DSA networks," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Oct. 2017, pp. 1–6.

[79] L. Li, X. He, and H. Li, "Learning the spectrum using collaborative filtering in directional millimeter wave networks," in *Proc. GLOBECOM IEEE Global Commun. Conf.*, Dec. 2017, pp. 1–7.

[80] OFCOM. (2015). *Implementing TV White Spaces*. [Online]. Available: https://www.ofcom.org.uk/_data/assets/pdf_file/0034/ 68668/tvws-statement.pdf

[81] S. Yrjölä and A. Jette, "Assessing the feasibility of the citizens broadband radio service concept for the private industrial Internet of Things networks," in *Proc. Int. Conf. Cogn. Radio Oriented Wireless Netw. Commun.*, Aug. 2019, pp. 344–357.

[82] P. Ojanen and S. Yrjölä, "Assessment of spectrum management approaches to private industrial networks," in *Proc. 13th Int. Conf. Cogn. Radio Oriented Wireless Netw. Commun.*, Jun. 2019, pp. 277–290.

[83] M. Mustonen, M. Matinmikko, M. Palola, S. Yrjölä, and K. Horneman, "An evolution toward cognitive cellular systems: Licensed shared access for network optimization," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 68–74, May 2015.

[84] M. Matinmikko, H. Okkonen, M. Palola, S. Yrjola, P. Ahokangas, and M. Mustonen, "Spectrum sharing using licensed shared access: The concept and its workflow for LTE-advanced networks," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 72–79, Apr. 2014.

[85] "Licensed shared access (LSA)," ECC, Osaka, Japan, ECC Rep. 205, 2014. [Online]. Available: https://www.ecodocdb.dk/download/baa4087d-e404/ECCREP205.PDF

[86] International Commission on Non-Ionizing Radiation Protection, "ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHZ)," *Health Phys.*, vol. 74, no. 4, pp. 494–522, 1998.

[87] (2007). *Small Cell Forum Ltd, Registered in the UK no. 6295097*. Accessed: 2019. [Online]. Available: https://www.smallcellforum.org/

[88] iWireless Solutions (iWS). *Small Cell Mast*. [Online]. Available: https://www.iwireless-solutions.com/

[89] "IMT traffic estimates for the years 2020 to 2030," ITU Radiocommunication Sector, Geneva, Switzerland, Tech. Rep. ITU-R M. 2370–0, 2015.

[90] A. Gawer, "Bridging differing perspectives on technological platforms: Toward an integrative framework," *Res. Policy*, vol. 43, no. 7, pp. 1239–1249, Jan. 2014.

[91] M. De Reuver, C. Sørensen, and R. C. Basole, "The digital platform: A research agenda," *J. Inf. Technol.*, vol. 33, no. 2, pp. 124–135, Jun. 2018.

[92] D. J. Teece, "Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world," *Res. Policy*, vol. 47, no. 8, pp. 1367–1387, Oct. 2018.

[93] C. E. Helfat and R. S. Raubitschek, "Dynamic and integrative capabilities for profiting from innovation in digital platform-based ecosystems," *Res. Policy*, vol. 47, no. 8, pp. 1391–1399, Oct. 2018.

[94] P. Ahokangas, M. Matinmikko-Blue, S. Yrjola, V. Seppanen, H. Hammainen, R. Jurva, and M. Latva-aho, "Business models for local 5G micro operators," *IEEE Trans. Cogn. Commun. Netw.*, vol. 5, no. 3, pp. 730–740, Sep. 2019.

[95] P. Ahokangas, M. Matinmikko-Blue, S. Yrjola, V. Seppanen, H. Hammainen, R. Jurva, and M. Latva-aho, "Business models for Local 5G micro operators," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw.*, Oct. 2018, pp. 1–8.

[96] S. Yrjola, P. Ahokangas, and M. Matinmikko-Blue, "Novel context and platform driven business models via 5G networks," in *Proc. IEEE 29th Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2018, pp. 1–7.

[97] T. Rasheed, A. Radwan, J. Rodriguez, J. Kibilda, R. Piesiewicz, C. Verikoukis, L. Di Gregorio, A. Gomes, and T. Moreira, "Business models for cooperation," in *Energy Efficient Smart Phones for 5G Networks*. Cham, Switzerland: Springer, 2015, pp. 241–267.

[98] M. M. Iivari, P. Ahokangas, M. Komi, M. Tihinen, and K. Valtanen, "Toward ecosystemic business models in the context of industrial Internet," *J. Bus. Models*, vol. 4, no. 2, pp. 42–59, Oct. 2016.

[99] R. L. Priem, M. Wenzel, and J. Koch, "Demand-side strategy and business models: Putting value creation for consumers center stage," *Long Range Planning*, vol. 51, no. 1, pp. 22–31, Feb. 2018.

[100] R. Casadesus-Masanell and G. Llanes, "Mixed source," *Manage. Sci.*, vol. 57, no. 7, pp. 1212–1230, 2011.

[101] B. Demil, X. Lecocq, and V. Warnier, "'Business model thinking', business ecosystems and platforms: The new perspective on the environment of the organization," *Management*, vol. 21, no. 4, pp. 1213–1228, 2018.

[102] S. P. Choudary, "Why business models fail: Pipes vs. platforms," *Innov. Insights, Wired Mag.*, vol. 2, p. 2015, May 2013.

[103] M. Patwary, S. K. Sharma, S. Chatzinotas, Y. Chen, M. Abdel-Maguid, R. Abd-Alhameed, J. Noras, and B. Ottersten, "Universal intelligent small cell (UnISCell) for next generation cellular networks," *Digit. Commun. Netw.*, vol. 2, no. 4, pp. 167–174, Nov. 2016.

[104] Ofcom, "Enabling wireless innovation through local licensing: Shared access to spectrum supporting mobile technology," Ofcom, London, U.K., Tech. Rep., Jul. 2019. [Online]. Available: https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

[105] Ofcom, "Wireless telegraphy (mobile spectrum trading) regulations 2011, as amended," Ofcom, London, U.K., Tech. Rep., 2011. [Online]. Available: http://www.legislation.gov.uk/uksi/2011/1507/contents

[106] Ofcom, "Tariff tables 2019/20," Ofcom, London, U.K., Tech. Rep., Mar. 2019. [Online]. Available: https://www.ofcom.org.uk/__data/assets/pdf_file/0032/ 141899/tariff-tables-2019-20.pdf

[107] I. Abdulqadder, D. Zou, I. Aziz, B. Yuan, and W. Dai, "Deployment of robust security scheme in SDN based 5G network over NFV enabled cloud environment," *IEEE Trans. Emerg. Topics Comput.*, to be published.

[108] J. Wang, Y. Huang, S. Jin, R. Schober, X. You, and C. Zhao, "Resource management for device-to-device communication: A physical layer security perspective," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 4, pp. 946–960, Apr. 2018.

[109] F. Tian, P. Zhang, and Z. Yan, "A survey on C-RAN security," *IEEE Access*, vol. 5, pp. 13372–13386, 2017.

[110] M. Lichtman, R. Rao, V. Marojevic, J. Reed, and R. P. Jover, "5G NR jamming, spoofing, and sniffing: Threat assessment and mitigation," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2018, pp. 1–6.

[111] J. Ni, X. Lin, and X. S. Shen, "Efficient and secure service-oriented authentication supporting network slicing for 5G-enabled IoT," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 3, pp. 644–657, Mar. 2018.

[112] J. Backman, S. Yrjola, K. Valtanen, and O. Mammela, "Blockchain network slice broker in 5G: Slice leasing in factory of the future use case," in *Proc. Internet Things Bus. Models, Users, Netw.*, Nov. 2017, pp. 1–8.

[113] I. Ahmad, S. Shahabuddin, T. Kumar, J. Okwuibe, A. Gurtov, and M. Ylianttila, "Security for 5G and beyond," *IEEE Commun. Surveys Tuts.*, to be published.

[114] H. C. Rudolph, A. Kunz, L. L. Iacono, and H. V. Nguyen, "Security challenges of the 3GPP 5G service based architecture," *IEEE Commun. Stand. Mag.*, vol. 3, no. 1, pp. 60–65, Mar. 2019.

[115] X. Lu, D. Niyato, N. Privault, H. Jiang, and P. Wang, "Managing physical layer security in wireless cellular networks: A cyber insurance approach," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 7, pp. 1648–1661, Jul. 2018.

[116] R. P. Jover, "The current state of affairs in 5G security and the main remaining security challenges," Apr. 2019, *arXiv:1904.08394*. [Online]. Available: https://arxiv.org/abs/1904.08394

[117] K. Xiao, W. Li, M. Kadoch, and C. Li, "On the secrecy capacity of 5G MmWave small cell networks," *IEEE Wireless Commun.*, vol. 25, no. 4, pp. 47–51, Aug. 2018.

[118] T. T. A. Dinh, R. Liu, M. Zhang, G. Chen, B. C. Ooi, and J. Wang, "Untangling blockchain: A data processing view of blockchain systems," *IEEE Trans. Knowl. Data Eng.*, vol. 30, no. 7, pp. 1366–1385, Jul. 2018.

[119] O. Novo, "Blockchain meets IoT: An architecture for scalable access management in IoT," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 1184–1195, Apr. 2018.

[120] L. Xie, Y. Ding, H. Yang, and X. Wang, "Blockchain-based secure and trustworthy Internet of Things in SDN-enabled 5G-VANETs," *IEEE Access*, vol. 7, pp. 56656–56666, 2019.

[121] A. Dorri, M. Steger, S. S. Kanhere, and R. Jurdak, "BlockChain: A distributed solution to automotive security and privacy," *IEEE Commun. Mag.*, vol. 55, no. 12, pp. 119–125, Dec. 2017.

[122] M. A. Rahman, M. M. Rashid, M. S. Hossain, E. Hassanain, M. F. Alhamid, and M. Guizani, "Blockchain and IoT-based cognitive edge framework for sharing economy services in a Smart City," *IEEE Access*, vol. 7, pp. 18611–18621, 2019.

[123] D. Magazzeni, P. Mcburney, and W. Nash, "Validation and verification of smart contracts: A research agenda," *Computer*, vol. 50, no. 9, pp. 50–57, Sep. 2017.

[124] R. Benbunan-Fich and A. Castellanos, "Digitization of land records: From paper to blockchain," in *Proc. Int. Conf. Inf. Syst.*, Dec. 2018.

[125] M. A. Rahman, M. S. Hossain, M. M. Rashid, S. J. Barnes, M. F. Alhamid, and M. Guizani, "A blockchain-based non-invasive cyber-physical occupational therapy framework: BCI perspective," *IEEE Access*, vol. 7, pp. 34874–34884, 2019.

[126] P. Sreehari, M. Nandakishore, G. Krishna, J. Jacob, and V. S. Shibu, "Smart will converting the legal testament into a smart contract," in *Proc. Int. Conf. Netw. Adv. Comput. Technol. (NetACT)*, Jul. 2017, pp. 203–207.

[127] M. Amoretti, G. Brambilla, F. Medioli, and F. Zanichelli, "Blockchain-based proof of location," in *Proc. IEEE Int. Conf. Softw. Quality, Rel. Secur. Companion (QRS-C)*, Jul. 2018, pp. 146–153.

[128] F. Boeira, M. Asplund, and M. Barcellos, "Decentralized proof of location in vehicular Ad Hoc networks," *Comput. Commun.*, vol. 147, pp. 98–110, Nov. 2019.

[129] F. Victor and S. Zickau, "Geofences on the blockchain: Enabling decentralized location-based services," in *Proc. IEEE Int. Conf. Data Mining Workshops (ICDMW)*, Nov. 2018, pp. 97–104.

[130] M. Zhanikeev, "The last man standing technique for proof-of-location in IoT infrastructures at network edge," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–12, Jun. 2019.

[131] V. Messie, G. Fromentoux, X. Marjou, and N. L. Omnes, "BALAdIN for blockchain-based 5G networks," in *Proc. 22nd Conf. Innov. Clouds, Internet Netw. Workshops (ICIN)*, Feb. 2019, pp. 201–205.

[132] Z. Chen, S. Chen, H. Xu, and B. Hu, "A security authentication scheme of 5G ultra-dense network based on block chain," *IEEE Access*, vol. 6, pp. 55372–55379, 2018.

[133] H.-N. Dai, Z. Zheng, and Y. Zhang, "Blockchain for Internet of Things: A survey," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8076–8094, Oct. 2019.

[134] K. Fan, Y. Ren, Y. Wang, H. Li, and Y. Yang, "Blockchain-based efficient privacy preserving and data sharing scheme of content-centric network in 5G," *IET Commun.*, vol. 12, no. 5, pp. 527–532, Mar. 2018.

[135] S. Kiyomoto, A. Basu, M. S. Rahman, and S. Ruj, "On blockchain-based authorization architecture for beyond-5G mobile services," in *Proc. 12th Int. Conf. Internet Technol. Secured Trans. (ICITST)*, Dec. 2017, pp. 136–141.

[136] B. Nour, A. Ksentini, N. Herbaut, P. A. Frangoudis, and H. Moungla, "A blockchain-based network slice broker for 5G services," *IEEE Netw. Lett.*, vol. 1, no. 3, pp. 99–102, Sep. 2019.

[137] K. Valtanen, J. Backman, and S. Yrjola, "Creating value through blockchain powered resource configurations: Analysis of 5G network slice brokering case," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, Apr. 2018, pp. 185–190.

[138] Y. Dai, D. Xu, S. Maharjan, Z. Chen, Q. He, and Y. Zhang, "Blockchain and deep reinforcement learning empowered intelligent 5G beyond," *IEEE Netw.*, vol. 33, no. 3, pp. 10–17, May 2019.

[139] J. Li, Z. Zhao, and R. Li, "Machine learning-based IDS for software-defined 5G network," *IET Netw.*, vol. 7, no. 2, pp. 53–60, Mar. 2018.

[140] L. F. Maimo, A. L. P. Gomez, F. J. G. Clemente, M. G. Perez, and G. M. Perez, "A self-adaptive deep learning-based system for anomaly detection in 5G networks," *IEEE Access*, vol. 6, pp. 7700–7712, 2018.

[141] J. Cao, P. Yu, X. Xiang, M. Ma, and H. Li, "Anti-quantum fast authentication and data transmission scheme for massive devices in 5G NB-IoT system," *IEEE Internet Things J.*, vol. 6, no. 6, pp. 9794–9805, Dec. 2019.

[142] K. Lee, S.-Y. Lee, C. Seo, and K. Yim, "TRNG (true random number generator) method using visible spectrum for secure communication on 5G network," *IEEE Access*, vol. 6, pp. 12838–12847, 2018.

[143] B. Bordel, A. B. Orue, R. Alcarria, and D. Sanchez-De-Rivera, "An intra-slice security solution for emerging 5G networks based on pseudo-random number generators," *IEEE Access*, vol. 6, pp. 16149–16164, 2018.

[144] S. Garg, K. Kaur, G. Kaddoum, S. H. Ahmed, and D. N. K. Jayakody, "SDN-based secure and privacy-preserving scheme for vehicular networks: A 5G perspective," *IEEE Trans. Veh. Technol.*, vol. 68, no. 9, pp. 8421–8434, Sep. 2019.

[145] J. Liu, L. Zhang, R. Sun, X. Du, and M. Guizani, "Mutual heterogeneous signcryption schemes for 5G network slicings," *IEEE Access*, vol. 6, pp. 7854–7863, 2018.

[146] X. Zhang, A. Kunz, and S. Schroder, "Overview of 5G security in 3GPP," in *Proc. IEEE Conf. Standards for Commun. Netw. (CSCN)*, Sep. 2017, pp. 181–186.

[147] V. Ortega, F. Bouchmal, and J. F. Monserrat, "Trusted 5G vehicular networks: Blockchains and content-centric networking," *IEEE Veh. Technol. Mag.*, vol. 13, no. 2, pp. 121–127, Jun. 2018.

[148] M. Hashem Eiza, Q. Ni, and Q. Shi, "Secure and privacy-aware cloud-assisted video reporting service in 5G-enabled vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 10, pp. 7868–7881, Oct. 2016.

[149] A. Hussein, I. H. Elhajj, A. Chehab, and A. Kayssi, "SDN VANETs in 5G: An architecture for resilient security services," in *Proc. 4th Int. Conf. Softw. Defined Syst. (SDS)*, May 2017, pp. 67–74.

[150] G. Arfaoui, P. Bisson, R. Blom, R. Borgaonkar, H. Englund, E. Felix, F. Klaedtke, P. K. Nakarmi, M. Naslund, P. O'Hanlon, J. Papay, J. Suomalainen, M. Surridge, J. Wary, and A. Zahariev, "A security architecture for 5G networks," *IEEE Access*, vol. 6, pp. 22466–22479, 2018.

[151] S. Shin and T. Kwon, "Two-factor authenticated key agreement supporting unlinkability in 5G-integrated wireless sensor networks," *IEEE Access*, vol. 6, pp. 11229–11241, 2018.

[152] M. G. Perez, A. H. Celdran, F. Ippoliti, P. G. Giardina, G. Bernini, R. M. Alaez, E. Chirivella-Perez, F. J. G. Clemente, G. M. Perez, E. Kraja, G. Carrozzo, J. M. A. Calero, and Q. Wang, "Dynamic reconfiguration in 5G mobile networks to proactively detect and mitigate botnets," *IEEE Internet Comput.*, vol. 21, no. 5, pp. 28–36, Sep. 2017.

[153] "5G Infrastructure requirements for the UK—LS Telcom report for the NIC, Version 3.0," NIC, London, U.K., Final Rep., 2016. [Online]. Available: https://www.nic.org.uk/wp-content/uploads/5G-Infrastructure-requirements-for-the-UK-LS-Telcom-report-for-the-NIC.pdf

MOHMAMMAD N. PATWARY (Senior Member, IEEE) received the B.Eng. degree (Hons.) in electrical and electronic engineering from the Chittagong University of Engineering and Technology, Bangladesh, in 1998, and the Ph.D. degree in telecommunication engineering from The University of New South Wales, Sydney, Australia, in 2005. He was with the General Electric Company of Bangladesh, from 1998 to 2000, and with Southern Poro Communications, Sydney, from 2001 to 2002, as a Research and Development Engineer. He was a Lecturer with The University of New South Wales, from 2005 to 2006, and then a Senior Lecturer with Staffordshire University, U.K., from 2006 to 2010. He was then a Full Professor of wireless systems and digital productivity and the Chair of the Centre of Excellence on Digital Productivity with Connected Services, Staffordshire University, until 2016. He is currently a Full Professor of telecommunication networks and digital productivity, and the Head of the Intelligent Systems and Networks (ISN) Research Group, School of Computing and Digital Technology, Birmingham City University, U.K. He is also a Principal Data Architect for a large-scale 5G testbed in the UK to accelerate digital productivity and develop urban connected community. His current research interests include sensing and processing for intelligent systems, wireless communication systems design and optimization, signal processing and energy-efficient systems, future generation of cellular network architecture, and business modelling for data-economy.

SYED JUNAID NAWAZ (Senior Member, IEEE) received the Ph.D. degree in electronic engineering from Mohammad Ali Jinnah University, Islamabad, Pakistan, in February 2012.

Since September 2005, he has worked on several research and teaching positions with COMSATS University Islamabad (CUI), Pakistan; Staffordshire University, U.K.; Federal Urdu University, Pakistan; The University of York, U.K.; and the Aristotle University of Thessaloniki, Greece. He is currently working as an Assistant Professor with the Department of Electrical Engineering, COMSATS University Islamabad (CUI), Islamabad. His current research interests include physical channel modeling, channel estimation and characterization, massive MIMO systems, adaptive signal processing, machine learning, pattern recognition, compressed sensing, mmWave channels, airborne internet, underwater communications, the Internet of Things, and vehicle-to-vehicle communications.

MD. ABDUR RAHMAN (Senior Member, IEEE) is currently an Associate Professor and the Chairman of the Department of Cyber Security and Forensic Computing, College of Computer and Cyber Sciences, University of Prince Muqrin (UPM), Medina, Saudi Arabia. He holds an Honorary External Research Fellowship of King's College London (KCL), U.K. His research interests include blockchain and off-chain solutions, augmented reality/virtual reality/mixed reality-based visualization for digital twin systems, explainable AI and digital twin for smart city, cyber physical multimedia systems, secure serious games, security for the Internet of Vehicles, UUV, UAV, EV and AVs, crowdsourcing and crowdsensing in smart city, cloud, fog and multimedia for healthcare security, the IoT and 5G security, secure smart city services, secure ambient intelligent systems, spatio-temporal multimedia big data security, and next generation media security. He has authored more than 105 publications. He has one US patent granted and several are pending. He has received more than 12 million SAR as a research grant from KACST, Saudi Arabia, and from other international funding bodies. He is the Founding Director of the Advanced Media Laboratory and Smart City Research Laboratory. He has received three best paper awards from the ACM and IEEE Conferences. He has successfully supervised two Ph.D. students. He has published in top-tier journals with very high impact factor such as the *IEEE Communications Magazine*, the IEEE INTERNET OF THINGS, the *Elsevier Future Generation Computer System*, IEEE ACCESS, the IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, the IEEE SENSORS, and the *Elsevier Parallel and Distributed Computing*, to name a few. He is a member of the ACM. He is a recipient of the BEST Researcher Award from UPM, for the year 2018, for winning the prestigious UK-GCC joint collaboration funding through British Council, U.K.

SHREE KRISHNA SHARMA (Senior Member, IEEE) is currently a Research Scientist with the SnT, University of Luxembourg. Prior to this, he worked as a Postdoctoral Fellow at the University of Western Ontario, Canada, and also worked as a Research Associate at the SnT being involved in different European, National, and ESA projects after receiving his Ph.D. degree in wireless communications from the University of Luxembourg, in 2014. His current research interests include 5G and beyond wireless, the Internet of Things, machine learning, edge computing and optimization of distributed communications, and computing and caching resources. He has published about 100 technical articles in scholarly journals, international conferences and book chapters, and has over 1900 Google Scholar citations. He is a recipient of several prestigious awards including the 2018 EURASIP Best Journal Paper Award, the Best Paper Award in CROWNCOM 2015 Conference, and the FNR Award for Outstanding PhD Thesis 2015 from the FNR, Luxembourg. He has been serving as a reviewer for several international journals and conferences; as a TPC member for a number of international conferences, including the IEEE ICC, the IEEE GLOBECOM, the IEEE PIMRC, the IEEE VTC, and the IEEE ISWCS; and an Associate Editor for IEEE ACCESS journal. He has co-organized a Special Session in the IEEE PIMRC 2017, a Workshop in the IEEE SECON 2018, worked as the Track Co-Chair for the IEEE VTC-Fall 2018 Conference, and is a Lead Editor of the IET book on *Satellite Communications in the 5G Era*.

MD. MAMUNUR RASHID is a Senior Research Fellow with the King's Business School, King's College London. He is currently working in a leading Digital Analytics Centre, Consumer and Organizational Digital Analytics Research Centre (CODA). Previously, he worked as a Scientific Research Computing Specialist with the Department of Engineering Science, University of Oxford, for three years. Prior to Oxford, he worked three years with the Physics Department, Imperial College London. He was awarded Ph.D. Scholarship to work at the European Organization for Nuclear Research (CERN), Switzerland, after he started his Ph.D. with the University of Cranfield. He was awarded a further scholarship by the Atlantic Association for Research in the Mathematical Sciences (AARMS), University of New Brunswick, Canada. He also obtained a CERN School of Computing Programming Diploma from the University of Gottingen, Germany. He worked on Big Data and its analysis of infrastructure development for running various natural disaster impact analysis models to estimate the loss and damage due to the extreme event. His research projects have involved large volume infrastructural data analysis in a distributed HPC environment on the commodity hardware. Coming from a strong infrastructure deployment and data analytical background as well as helping building a number of data-intensive systems, he now works on solving the diverse set of problems for finding impacts of state-of-the-technology in the area of the IoT, big data, block chain, pattern recognition, smart infrastructure, future cities, and distributed HPC. In his research career, he has successfully secured a number of scientific research and travel grants from the Natural Environment Research Council (NERC) and Newton Fund (British Council) with Brazil, Thailand, Turkey, Peru, China, Bangladesh, Kazakhstan, Azerbaijan, Dubai, Vietnam, and Azerbaijan. Alongside his current position, he is also involved in a number of international multidisciplinary collaborative research activities. He has interests in multidisciplinary research spectrums focusing on a force for innovation, scientific discovery, and potentially those can make a worldwide impact.

STUART J. BARNES is currently a Chaired Professor and the Director of the Centre for Consumer and Organisational Digital Analytics (CODA), King's Business School, King's College London. He joined King's College London, in September 2015, having held chair positions at other universities, since 2005. A polymath, he is opposed to disciplinary silos and enjoys working across a number of academic disciplines. He reviews for many leading research grant bodies and journals, is an Associate Editor of *Information and Management*, and has been involved as programme committee member or track chair in more than 50 academic conferences. His recent research projects have focused on the sharing economy, social media, big data, mobile communications, virtual reality, and virtual worlds. He has published five books (one a bestseller for Butterworth–Heinemann) and more than two hundred articles in leading outlets.

• • •