IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received January 29, 2021, accepted February 26, 2021, date of publication March 8, 2021, date of current version March 18, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3064405

5G Experimentation for Public Safety: Technologies, Facilities and Use Cases

MOJCA VOLK [1], (Member, IEEE), AND JANEZ STERLE [2]
[1]Laboratory for Telecommunications, Faculty of Electrical Engineering, University of Ljubljana, 1000 Ljubljana, Slovenia
[2]Internet Institute Ltd., 1000 Ljubljana, Slovenia

Corresponding author: Mojca Volk (mojca.volk@fe.uni-lj.si)

This work was supported in part by the Republic of Slovenia and the European Union from the European Regional Development Fund under Grant C3330-18-952019 (5G Safety); and in part by the European Horizon 2020 Programme for research, technological development and demonstration, under Grant 957400 (5G-LOGINNOV), Grant 957403 (Int5Gent), and Grant 101016448 (5GASP).

ABSTRACT Today, legacy PMRs continue to be the only group of tested, verified and certified technologies for the Public Protection and Disaster Relief (PPDR) sector. For the fifth generation (5G) to follow suit, substantial hands-on experimentation with functional, architectural and deployment aspects is required, and further test trials need to take place in order to inform and enable future verification and certification procedures for 5G to become a proven PPDR technology. This paper studies 5G PPDR experimentation associated with novel virtualized and cloud-native 5G technologies, architectures and deployment options, as well as feasibility studies and field performance and verifications trials involving vertical-specific 5G infrastructures and applications. Key enabling technologies, such as massive multiple input multiple output (MIMO), device-to-device (D2D), network slicing and multi-access edge computing (MEC) are discussed and 5G PPDR architecture and deployment options are investigated. A dedicated 5G PPDR experimentation facility is presented, and a case study of hands-on experimentation is provided. Two distinct scenarios are discussed, i.e., emergency augmentation of the terrestrial 5G PPDR network with rapidly deployable on-site capacities in the area of a public safety incident, and availability and reliability of decision-support PPDR applications on the field. Experience with the deployment and verification insights are accompanied by the results of quality of service (QoS) and non-functional key performance indicators (KPI) assessment that were exhibited during the experiment. The experimentation outcomes confirm the ability of the facility to support emulated laboratory experimentation specifically designed to tackle 5G challenges for this particular vertical as well as field studies recreating realistic public safety operations.

INDEX TERMS 5G, mobile communications, public safety, public protection and disaster relief, mission critical communications, network architecture, network deployment, experimentation, field trial.

I. INTRODUCTION

The 5th generation of mobile technologies (5G) is unanimously identified as the enabling technological advancement for the development of future communications solutions across all sectors of industry and society. 5G technologies are currently advancing to their adoption phase with a growing number of deployments taking place around the globe [1]. While commercial 5G services are becoming available, however, the introduction of 5G into practice within specialized industrial verticals continues to bring along a multitude of new requirements, challenges and dilemmas that require close attention through high-quality experimentation prior to its entry into operational practice.

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

Public protection and disaster relief (PPDR) is one such vertical that stands to benefit substantially once 5G is properly matured, which will enable rollout of 5G-based public safety networks (PSN). Despite numerous concerns and reservations, for example regarding the use of commercial technologies to deliver mission critical (MC) services, infrastructure sharing concepts and security aspects, the expectations are for the next generation of the PPDR communications to predominately reside on commercial infrastructures or as a combination of public and private deployments [2]. This is a result of a visible increase in the scope of requirements and needs of the PPDR vertical to complement the traditional voice-centric MC communications also with new applications and smart devices, for example search and rescue support using emergency robots and unmanned aerial vehicles (UAVs), or sensing of the affected areas using high definition video streaming and massive Internet of Things (IoT), as well as to benefit from wireless broadband services with significantly improved capacities and coverage in dense urban and remote areas. Such additional capabilities and applications can contribute significantly in terms of quicker response times, better situational awareness, and more efficient and informed disaster management but also present several orders of magnitude more demanding performance constraints, collectively known as broadband PPDR (BB PPDR) requirements that cannot be met with the currently used narrow-band professional mobile radio systems (PMR), such as terrestrial trunked radio (TETRA) and TETRA for police (TETRAPOL) in Europe and Association of Public-Safety Communications Officials Project 25 (APCO P25) in North America [3]–[5]. At the same time, the shared infrastructure approach and the use of commercial instead of proprietary technologies stands to eliminate the problem of affordability and economy of scale [6], which in the past has pushed the public safety vertical into a state of lagging several technological generations behind the commercial sector.

Today, we can already observe examples of such nation-wide BB PPDR deployments hosted on the commercial fourth generation (4G) infrastructures of mobile operators, including FirstNet in the United States, Emergency Service Network in the UK, and SafeNet in Korea [3], [7]. Transitioning to and adoption of 5G in PPDR practice, however, continues to be a multidimensional challenge associated, among others, with technical challenges such as sharing of the same commercial infrastructure with other users and industrial sectors and competing for the available resources, as well as with aspect of designing physical and virtual 5G PPDR architectures in terms of ownership and sharing models, migration strategies and backward compatibility, and functional architecture designs capable of meeting stringent PPDR performance characteristics. There are also numerous sector-specific requirements imposed on the 5G for PPDR, such as extremely high availability and reliability, mission-critical services support, direct device-to-device operation, ad-hoc coverage augmentation, isolated operation and network resilience during disaster scenarios, and quality guarantees and priority access in both day-to-day operations as well as under disaster circumstances. For the time being, however, legacy PMRs continue to be the only group of tested, verified and certified technologies for the PPDR sector. For 5G to follow suit, further hands-on experimentation with functional, architectural and deployment aspects is required, and test trials need to take place in order to inform and enable future verification and certification procedures for 5G to become a proven PPDR technology.

In this respect, experimental infrastructures have always played a crucial role in the development of new networking technologies and applications. The ability to test and validate the behavior and performance under realistic circumstances is of utmost importance, a prerequisite for a timely commercial rollout and successful adoption of new technologies and solutions in any given vertical. Review of available literature, however, shows a concerning underrepresentation of 5G facilities supporting PPDR-centric experimentation and trials, and there continues to be a scarcity of available performance studies of broadband 5G networks for PPDR needs conducted in real-world experimental deployments. The available infrastructures are typically bound to a horizontal approach that facilitates studies in a specific technological area across a number of different application domains and thus typically fail in providing a sufficient level of specialization and realism.

In this paper, we seek to enable the next leap in experimentation for the public safety vertical by presenting a 5G PPDR experimentation facility supporting hands-on experiments associated with novel virtualized and cloud-native 5G PPDR architectures and deployment options, feasibility studies and performance tests, experimentation with security architectures, availability, reliability and resilience of 5G PPDR implementations, and deployment and testing of novel MC and decision support services and applications. The main motivation for this paper is to provide a comprehensive review of the current state of affairs in 5G PPDR and show how to conduct realistic 5G PPDR experimentation in laboratory and field settings. Our work complements other works recognized in this paper by 1) providing a comprehensive review of families of BB PPDR use cases and services and their respective requirements profiles, 2) reviewing the key enabling 5G and cloud-native technologies and deployment options specifically in the context of PPDR and illustrating aspects where further experimentation is required prior to adoption of the technology in operational practice, and 3) providing a case study of conducting realistic hands-on experimentation based on a dedicated 5G PPDR facility through an illustrative scenario of a massive natural incident.

The remainder of this article is organized as follows. First, we provide an exhaustive study of PPDR services, use case families and their respective 5G requirements. Next, we provide a review of 5G and cloud-native technology enablers specifically in the context of PPDR and an overview of possible 5G PPDR architectures and deployment options, followed by a review and a discussion of the current state of the art in 5G PPDR experimentation. Then, we present a novel 5G PPDR experimentation facility and discuss its use to support a variety of laboratory and field experiments. The discussion is supported with a case study based on a public safety scenario involving emergency network augmentation and experimenting with custom PPDR applications. Finally, we conclude the paper with final remarks and future research and experimentation prospects.

II. PPDR REQUIREMENTS AND SERVICE CATEGORIES

The primary role of a PSN is to provide both day-to-day and disaster relief PPDR services to public safety professionals, including the police, fire fighters, and paramedics. The strategic importance of the sector and specifics of its businesses guide an accordingly comprehensive body of works focused on various aspects of requirements, from a technology perspective, such as for example technical PSN requirements for 5G and earlier technology generations (e.g., 4G, TETRA, DMR) and in the context of operational requirements associated with services and user experience from the practitioners' perspective. Namely, concrete types of services and usage scenarios are crucial to determine the technical use cases and the pertaining Key Performance Indicators (KPIs) for the PPDR sector, which inform the architectural and technological choices in how 5G is designed and implemented for this vertical.

There is a comprehensive body of available requirements studies of legacy PSNs. For example, [5] discusses the mechanism of inheriting PSN requirements through the evolution of generations of land mobile radio systems (LMRS) and provides a service categorization and an analysis of requirements for LTE-based PSNs. Similarly, [3] and [8] provide comparative surveys of legacy PSNs, and discuss convergence towards LTE-based deployment and mission-critical push-to-talk over LTE. [9] investigates the ability of the LTE to meet the requirements of the PSNs. [10] and [11] discuss the history of LMRS and prospects, opportunities and challenges of evolution towards LTE and in [12] the authors discuss PPDR services provisioning through dedicated and commercial LTE networks. [6], [13] and [14] discuss user requirements and spectrumneeds for narrowband and broadband services in the context of radio spectrum policy discussions.

The prospects of 5G in the context of performance and user-perceived experiences are expected to take the capabilities much closer to ultra-high availability and ultra-low latency communications with support of seamless integration of multiple radio and network technologies, and the creation of prioritized and secure private PPDR networks on public 5G infrastructures. Along with the development of the baseline 5G technologies to deliver such performances, there is also a multitude of other emerging technology fields made possible with 5G and with clear value proposition for the PPDR, including for example advanced visualization technologies, cloud-native principles, big data and artificial intelligence, sensor technologies and the Internet of Things (IoT), UAVs and robotic systems, augmented, virtual and extended reality (AR, VR, XR). Thus, the extent of various technologies and fields of their application in the 5G PPDR context has taken on a much broader scope compared to traditional PSNs, and the requirements must be studied in an accordingly broad and evolving context as new technologies of interest emerge. Project BroadMap [15], for example, conducted a comprehensive study that identified and prioritized requirements of individual PPDR agencies, confirming the need for a range of BB PPDR services much broader than the conventional list of MC voice, data and video communications typically associated with a PSN. The same fact has been recognized and confirmed also in a 3GPP study of use cases and requirements addressed by emerging mobile technologies, including 5G [16]. The above studies are complemented with detailed narrowly focused studies of PPDR requirements towards 5G for specific services or technologies. [17], for example, investigates latency KPIs for delay critical use cases, including MC PPDR services. [18] analyzes use case requirements for network slicing in public safety and other verticals, and [4] and [8] are concerned with the implementation of MC PTT services on 5G.

We provide in Table 1 such a synthesis of BB PPDR service categories in the context of 5G, based on the results published in [15], with further refinements and examples drawn from [3], [6]–[8], [18]–[21]. The overview includes three main service groups, voice services, multimedia services and data services. The list is non-exhaustive and comprises service types that PPDR stakeholders, according to the referenced literature, found most impactful and therefore required. A visual representation of the relative importance of the identified services is represented on the right-hand side of the table. Four levels have been defined based on the information received from the respective PPDR stakeholders (law enforcement, fire fighters and ambulance services) included in the source analysis published in [15] and other referenced literature. PPDR voice services continue to hold the highest overall importance and particularly for MC voice services with traditionally very high reliability, availability and quality, in legacy and emerging PSNs. The second group, multimedia services, is the fastest growing service group that delivers a broad range of novel capabilities that were not possible in legacy PSNs, by exploiting video and data fusion in combination with other innovative technologies, such as unmanned aerial vehicles (UAVs), robotics, immersive user experience or artificial intelligence (AI) [13]. This renders a very broad range of service requirements depending on the type of media used, real-time operation, data transmission intensity, MC nature etc. Examples of this broad category include basic sharing of videos and images, video surveillance using UAVs, automated body-worn sensor- and camera-based evidence collection, as well as advances services such as remote emergency robot navigation using AR/VR. The third group, PPDR data services, combines various legacy and emerging capabilities, ranging again across a broad portfolio of services designed for preparedness, response, recovery and mitigation operations, from traditional e-mail to sophisticated solutions such as AI-powered digital forensics. Specifically, the sensor services category embraced together with multimedia by the IoT concept have recently gained specific attention in the PPDR sector after reaching a mature industrial stage in other sectors. IoT technologies are currently recognized for their potential to enhance the objectivity, efficiency and accuracy of monitoring and early warning [22] as well as for numerous sensing and decision support applications to be used in situational surveillance and during emergency operations, using combinations of sensor technologies and multimedia services as well as data fusion and AI [23]. Despite seemingly varied scenarios where such services are applied,

TABLE 1. BB PPDR service categories.

CATEGORY	SERVICE TYPE*	REERENCES	IMP.**
VOICE SERVICES			
One-on-one voice services	Full duplex call	[5][13][14][19]	••
	Half-duplex PTT	[3][5][8][18][19]	••••
Group voice services	Group call	[5][7][19]	••••
Emergency voice	Emergency call	[5][15][19]	••••
	Ambient listening	[5]	•••
	Direct mode calls (individual, group, PTT)	[7][18][19]	••••
MULTIMEDIA SERVICES			
Video Services	Real-time video streaming	[5][6][11][13][14]	•••
	Group video streaming	[15]	•••
	Video call (one-on-one, group)	[5]	••
	Video on demand (non-real-time)	[13]	•
	Video surveillance (real-time)	[6][14]	••••
	Body-worn camera-based video (streaming, recording, uploading)	[5][6][13][14]	••••
	Drone-based video surveillance (real-time)	[11][14][15]	••
	Remote patient monitoring	[6][13]	•••
Immersive services	Extended, augmented and virtual reality services	[7]	•
Information services	Sharing of multimedia contents (photos, video clips, maps etc.)	[5][6][13]	••••
	Biometrics identification	[5][13]	•
	Broadcast multimedia sharing	[5][15]	•••
DATA SERVICES			
Services related to location and/or area monitoring	Location and tracking services	[14][15][16][19]	••••
	GIS services (localization, map retrieval and reading, positioning info exchange)	[13][14][15]	••••
	Remote device control services /UAVs, robots)	[13]	••
Information services	Text messaging	[5][14][15]	••
	Instant messaging	[15]	••
	Push notifications	[14][15]	••
	Internet access	[13]	•
	E-mail	[13][14][15]	•
	Public warning alerts	[13][16]	••••
	Data query services (information about individuals, inventory registries, HAZMAT databases etc.)	[13][14]	•••
	Sharing of MSD data in an emergency context (112 call, e-call)	[13][15]	••
	Context sharing (network signal strength, battery life, network speed etc.)	[15]	••
	Status (presence info)	[13][15]	•••
	Data/traffic recording (voice, video, data), storage, query and playback	[15]	••
Sensor services	Medical sensor services	[13][14][15]	••
	Sensor services for environment monitoring and incident detection (e.g., theft sensors, acoustic gunshot detection, fire/smoke detection)	[15]	•
	Wireless sensor network services	[5][13]	••
	Vital signs monitoring	[5][15]	•••

*Column two provides service types that the available results of surveys from the referenced literature identified as those the PPDR stakeholders (fire fighters, emergency medical services, law enforcement) found most impactful and therefore required. Hence, the list of service types is non-exhaustive and focuses primarily on most critical types of services, including legacy communications and most mature and promising emerging services.

**Column four (right-hand side) provides a visual representation of the relative importance of each of the identified service categories/types according to the opinions of the PPDR stakeholders. Each category/type is assigned a level on a scale of one to four following the methodology used in [15] (one dot = least important, four dots = most important).

the expected capabilities are authoritative and take place under challenging conditions where human life or health is in danger. They involve highly reliable time-sensitive operations exploiting massive numbers of sensing devices and integrated through various wireless technologies, including e.g., 4G/5G narrowband IoT (NB IoT) and other terrestrial proprietary low-power wide area networks (LoRa, SigFox) [24] to foster network diversity in response to challenging mission-critical circumstances whilst still ensuring high reliability and availability [21]. Examples of such MC sensing services include patient monitoring by means of medical sensors, sensor-based incident detection (e.g., acoustic gunshot detection, theft detection), environmental monitoring and early warning services (e.g., in risk areas for massive

TABLE 2. Categories of additional non-interactive PPDR capabilities.

CATEGORY	SERVICE TYPE*	REFERENCES	DESCRIPTION AND EXAMPLES	IMP.**
NON-INTERACTIVE CAPABILITIES AND SERVICES				
Network coverage and capacity capabilities	Ad-hoc connectivity in areas without network coverage	[6][15]	Broadband connectivity set up ad-hoc using portable or mobile solutions in areas where native network coverage is not available (tunnels, remote areas etc.)	••
	Coverage area and/or capacity (throughput) augmentation	[3][5][7][8][15][22]	Ability to extend the coverage area or capacity (throughput) of the network using deployables, for example vehicle-mounted and portable network nodes, drone-mounted access points or satellite communication	••
	High-Power User Equipment	[7]	High-power devices for PPDR bands that can operate at several time the power of commercially available devices; provides better rural coverage at the network's edge, greater penetration in urban environments (including indoor and underground), and the ability to rely on cloud services for operational needs	••
Resilience	Isolated operation	[7][15][18]	Capabilities of network segments to continue to operate in the event of failure of other (backhaul/core) parts of the network	•••
	Edge/fog computing	[15]	Storage and compute capabilities available locally or at edge of the network using cloud principles, such as 5G MEC, to maintain service operation in case of failure of other (backhaul/core) parts of the network	•••
	DB synchronization	[15]	Capabilities for synchronization of databases, for example after partial failure of the infrastructure where geo-redundant storage locations are used	•••
	Prioritization and preemption	[6][7][9][18][21]	Prioritization and preemption of traffic belonging to critical PPDR communications services, e.g., through barring regular users before PPDR users or prioritizing radio resource allocation.	••••
	Graceful degradation	[15]	Degradation of service capabilities in case of loss of network connectivity in a way that certain capabilities remain available and the services/applications continues to be useful	•
Security	Authentication and authorization	[15][19]	Access to services must be enabled only to authenticated and authorized users	••
	Security protocols	[7][15]	The use of security protocols on application layer and network-layer security interfaces to ensure secure end-to-end transmission of information	••••
	Encryption and integrity	[3][7][19][21]	The use of air interfaces encryption and integrity to protect communication over air interface, and encapsulation and encryption to protect PPDR communication transmitted over private or public networks	••••
Interoperability	TETRA/DMR interoperability	[5][11][18][19]	Interoperability of BB PPDR system with TETRA/DMR systems	••••
	Satellite interoperability	[5][21]	Interoperability of BB PPDR system with satellite systems	••
	Application interoperability	[15]	Interoperability of applications used by individual agencies to allow mutual cooperation	••

This category represents required capabilities and services of a future PPDR system on network and application levels that are typically system-wide, not interactive in their nature of operation and do not require actions on behalf of the end users.

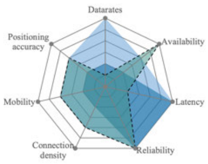
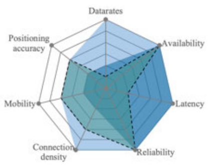
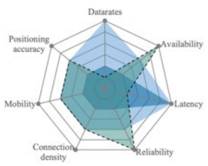
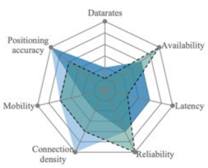
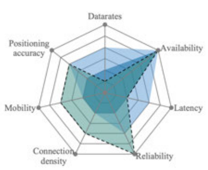
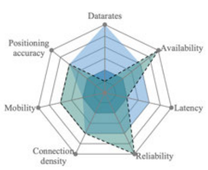
*Column two provides service types that the available results of surveys from the referenced literature identified as those the PPDR stakeholders (fire fighters, emergency medical services, law enforcement) found most impactful and therefore required. Hence, the list of capabilities is non-exhaustive and focuses primarily on most critical types of services.

**Column five (right-hand side) provides a visual representation of the relative importance of each of the identified service categories/types according to the opinions of PPDR stakeholders. Each category/type is assigned a level on a scale of one to four following the methodology used in [15] (one dot = least important, four dots = most important).

flooding, avalanche, wildfire) and vital signs monitoring applications for frontline professionals.

Furthermore, Table 2 documents a range of additionally required characteristics and capabilities of a BB PPDR system that are typically implemented on a system-wide level and implicitly impact the user perceived performance but do not involve direct end-user interaction. This includes capabilities associated with network coverage and availability, e.g., capabilities to set up ad-hoc connectivity in areas without network coverage, such as tunnels and remote rural areas, and capabilities for coverage and capacity augmentation, which is a necessity typically encountered in areas affected by massive natural disasters. Another crucial requirement is resilience. This includes the ability of the network to withstand severe disruptions using capabilities to maintain key operational functions and service continuity in the event of failure of

TABLE 3. BB PPDR use case families, examples and requirements.

USE CASE FAMILY		EXAMPLES	REQUIREMENTS
HIGHER RELIABILITY, LOWER LATENCY			
	Reliability 99.999% 10k sensor nodes per 10 km^2 Latency below 10 ms (incl. coding/decoding) Video frame rate 120 fps	Local UAV collaboration (suspect search, disaster area monitoring)	5 ms one-way latency for direct inter-UAV radio links Low altitude coverage (10-1000m), up to 200 kmph
		Real-time 360° video transmission	250 Mb/s (8K stereo video) 2-4 ms RTT delay
HIGHER RELIABILITY and AVAILABILITY, LOWER LATENCY			
	Minimum downtime Latency (1-10 ms) Reliability 99.999% Availability almost 100% Dynamic cloud/edge resource allocation Isolation and prioritization of critical traffic	Remote drone control	Low altitude coverage (10-1000m), mobility up to 200 km/h
		Moving ambulance and bio-connectivity	Fast & seamless RAT handower Edge/Fog processing More than 100 Mbps throughput Mobility up to 120 km/h
		Industrial control	High reliability High uplink bandwidth (10 Mbps per device in a dense area)
VERY LOW LATENCY			
	Latency below 1ms Varying data rate requirements High level of security	Tactile internet (remote real-time operation of emergency robots/UAVs on a disaster area with video and tactile feeds)	Extremely low latency below 1 ms one way (audio, video and haptic feeds between human operator and robot) High reliability (99.999%) Throughput 100 – 1000 Mbps (subject to additional characteristics, e.g., resolution, edge/fog processing, specialized encoding etc.)
HIGHER ACCURACY POSITIONING			
	Very accurate positioning from 10 m to less than 1 m in more than 80% of situations Better than 1 m accuracy indoors Low latency, low data rates High availability High reliability (at least 95% of service area)	Autonomous driving at high speed	Mobility support up to 200 km/h Positioning accuracy 1m or less Two-way positioning delay 10-15 ms
		Low- altitude UAV-supported positioning and sensing	Low altitude coverage (10-1000 m), mobility up to 200 km/h Position accuracy 10 cm Near 100% reliability
HIGHER AVAILABILITY			
	Moderate data rates, reliability and latency Wide coverage Satellite access Service continuity	Coverage and connectivity augmentation in disaster scenarios	Satellite backhaul support Very high availability 100% Very long battery/power lifetime
MISSION CRITICAL (MC) SERVICES			
	Enforced priority – of users and traffic; priority access, guaranteed quality Preemption Dynamically adaptable service architecture (/w local/edge/cloud capabilities) Low end-to-end latency (10 ms)	Isolated operation	Direct device connections with high data rates (100 Mb/s) Preferential traffic handling
		Remote patient monitoring	Mobility support up to 120 km/h Net capacity 100 Mb/s

The diagrams on the left depict the KPI profiles associated with the defined use case families. The dark blue markers represent the most stringent requirements whereas the light blue markers represent average categories of requirements that also apply to the family but can vary between concrete use cases. Green markers depict an approximation of the achievable 4G KPIs. The requirements are derived from a multitude of sources referenced in Table 1 and Table 2.

backhaul or core parts of the infrastructure, as well as recovery mechanisms once the capacities are restored. Security capabilities include authentication and authorization mechanisms, preferably customizable to the PPDR agency's chain-of-command structure, the use of security protocols for secure end-to-end data transmission, and encryption and encapsulation mechanisms to protect PPDR traffic transmitted over dedicated or public networks. Finally, interoperability with other PSNs is required, which includes backward compatibility with TETRA and DMR systems and integration of satellite services, as well as interoperability of applications to support national inter-agency and international cross-border operations. The same methodology of determining the list of requirements and visually representing their relative importance was used as in Table 1.

Table 3 provides a discussion of 5G PPDR requirements following the 3GPP's definition of the six baseline use case families in the area of critical communications as part of their requirements study in [16]. Each use case family is illustrated with a profile of 5G KPIs derived from the key technical requirements towards 5G for the selected scenarios. The profiling is prepared against the nominal 5G KPIs as defined by the ITU 31 [20] and 3GPP [25] (white heptagonal area) in comparison to 4G (green area), as depicted in Figure 1. It has to be noted that the actually achieved KPIs in a given communications system will be deployment-specific regardless of its technological generation and the supported KPI targets will be guided by the concrete usage scenarios and overall importance of the designed services. The profiles therefore provide target KPI ranges rather than definitive values (Figure 1, average KPI targets in light blue, maximum KPI targets in dark blue) and are intended to demonstrate use case feasibility for average 4G and 5G implementations.

The interpretation of the PPDR requirements towards 5G is meaningful if compared to KPIs defined and achievable for mission critical services in previous generations of the PSNs. 3GPP's technical requirements for mission critical services in LTE [25], for example, specify delay bucket in the range of 75 ms for MC PTT with 95% reliability and 10-2 packet loss, 100 ms delay and 10-3 packet loss for MC video, and 200 ms delay and 10-6 packet loss for MC data services, all of which are achievable in 4G and at the same time much lower than the KPIs promised in 5G [18], [21], [26]. Latency, reliability and availability are the most challenging KPIs but can be met with improved radio interface, architecture optimizations and dedicated core and radio resources, both in 4G and 5G, whereas requirements such as high bandwidth, high connection density, low power consumption or massive number of connected devices are often less relevant in the strict context of legacy MC services [26]. This, however, cannot be said for a variety of emerging PPDR applications, as demonstrated with the presented profiles, for example real-time disaster area surveillance using UAV-assisted high-definition video streaming (Table 3, higher reliability, lower latency use cases), or remote control of emergency robots using tactile

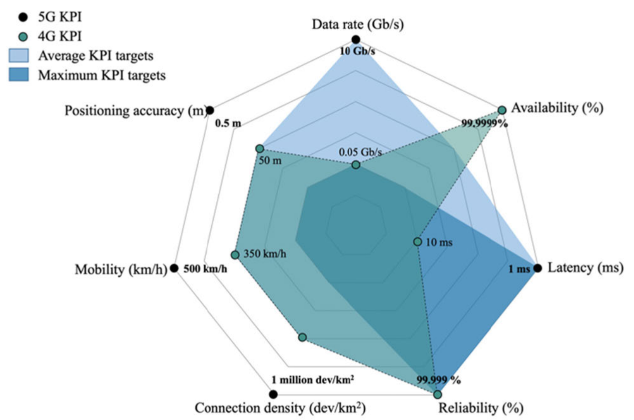


FIGURE 1. The methodology of use case KPI profiles compared to nominal 4G and 5G KPI targets. The white heptagonal area represents the range of KPIs promised with 5G. The green area shows comparatively the achievable 4G KPIs. The profiles (demarcated with blue color) demonstrate use case KPI requirements (average and maximum) and the fact that advanced BB PPDR scenarios can only be met with 5G.

Internet (Table 3, very low latency use cases), where the required KPIs are much more demanding and cannot be met with 4G.

III. 5G ENABLERS FOR PPDR

As demonstrated in the previous section, 5G is a prerequisite for a number of emerging PPDR applications, the KPI requirements of which surpass the achievable performances and capabilities within the existing PSNs and even 4G. We provide hereafter a short review of the key enabling technologies in 5G that will be used to achieve these goals. Some of the key references to be studied in this review related to existing and emerging 5G PPDR technologies are classified in Table 4 and key research directions are summarized.

A. RADIO ACCESS TECHNOLOGIES

The Radio Access Network (RAN) in 5G is designed to meet the capabilities and coverage required by numerous simultaneously operating vertical industries. This is achieved by means of dynamically combining a number of advanced technologies that complement each other's capabilities and characteristics, thus resulting in a combined ability to meet the 5G performance targets. These according to [7] include a more consistent performance over the coverage area, supported peak theoretical rates of 20 Gbps in the 800 MHz band, peak user-experienced throughput of 1 Gbps and 95% of user experienced throughputs at least 100 Mbps in the 400 MHz band, peak theoretical speeds of 2-4 Gbps in early devices, a 50% greater spectral efficiency compared to LTE assuming same-order Multiple Input Multiple Output (MIMO) and full implementation of 5G optimizations, and support for ten times as many devices.

For BB PPDR, the 5G RAN targets are to achieve ultra-reliability and improved coverage and performance. Ultra-reliability relies on designing the radio access to

TABLE 4. Literature overview on existing and emerging 5G PPDR technologies.

Research field	Require-ments	Role in the PSN	Surveys	Modelling, simulations	System design, architectures	Testbeds, facilities, field studies	Key research directions (PPDR specific)
mmWave		[28][54]		[2] [28]-[31] [54][66]		[2]	Propagation modelling (urban, indoor, UAVs) Beamforming techniques, performance reliability
Massive MIMO		[34]-[37]		[34][35][37]			Coverage augmentation (cell edge, remote locations, indoor, mobility scenarios, UAVs) Dynamic coverage adaptation techniques
D2D		[38] [40]-[43] [78]	[27][36] [38][43] [78]	[36] [42]-[44]	[40] [41]		Ad-hoc coverage/capacity deployments Device discovery strategies Resource allocation, interference and transmission power management
UAVs	[16][26] [35][77]	[47][52] [56][72] [78][79]	[47][49] [55]-[57] [59][72] [74][77]	[30][31][45] [49][52][53] [55][59][65] [66][69][71] [78][77]	[47][49] [72][160]	[61][65] [75][168]	Deployment strategies (coverage, altitude, fleet size, energy consumption, spectrum access) CR and SDR for spectrum sharing and offloading Hybrid UAV-terrestrial deployments AI for autonomy and distributed deployment optimization, fleet placement/reconfiguration strategies Energy efficiency
SatCom	[21]	[21]	[21] [95]-[98] [101]	[84][100] [102][109]	[101] [104]-[106] [108]	[90]-[94] [106][107]	5G terrestrial, aerial and satellite network integration SDN, NFV, slicing and MEC in SatCom Sophisticated cooperation mechanisms 5G SatCom PPDR experiments
Capacity and coverage augmenta-tion	[13][48]	[5][18] [37][38] [44]-[47] [50][59]	[38][48] [56][60] [74][77]	[47][52][54] [77]	[38][46][50] [56][91]	[46][50][91] [162]	Deployment and relocation strategies Highly dynamic mobility support Energy efficiency Spectrum access
MC capabilities	[5][8][9] [13] [15]-[17] [19][26] [121]	[3][5][10] [11]	[3][5] [9]-[12]	[5][8][117]	[17][110] [117][158]	[17][50][153] [158]	MC interworking Combined eMBB/URLLC deployments Hybrid RAN deployments, performance optimization Reliability, preemptive/prioritized resource allocation
mMTC	[16][114]	[23][114]	[23][113] - [115]	[116]			Combined URLLC and mobility deployments Multi-access, ad-hoc and D2D networking mcMTC performances
SDN/NFV		[91][151] [161]	[91][94] [151]				Dynamic resource management Mobility in hybrid-RAT deployments Backwards compatibility/integration with legacy PSNs
Network slicing	[16][18]		[120] [122]	[4][126][159]	[4][55][128] [157][159]	[17][50] [94][159]	Slice security Intra/inter-slice isolation techniques Advanced orchestration and resource allocation techniques
MEC		[110]			[110][158]	[73][156]	Resiliency and autonomy in catastrophic scenarios nonMC offloading strategies Mobility/UABS deployments and handover strategies

support diversity of the used communication paths using a number of mechanisms, including multi-connectivity with packet duplication support, device-to-device (D2D) communication, massive MIMO and beamforming. Coverage and performance improvements are primarily addressed with the use of spectrum bands above 6 GHz (mmWave), massive MIMO techniques and interference management mechanisms, and ad-hoc RAN deployments for capacity and coverage augmentation. Some specific aspects of using 5G RAN enablers for BB PPDR are addressed hereafter.

mmWave – One of the most promising enablers in 5G to overcome the current shortage of resources and spectrum congestion in the bands below 6 GHz is the utilization of the millimeter wave (mmWave) bands [1]. The massive bandwidths can enable several magnitudes greater throughput and ultra-low latency compared to conventional LTE systems, and thus 5G applications such as high-definition video surveillance, tele surgery or real-time aerial and ground disaster area reconnaissance using robotic vehicles and UAVs. The application of the mmWave communication, however, is associated with a number of technical challenges, including high propagation loss and susceptibility to attenuation and blockage, which requires directivity and makes the technology applicable primarily for short-range line-of-sight and indoor scenarios [1]. The deployment of mmWave for 5G is therefore considered as small cells or backhaul with a cover range in order of 100-200 m [27]. In addition, further research is needed to resolve challenges associated with urban cellular network modelling, mmWave propagation models, advanced beamforming techniques, and the associated formulation of performance metrics.

The application of mmWave in PPDR is still very much in its infancy. Susceptibility to attenuation and blockage, including bad weather, buildings and even human bodies, challenges the use of highly directional mmWave beams in a number of emergency scenarios, in particular if combined with mobility [1]. Examples include indoor and underground rescue operations, directional backhaul mmWave links or the use of UAVs and robots in disaster scenarios [28]–[31] Most promising candidates to address the problem of variable channel quality are beam tracking and beam alignment protocols, the use of which for PPDR, however, remains to be investigated.

Massive MIMO – MIMO is another crucial 5G enabler to overcome capacity shortages by means of using a large number of antennas on a single Base Station (BS) that are capable of transmitting gigabits of traffic simultaneously and on a time division principle to a large number of users in the same frequency band [32]. The capability to use focused beams on short-range areas leads to significantly improved capacity and energy efficiency. Massive MIMO demonstrates particularly promising improvements if combined with other 5G RAN enablers, such as mmWave, multiple access and D2D. Combined with heterogeneous networks and multiple access technologies, massive MIMO improves both transmission rates and network coverage probability [33]. With mmWave, because of a smaller wavelength, multiple antenna arrays can be deployed on a limited space, thus implementing real massive MIMO system resulting in improved transmission capacities. If used together with D2D, spectral efficiency can be improved. A number of research challenges remain open, however, including channel modelling and the pertaining performance evaluations [32].

The expectations for the use of massive MIMO in PPDR are primarily focused on improving network coverage, in particular at the cell edges and including remote locations where network coverage is relatively weak, as well as in scenarios involving mobility [34]–[36]. The use of UAVs in combination with massive MIMO is an emerging field in this respect [35] as well as proposals such as private body-worn antennae PSN deployments for improved indoor coverage [34], [37]. The capability of dynamic coverage adaptation to deliver a uniform user experience is specifically promising in this respect although significant research of the use of massive MIMO in PPDR is yet to take place.

D2D – The core capability of D2D is to transmit traffic directly between two devices located in each other's vicinity without the need to traverse through RAN or CN. This contributes to improved reliability and performance, shortens delays and increases energy efficiency [27], [32]. When the communication takes place in the licensed spectrum allocated to the mobile operator, the D2D is in in-band mode, and alternatively in out-band mode if using unlicensed spectrum, such as 5 GHz WiFi [38].

D2D is an important PPDR enabler due to its ability to support peer-to-peer communication services without the need for terrestrial infrastructure. It can be used for ad-hoc networking to increase reliability or to extend network coverage, as well as a back-up solution in case of unavailability of the terrestrial network infrastructure as a result of massive incidents causing network outages or even complete failure [38]–[40]. Offloading the traffic from the cellular RAN has positive effects also on spectrum usage and facilitates exploitation of unlicensed spectrum bands, although spectrum scarcity is not a typical constraint in PPDR. Furthermore, because of close proximity of the devices requiring lower transmission powers, improved energy efficiency can be achieved, which is another vital aspect in particular to support prolonged massive disaster response operations [41].

D2D, however, is associated with a number of technical challenges and requires further attention in terms of its efficiency if used in different PPDR scenarios. This includes further studies of D2D architectures within the cellular ecosystems, in particular for device discovery, connection setup and resource allocation, and interference management with cellular users by means of appropriate resource allocation strategies and transmission power management [32], [42]–[44]. Another research challenge is associated with the fact that D2D technology was initially planned for relaying mobile communications, but has since attracted attention for a number of other use cases as well, including peer-to-peer communications, vehicle to X (V2X), UAVs, multicasting and M2M communications, which requires further feasibility studies in the context of PPDR.

Capacity and coverage augmentation – The capability of 5G to augment capacity and coverage quickly and as seamlessly as possible is a valuable capability for PPDR in a number of situations. This includes scenarios to support operations in regions outside of terrestrial coverage, e.g., search and rescue missions in mountainous or underground areas, as well as scenarios in response to massive catastrophes causing the terrestrial infrastructure to become either congested or partially or even fully unavailable [18], [38], [45]–[47]. Successful and effective ad-hoc deployment, however, is quite challenging and associated with a number of requirements, including the ability to provide immediate services, utilize any existing infrastructure, interoperate with heterogeneous technologies, possibly support self-organization and ensure robust and reliable operation [48].

In general, there are two complementary and orthogonal approaches, user-side augmentation based on D2D capabilities as explained in the previous section, and network-side solutions in the form of Dynamic Wireless Networks (DWN) [38]. DWNs are constructed using portable and mobile terrestrial cells transported to the sites using ground vehicles, known as Cells on Wheels (COW) and Cells on Light Trucks (COLT) [3], and air-born cells using low-altitude platforms, e.g., UAVs [49], and high-altitude platforms, e.g., unmanned aircrafts and airships [21], or a hybrid combination of both. DWNs are built either as standalone ad-hoc deployments leveraging for example IEEE 802.11p, Bluetooth or WiFi-based [46] networking or even localized 5G, or with backhaul integration if the terrestrial network is operational, e.g., based on LTE or 5G [50].

The use of DWNs, however, is associated with a number of research challenges. Such deployments are characterized by high mobility yielding dynamic interference patterns and challenges associated with coordinating the exact locations and trajectories of the deployed BSs [38], [51]–[53]. Energy efficiency is a major constraint, in particular in hybrid and dynamically reconfigurable settings, as well as reliability and sufficient bandwidth capacities to support BB PPDR services where mmWave is a promising candidate [46], [54]. Recently, the use of UAV-based DWNs in PPDR has gained specific attention for its prospects to enable rapid, affordable and dynamically reconfigurable aerial deployments suitable for extreme emergency circumstances [55]. In such settings, enabling 5G technologies including mmWave and D2D communications as well as the use of massive MIMO and the concept of edge computing are regarded as specifically promising in resolving the above-identified challenges. Specifics of UAV-based DWNs for capacity and coverage augmentation in PPDR are further addressed in the following.

UAV-assisted wireless communications – The UAVs have historically served the military for intelligence, surveillance and reconnaissance missions, but have since evolved and diversified into a number of application areas serving the public safety [56], [57]. Recently, the use of unmanned aerial base stations (UABSs), i.e. BSs and relays mounted on UAVs, such as helikites, balloons and drones, has gained specific attention for coverage and capacity augmentation in areas where terrestrial infrastructure is not available (e.g., remote areas) or has become congested or even damaged [41], [49], [52], [58]. The core benefits of using UAVs in this respect are mobility, low costs and the ability to self-organize if used in swarms and combined with advanced or even AI-supported logic, which enables rapid deployment of aerial communications platforms that assist or in some cases even replace terrestrial networks. Low-altitude communication platforms are particularly advantageous in demanding public safety circumstances, such as in hostile and disaster scenarios, due to better accessibility, fast deployment, higher chances of establishing reliable line-of-sight (LOS) in the targeted areas (e.g., mountainous terrain or urban environments), and additional coverage and performance enhancements opportunities because of their mobility and rapid reconfiguration capabilities in the three-dimensional aerial space [38], [49], [59], [60]. Nokia's F-Cell [61], Facebook Aquila [62], Eurecom's Perfume [63] and Huawei's Digital Sky [64] are examples of well-known applications of 5G small-cell UABSs.

UABS applications in PPDR, however, are associated with a number of research challenges. Research on optimal deployment strategies of UABS is underway with regards to coverage areas, altitude, fleet size, energy consumption and spectrum access (especially in urban settings) [34], [41], where mmWave UAV applications combined with advanced MIMO techniques seem promising for PPDR [30], [31], [65], [66]. Another related aspect is concerned with UAVs operating in unlicensed bands and hence competing for spectrum resources with immense numbers of other devices, in particular those utilizing WiFi and Bluetooth spectrum ranges, including IoT and V2X communications [67]. In this respect, Cognitive Radio (CR) based on Software Defined Radio (SDR) technology is emerging in 5G as a promising approach to solving spectrum scarcity [48], [67], [68]. The optimization problem is particularly challenging with respect to spectrum sharing and offloading strategies in settings combining macro and small terrestrial BS cells with large UABS fleet deployments [49], [55]. Some promising research directions address the use of AI for autonomy, distributed deployment optimization and swarm coordination [30], [41], [69], and approaches involving for example game theory, genetic algorithms and deep learning are investigated in this respect [49], [58], [70].

Energy efficiency and battery life optimization is another related research area of major interest in UAV-based DWN implementations. Various deployment approaches are currently investigated where requirements depend on the concrete application scenario and are subject to a multitude of factors, including those discussed above. Energy efficiency optimization strategies are subject to fleet placement and reconfiguration capabilities, UAV characteristics and payload, flight trajectory and duration, coverage area and ground user density, on-board processing, and data transmission volume and frequency [69], [71], [72]. Various deployment and recharging approaches are being investigated in the literature, works have been focusing for example on scheduling optimizations of the transmitted signal and on innovative recharging methods using round robin swaps or solar power charging [34], as well as on fleet placement and transmission optimizations [49], but the aspect continues to be a considerable research challenge [48].

An interesting research direction extends the concept of UABS with UAV-boarded core network functions and edge cloud capabilities to complement terrestrial core network functions, e.g., to deploy UAV-boarded 5G access, mobility and session management functions or user processing functions implementing MEC local capabilities [73]. The approach is promising in terms of improving resiliency, autonomy and reliability of PPDR deployments, in particular in disaster scenarios. Limited energy and computational resources are the main challenge in this respect. In terms of other relevant research directions for UABS applications and the use of UAVs in PPDR more generally, there is a pressing need for further efforts on legislation to allow the deployment of single and multiple UAV applications in practice [41], [69], and advancements in the UAV device construction and robustness in particular to sustain heavy loads and detrimental weather conditions [41]. Other relevant directions include also advanced multi-source localization techniques [41], and physical and cyber security of UAV deployments in the context of PPDR [58], [69], [74]–[76].

In addition to the UABS concept, also known in the literature as UAV-assisted wireless communications [77], the use of UAVs in combination with 5G has found numerous other promising applications for PPDR that extend their use into areas such as monitoring and remote sensing of locations of interest by means of live video feeds, imagery and sensor data gathering and analysis, search and rescue missions, as well as transportation and logistics support, e.g. delivery of equipment and medical supplies to inaccessible areas [30], [59], [78], [79]. Commonly referred to as cellular-connected UAVs [77], in these applications the UAVs are considered new aerial users acting in the context of PPDR usage scenarios. 5G in this respect provides the required enablers realizing high-bandwidth and low-latency communications, with a capacity to facilitate transmission of large quantities of data from remote UAVs in video and sensor scenarios, as well as to offload the burden of compute and energy intensive artificial intelligence algorithms to the cellular edge while sustaining dynamic high velocity drone deployments by means of low-latency D2D and backhaul connectivity [45]. The deployment and experimentation with UAVs in the context of 5G PPDR usage scenarios is further discussed in Section VI.

Satellite-based PPDR communications – Satellite communications (SatCom), another type of non-terrestrial networks (NTN) besides airborne DWNs, have traditionally played an important role in PPDR in providing ubiquitous and reliable MC communications and representing the third network stratum of heterogeneous communications systems complementing terrestrial and aerial networks [21]. At the cost of higher deployment costs and decreased delay performances, their inherent benefits for PPDR include global and scalable coverage at land, sea and air, with resilience to terrestrial malfunctions. Legacy PPDR SatCom deployments have predominately served for voice services and early warning systems based on geostationary earth orbit satellites (GEO). Some of the well-known examples include Iridum's PTT services [80], Inmarsat's satellite phones and rapidly movable satellite-based COLTs used by FirstNet [81], GEO-based early warning systems provided by COSPAS-SARSAT for maritime applications [82], and J-Alert in Japan [83].

Recently, mega-constellations of low earth orbit (LEO) satellites have started to emerge [84], [85], complementing terrestrial networks in terms of coverage and scalability, and GEO deployments in terms of reducing deployment costs and improving performances [85]. Early studies for example indicate promising delay performance enhancement opportunities in particular when deployed as low-altitude and high-density constellations and utilizing advanced signal processing methods [84]. While delay performance requirements for legacy MC applications seem achievable (typically in the range between 20 and 80 ms), however, these are expected to become more demanding with the emergence of advanced multimedia, haptic and augmented reality services.

For PPDR SatCom, the biggest challenge is to contribute to extremely high availability of communications resources in disaster areas and in disaster-safe locations, with resilience to sporadic nature to such circumstances. Simultaneous and integrated deployments with terrestrial and airborne networks are researched in this respect [21]. 5G is the technology expected to act as the enabling core for a deeper and more systemic integration, to achieve considerably improved network efficiency in particular in sparse environments and when combined with the emerging LEO deployments, as well as to ensure improved service reliability through diversity gains achieved in areas with simultaneous presence of different overlapping satellite, airborne and terrestrial technologies. 3GPP standardization activities have been underway respectively since Release 14 that initiated NTN, followed by 5G SatCom feasibility studies in Release 15 and 16 [86], [87], whereas further specifications are expected in Release 17 [88], [89].

Advanced satellite-based 5G communications in PPDR, however, are associated with a number of research challenges. There is currently a rather limited body of integrated 5G SatCom proof of concept studies available in the literature, such as those reported in [90]–[94], while the vast majority of attempts continue to either use simplified 5G emulation approaches or rely predominately on loose integration with 3G/4G where satellite and terrestrial networks are interconnected but operated independently on the level of network and spectrum management [21]. In general, the core challenges in integrating satellite networks with other 5G subnetworks (terrestrial and airborne) are associated with requirements for sophisticated cooperation mechanisms [90], [95]. Seamless vertical and horizontal service continuity requires advanced resource allocation and handover strategies, which is a major research challenge [96]–[98]. Horizontal inter-satellite handovers in large LEO deployments, for example, affect the delay performances; challenges are similar to those in ultra-dense cellular networks and involve increased traffic load and retransmission, increased interference risks and handover frequency management. Vertical handover is another challenge associated with service continuity assurance where proactive algorithms are required with capabilities to adapt to differences in cell size (1-50 km diameter in terrestrial networks, 2.000-20.000 km in satellite networks) and cell mobility (in case of LEO) requiring tracking as well as specific mobile-to-fixed handover capabilities [21]. Other integration challenges involve advanced interference management [84], functional and performance adaptations of terrestrial and airborne networks, including e.g., adaptation of time-dependent processes such as synchronization and scheduling to ensure resilience to longer RTT delays of satellite systems, frequency reuse strategies coordinated with spectrum sharing between the integrated wireless networks [99], [97], as well as Doppler frequency tracking and compensation to compensate speed differences between satellite (approx. 7 km/s) and terrestrial (up to 500 km/h) networks [21], [98].

Softwarization, slicing, and edge computing, which have been extensively studied in the context of 5G, demonstrate promising research prospects also for satellite subnetwork [90], [91], [93], [97], as well as the application of mmWave and MIMO technologies [98], [100]. Typically, functions performed in terrestrial networks can with certain design adaptations potentially be applied also in space, e.g., by introducing dynamic and distributed SDN/NFV control functions for improved system reliability in hybrid deployments combining heterogeneous terrestrial, aerial and satellite deployments [101], [102]. Cybersecurity is another major topic of interest in such integrated 5G systems requiring a system-wide attention [103]. Some promising research directions involve design of secure routing approaches to overcome security risks introduced by frequent handovers for service continuity in highly mobile LEO deployments and increased threats associated with heterogeneity of handover mechanisms in multi-subnetwork 5G ecosystems. Other works are investigating decentralization in terms of satellite edge computing applications in space, where dynamic network virtualization techniques and cooperative computation offloading schemes between terrestrial, aerial and satellite subnetworks seem promising [104], [105]. Adoption of advanced technologies, such as data fusion and AI [95], [105], and sensing technologies and IoT [24], [106], [107] in combination with satellite networks for PPDR are also gaining traction. Emerging research directions are currently focused e.g., on aspects of automated and autonomous swarm operations and inter-satellite cooperation by means of deep learning and collective intelligence concepts, with potential applications targeting foremost massive LEO-based IoT satellite swarms [21], [108], [109]. These research directions, however, are still rather new and more concrete investigations for NTN are yet to take place, with further research insights reaching deeper also into reliability, quality and application aspects for PPDR.

B. MISSION-CRITICAL (MC) CAPABILITIES

The concept of using commercial technologies for PPDR has become attractive already with the standardization of mission-critical (MC) communication capabilities as part of the 4th generation (4G) of mobile technologies standardized by the 3rd generation partnership project (3GPP) [3], [4], [8], [110]. In particular, LTE Release 12 has focused on Proximity Services (ProSec) for direct device-to-device (sidelink) communication, and Group Communications System Enablers (GCSE) for unicast and broadcast voice, video and data communications. These have been further improved in Release 13 and new capabilities have been introduced, including one-to-one and one-to-many Mission-Critical Push-To-Talk (MCPTT), relayed communications for out-of-coverage devices and Isolated Evolved-Universal Terrestrial Radio Access Network (E-UTRAN) Operations (IOPS) allowing the base stations to offer services even if the backhaul connectivity is lost. In Release 14, MCPTT has been extended and Mission-Critical Video (MC Video) and Mission-Critical Data (MC Date) have been added as well as Mission-Critical Services Common Requirements (MC CoRe). These as well as proximity services have been further enhanced in Release 15 of 4G, which has introduced also Phase 1 of 5G. However, several technical and operational challenges in 4G-based PMR have undermined its adoption, in particular prioritization or mission-critical users over commercial users and network congestion management during large operations, interoperability issues, network coverage limitations compared to traditional PMS, spectrum scarcity and security problems.

Further enhancements and extensions to the portfolio of 4G critical communications capabilities are included in Release 16, in particular to cover for MC interworking and interconnect enhancements as well as further specification of MC capabilities and architectures for specific areas of application, including railway and maritime [111]. Release 16 delivered also Phase 2 of 5G, part of which are MC Service Priority and QoS specifications [21]. The evolved 5G capabilities are expected to be extensively influenced by the MC capabilities developed in 4G [110] and at the same time deliver ultra-reliable and low-latency (URLLC) communications, extended broadband capabilities and coverage (enhanced Mobile Broadband – eMBB), and capabilities for massive Machine Type Communications (mMTC) allowing for high connection density, energy efficiency and extended coverage when connecting enormous numbers of devices. Therefore, in Release 16 a Study on Mission Critical services support over 5G System (MCOver5GS) has been launched, targeting to identify the impacts and necessary changes in the existing specifications to ensure MC services can be supported over 5G [112].

C. MASSIVE MACHINE TYPE COMMUNICATION

Another crucial 5G enabler that has been designed in response to the explosive growth of machine-type communications and sensor deployments is the massive Machine Type Communication (mMTC). Its target is to alleviate the ultra-high traffic density problem and support a huge number of simultaneous connections [32] by means of facilitating sporadic uplink-dominated transmissions of small data packets at relatively low data rates for a huge number of connected devices [113]. Further technical challenges associated with mMTC include random access overload resolution and intra-cell and inter-cell interference mitigation techniques, because of a massive number of devices simultaneously tying to access the radio resources, and improved energy efficiency to sustain uninterrupted device operation on a scale of ten years and beyond. Additionally, the application of mMTC is typically paired with other multi-faceted application-specific requirements depending on the concrete type of supported use cases, for example ultra-low latency to support tactile internet services, energy efficiency for device autonomy in ultra-massive deployments, or ultra-high device density and device to device connectivity support at massive events, where the support of specific mMTC must not contradict the other two operating modes, namely the eMBB and the URLLC [114].

For PPDR, the application of mMTC falls within the scope of the so-called mission critical mMTC (mcMTC) applications that, compared to other sectors, require higher availability and reliability, improved safety and lower latency [115]. From the 5G perspective, low latency and mobility support represent the core mMTC challenges. Numerous research efforts have considered multi-access approaches, ad-hoc and device-to-device networking, UAV-assisted connectivity and mobility management to improve reliability, robustness and utilization of spectrum resources of critical mMTC deployments [116]. From a practical perspective, the applications of mcMTC for PPDR are expected to initially fall within the domain of non-MC commercial services and will follow deployment and operations practice of business critical mcMTC applications in other industrial sectors with similar reliability and availability requirements and constraints, for example in industrial automation and e-health. On the long term, however, once MC data and MC video services mature, the mcMTC for PPDR is also expected to emerge as a mission-critical 5G capability.

D. SOFTWARE-DEFINED NETWORKING

Software-Defined Networking (SDN) focuses on decoupling of the software-based control plane from the hardware-based user plane, thus allowing the control and configuration nodes of the network infrastructure to dynamically adjust the behavior of network nodes in charge of user plane traffic transmission [7], [117]. This, among other benefits, enables implementation of efficient resource allocation and facilitates integration of multiple RATs.

The SDN architecture consists of an infrastructure layer, representing the devices and hardware that implement data transmission functions, the behavior of which is managed by the control layer, where the entire intelligence of an SDN network is logically centralized and manages all physical and virtual resources. The behavior implemented by the control layer is determined based on the business applications in the application layer that define control parameters such as required bandwidth, access control, QoS, energy consumption etc.

Dynamic management of resources in real time, including cloud and edge capabilities, and dynamic resource allocation and seamless mobility across a multitude of diverse RATs are some of the benefits of SDN exploited in 5G. On the other hand, deployment of SDN into PPDR practice is challenging from a variety of aspects, such as compatibility between legacy and SDN-enabled components in individual types of PSNs, centralization of the control intelligence and guarantees of performance, high availability and fault tolerance to ensure stable operation of SDN-enabled networks, including for MC services [21].

E. NETWORK FUNCTION VIRTUALIZATION

Network Function Virtualization (NFV) is based on the ability to deploy network functions as software components, i.e., Virtual Network Functions (VNF) and Cloud Native Functions (CNF), thus introducing another layer of abstraction that separates the logic of the function from its actual deployment, which can be completed using standardized hardware. This simplifies network deployment, control and upgrades, lowers the costs and improves energy efficiency.

The architecture of NFV [118] consists of the Network Function Virtualization Infrastructure (NFVI), which provides the virtual resources for the execution of the Virtualized Network Functions (VNFs), which are software implementations of the network functions. The NFVI and the numerous deployed VNFs are controlled by the NFV Management and Orchestration (NFV M&O), which is responsible for orchestration and lifecycle management of the NFV hardware and software network resources and builds connections among the different VNFs [32].

Exploitation of benefits introduced with such flexibility and capabilities to efficiently serve on-demand requests, however, require implementation of advanced orchestration mechanisms, management of network functions and resource allocation, which remains one of the challenging aspects of NFV. In addition, implementation of NFV introduces a range of new and emerging security concerns that require further attention. European Telecommunications Standards Institute (ETSI) is currently addressing this through their Security Expert Group (SEG) [119].

SDN and NFV together with the introduction of cloud and edge computing into network infrastructures represents the key aspect of network transformation that makes improved reliability and performance possible together with reduced expenditures and operating costs [117], which are essential capabilities to meet the stringent PPDR requirements. Also, network softwarization is essential in ensuring isolation of the PPDR traffic, end-to-end policy enforcement and QoS guarantees, and reliable and prioritized delivery of user plane data if so required.

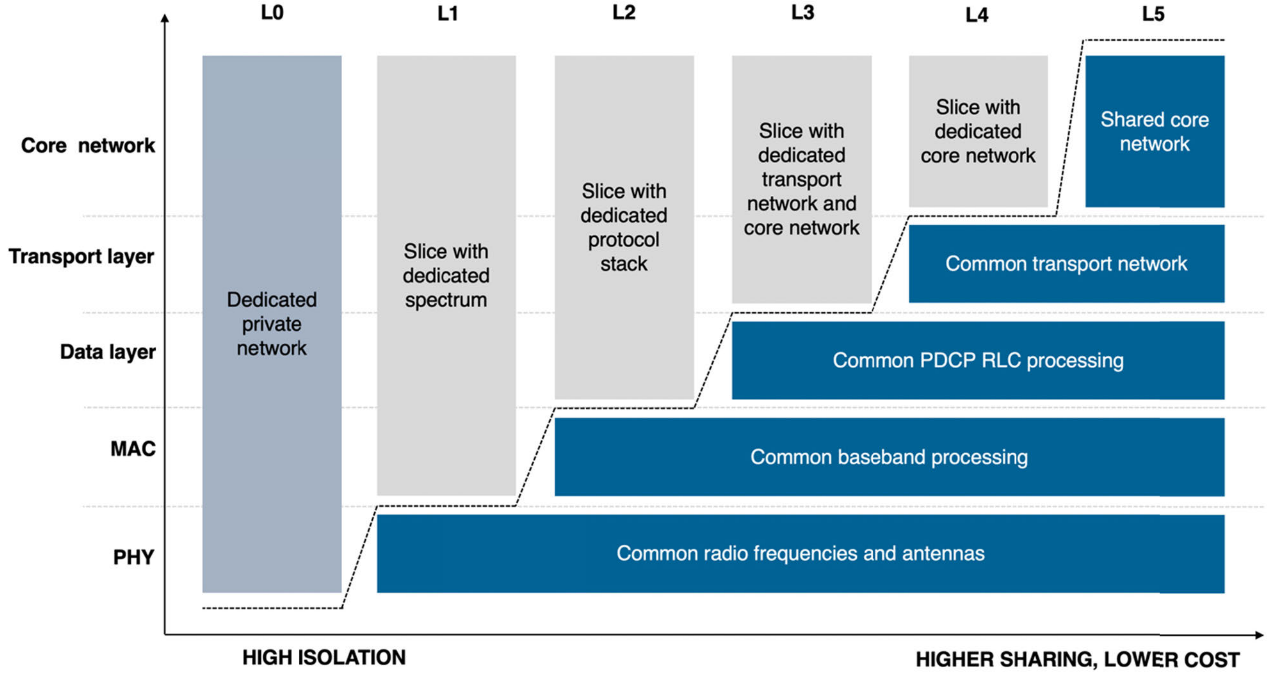


FIGURE 2. **Network isolation. Slicing can provide two orthogonal types of isolation, operational and network isolation [18]. In operational isolation, a vertical user is provided with the ability to influence the operational characteristics of the slice, including e.g., slice monitoring, control and configuration capabilities. In network isolation, on the other hand, network functions or resources are dedicated to a single user and once dedicated to a slice, not shared with others. A number of network isolation levels are possible depending on which functions or resources are reserved for a single user, as shown on the figure. The level of network isolation decides also cost efficiency; the left-most option represents a private network, which is preferable for PPDR security-wise and provides highest isolation, but comes at a very high cost.**

F. NETWORK SLICING

The behavior of a 5G network is managed using the principle of network slicing, a technique that is central to 5G and serves to create for each individual use case an entire self-contained virtual network (slice) on top of a shared physical infrastructure, without interfering with other simultaneously served use cases [39], [120]. This way, distinct characteristics of the individual use cases can be met in a structured, automated and elastic way [32]. For example, simultaneous slices can be created for tele surgery, featuring ultra-low latency and high reliability, and for real-time drone-assisted HD video surveillance with guaranteed enhanced mobile broadband. Improved energy and cost efficiency of the utilized infrastructure and resources are among the benefits of network slicing compared to traditional networks.

Slicing of the 5G Core network (5GC) is specified in 3GPP Rel.15 with further extensions introduced in Rel.16 [121], and 5G RAN slicing is targeted in Rel.17. Core network slices, radio access network slices and radio slices are interconnected either statically or dynamically through dedicated pairing functions [122]. Each slice is associated with specific behavioral characteristics, e.g., bandwidth, security, data flow isolation, quality of service, reliability etc., and integrates network and cloud resources in the core and at the edge of the network to create complete private virtual networks or dedicated virtual networks for specific services [120]. Standardization efforts, however, require further work, in particular to support multi-RAT slicing, as well as a number of other technically challenging aspects, including efficient orchestration and resource allocation in multi-tenant scenarios where SLA agreements pose varying network operation requirements.

For PPDR, slicing represents a crucial capability of 5G in meeting a myriad of requirements and in particular to ensure isolation and guaranteed operation of PPDR services hosted on a shared 5G infrastructure (Figure 2). This includes creation of dedicated PPDR slices that are not shared with other users or use cases, i.e., network level isolation, implementation of different security models and isolation properties of the slice to complement and extend application-level security measures (e.g., end-to-end encryption), prioritization and pre-emptive behavior and allocation of radio bearers with better bandwidth and/or latency characteristics for MC traffic.

Sharing of the physical resources and logical instead of physical isolation of network resources, however, continues to represent a key security concern for PPDR and slice security is a major research challenge. Distributed Denial of Service attacks (DDoS), side channel attacks across slices, and exhaustion of security resources are the most prevalent threats and a number of approaches and techniques are proposed to mitigate them and ensure end-to-end slice security [123]–[125]. Numerous different approaches exist that in general rely on intra-slice and inter-slice isolation, which constitutes a number of further aspects, including reservation of host and network resources for a particular slice, smart resource allocation techniques and end-to-end quality of service (QoS) guarantees [126]. Besides technical security and isolation measures applied during slice lifecycle management, the choice and application of isolation approaches and the resulting level of security depend also on ownership and operation principles of the shared 5G infrastructure where isolation can be achieved by implementing combinations of private and public RAN and 5GC segments and termination of private and public PPDR slices at security anchor point on different network levels [127]–[129]. Ownership and management related network isolation principles are discussed in more detail in Section IV.

G. MULTI-ACCESS EDGE COMPUTING

In response to the PPDR needs for resilience, low latency communications and isolated operation as well as to exploit cloud and edge processing principles to alleviate power consumption of end devices and support massive IoT deployments, 5G has introduced another enabling technology, Multi-access Edge Computing (MEC) [110]. MEC is an ETSI standard [130] that exploits SDN and NFV capabilities of 5G and augments cloud capabilities with storage and processing resources in the RAN, which significantly improves service responsiveness and reduces bandwidth consumption since the core network is no longer in the transmission path [39], [131]. Providing cloud computing services at the edge of the RAN allows for deployment of computationally intensive and delay sensitive applications to be deployed in close proximity to end users and guarantees of ultra-low latency, high bandwidth and real-time access to radio resources and data analytics [32], as well as to gain from the ability of the MEC to provide real-time awareness and context of the local environment through its standardized management and orchestration (MANO) and open Application Programming Interfaces (APIs) [131]. For integrated 5G MEC deployments, the MEC applications are mapped to application functions (AF) of the 5G architecture and are provisioned through the configured 5G slices following the established 5G discovery, policing and orchestration mechanisms while traffic steering is delegated directly to the user processing functions (UPF) following the AF-issued requests for local UPF selection [131].

Real-time HD video stream analytics, computation offloading and MEC-enabled IoT services, and delay-sensitive AR/VR are examples of new MEC-enabled applications that carry immediate value for PPDR [7]. Also, MEC plays a crucial role in ensuring reliable and resilient on-site PPDR applications supporting emergency response and disaster management operations during large catastrophes when terrestrial network is affected and connectivity to centralized cloud and application provisioning services is interrupted. For example, a MEC-enabled situational awareness and dispatch application combined with IOPS network features runs application instances on local MEC infrastructure deployed as part of the on-site 5G network and is available locally until backhaul connectivity is restored. Also, access to network capabilities and quality-related parameters available to MEC AFs in 5G can enable PPDR applications with improved QoS, reliability and availability characteristics or even real-time adaptive behavior, for example to support offloading scenarios for non-MC services in case of low RAN resources, as well as advanced location services based on current RAN information. Early research results are promising and indicate e.g., at possibilities for significantly improved delay performances for MEC-enabled MCPTT applications [8]. The use of MEC for PPDR is expected also in mobility use cases, e.g., when combined with UABS deployments, which continue to be a challenging and are currently under investigation [131]. Application instance relocation and context mobility are required that can enable seamless handover of MEC capabilities between the cells that the user is passing through.

IV. 5G PPDR ARCHITECTURE AND DEPLOYMENT OPTIONS

Software-defined networking (SDN) and network functions virtualization (NFV) are the two core concepts that have impacted the transformation of network architecture and improvement of its flexibility in 5G compared to previous generations of wireless networks. With the adoption of cloud deployed SDN/NFV, network functions as well as other types of applications in 5G can be deployed as virtualized software instances running in data centers located centrally, distributed or as a combination thereof [7], [117], [132]. Virtualization of 5G is expected to gradually progress from the core network, which is easier to implement because of a smaller number of nodes, towards RAN, the virtualization of which is more complex and limited up to the point of terminating the radio interface, but provides the greatest network efficiency gains, in particular for small-cell deployments with cell and interference coordination support [7]. A number of standardization bodies and industry initiatives are involved in standardization of NFV concepts and specification of reference architectures and interfaces, including ETSI NFV Industry Specification Group [133], the Open Networking Foundation [134], OpenStack [135], OpenDaylight [136], and Linux Foundation's Open Platform for NFV (OPNFV) [137]. Also, there are numerous industry efforts aimed at defining open interfaces to facilitate softwarized implementation of radio and network functions in an interoperable vendor ecosystem, including the 3GPP, the Open RAN Alliance (developing O-RAN) [138], the Common NFVI Telco Taskforce (CNTT) hosted between the Linux Foundation and the GSMA [139], the Common Public Radio Interface (CPRI) Cooperation [140], and the Open Network Automation Platform (ONAP) project [141]. Such capabilities result in the adaptability of the 5G architecture in several aspects relative to network ownership and management, migration paths and functional requirements, as discussed in more detail in the following.

A. OWNERSHIP AND MANAGEMENT OPTIONS

Firstly, 5G network softwarization and the concept of slicing enable a shared use of a 5G network in the form of virtual 5G networks with guaranteed Service Level Agreement (SLA), including for example relative priority of users and services, preemptive behavior in case of capacity shortage, specialized capabilities such as IOPS or D2D, and end-to-end security support of control and user traffic. This in practice leads to the ability of the 5G to create and operate a private 5G PPDR network on top of a commercial infrastructure with private characteristics mirroring those of traditional public safety networks [127].

Hence, when planning a 5G PPDR deployment, a number of ownership options are possible. These range from an entirely privately owned and dedicated 5G PPDR network to a fully hosted deployment (Mobile Virtual Network Operator – MVNO model) as well as hybrid options where a dedicated private public safety network is connected to commercial networks with roaming support for coverage or capacity augmentation. In a fully privately owned and managed 5G PPDR model the major benefits include the possibility to have full control over the network, coverage, capacity and availability, and the possibility to introduce specific functionalities and security architectures. This, however, comes at a cost of high investment and operational costs, which in most cases is not an affordable option in the PPDR sector. On the other hand, a private PPDR network hosted on a shared infrastructure and managed by a commercial 5G network operator benefits from the mainstream technology developments and the economy of scale. In this case, however, performance and operational aspects such as capacity, coverage, prioritization and preemption, as well as security and availability are subject to SLA agreements and not under direct control of the PPDR authority. The third option, hybrid deployment models, stand to strike a favorable balance between both aforementioned extremes and offer the possibility for the PPDR sector to retain at least partial control over the core performance and operational capabilities while reducing investment and operational costs on the account of RAN/access and backhaul augmentation by means of commercial networks. A fourth option exists also, where a MVNO-based PPDR deployment is augmented with either a private spectrum or private RAN and backhaul deployments; the latter option is particularly promising for cases where commercial networks fail to ensure sufficient coverage of certain areas, e.g., mountainous regions, as well as for localized or ad-hoc capacity and coverage augmentation in case of massive response missions, for example.

Within these options, network management represents an additional dimension and again multiple variants are possible. In addition to including classical multi-operator RAN and multi-operator core models, 5G allows even more management flexibility, for example split management on user and control levels between RAN and core network, and in combination with management policies enforced through network slicing [127]. In practice, the choice of realistic ownership-management combinations is expected to follow concrete use cases, plausibility of business models and particularities of spectrum licensing, and for the 5G PPDR particularly also currently established practices, access to sufficient expertise for management of networks and services, existing PSNs as well as the pertaining national regulation.

B. EVOLUTION PATHS AND DEPLOYMENT OPTIONS

Another important aspect when discussing deployment options is concerned with a number of possible evolution paths toward 5G as specified in Release 15 of the 3GPP [142], [143]. Two primary 5G deployment models include a non-standalone (NSA) deployment of NR integrated with an existing LTE network and connected either into the Evolved Packet Core (EPC) or into the 5G Core (5GC), and a standalone (SA) 5G option reliant on NR and connected into the 5GC (whereas LTE connected into the EPC is considered a legacy 4G SA). A number of deployment configurations result from the NSA and the SA models with different RAN combinations and the applicable integration and roaming mechanisms as specified for 5G in [121] and [144], denominated as Option 1 through 7 with further subvariants (Figure 3). Option 1 represents the legacy 4G deployment of LTE connected to EPC, and Option 2 represents the targeted 5G-only deployment of NR connected to 5GC.

For PPDR specifically, the research on 5G migration paths and deployment options has yet to take place. The migration is expected to progress gradually and through a number of consecutive stages, first with the introduction of new non-MC services benefitting from 5G performances, followed by gradual migration of MC services. Non-MC BB PPDR services have insofar been scarce and available predominately through commercial 4G networks. There was little if any integrations with the PSNs and their migration, if applicable at all, is expected to follow the migration strategies implemented by commercial network operators. For MC services, on the other hand, the exact strategy depends on the current state of legacy PSN portfolio as well as on the pertaining ownership and management models. For example, for 4G PPDR network owners, migration strategies apply that offer protection of existing investments while allowing for gradual network upgrades with continuous MC services operation. For PPDR users migrating from legacy PSNs and opting for hosted and hybrid models abandoning legacy PSNs, on the other hand, the deployment options will depend on the exact ownership and management model as well as on national strategies and regulation. The timing and choices will be guided also by a number of PPDR-specific requirements, including wide area coverage guarantees versus 5G performances, interworking support and service continuity, as well as availability of native 5G MC features and specific PPDR capabilities.

Looking at the SA and NSA deployment models for PPDR, among a number of different possibilities, Options 2 and 3/3× seem like the most promising candidates. Option 3 is an NSA model where NR is connected to LTE/EPC and exploits E-UTRAN - NR Dual Connectivity to boost throughput of

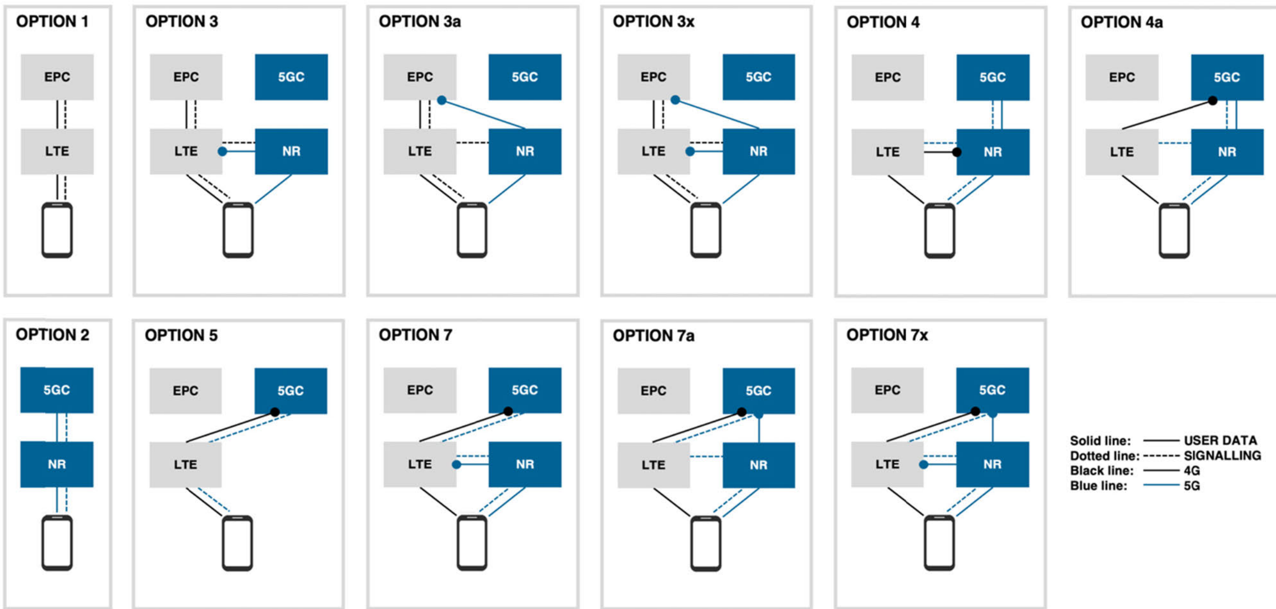


FIGURE 3. 5G NSA and SA deployment models. The multiple connectivity alternatives in 3GPP 5G architecture include Options 1 through 7 with several further subversions available for NSA models. Stand Alone (SA) models include only one independent RAT (LTE or NR) that is connected to either the EPC or to the 5GC. In Non-Standalone (NSA) models both RATs are present and one of the RATs assists the other in connecting either to the EPC or to the 5GC. Please note that Option 6 has later been abandoned by the 3GPP because of its very unlikely applicability in practice, and is therefore omitted from this figure.

a device that is simultaneously connected to both RANs. Its variant 3× enables transmission of user plane data either directly between NR and EPC or via LTE, which introduces improved load balancing capabilities and support of eMBB use cases through direct NR-EPC connectivity. This is an interesting short-terms option that would allow a 4G PPDR operator to protect existing investments and at the same time offer 5G throughput performances to their PPDR users. Load sharing of data over a single bearer of 4G and 5G would allow for continuity of data services even in initial stages when NR coverage is limited. Option 2, on the other hand, is a SA option where the UE connects using only 5G technology, i.e., NR and 5GC whereas LTE/EPC, if available, remains operational to support legacy devices. This option applies to PPDR end-users who have previously used legacy PSNs and are migrating to a hosted or hybrid model with a commercial 5G operator, as well as to PPDR operators in migration from Option 3 towards SA 5G. This is a favorable strategy for both cases as it provides wide-area LTE coverage to allow gradual NR rollout, a fully 5G connectivity with all performance benefits within areas of NR coverage, as well as interworking capabilities with legacy PSNs through 4G if so required. Another intermediate NSA alternative on the path towards SA 5G is Option 4, where the network core is upgraded to 5GC and connected to both LTE and NR radio access technologies. This option, however, requires an enhanced LTE (eLTE) deployment and is therefore considered as a less frequent choice. The combined most likely 4G to 5G PPDR migration path through Options 1, 3 and 2 is depicted in Figure 4.

C. FUNCTIONAL DEPLOYMENT OPTIONS

A third deployment aspect exists as well, orthogonal to ownership, management and migration strategies, and is concerned with flexibility of the 5G architecture from a functional and performance perspective to accommodate sector specific or even use-case specific requirements. The combined capabilities of splitting 5G control plane and user plane functions, and SDN/NFV and MEC/cloud support facilitate flexibility in the distribution of user and control plane functions, which can be placed either centrally or pushed deeper into the edge of the network. Three distinct PPDR scenarios are used in Figure 5 to demonstrate the adaptations to prioritize mMTC, eMBB, cMTC and resilience capabilities.

In option A, the 5G architecture is centralized and capable of supporting mMTC use cases, such as for example a deployment of risk area sensing infrastructure where either fixed or mobile sensors can be used for predicting and detecting flooding events. The use of low-complexity sensors increases the amount of control plane signaling relative to user plane traffic and in high mobility cases tracking services also contribute with a significant burden on the network.

Option B implements eMMB communications to deploy for example real-time aerial surveillance of a disaster area using UAVs and advanced video processing (possibly with AR interfaces). Transmission of high-definition video in real time presents heavy network load in terms of bandwidth and transmission delays, as well as in terms of processing power on the level of the application. To accommodate large capacity and low latency, the user plane is pushed closer towards the edge of the network.

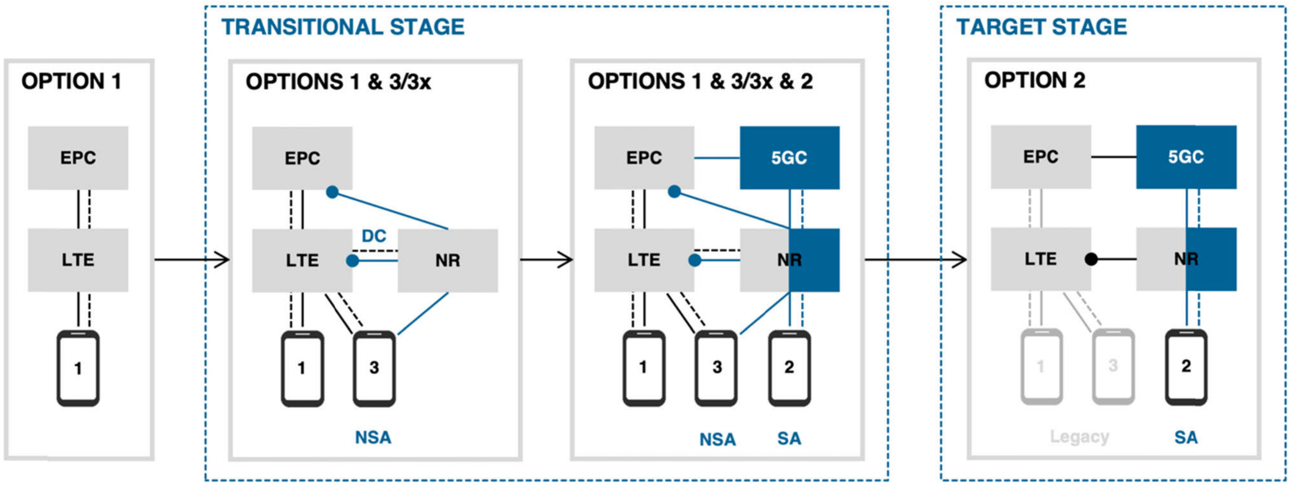


FIGURE 4. **A possible PPDR migration scenario from 4G to 5G through NSA and SA models based on Options 1, 2 and 3/3×. The migration scenario assumes Option 1 as a starting point, i.e., a 4G deployment. In a transitional stage, Option 3/3× is introduced initially where both LTE and LTE-assisted MR are connected to the EPC; if Option 3× is deployed, direct user plane connectivity between NR and the EPC is also enabled, providing for improved load balancing and eMBB performances. Later, Option 2 is introduced in addition. This combination ensures a wide-area coverage while NR is gradually rolled out; SA NR Option 2 is used in areas with good NR coverage, NSA NR Option 3/3× is used where NR is available only on partial spectrum, and SA LTE Option 1 is used outside of NR coverage areas. LTE-NR mobility is implemented with the 3GPP EPC-5GC interworking mechanisms [121]. In the long-term, when NR coverage is expanded, the deployment transitions into Option 2 only. EPC/LTE remains available to serve legacy UEs.**

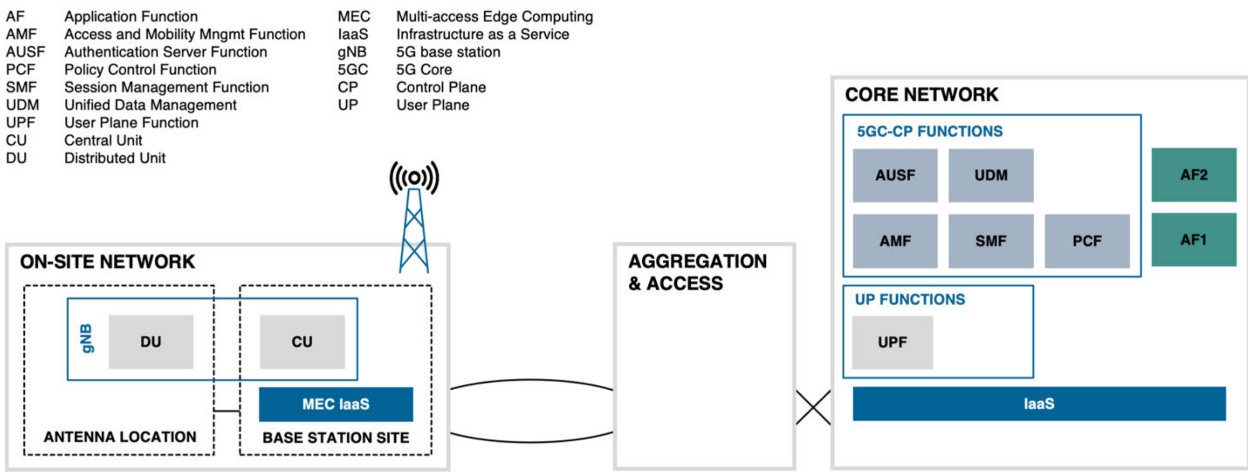
Option C targets implementation of most demanding scenarios in the BB PPDR requiring either ultra-low latency or maximum availability. The first scenario involves emergency robot control, e.g., in incidents where robots are used for disarming of explosive bodies; this scenario requires ultra-low latency and extreme availability, which is achieved by deploying both control and processing powers as close to the intervention site as possible, i.e., on the closest base station site in the field. The second scenario supported with this architectural option is resilience of field 5G communications during large disasters when backhaul and core parts of the infrastructure experience partial of complete outage. In this case, resilience is achieved by deploying crucial control logic and processing capabilities as well as mission critical applications at the edge of the network, which corresponds to the tactical PPDR level, typically located on the field. The on-site deployment can be either fixed, portable (COW/COLT) or mobile (compact carry-on). Both depicted scenarios can take place at the same time, e.g., during a massive incident.

V. 5G PPDR SPECTRUM

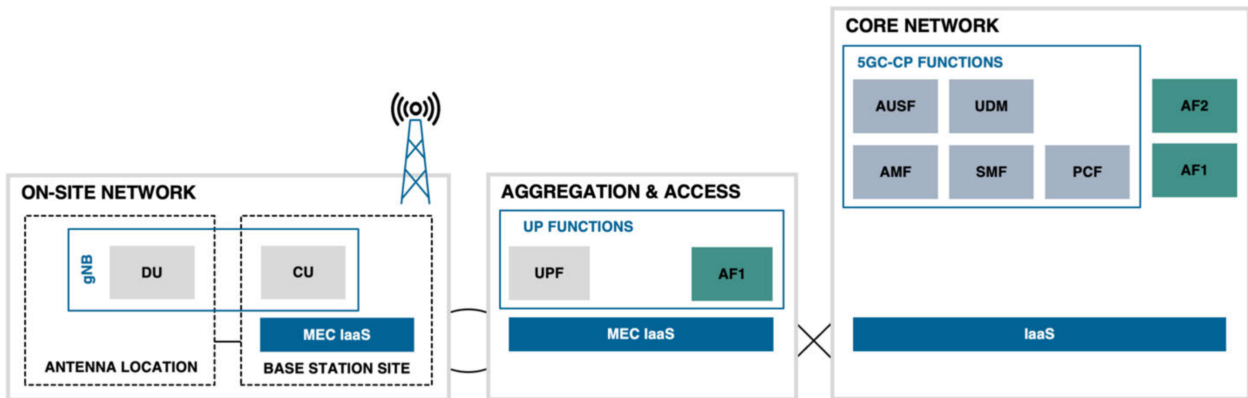
The strategies of introducing 5G into PPDR practice depend also on the availability and access to spectrum. Significant efforts are underway globally and on national levels to align the most suitable 5G frequency spectrum for the public safety sector. In general, the 5G spectrum is split into three sections [145]: low-band spectrum below 1 GHz, mid-band spectrum between 1 GHz and 6 GHz, and high-band spectrum above 24 GHz. Specific characteristics of each band determine its suitability for a particular deployment scenario. Low-band spectrum has good propagation characteristics and is a favorable choice for scenarios requiring large coverage areas, mobility support, indoor penetration and high aggregation of low bandwidth users. High-band spectrum, on the other hand, provides high capacity, low latency and a large available spectrum, but at a cost of limited coverage and indoor penetration. Mid-band spectrum offers a balance of these characteristics, with improved capacity compared to low-band spectrum and coverage suitable mostly for urban deployments.

The 400 MHz and 700 MHz are the preferred spectrum bands for PPDR needs due to their superior propagation characteristics. The choice corresponds to the requirements of the core mission critical services for user data rates in the range of 100 kbps – 10 Mbps (both DL and UL), 1 – 10 ms latency, and mobility support in the range of 0 – 120 km/h. In terms of capacity, the RSPG Report on Strategic Sectoral Spectrum Needs [143], prepared by the Radio Spectrum Policy Group on request by the European Commission, reported the minimum required spectrum capacity for dedicated broadband PPDR network to be 2 × 10 MHz, with possible additional national requirements for Direct Mode Operations (DMO), Air-Ground-Air (AGA), ad-hoc networks and voice communications over the wireless access networks.

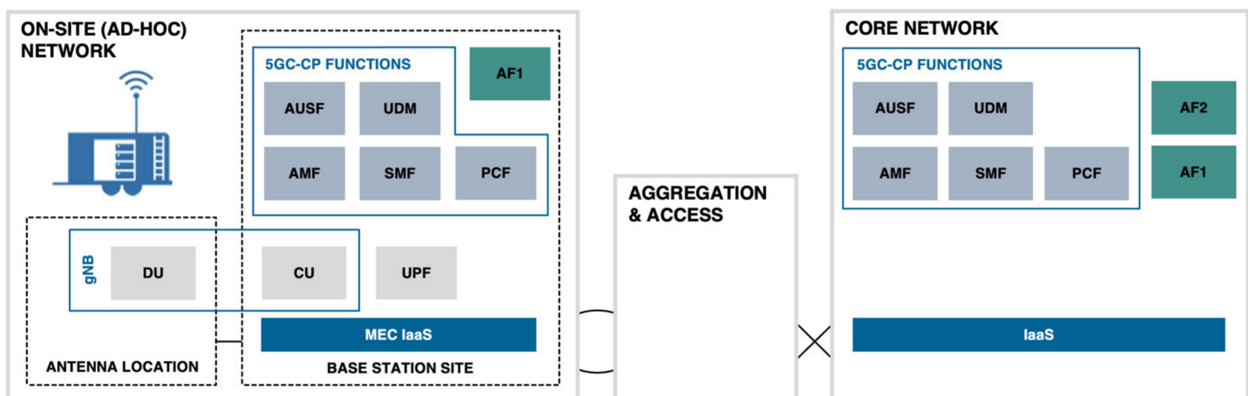
The European Commission is currently investing considerable efforts in cooperation with the Member States into ensuring that sufficient spectrum is made available for PPDR in the EU under harmonized conditions, the goal of which is to create conditions for interoperability and an open market benefitting from economies of scale. In 2016, the Commission Implementing Decision on the 700 MHz band [146] was adopted, harmonizing technical conditions for terrestrial wireless broadband services in the bands 703-733 MHz and 758-788 MHz, with availability of additional parts of the



(a) OPTION A: massive machine-type communications (mMTC) to deploy day-to-day risk area sensing, e.g.in a large geographical area prone to disastrous flooding events; the scenario features a large number of geographically dispersed low-complexity sensors, resulting in increases in control plane signaling relative to user plane traffic. Mobility tracking in case of portable/mobile sensors can also contribute to an increase in the network load.



(b) OPTION B: enhanced massive broadband communications (eMBB) to deploy real-time UAV-supported aerial surveillance with video analysis, e.g., during the course of a disaster recovery mission where real-time video surveillance is in place using swarms of drones and video analysis or augmented reality monitoring is enabled. User plane is distributed closer to the area to optimize the access to the application in terms of capacity and latency.



(c) OPTION C: Resilient low-latency communications with critical machine-type communications (cMTC) for emergency robot control or resilient field 5G communications during disaster response. Ultra-low latency and extreme availability are met by placing user plane functions, processing power as well as critical control plane functions as close to the mobile edge as possible (i.e., on base station site). In case of a massive disaster, this deployment option allows for network resilience in case of failure of backhaul and core parts of the network.

FIGURE 5. Examples of adapted 5G PPDR architectures – (a) massive machine-type communications (mMTC, deployment option A), (b) enhanced mobile broadband communications (eMBB, deployment option B), and (c) resilient ultra-low latency communications (URLLC, deployment option C).

700 MHz band for PPDR, the use of which is left to Member States to decide on a national level. 20.2% of the 700 MHz spectrum has already been assigned in six European countries until December 2019 [144], whereas the majority of Member States are expected to carry out the 700 MHz auctions until end of 2020, thus facilitating the launch of a harmonized 5G PPDR in Europe. Similarly, the FCC in the USA, ISED in Canada and South Korea designated 20 MHz in the 700 MHz spectrum to deploy national broadband PSNs [5]. Herein, the USA is specific in the fact that it allows sharing the allocated band also for commercial needs on condition that the PPDR traffic keeps priority and preemption rights.

Furthermore, PPDR is expected to compete for spectrum resources also in commercial frequency bands where much larger bandwidth capacities are available. PPDR services that fall outside of the narrow interpretation of the MC PPDR services and can withstand sharing of the spectrum with other non-PPDR consumers are expected to follow this strategy. And finally, with the Release 16 support for 5G NR operation in Unlicensed spectrum (NR-U), both licensed assisted and standalone modes will pave the way for additional spectrum capacity required to implement also the most demanding and bandwidth intensive PPDR use cases.

VI. 5G PPDR FACILITIES AND USE CASES

As demonstrated thus far, 5G and its enabling technologies carry a tremendous potential for PPDR. While the technology matures and has reached a stage of commercial adoption in the commercial sector, however, further technology development, experimentation, trials and verification are required to render it functionally and operationally applicable also for the PPDR. The availability of appropriate sector-specific 5G PPDR facilities is essential in this respect, but there is currently a concerning underrepresented of such capacities in the 5G research and innovation arena, as demonstrated hereafter.

Review of relevant literature shows that a number of experimentation facilities exist in the 5G domain, either as generic infrastructure-oriented testbeds focused on experimenting with SDN, NFV, cloud capabilities and edge networking concepts, and on reconstruction and optimization of 5G network architectures, in particular to improve latency and throughput characteristics, or as sector-specific facilities that support research and innovation for specific 5G verticals and investigations of cross-sectorial implications on the underlying infrastructure, primarily in media, automotive, manufacturing, energy and health verticals. In Europe, the European Commission and the European ICT industry are currently investing considerable efforts through their joint 5G Infrastructure Public Private Partnership (5G PPP) into cultivating 5G research and innovation in different vertical sectors, including public safety [147], as follows.

In Phase 2 of the 5G PPP program, NGPaaS tackled 5G network deployment options using eMBB services to deliver mission-critical push to talk, focusing primarily on flexibility, scalability and resilience of the underlying infrastructure [148]. SaT5G investigated the use of 5G cellular backhauling in rural areas to support rapid disaster response scenarios [149]. METRO-HAUL demonstrated the use of SDN-based orchestration, edge computing, and low latency and high-capacity re-configurable optical metro network capabilities for video surveillance [150], [151]. 5G-Xcast included a trial on advanced public warning system with localization and media-rich content support using eMBMS capabilities and spectrum sharing with priority management [152], [153]. MATILDA developed a 5G PPDR pilot, focused on service orchestration and SLA enforcement for improved scalability, reliability and resilience of 5G services for PPDR users [17], [154]. In 5G ESSENCE, the mission critical vertical application was focused on the use of 5G slicing and SLA management capabilities for priority users [155]–[158]. SLICENET validated its 5G provisioning, control, management and orchestration approach also in a remote water level monitoring use case and in remote ultra-HD video services for eHospital connected ambulance [159]. NRG5 focused on 5G security, resilience and high availability in the smart energy sector, and addressed aerial monitoring and incident localization with sensing [160], [161].

In Phase 3, three generic pan-EU 5G infrastructures were funded in 5GENESIS [162], 5G EVE [163] and 5G VINNI [164], with further trials currently underway in various vertical sectors. 5G VINNI [91], [164] and 5GENESIS [94], [162] platforms both target delivery of an end-to-end 5G infrastructure that incorporate a satellite connected vehicle node to support 5G satellite backhaul connectivity for PPDR needs. 5GDrones specializes in UAVs in the context of 5G for situational surveillance and search and rescue missions [165]. LOCUS focuses on advanced network-native location services and contextualization and will trial these new 5G capabilities also for public safety [166]. PriMO-5G targets PPDR use cases using in-vehicle mmWave connectivity, robots and UAV fleets to support fire fighter operations with immersive video services [167], [168].

Beyond the scope of the EC's 5G PPP ecosystem, a large number of other private and public research efforts also led to implementation of a considerable number of 5G platforms that are currently supporting experimentation and case studies, many of which are accessible also to third party experimenters and technology developers. Fed4FIRE and its successor Fed4FIRE+ [169] and OneLab [170] in Europe, and GENI [171] in the United States, for example, represent large ecosystems of federated testbeds to facilitate 5G-related experiments in the area of NFV. 5G Barcelona [172] supports a collection of labs facilitating research in 5G, in particular for IoT aspects, including PPDR case studies, such as emergency management with drones. Virginia Tech's 5G-CORNET [173] provides a cloud-based 5G Infrastructure as a Service (IaaS) supporting cognitive radio experimentation with network architectures, performance testing, and spectrum and network sharing using SDR cluster computing. Similarly, 5G-EmPOWER [174] has devised a RAT-agnostic

TABLE 5. 5G PPDR experimentation infrastructures, projects and research areas.

RESEARCH AREA	PROJECT/INFRASTRUCTURE
Network flexibility, scalability and resilience	NGPaaS [150], MATILDA [17][154], NRG5 [160][161]
Network virtualization, SDN	Fed4FIRE+ [169], OneLab [170], GENI [171], 5G-EmPOWER [174], METRO-HAUL [150][151], 5GINFIRE [177]
5G cellular and satellite backhauling	SaT5G [149], 5GENESIS [94][164], 5G VINNI [164]
Orchestration and reconfigurability	METRO-HAUL [151], MATILDA [17][154], SLICENET [159]
Edge computing	METRO-HAUL [151], MONROE [8]
Localization and media delivery	5G-XCast [152][153]
Spectrum sharing, prioritization, mmWave, SDR	PriMO-5G [152], 5G-CORNET [173], 5G-Xcast [152][153]
Slicing	5G ESSENCE [155][156][157][158], SLICENET [159], MATILDA [17][154]
5G UAVs, IoT	5GDrones [165], PriMO-5G [167][168], 5G Barcelona [172], SLICENET [159], NRG5 [160], AERPAW [176]
Location services, contextualization	LOCUS [166]
Mission Critical services	NGPaaS [148], MONROE [8], 5GENESIS [158][162]

open-source SDN platform to experiment with network-level capabilities while abstracting specific underlying radio technologies. MONROE [8] is an alliance offering a transnational platform for broadband performance measurements and evaluation over 4G cellular networks, including experimentation with MEC, POC and MCPTT capabilities and performances in 4G and NSA 5G deployments [8], [175]. A United States project AERPAW targets establishment of a 5G aerial wireless experimentation platform [176]. Last but not least, 5GINFIRE [177] built a 5G NFV-based ecosystem to support experimentation in different verticals, part of which is also a 5G PPDR facility presented and studied in the remainder of this paper.

Notwithstanding the above evidence of ongoing 5G PPDR experimentation, a closer investigation shows that the proportion of research and experimentation efforts dedicated to PPDR is very small in comparison to other mainstream 5G verticals, such as automotive, media, logistics, energy etc. It reveals also that there is a concerning underrepresentation of facilities customized specifically for 5G PPDR experimentation. A review of the currently ongoing 5G vertical trials and test spectrum usage in the EU prepared by the 5G Observatory [144], for example, reported that out of 181 reported trials only 5 are dedicated to PPDR. Also, the was majority of reported frequency bands tested insofar fall within the 3.4 – 3.8 GHz band whereas there is only 2 % of trials active on the 700 MHz band [178]. This points at a concerning shortage of experimentation dedicated to 5G PPDR.

In the next section, we provide a case study and practical insights into architectural, functional and deployment related 5G experimentation using a facility specifically customized for PPDR.

VII. 5G PPDR EXPERIMENTATION: A CASE STUDY

We hereafter present a case study of a 5G PPDR experiment investigating deployment and provisioning of a 5G PPDR communications infrastructure and services required during large public safety incidents, e.g., a devastating flooding or a destructive earthquake. The case study demonstrates the ability of conducting experiments with 5G network deployments and service provisioning mechanisms, including performance monitoring in a specific PPDR setting.

The experiment was conducted on a dedicated 5G PPDR experimentation facility PPDRone, which was implemented through the EC's 5GINFIRE platform [177] and is, to the best of our knowledge, unique in its ability to support generic 5G as well as sector-specific 5G PPDR experimentation in laboratory and real-world settings.

Two distinct aspects were investigated during the course of the experiment: (1) emergency augmentation of the terrestrial 5G PPDR network with rapidly deployable on-site capacities in the area of a public safety incident, and (2) PPDR applications availability and reliability on the field, and quality and performance monitoring of the supported network and services using facility provided PPDR applications and monitoring tools.

A. BRIEF FACILITY OVERVIEW

PPDRone is composed of an SDR and Cloud RAN based (C-RAN) radio and core mobile system with flexible configuration options and an OpenStack-based IaaS backend infrastructure with support for NFV-enabled orchestration. For the case of SDR, the supported frequency spectrum ranges from 70 MHz up to 6 GHz and includes both pioneering 5G frequency bands and the 700 MHz PPDR band. Experiments can benefit from flexible RF channel bandwidth from 200 kHz (NB-IoT) and up to 50 MHz in case of 5G NR (SA and NSA), with carrier aggregation. The system benefits from KVM-based virtualization and incorporates an OpenStack IaaS cloud/edge.

Two separate PPDRone deployments are available. A fixed facility supports indoor laboratory-based experimentation in operational frequencies from 70 MHz up to 6 GHz, and outdoor experimentation supporting field operations in the 700 MHz (LTE B28; 5G n28) band and 3500 MHz (LTE B42; 5G n78) band with the total air capacity of 110 Mhz. A compact portable PPDRone facility is also available for field experimentation (Figure 6). It contains the entire range of functionalities in a compact ruggedized format optimized for in-vehicle (COW/COLT) and portable (compact carry-on) field use. This allows running of experiments independent of its location, either in specialized labs or as part of field experiments (e.g., in remote/mountain areas, on the sea etc.), allowing for recreating realistic PPDR scenarios and

FIGURE 6. **Portable PPDRone mobile system facility deployment (left) and PPDR IoT toolkit for field use (right).**

FIGURE 7. **PPDR applications available in the PPDRone facility – an intervention monitoring dashboard (top left) with field triage and tracking mobile application (top right); a sensor gateway (bottom left), and a drone and ultrasonic water level sensors (bottom right).**

conducting experiments concerned with resilience, survivability, high availability and isolated operation of 5G.

The facility is designed for laboratory and field 5G experiments in areas of emergency response, disaster relief, and critical infrastructure protection. In this respect, reference PPDR services and applications are provided for testing, demonstration and validation purposes, including an intervention monitoring system with field triage, tracking and ground and UAV-based video monitoring capabilities (Figure 7), and PPDR IoT toolkit for sensor deployment automation and management including a sensor gateway, ultrasonic water level sensors and a drone for real time video streaming. A telco-grade network and service testing, verification and benchmarking system is also included for performance monitoring and KPI validation (Figure 8), with various measurement agent probe implementations, including cloud backend, industrial and mobile editions.

The facility supports experimentation with 5G network architectures and services, as well as deployment and management options for different PPDR stakeholder roles, i.e., Network Provider, Service Provider and End Users. The definition of these roles can correspond to

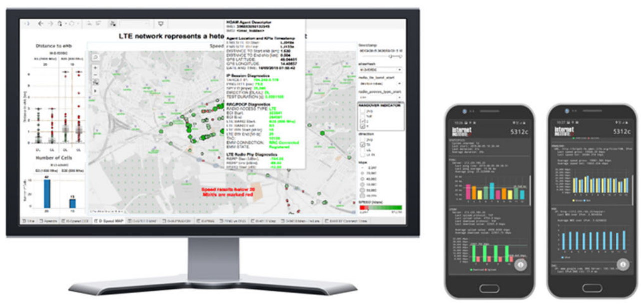


FIGURE 8. **PPDR applications available in the PPDRone facility – a production-grade network and service testing, verification and benchmarking system with a dashboard (left) and mobile agent probes (right).**

responsibilities of the telecommunications operators, commercial and sector-specific service providers, and public safety authorities including blue light services (law enforcement, fire fighters, emergency medical service), depending on the implemented deployment, ownership and management policies. Table 6 provides a non-exhaustive overview of the varied experimentation aspects supported with PPDRone mapped to the key 5G PPDR research areas.

B. RAPIDLY DEPLOYABLE 5G

The first part of the experiment investigated the process of deploying an emergency on-site 5G infrastructure. The following layout was drawn for the conducted experiment. (1) A large-scale emergency took place, the size and duration of which required prolonged on-site disaster management operations. A so-called Base of Operations (BoO) was set up in the affected area for the purpose of disaster response coordination and communications support. Typically, this constitutes tactical command vehicles or temporary sheltering hosting on-site emergency communications infrastructure, tactical command posts, logistics capacities, emergency power supply etc. (2) An emergency deployment of an on-site network was required as a result of insufficient network coverage/capacity, either due to failure of the terrestrial infrastructure incurred during the emergency (urban area case) or the area being underserved and with poor network coverage (remote area case). The conditions mandated a rapidly deployable compact solution (limited space, ruggedized encasing) available within a very short timeframe (hours). (3) Access to spectrum was considered available, either through previously procured licenses available with the provider or end user, or as part of expedited procurement processes carried out in cooperation with the regulatory authority (and other operators in case of emergency access to already licensed spectrum bands). (4) Ad-hoc sensor deployments and video surveillance using UAV-based reconnaissance flights were planned, for monitoring of the affected area to be set up in the BoO through real-time cloud-based dashboard services. This mandated a local backend IaaS infrastructure, capable of ensuring availability of essential cloud-based applications in the event of issues with backhaul connectivity.

TABLE 6. Supported PPDRone experimentation areas for PPDR network operators and for PPDR service providers and end users.

PPDR NETWORK OPERATORS	mmWave	Massive MIMO	D2D	UAVs	SatCom	Capac.& coverage augment.	MC capab-ilities	mMTC	SDN/ NFV	Net. slicing	MEC
PPDR architectures and feasibility testing, with radio, mobile network and cloud infrastructure elements	x	x		x	x	x	x	x	x	x	x
Dedicated PPDR base station deployments with flexible bands and channel configurations	x	x		x	x	x		x	x		x
Radio experiments from functional and performance aspects (Carrier aggregation, NB-IOT/MEC)	x	x					x	x			
QoS enforcement mechanisms (QCI, ARP, GBR, MBR, AMBR, default/dedicated bearer) and performance verification				x		x	x	x			
Security architectures and deployment models with multi-level authentication (USIM, APN user based) and end-to-end encryption			x	x	x		x			x	x
PPDR network resilience and high availability architecture verification				x	x	x			x		x
PPDR IaaS environment deployments in centralized and distributed model supporting 3GPP IOPS and portable system modes				x		x	x	x	x	x	x
End-to-end performance testing of network architecture, IaaS nodes and network services				x	x	x		x	x	x	x
PPDR SERVICE PROVIDERS AND END USERS											
Deployment and testing of mission critical video and data services			x	x	x		x				
Deployment and testing of PPDR mobile applications			x	x	x	x	x	x	x	x	x
Verification of deployment models and architectural aspects of PPDR services in IaaS						x			x	x	x
Performance verification of deployed services (cloud and end-to-end perspectives)				x	x	x			x	x	x
Verification of new 5G-assisted PPDR operational procedures			x	x	x		x	x			

The experiment setup is represented in Figure 9. A rapidly deployable compact carry-on implementation of the PPDRone was co-located with the tactical command infrastructure as part of the BoO. The deployed PPDRone macro cell-site with 20 W Remote Radio Head (RRH) implementing the DU was providing coverage in the range of approx. 5 km. This comprised a C-RAN base station with a 2×2 MIMO RRH, operating at 3.5 GHz (B42, channel BW 20 MHz) in TDD mode; a Base Band Unit (BBU; implementation model of CU) implemented in software and hosted on $\times 86$ based network appliance with $4\times$ CPRI optical connectivity; featuring 3GPP Rel.14 LTE/LTE-A/NB-IoT. In addition to the SDR-based mobile system the node deployed also a local MEC IaaS instance capable of ensuring local or even isolated compute/storage/processing capabilities for critical applications. The site IaaS was implemented with a router GW, a networks Appliance Server, Openstack VIM with OSM 4 and 5 enabled, featuring MEC capabilities and two VIM controlled applications, a cloud-native intervention monitoring dashboard (Figure 7, top left) and performance monitoring agent and server engines (Figure 8). Backhaul connectivity was established through an Ethernet-based fixed line connectivity into the existing terrestrial infrastructure, connecting the deployed cell-site PPDRone mobile system with the fixed PPDRone facility instance at the edge/core site and with global Internet services.

C. FACILITY PERFORMANCE AND MONITORING CAPACITIES

In the second part, a setup of cloud-based PPDR applications provided with the PPDRone facility was trialed to investigate the facility's QoS performances and availability, reliability, resource usage and isolated operation capacities. The scenario on the level of applications involved real

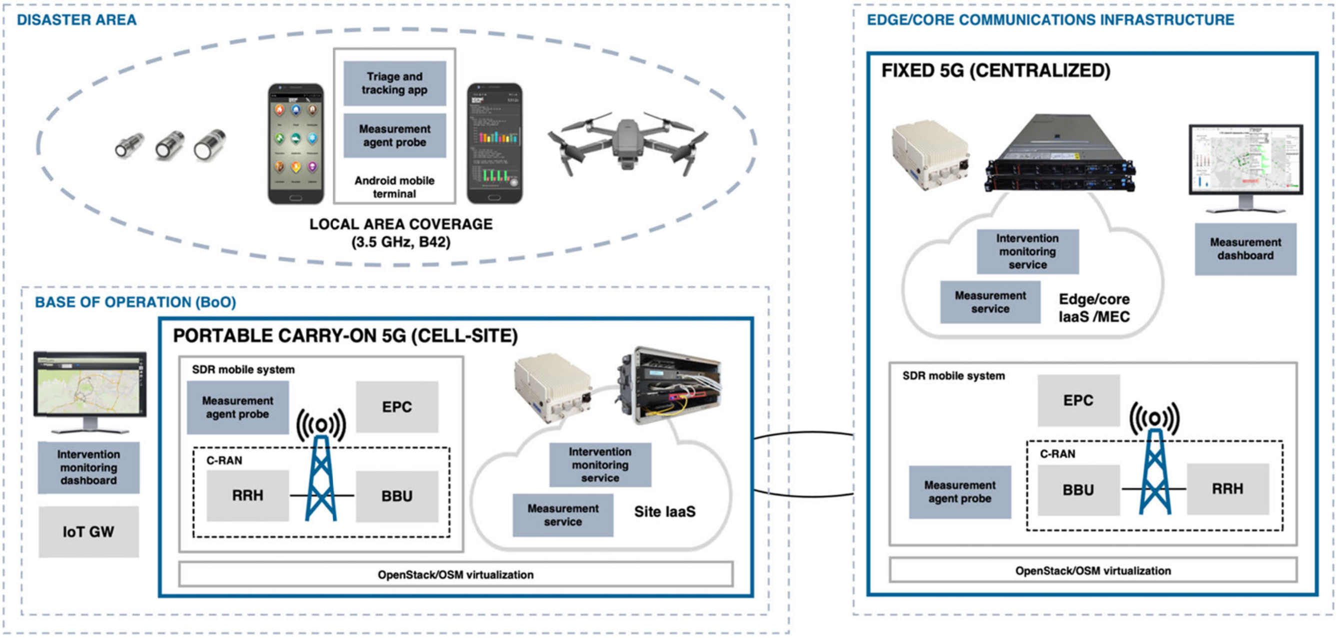


FIGURE 9. 5G PPDR experimentation case study – deployment setup.

time monitoring of a large-scale intervention through sensor deployments and the use of the field triage and tracking solution provided with the facility, which enables continuous location tracking and triage reporting about on-site events and conditions. Aspects of local availability and compute, store and processing capacities were investigated in the context of distributed cloud-based application provisioning under harsh conditions causing interrupted backhaul connectivity. Also, other performance aspects were investigating with respect to various PPDR application requirements.

The experimentation setup was based on the distributed deployment (on-site and central) of the network and cloud capabilities (edge/core IaaS), described in the previous scenario. At the edge, the following components were deployed (Figure 10). An industrial-grade gateway, providing on-site and mobile backhaul connectivity connecting BoO user equipment with the deployed PPDRone edge/core IaaS systems where intervention monitoring dashboard application components were deployed using cloud-native principles. Such setup was used for on-site BoO emulation (tactical command base), and for connecting hardware and software components used by first responders on the field (disaster area). The latter included Android terminals with the field triage and tracking application (Figure 7, top right) and an industrial IoT gateway with ultrasonic sensors for water level measurements (Figure 7, bottom left and bottom right). This setup allowed for on-site intervention monitoring emulation using sensor deployments, manual field triage reporting and real-time tracking of the deployed units. Field devices and applications were used to collect and transmit locally gathered information from the disaster area via mobile connectivity into the edge/core IaaS. On the cloud side, an instance of the intervention monitoring dashboard (Figure 7, top left) was deployed in edge and core IaaS location. Data consistency between the locally and centrally deployed instances was provided by the database replication and synchronization mechanisms initiated between the deployed database components, ensuring application resilience. The emulated laboratory setting is displayed in Figure 10.

For the deployed setup, an evaluation of the Quality of Service (QoS) and other non-functional Key Performance Indicators (KPIs) was conducted. The focus was placed on resource usage monitoring and service availability and reliability. To do so, a telco-grade performance testing and benchmarking solution provided with the experimentation facility was used to conduct the system testing and evaluation. This comprised distributed agent probes, which were installed on the on-site Android terminals (Android app agent instance shown on Figure 8, right) and in the BoO site gateway (cloud instance) to assure and monitor network and user quality experience on an end-to-end basis. The collected results were captured in the backend system, installed in the core IaaS, through the collector element. Test results exposure and analytics features of a dedicated dashboard were used to analyze the results using a combination of Tableau and Grafana outputs (analytics dashboard shown in Figure 11, test results in Figure 12 through Figure 18).

End-to-end network and services testing was performed between the agent probes deployed on Android terminals (disaster area) and site gateway (BoO), and the IaaS in the edge/core instance, passing through the deployed BoO network, portable carry-on mobile system, and backhaul connectivity to the centralized mobile core and the core IaaS, where reference test servers were deployed. The testing

FIGURE 10. Emulated laboratory PPDRone facility experiment setup to conduct QoS and KPI performance tests.

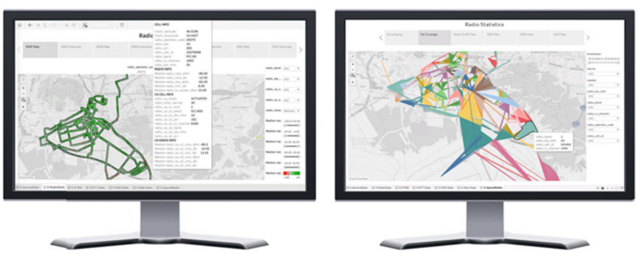


FIGURE 11. Emergency 5G infrastructure and PPDR applications performance/quality monitoring through monitoring dashboard capabilities of the PPDRone facility.

methodology was based on active network and services traffic emulation using native protocols (e.g., TCP, HTTP, and DNS) and industry-recognized toolset (e.g., Iperf, DNS dig) that were run on the distributed agent probes to collect the observed KPIs and to perform cyclic performance testing against the criteria defined in Table 7. Each test cycle consisted of several consecutive test rounds, delivering for each cycle numerous test tickets per each observed parameter. The results are presented in Figure 12 through Figure 18.

TABLE 7. Emergency 5G infrastructure and PPDR applications acceptance criteria.

KPI	Description	Acceptance criteria
Bandwidth	Sufficient bandwidth performance for data-intensive applications (e.g., triage reporting, drone-based video streaming)	~ 20 Mbps/user
Latency	End-to-end latency for interactive applications (e.g., database query)	< 20 ms
	End-to-end latency for MC applications (e.g., robot remote control with AR)	< 1 ms
Availability	Service availability	> 99.99%
	Network availability	> 99.99%
Reliability	Service reliability	> 99.99%
	Network reliability	> 99.99%
Resource usage	Compute/storage/networking resource usage monitoring	Available at all times (zero downtime)
Resource usage	Compute/storage/networking resource usage monitoring	Available at all times (zero downtime)

Several test cycles were performed over the period of six months in order to collect a considerable body of results allowing for detailed observations of the facility's behavior and performances. This deliberately included also intermediate system upgrades and reconfigurations (e.g., OSM upgrade, SW upgrade of RAN and core network components) to arrive at results that are as realistic as possible and reflect the performances one can expect over a longer period of time when conducting experiments (taking into account that all longer experimentation periods include also any necessary facility maintenance performed in between). This approach resulted in a large number of collected test tickets presented in Figure 12 through Figure 18 for the observed KPIs (# Tickets provided with numbers on histogram bars; bars represent buckets of measurement ranges as indicated on the horizontal axes). For example, the total number of collected test tickets for parameter Round Trip Time (RTT) is 624.992 (sum of all # Ticket values on histogram bar charts, right hand side vertical axis), and 146.104 for the 25-30 ms bucket. Operator code and used frequency band (i.e., B42) are also shown on the left side of each figure.

The first KPI, sufficient bandwidth performance required for data-intensive applications, is observed with the measured Iperf download (DL) and Iperf upload (UL) metrices. The results show that the calculated median Iperf DL was 37.959 Mbps (Figure 12, Iperf DL BoxPlot, min 9.306 Mbps, max 41.1 Mbps). The histogram and CDF charts show that only approx. 20.73% of all Iperf DL measurements were below the 20 Mbps acceptance threshold (the CDF % at the 20 Mbps bin). The calculated median Iperf UL was 11.675 Mbps (Figure 13, Iperf UL BoxPlot, min 3.081 Mbps, max. 14.480 Mbps) and only 17.4% of all Iperf UL measurements were below 4 Mbps. As can be observed, the measured UL bandwidth performances of the facility were more limited, which was a result of the use of LTE TDD mode

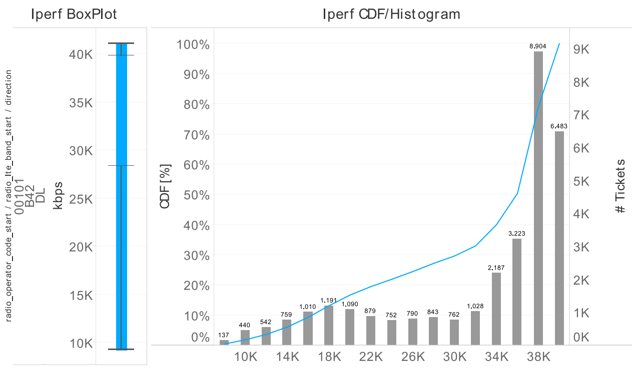


FIGURE 12. **Iperf download (DL) results.**

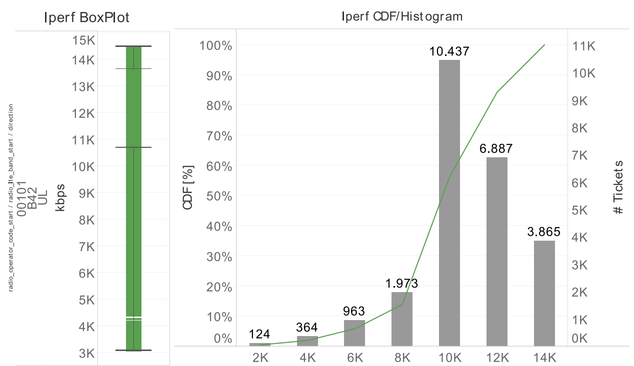


FIGURE 13. **Iperf upload (UL) results.**

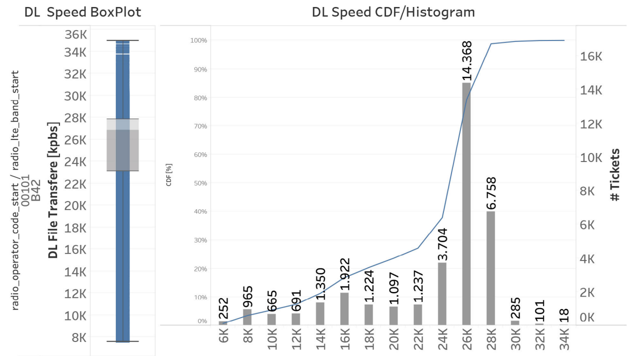


FIGURE 14. **Download (DL) speed results.**

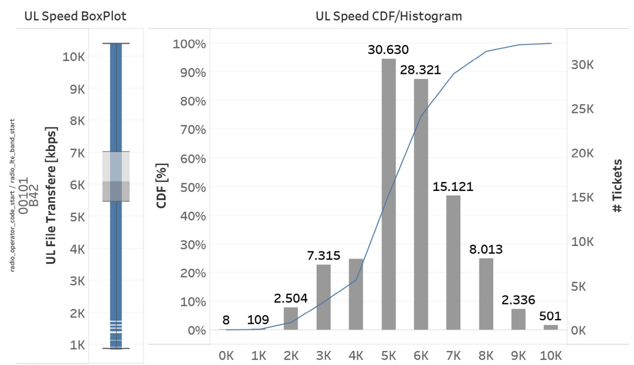


FIGURE 15. **Upload (UL) speed results.**

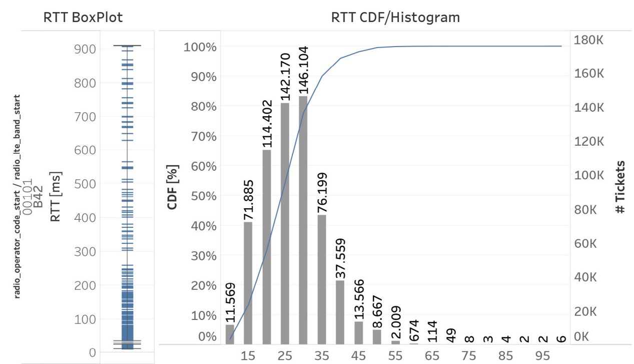


FIGURE 16. **Round Trip Time (RTT) results.**

where channel bandwidth of 20 MHz was split between upload and download radio transmission, and should therefore be interpreted in the context of concrete applications. For example, a live drone-based video streaming in 720p resolution requires 2-3 Mbps UL bandwidth, in 1080p resolution 5-8 Mbps and a 4K live video stream with codec requires 16-20 Mbps. The measurements showed sufficient capacities for 720p and 1080p, whereas enhancements were required in order to support 4K video. It has to be noted, however, that further service parameters and the envisioned operational modes decide the exact requirements calculations, including e.g., the choice of codec, drone flight altitude etc. This in practice would for example constitute the use of drone-based 4K video streaming for high-altitude video reconnaissance followed by 1080p low-altitude drone-based video scanning of the detected risk areas. The resulting requirements can e.g., be taken into account also to fine-tune the used LTE TDD radio split ratio.

The application-level speed was measured between the agent probes and the reference test server for transfer of an image file (10 MB size). The results showed median speed of 26.844 Mbps (Figure 14, DL Speed BoxPlot, min 7.608 Mbps, max. 34.981 Mbps) in the download direction and 6.088 Mbps (Figure 15, UL Speed BoxPlot, min 0.878 Mbps, max. 10.390 Mbps) in the upload direction. Interpreting the results for a triage report service serving PPDR personnel to send high-resolution images from the field, ten 4 MB images require sending of 40 MB of data, which at 5 Mbps UL speed would require 67s and at the measured median 6.088 Mbps 53s, which is below one minute and well within the limits of the generally acceptable criteria of 2 to 3 minutes. This was confirmed also on the user level by successfully sending image files (taken with a quality smartphone camera) from the field triage and tracking application to the intervention monitoring dashboard.

The latency KPI was observed with the RTT delay metric measured between the user terminal and the reference server deployed in the core IaaS. The measured median RTT was 29.0 ms (Figure 16, RTT BoxPlot, min. 12.0 ms, max. 909.0 ms), which was well below the acceptance criteria for interactive applications, such as e.g., a remote database (DB)

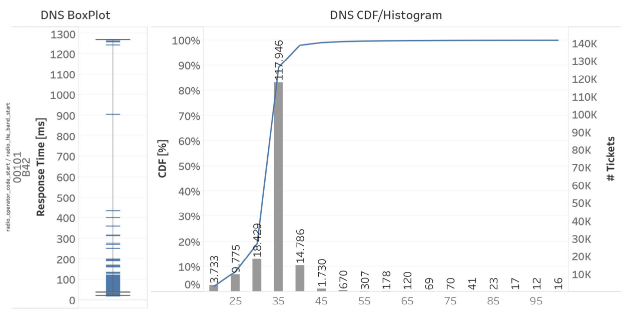


FIGURE 17. **DNS latency results.**

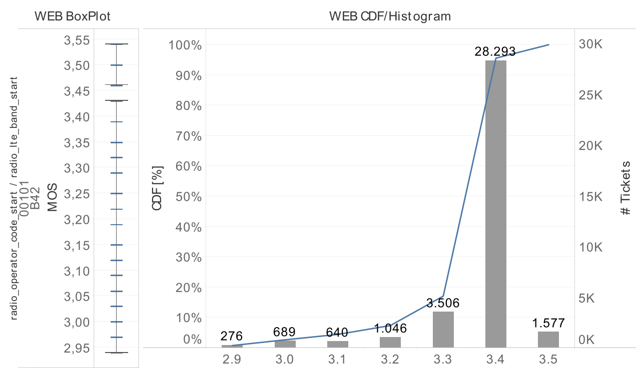


FIGURE 18. **WEB mean opinion score (MOS) results.**

query in case of the intervention monitoring solution with database components deployed centrally in the core IaaS, where a RTT of 1s or below is generally considered acceptable (including e.g., DB-read latency, which in this case is in the range of sub-ms and considered negligible). This was confirmed also with the DNS latency results demonstrating a median of 37 ms (Figure 17, DNS BoxPlot, min. 22 ms, max. 1268 ms), and only 0.03% of DNS latency measurements above 1 s. On the other hand, 13.35% of the RTT measurements and 2.2% of DNS latency measurements were below the 20 ms threshold, showing that the facility at the time of conducting the tests was capable of supporting also applications such as e.g., drone remote control (acceptable one way network latency 50 ms between eNB and UAB [179]) whereas ultra-low latency applications foreseen in 5G with <1 ms acceptance criteria were not supported (e.g., emergency robot remote control with AR interface). This was expected given the fact that the experiment was at the time conducted over 4G.

Finally, WEB mean opinion score (MOS) was also measured, which is a methodology for converting application-level performance parameters into an objective measure of quality on a scale from 1 (worst) to 5 (best). The measurement system used in the experiment calculated MOS based on WEB service response times using Markov chain and a transition matrix of user's satisfactory states as defined in [180]. Kepler ETSI WEB page was used to setup a reference server [181]. The results show that the facility was able to reach good MOS scores with median calculated at 3.43 (Figure 18, WEB BoxPlot, min. 2.94, max. 3.54). The corresponding measured median WEB service response time was 0.6 s (min. 0.2 s, max. 2.1 s), which is within the generally acceptable criteria of 0.5 to 1 s. This is significant for PPDR experiments focusing on web-based application, service and user experience aspects where an appropriate level of user satisfaction is required with respect to available service response times (also in MC scenarios), which in this case was relevant when conducting user-level tests of the intervention dashboard features.

Over the period when the performance tests were conducted, selected time windows were chosen when no facility maintenance was planned to measure another aspect of the observed KPIs, i.e., the ratio of successfully completed tests against all conducted tests per each KPI (test success ratio). This metric was collected to observe the resource usage, and service and network availability and reliability KPIs during normal facility operation (without controlled outages). The results are collected in Table 8. Service availability and reliability were assessed based on test success ratios of KPIs RTT, DNS latency and MOS. As can be seen from Table 8, the acceptance criteria set at >99.99% was in fact achieved through test success ratios of the three KPIs for the case of the deployed on-site and cloud-native services. Similarly, network availability and reliability were measured with Iperf and speed tests (UL and DL) where the 100% test success ratios for all four KPIs exceed the set acceptance threshold of >99.99%. Lastly, regarding resource usage, the acceptance criteria was set to 100%, i.e., availability of compute, storage and networking resources at all times and with zero downtime. Any noticeable shortage of these resources would have affected the availability and performance of the reference test servers used to conduct the measurements, which would be reflected in the results by considerably lowering the test success ratios of the observed KPIs. As can be seen from Table 8, no significant degradations were observed, confirming that the required resources were available at all times and that the used cloud infrastructure was stable enough to be used also for the most demanding MC services. Also, the ability of isolated on-site operation was validated when backhaul connectivity to the centralized IaaS was interrupted, followed by automated reconnection and synchronization on the centralized location after the connectivity was recovered.

The results confirmed sufficient capacities to meet the bandwidth, availability and reliability KPIs as well as latency capabilities and isolated operation suitable for the cloud-native, multimedia-rich and interactive PPDR applications included in the experiment as well as for other emerging PPDR services, such as drone-based live video surveillance, whereas the need for further enhancements was indicated to support also ultra-low latency capabilities required for MC applications as expected in 5G. To this end, the PPDRone facility subsequently underwent significant upgrades (after the experiment end) to support 5G capabilities (5G NR gNB

TABLE 8. Emergency network performance monitoring results.

KPI	# of performed tests	Test success ratio (%)
Round Trip Time (RTT)	14165	99.99
DNS latency	14165	99.99
Web Mean Opinion Score (MOS)	2833	100
Upload speed	2833	100
Download speed	2833	100
Iperf download speed	2833	100
Iperf upload speed	2832	100

Please note that the number of performed tests and the calculated test success ratio are provided for selected time windows when the facility was operating continuously and without interruptions due to maintenance.

and 5GC, NSA and SA options) where such performances are now possible and available for future experimentation, as outlined in more detail in Section VII.E.

D. EXPERIMENTAL FIELD STUDIES WITH PPDR APPLICATIONS

Last but not least, the presented experimentation setup was trialed also as part of field studies and official public safety exercises. This allowed for demonstration and field experiments under conditions recreating realistic public safety situations, which is particularly important in the context of feasibility and usability studies requiring end-user involvement and operational validation in the field. Figure 19 shows an example of a field installation trialed during the International Rescue Dog Exercise taking place in Ljubljana, Slovenia.

The portable carry-on node and the industrial outdoor gateway were deployed in a temporary shelter of the BoO. A working station was set up with the intervention monitoring dashboard with the purpose of tracking the competing rescue teams in the filed through the mobile triage and tracking application. The conducted experiment served to trial the deployment of the on-site infrastructure under realistic conditions (temporary sheltering without fixed infrastructure, exposure to environmental elements, ruggedized terminals). Also, the mobile triage and tracking application and the intervention monitoring dashboard were tested for their reliability under stressful conditions and usability in the context of the exercise's protocols and without prior training of the rescue personnel. The outcomes confirmed the ability of the PPDRone facility to support on-site experimentation with reliability and realism to the extent of being used as part of officially trialed public safety operations.

FIGURE 19. Field experimentation with the PPDRone facility and tools at the International Rescue Dog Exercise in Ljubljana, Slovenia. The figure displays the BoO with the tactical command vehicles and communications infrastructure (top), the mobile triage and tracking application installed on a ruggedized smartphone (middle left), the industrial IoT gateway (middle right), and the intervention monitoring dashboard set up at a workstation in a temporary BoO sheltering (bottom).

E. FURTHER EXPERIMENTAL DIRECTIONS

Further experiments are possible and planned with the presented setup base on the presented capabilities as well as a result of recent facility upgrades and extensions.

Firstly, a subsequent experiment investigating the facility's QoS performances and availability, reliability, resource usage and isolated operation capacities is in order following the implemented upgrades to 5G capabilities, as well as to conduct more in-depth performance studies for interaction intensive and ultra-low latency PPDR applications. Next, experiments involving non-terrestrial 5G sub-networks, i.e., UAVs and SatCom, is a prominent research direction requiring experimentation in numerous technological areas as well as in the context of their application in different deployment and usage scenarios of PPDR and other industrial sectors. Drone-based security applications in business-critical sectors, e.g., seaport operations, is one such example of supported experiments that will be investigated and trialed as part of the 5G-LOGINNOV project [182] for the case of security surveillance in European ports. The Int5Gent [183] project, on the other hand, will investigate the implementation of a drone-supported live video monitoring of disaster areas in a public safety context using the presented PPDRone facility. Another interesting experimentation direction pertaining to Industry 4.0 tackles innovative approaches in 5G-enabled industrial network and services quality assurance tools and methodologies assisted with automated UAV capabilities. One such application, pursued in the 5G-INDUCE project [184], will investigate the possibilities to implement and conduct drone-assisted mobile network and services performance measurements in industrial environments, such as large factory plants and seaports, where physical terrestrial access is difficult or limited for security and safety reasons. The PPDRone facility will be used in combination with drone-mounted agent probes to facilitate aerial access to the 5G infrastructure.

Other possible research directions include experimentation with availability and application resilience with respect to local IaaS/MEC hosting core network components and critical applications in case of backhaul connectivity issues, and the use of virtualization techniques to achieve distributed application deployment and scalability using OpenStack or OSM. In this respect, a pilot implementation deploying 5G IOPS and critical applications will be pursued as part of the 5GASP [185] project using novel cloud-native techniques to achieve distributed application deployment and required services resilience exploiting OpenStack, Kubernetes, OSM and ONAP concepts. Furthermore, experiments with backhaul connectivity and multi-RAT principles can investigate advanced cooperation strategies, alternative connectivity options and dynamic channel selection automation using different 5G sub-networks, including e.g., wireless point to point links, D2D, aerial DWNs or leased satellite backhaul services, as illustrated in [186]. Collaboration between rapidly deployable public safety networks and commercial networks is another possible research avenue including the use of security mechanisms to establish direct interconnectivity, custom roaming provisions, and the use of commercially supplied dedicated PPDR slices. In this respect, dynamic slice provisioning between rapidly deployable 5G PPDR networks and the use of machine learning and artificial intelligence to implement control strategies and dynamic adaptivity for critical communications is another promising experimentation direction. The virtualized mobile core and MEC capabilities of fixed and portable PPDRone node deployments allow also for experimenting with infrastructure deployment using virtualization principles, slice provisioning and service orchestration, as was demonstrated in the course of the MATILDA project [154] and will be further investigated in the scope of the logistics vertical in the 5G-LOGINNOV project [182]. A broad range of other experimentation directions not mentioned here are possible and new ones are expected to emerge on a continuous basis as the presented facility is further evolved with the advancements of 5G technologies and deployment options in the future.

VIII. CONCLUSION

This paper discusses how to conduct experimentation with novel 5G technologies, architectures, sector-specific capabilities and applications with respect to the specific needs of the PPDR vertical. A discussion of the BB PPDR requirements is provided, shedding light on the scope and complexity of the required capabilities and capacities towards communications technologies and networks. The results of the investigation clearly demonstrate that the scope of required services and supported use cases mandates an extremely broad range of performance and operational requirements, a considerable part of which cannot be met with the currently available PSNs or even 4G, and that progressive migration towards 5G is both necessary and unavoidable. Key enabling technologies, including e.g., mmWave, massive MIMO, UAVs, SatCom, D2D, network slicing and MEC, are discussed and specifics of their application in the PPDR vertical are tackled. 5G PPDR architecture and deployment options are also investigated, drawing from the impacts of the increased complexity in terms of ownership, management, functional deployment options and most probable migration paths. While considerable research efforts are underway in the application of 5G technologies and architectures into the PPDR vertical, a comprehensive body of efforts in practical design, application and experimentation trials is yet to take place. A review of the current state of the art in the domain of 5G PPDR experimentation confirms this fact and a concerning underrepresentation of 5G experiments specifically customized for the PPDR vertical can be observed in the current 5G research landscape.

In response and in an effort to facilitate further progress in introducing 5G into the PPDR vertical, this paper presents possibilities to conduct a range of experiments using a dedicated 5G PPDR facility PPDRone. A case study of a 5G PPDR experiment is give, investigating deployment and provisioning of a 5G PPDR communications infrastructure and services required during large public safety incidents. Two distinct scenarios are demonstrated, i.e., emergency augmentation of the terrestrial 5G PPDR network with rapidly deployable on-site capacities in the area of a public safety incident, and experimentation with PPDR applications availability and reliability as part of a field trial setup. The case study demonstrates the ability of the PPDRone experimentation facility in supporting such sector-specific experiments with 5G and cloud-native technologies in both laboratory and real-world settings. The results of the experiment in each of the addressed scenarios indicate that the technologies, capabilities, and tools provided with the facility are good enablers to conduct advanced experiments in a number of research directions, and that the facility itself provides sufficient capacities to carry out feasibility studies and performance and user experienced quality measurements of realistic public safety use cases also in practical applications. Last but not least, the results of the presented research shed light on numerous future 5G PPDR experimentation avenues that challenge the facility's capabilities and capacities in supporting such advanced experimentation aspects.

REFERENCES

[1] C. Blackman and S. Forge. (Apr. 2019). *5G Deployment: State of Play in Europe, USA and Asia, Policy Department for Economic, Scientific and Quality of Life Policies Directorate-General for Internal Policies*. European Parliament. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/IDAN/2019/631060/IPOL_IDA(2019)631060_EN.pdf

[2] M. Mezzavilla, M. Polese, A. Zanella, A. Dhananjay, S. Rangan, C. Kessler, T. S. Rappaport, and M. Zorzi, "Public safety communications above 6 GHz: Challenges and opportunities," *IEEE Access*, vol. 6, pp. 316–329, 2018.

[3] A. Kumbhar, F. Koohifar, I. Guvenc, and B. Mueller, "A survey on legacy and emerging technologies for public safety communications," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 97–124, 1st Quart., 2017.

[4] D. Marabissi and R. Fantacci, "Heterogeneous public safety network architecture based on RAN slicing," *IEEE Access*, vol. 5, pp. 24668–24677, 2017.

[5] A. Jarwan, A. Sabbah, M. Ibnkahla, and O. Issa, "LTE-based public safety networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1165–1187, 2nd Quart., 2019.

[6] *RSPG Report on Strategic Sectoral Spectrum Needs*, document RSPG13-540 (rev2), European Commission, Radio Spectrum Policy Group, Nov. 2013. [Online]. Available: https://circabc.europa.eu/d/d/workspace/SpacesStore/f15d622c-183f-44d4-8412-19f2335a714d/RSPG13-540rev2_RSPG%20Report%20on%20Sectoral%20needs.pdf

[7] RYSAVY Research. (Sep. 2019). *Global 5G: Implications of a Transformational Technology*. [Online]. Available: https://www.5gamericas.org/global-5g-implications-of-a-transformational-technology/#:~:text=Global%205G%3A%20Implications%20of%20a%20Transformational%20Technology%2C%20a%205G%20Americas,a%20timeline%20of%20future%20developments

[8] A. Sanchoyerto, R. Solozabal, B. Blanco, and F. Liberal, "Analysis of the impact of the evolution toward 5G architectures on mission critical push-to-talk services," *IEEE Access*, vol. 7, pp. 115052–115061, 2019.

[9] T. Doumi, M. F. Dolan, S. Tatesh, A. Casati, G. Tsirtsis, K. Anchan, and D. Flore, "LTE for public safety networks," *IEEE Commun. Mag.*, vol. 51, no. 2, pp. 106–112, Feb. 2013.

[10] A. Paulson and T. Schwengler, "A review of public safety communications, from LMR to voice over LTE (VoLT E)," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, London, U.K., Sep. 2013, pp. 3513–3517.

[11] A. U. Chaudhry and R. H. M. Hafez, "LMR and LTE for public safety in 700 MHz spectrum," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–17, Jun. 2019.

[12] R. Ferrus, O. Sallent, G. Baldini, and L. Goratti, "LTE: The technology driver for future public safety communications," *IEEE Commun. Mag.*, vol. 51, no. 10, pp. 154–161, Oct. 2013.

[13] "User requirements and spectrum needs for future European broadband PPDR systems (wide area networks)," Electron. Commun. Committee Working Group Freq. Manag. (ECC WG-FM), Copenhagen, Denmark, Tech. Rep. 199, May 2013. [Online]. Available: https://docdb.cept.org/download/35f6a2e2-1724/ECCREP199.PDF

[14] *Spectrum Needs for Public Protection and Disaster Relief (PPDR)*, document ITU-R M.2415-0, ITU-R, Nov. 2017.

[15] A.-L. Muresan, M. Baranescu, L. Baicu, D. Alexandru, E. Iafrate, A. Bonucci, M. Porfiri, M. Borgquist, and M. Periy, "Prioritised and categorised requirements knowledgebase—Final," BroadMap Tech. Deliverable D3.3, version 5.7, Tech. Rep. D3.3, Apr. 2018. [Online]. Available: https://cordis.europa.eu/project/id/700380

[16] *Feasibility Study on New Services and Markets Technology Enablers; Stage 1 (Release 14)*, document TR 22.891 V14.2.0, 3GPP, Sep. 2016.

[17] K. X. Du, G. Carrozzo, M. S. Siddiqui, O. Carrasco, B. Sayadi, F. Lazarakis, A. Kourtis, J. Sterle, and R. Bruschi, "Definition and evaluation of latency in 5G: A framework approach," in *Proc. IEEE 2nd 5G World Forum (5GWF)*, Dresden, Germany, Sep. 2019, pp. 135–140.

[18] GSMA. (Apr. 2018). *Network Slicing: Use Case Requirements*. [Online]. Available: https://www.gsma.com/futurenetworks/wp-content/uploads/2018/04/NS-Final.pdf

[19] TCCA Limited, Gosforth, Newcastle, United Kingdom. (Dec. 2013). *TETRA versus DMR*. [Online]. Available: https://tcca.info/documents/2013-December_SME_TETRA_v_DMR.pdf/

[20] *Minimal Requirements Related to Technical Performance for IMT-2020 Radio Interfaces*, document ITU-R M.2410-0, ITU-R, Nov. 2017.

[21] A. Anttonen and M. Höyhtyä, "Emerging 5G satellite-aided networks for mission-critical services: A survey and feasibility study," New Space Technol., Oulu, Finland, Tech. Rep. VTT-R-01049-19, 2019. [Online]. Available: https://www.researchgate.net/publication/340173872_Emerging_5G_satellite-aided_networks_for_mission-critical_services_A_survey_and_feasibility_study

[22] G. Mei, N. Xu, J. Qin, B. Wang, and P. Qi, "A survey of Internet of Things (IoT) for geohazard prevention: Applications, technologies, and challenges," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 4371–4386, May 2020.

[23] C. K. Wu, K. F. Tsang, Y. Liu, H. Zhu, H. Wang, and Y. Wei, "Critical Internet of Things: An interworking solution to improve service reliability," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 74–79, Jan. 2020.

[24] S. Cioni, R. D. Gaudenzi, O. D. R. Herrero, and N. Girault, "On the satellite role in the era of 5G massive machine type communications," *IEEE Netw.*, vol. 32, no. 5, pp. 54–61, Sep./Oct. 2018.

[25] *Policy and Charging Control Architecture (Release 16)*, document TS 23.203, V16.2.0, 3GPP, Dec. 2019.

[26] *Feasibility Study on New Services and Markets Technology Enablers for Critical Communications; Stage 1 (Release 14)*, document TR 22.862 V14.1.0, 3GPP, Sep. 2016.

[27] F. Jameel, Z. Hamid, F. Jabeen, S. Zeadally, and M. A. Javed, "A survey of device-to-device communications: Research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2133–2168, 3rd Quart., 2018.

[28] Q. Cao, H. Rutagemwa, F. Zhou, P. Yu, L. Feng, W. Li, A. Xiong, and X. Qiu, "Capacity enhancement for mmWave multi-beam satellite-terrestrial backhaul via beam sharing," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kansas City, MO, USA, May 2018, pp. 1–6.

[29] A. Ometov, E. Sopin, I. Gudkova, S. Andreev, Y. V. Gaidamaka, and Y. Koucheryavy, "Modeling unreliable operation of mmWave-based data sessions in mission-critical PPDR services," *IEEE Access*, vol. 5, pp. 20536–20544, 2017.

[30] W. Xia, M. Polese, M. Mezzavilla, G. Loianno, S. Rangan, and M. Zorzi, "Millimeter wave remote UAV control and communications for public safety scenarios," in *Proc. 16th Annu. IEEE Int. Conf. Sens., Commun., Netw. (SECON)*, Boston, MA, USA, Jun. 2019, pp. 1–7.

[31] M. Boschiero, M. Giordani, M. Polese, and M. Zorzi, "Coverage analysis of UAVs in millimeter wave networks: A stochastic geometry approach," in *Proc. Int. Wireless Commun. Mobile Comput. (IWCMC)*, Limassol, Cyprus, Jun. 2020, pp. 351–357.

[32] M. A. Habibi, M. Nasimi, B. Han, and H. D. Schotten, "A comprehensive survey of RAN architectures toward 5G mobile communication system," *IEEE Access*, vol. 7, pp. 70371–70421, 2019.

[33] J. Ma, C. Liang, C. Xu, and L. Ping, "On orthogonal and superimposed pilot schemes in massive MIMO NOMA systems," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2696–2707, Dec. 2017.

[34] E. Crespo-Bardera, M. Sanchez-Fernandez, A. Garcia-Armada, A. G. Martin, and A. F. Duran, "Analysis of a LTE-based textile massive MIMO proposal for public safety networks," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Toronto, ON, Canada, Sep. 2017, pp. 1–5.

[35] P. Chandhar and E. G. Larsson, "Massive MIMO for connectivity with drones: Case studies and future directions," *IEEE Access*, vol. 7, pp. 94676–94691, 2019.

[36] E. Yaacoub, M. Husseini, and H. Ghaziri, "An overview of research topics and challenges for 5G massive MIMO antennas," in *Proc. IEEE Middle East Conf. Antennas Propag. (MECAP)*, Beirut, Lebanon, Sep. 2016, pp. 1–4.

[37] E. Crespo-Bardera, E. Rajo-Iglesias, M. Rodriguez, R. Feick, M. Sanchez-Fernandez, and R. A. Valenzuela, "Empirical rates characterization of wearable multi-antenna terminals for first-responders," *IEEE Access*, vol. 7, pp. 6990–7000, 2019.

[38] W. Yu, H. Xu, J. Nguyen, E. Blasch, A. Hematian, and W. Gao, "Survey of public safety communications: User-side and network-side solutions and future directions," *IEEE Access*, vol. 6, pp. 70397–70425, 2018.

[39] "5G for mission critical communication," Nokia, Espoo, Finland, White Paper C401-011946-WP-201601-1-EN, 2016. [Online]. Available: http://www.hit.bme.hu/~jakab/edu/litr/5G/Nokia_5G_for_Mission_Critical_Communication_White_Paper.pdf

[40] G. Fodor, S. Parkvall, S. Sorrentino, P. Wallentin, Q. Lu, and N. Brahmi, "Device-to-device communications for national security and public safety," *IEEE Access*, vol. 2, pp. 1510–1520, 2014.
[41] M. Usman, A. A. Gebremariam, U. Raza, and F. Granelli, "A software-defined device-to-device communication architecture for public safety applications in 5G networks," *IEEE Access*, vol. 3, pp. 1649–1654, 2015.
[42] J. Z. Moghaddam, M. Usman, and F. Granelli, "A device-to-device communication-based disaster response network," *IEEE Trans. Cognit. Commun. Netw.*, vol. 4, no. 2, pp. 288–298, Jun. 2018.
[43] Z. Kaleem, A. Khan, S. A. Hassan, N.-S. Vo, L. D. Nguyen, and H. M. Nguyen, "Full-duplex enabled time-efficient device discovery for public safety communications," *Mobile Netw. Appl.*, vol. 25, no. 1, pp. 341–349, Feb. 2020.
[44] Z. Kaleem, N. N. Qadri, T. Q. Duong, and G. K. Karagiannidis, "Energy-efficient device discovery in D2D cellular networks for public safety scenario," *IEEE Syst. J.*, vol. 13, no. 3, pp. 2716–2719, Sep. 2019.
[45] A. Yarali, *Public Safety Networks From LTE to 5G*, 1st ed. Chichester, U.K.: Wiley, 2020.
[46] A. Khan, A. Munir, Z. Kaleem, F. Ullah, M. Bilal, L. Nkenyereye, S. Shah, L. D. Nguyen, S. M. R. Islam, and K.-S. Kwak, "RDSP: Rapidly deployable wireless ad hoc system for post-disaster management," *Sensors*, vol. 20, no. 2, p. 548, Jan. 2020.
[47] L. Rabieekenari, K. Sayrafian, and J. S. Baras, "Autonomous relocation strategies for cells on wheels in public safety networks," in *Proc. 14th IEEE Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2017, pp. 41–44.
[48] S. Ghafoor, P. Sutton, C. Sreenan, and K. Brown, "Cognitive radio for disaster response networks: Survey, potential, and challenges," *IEEE Wireless Commun.*, vol. 21, no. 5, pp. 70–80, Oct. 2014.
[49] H. Zhang, L. Song, and Z. Han, *Unmanned Aerial Vehicle Applications Over Cellular Networks for 5G and Beyond*. Cham, Switzerland: Springer, 2020.
[50] M. Hoyhtya, K. Lahetkangas, J. Suomalainen, M. Hoppari, K. Kujanpaa, K. T. Ngo, T. Kippola, M. Heikkila, H. Posti, J. Maki, T. Savunen, A. Hulkkonen, and H. Kokkinen, "Critical communications over mobile operators' networks: 5G use cases enabled by licensed spectrum sharing, network slicing and QoS control," *IEEE Access*, vol. 6, pp. 73572–73582, 2018.
[51] *Mission Critical Communication Interworking with Land Mobile Radio Systems; Stage 2 (Release 17)*, document TS 23.283 V17.1.0 (2019-12), 3GPP, Dec. 2012.
[52] A. Merwaday, A. Tuncer, A. Kumbhar, and I. Guvenc, "Improved throughput coverage in natural disasters: Unmanned aerial base stations for public-safety communications," *IEEE Veh. Technol. Mag.*, vol. 11, no. 4, pp. 53–60, Dec. 2016.
[53] W. Khawaja, I. Guvenc, and D. Matolak, "UWB channel sounding and modeling for UAV air-to-ground propagation channels," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, p. 17.
[54] D. Saluja, R. Singh, N. Saluja, and S. Kumar, "Energy-efficient strategy for improving coverage and rate using hybrid vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, early access, Aug. 6, 2020, doi: 10.1109/TITS.2020.3011890.
[55] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, "A tutorial on UAVs for wireless networks: Applications, challenges, and open problems," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2334–2360, 3rd Quart., 2019.
[56] S. A. R. Naqvi, S. A. Hassan, H. Pervaiz, and Q. Ni, "Drone-aided communication as a key enabler for 5G and resilient public safety networks," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 36–42, Jan. 2018.
[57] H. Ullah, N. G. Nair, A. Moore, C. Nugent, P. Muschamp, and M. Cuevas, "5G communication: An overview of vehicle-to-everything, drones, and healthcare use-cases," *IEEE Access*, vol. 7, pp. 37251–37268, 2019.
[58] B. Brik, A. Ksentini, and M. Bouaziz, "Federated learning for UAVs-enabled wireless networks: Use cases, challenges, and open problems," *IEEE Access*, vol. 8, pp. 53841–53849, 2020.
[59] H. Shakhatreh, A. H. Sawalmeh, A. Al-Fuqaha, Z. Dou, E. Almaita, I. Khalil, N. S. Othman, A. Khreishah, and M. Guizani, "Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges," *IEEE Access*, vol. 7, pp. 48572–48634, 2019.
[60] Q. Wu, J. Xu, Y. Zeng, D. W. K. Ng, N. Al-Dhahir, R. Schober, and A. L. Swindlehurst. (Oct. 2020). *5G- and-Beyond Networks With UAVs: From Communications to Sensing and Intelligence*. [Online]. Available: https://www.researchgate.net/publication/344756687_5G-and-Beyond_Networks_with_UAVs_From_Communications_to_Sensing_and_Intelligence
[61] Nokia. (2016). *F-Cell Technology From Nokia Bell Labs Revolutionizes Small Cell Deployment by Cutting Wires, Costs and Time*. [Online]. Available: https://www.nokia.com/about-us/news/releases/2016/10/03/f-cell-technology-from-nokia-bell-labs-revolutionizes-small-cell-deployment-by-cutting-wires-costs-and-time/
[62] Facebook. (2015). *Building Communications Networks in the Stratosphere*. [Online]. Available: https://code.facebook.com/posts/993520160679028/building-communications-networks-in-the-stratosphere/
[63] PERFUME. (2015). *Eurecom*. [Online]. Available: http://www.ercperfume.org/about/
[64] Huawei. *MBBF2017 Connected Aerial Vehicle Live*. Accessed: Dec. 17, 2020. [Online]. Available: https://www.huawei.com/en/industry-insights/outlook/mobile-broadband/xlabs/use-cases/mbbf2017-connected-aerial-vehicle-live
[65] Y. Gao, J. Cao, P. Wang, J. Yin, M. He, M. Zhao, M. Peng, S. Hu, Y. Sun, J. Wang, S. Cheng, Y. Guo, Y. Du, Y. Cai, J. Huang, and K. Qiu, "Intelligent UAV based flexible 5G emergency networks: Field trial and system level results," in *Proc. IEEE INFOCOM-IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Toronto, ON, Canada, Jul. 2020, pp. 138–143.
[66] Z. Xiao, L. Zhu, and X.-G. Xia, "UAV communications with millimeter-wave beamforming: Potentials, scenarios, and challenges," *China Commun.*, vol. 17, no. 9, pp. 147–166, Sep. 2020.
[67] G. M. D. Santana, R. S. Cristo, C. Dezan, J.-P. Diguet, D. P. M. Osorio, and K. R. L. J. C. Branco, "Cognitive radio for UAV communications: Opportunities and future challenges," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Dallas, TX, USA, Jun. 2018, pp. 760–768.
[68] Y. Saleem, M. H. Rehmani, and S. Zeadally, "Integration of cognitive radio technology with unmanned aerial vehicles: Issues, opportunities, and future research challenges," *J. Netw. Comput. Appl.*, vol. 50, p. 1531, Apr. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1084804514002811
[69] R. Shakeri, M. A. Al-Garadi, A. Badawy, A. Mohamed, T. Khattab, A. K. Al-Ali, K. A. Harras, and M. Guizani, "Design challenges of multi-UAV systems in cyber-physical applications: A comprehensive survey and future directions," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3340–3385, 4th Quart., 2019.
[70] H. Hellaoui, M. Bagaa, A. Chelli, and T. Taleb, "Joint sub-carrier and power allocation for efficient communication of cellular UAVs," *IEEE Trans. Wireless Commun.*, vol. 19, no. 12, pp. 8287–8302, Dec. 2020.
[71] X. Li, H. Yao, J. Wang, X. Xu, C. Jiang, and L. Hanzo, "A near-optimal UAV-aided radio coverage strategy for dense urban areas," *IEEE Trans. Veh. Technol.*, vol. 68, no. 9, pp. 9098–9109, Sep. 2019.
[72] S. Shakoor, Z. Kaleem, M. I. Baig, O. Chughtai, T. Q. Duong, and L. D. Nguyen, "Role of UAVs in public safety communications: Energy efficiency perspective," *IEEE Access*, vol. 7, pp. 140665–140679, 2019.
[73] O. Bekkouche, K. Samdanis, M. Bagaa, and T. Taleb, "A service-based architecture for enabling UAV enhanced network services," *IEEE Netw.*, vol. 34, no. 4, pp. 328–335, Jul./Aug. 2020.
[74] A. Fotouhi, H. Qiang, M. Ding, M. Hassan, L. G. Giordano, J. Yuan, and A. Garcia-Rodriguez, "Survey on UAV cellular communications: Practical aspects, standardization advancements, regulation, and security challenges," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3417–3442, 4th Quart., 2019.
[75] D. He, S. Chan, and M. Guizani, "Drone-assisted public safety networks: The security aspect," *IEEE Commun. Mag.*, vol. 55, no. 8, pp. 218–223, Aug. 2017.
[76] B. Yang, T. Taleb, Z. Wu, and L. Ma, "Spectrum sharing for secrecy performance enhancement in D2D-enabled UAV networks," *IEEE Netw.*, vol. 34, no. 6, pp. 156–163, Nov./Dec. 2020.
[77] Y. Zeng, Q. Wu, and R. Zhang, "Accessing from the sky: A tutorial on UAV communications for 5G and beyond," *Proc. IEEE*, vol. 107, no. 12, pp. 2327–2375, Dec. 2019.
[78] A. A. R. Alsaeedy and E. K. P. Chong, "5G and UAVs for mission-critical communications: Swift network recovery for search- and-rescue operations," *Mobile Netw. Appl.*, vol. 25, no. 5, pp. 2063–2081, Oct. 2020.
[79] C. Luo, W. Miao, H. Ullah, S. McClean, G. Parr, and G. Min, "Unmanned aerial vehicles for disaster management," in *Geological Disaster Monitoring Based on Sensor Networks*. Singapore: Springer Verlag, 2017.
[80] Iridium. (2021). *Iridium Extreme PTT*. [Online]. Available: https://www.iridium.com/products/iridium-extreme-ptt/
[81] Inmarsat Government. (2021). *Satellite Solutions for FirstNet*. [Online]. Available: https://www.inmarsatgov.com/firstnet/learn-about-our-solutions/

[82] (2021). *Cospas-Sarsat System, Cospas-Sarsat*. [Online]. Available: https://www.cospas-sarsat.int/en/system-overview/cospas-sarsat-system
[83] eSOLIA. (2021). *Japan J-ALERT Emergency Broadcast System*. [Online]. Available: https://esolia.com/japan-emergency-broadcast-system-j-alert/
[84] I. D. Portillo, B. G. Cameron, and E. F. Crawley, ''A technical comparison of three low Earth orbit satellite constellation systems to provide global broadband,'' *Acta Astronautica*, vol. 159, pp. 123–135, Jun. 2019.
[85] I. Leyva-Mayorga, B. Soret, M. Roper, D. Wubben, B. Matthiesen, A. Dekorsy, and P. Popovski, ''LEO small-satellite constellations for 5G and beyond-5G communications,'' *IEEE Access*, vol. 8, pp. 184955–184964, 2020.
[86] *Study on New Radio (NR) to Support Non-Terrestrial Networks (Release 15)*, document TR 38.811 V15.4.0, 3GPP, Sep. 2020.
[87] *Study on Using Satellite Access in 5G; Stage 1 (Release 16)*, document TR 22.822 V16.0.0, 3GPP, Jun. 2018.
[88] *Service Requirements for the 5G System; Stage 1 (Release 17)*, document TR 22.261 V17.5.0, 3GPP, Dec. 2020.
[89] *Study on Architecture Aspects for Using Satellite Access in 5G (Release 17)*, document TR 23.737 V17.1.0, 3GPP, Jul. 2020.
[90] F. Völk, K. Liolis, M. Corici, J. Cahill, R. T. Schwarz, T. Schlichter, E. Troudt, and A. Knopp, ''Satellite integration into 5G: Accent on first over-the-air tests of an edge node concept with integrated satellite backhaul,'' *Future Internet*, vol. 11, no. 9, p. 193, Sep. 2019.
[91] C. Politis, K. Liolis, M. Corici, E. Troudt, Z. Szabo, and J. Cahill, ''Design of moving experimentation facility to showcase satellite integration into 5G,'' in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Valencia, Spain, Jun. 2019, pp. 177–181.
[92] J. Kim, G. Casati, A. Pietrabissa, A. Giuseppi, E. Calvanese Strinati, N. Cassiau, G. Noh, H. Chung, I. Kim, M. Thary, J.-M. Houssin, F. Pigni, S. Colombero, P. Dal Zotto, L. Raschkowski, and S. Jaeckel, ''5G-ALLSTAR: An integrated satellite-cellular system for 5G and beyond,'' in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, Seoul, South Korea, Apr. 2020, pp. 1–6.
[93] K. Liolis, J. Cahill, E. Higgins, M. Corici, E. Troudt, and P. Sutton, ''Over-the-air demonstration of satellite integration with 5G core network and multi-access edge computing use case,'' in *Proc. IEEE 2nd 5G World Forum (5GWF)*, Dresden, Germany, Sep. 2019, pp. 1–5.
[94] G. Gardikis, N. Papadakis, A. Perentos, M. Fotiou, A. Phinikarides, M. Georgiades, L. Ottavj, M. Diarra, T. Masson, A. J. Morgado, S. Mumtaz, J. S. D. Puga, C. E. Palau, C. Skiadasn, H. Koumaras, and M. A. Kourtis, ''The 5GENESIS testing facility as an enabler for integrated satellite/terrestrial 5G experimentation,'' in *Proc. IEEE Wireless Commun. Netw. Conf. Workshop (WCNCW)*, Marrakech, Morocco, Apr. 2019, pp. 1–6.
[95] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis, ''Satellite communications in the new space era: A survey and future challenges,'' *IEEE Commun. Surveys Tuts.*, vol. 23, no. 1, pp. 70–109, 1st Quart., 2021.
[96] M. Bacco, L. Boero, P. Cassara, M. Colucci, A. Gotta, M. Marchese, and F. Patrone, ''IoT applications and services in space information networks,'' *IEEE Wireless Commun.*, vol. 26, no. 2, pp. 31–37, Apr. 2019.
[97] F. Rinaldi, H.-L. Maattanen, J. Torsner, S. Pizzi, S. Andreev, A. Iera, Y. Koucheryavy, and G. Araniti, ''Non-terrestrial networks in 5G & beyond: A survey,'' *IEEE Access*, vol. 8, pp. 165178–165200, 2020.
[98] S. Chen, S. Sun, and S. Kang, ''System integration of terrestrial mobile communication and satellite communication—The trends, challenges and key technologies in B5G and 6G,'' *China Commun.*, vol. 17, no. 12, pp. 156–171, Dec. 2020.
[99] G. Gur, ''Spectrum sharing and content-centric operation for 5G hybrid satellite networks: Prospects and challenges for space-terrestrial system integration,'' *IEEE Veh. Technol. Mag.*, vol. 14, no. 4, pp. 38–48, Dec. 2019.
[100] M. Giordani and M. Zorzi, ''Satellite communication at millimeter waves: A key enabler of the 6G era,'' in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Big Island, HI, USA, Feb. 2020, pp. 383–388.
[101] Y. Shi, Y. Cao, J. Liu, and N. Kato, ''A cross-domain SDN architecture for multi-layered space-terrestrial integrated networks,'' *IEEE Netw.*, vol. 33, no. 1, pp. 29–35, Jan./Feb. 2019.
[102] A. Papa, T. D. Cola, P. Vizarreta, M. He, C. Mas-Machuca, and W. Kellerer, ''Design and evaluation of reconfigurable SDN LEO constellations,'' *IEEE Trans. Netw. Service Manage.*, vol. 17, no. 3, pp. 1432–1445, Sep. 2020.
[103] 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.*, vol. 22, no. 1, pp. 196–248, 1st Quart., 2020.
[104] Z. Zhang, W. Zhang, and F.-H. Tseng, ''Satellite mobile edge computing: Improving QoS of high-speed satellite-terrestrial networks using edge computing techniques,'' *IEEE Netw.*, vol. 33, no. 1, pp. 70–76, Jan. 2019.
[105] J. Zhang, X. Zhang, P. Wang, L. Liu, and Y. Wang, ''Double-edge intelligent integrated satellite terrestrial networks,'' *China Commun.*, vol. 17, no. 9, pp. 128–146, Sep. 2020.
[106] I. F. Akyildiz and A. Kak, ''The Internet of space things/CubeSats: A ubiquitous cyber-physical system for the connected world,'' *Comput. Netw.*, vol. 150, pp. 134–149, Feb. 2019.
[107] M. Marchese, A. Moheddine, and F. Patrone, ''UAV and satellite employment for the Internet of Things use case,'' in *Proc. IEEE Aerosp. Conf.*, Big Sky, MT, USA, Mar. 2020, pp. 1–8.
[108] L. Tian, N. Huot, O. Chef, and J. Famaey, ''Self-organising LEO small satellite constellation for 5G MTC and IoT applications,'' in *Proc. 11th Int. Conf. Netw. Future (NoF)*, Bordeaux, France, Oct. 2020, pp. 100–104.
[109] J. Chu, X. Chen, Q. Qi, C. Zhong, H. Lin, and Z. Zhang, ''On the design of B5G multi-beam LEO satellite Internet of Things,'' in *Proc. IEEE 91st Veh. Technol. Conf. (VTC-Spring)*, Antwerp, Belgium, May 2020, pp. 1–6.
[110] R. Solozabal, A. Sanchoyerto, E. Atxutegi, B. Blanco, J. O. Fajardo, and F. Liberal, ''Exploitation of mobile edge computing in 5G distributed mission-critical push-to-talk service deployment,'' *IEEE Access*, vol. 6, pp. 37665–37675, 2018.
[111] 5G Americas. (Jan. 2020). *The 5G Evolution: 3GPP Releases 16–17*. [Online]. Available: https://www.5gamericas.org/wp-content/uploads/2020/01/5G-Evolution-3GPP-R16-R17-FINAL.pdf
[112] *Study on Mission Critical Services Support Over 5G System (Release 16)*, document TS 23.783 V0.12.0 (2020-09), 3GPP, Sep. 2020.
[113] T. Salam, W. U. Rehman, and X. Tao, ''Data aggregation in massive machine type communication: Challenges and solutions,'' *IEEE Access*, vol. 7, pp. 41921–41946, 2019.
[114] N. A. Mohammed, A. M. Mansoor, and R. B. Ahmad, ''Mission-critical machine-type communication: An overview and perspectives towards 5G,'' *IEEE Access*, vol. 7, pp. 127198–127216, 2019.
[115] G. A. Akpakwu, B. J. Silva, G. P. Hancke, and A. M. Abu-Mahfouz, ''A survey on 5G networks for the Internet of Things: Communication technologies and challenges,'' *IEEE Access*, vol. 6, pp. 3619–3647, 2018.
[116] A. Orsino, A. Ometov, G. Fodor, D. Moltchanov, L. Militano, S. Andreev, O. N. C. Yilmaz, T. Tirronen, J. Torsner, G. Araniti, A. Iera, M. Dohler, and Y. Koucheryavy, ''Effects of heterogeneous mobility on D2D- and drone-assisted mission-critical MTC in 5G,'' *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 79–87, Feb. 2017.
[117] V. Petrov, M. A. Lema, M. Gapeyenko, K. Antonakoglou, D. Moltchanov, F. Sardis, A. Samuylov, S. Andreev, Y. Koucheryavy, and M. Dohler, ''Achieving end-to-end reliability of mission-critical traffic in softwarized 5G networks,'' *IEEE J. Sel. Areas Commun.*, vol. 36, no. 3, pp. 485–501, Mar. 2018.
[118] ''Network function virtualization-introductory white paper,'' in *Proc. ETSI, SDN Openfow World Congr.*, Darmstadt, Germany, 2012, pp. 1–16. [Online]. Available: https://portal.etsi.org/NFV/NFV_White_Paper.pdf
[119] *Network Functions Virtualisation (NFV); NFV Security; Security and Trust Guidance*, document GS NFV-SEC 003 V1.1.1, ETSI, Dec. 2014.
[120] J. Ordonez-Lucena, P. Ameigeiras, D. Lopez, J. J. Ramos-Munoz, J. Lorca, and J. Folgueira, ''Network slicing for 5G with SDN/NFV: Concepts, architectures, and challenges,'' *IEEE Commun. Mag.*, vol. 55, no. 5, pp. 80–87, May 2017.
[121] *System Architecture for the 5G System (5GS); Stage 2 (Release 16)*, document TS 23.501 V16.6.0, 3GPP, Sep. 2020.
[122] L. U. Khan, I. Yaqoob, N. H. Tran, Z. Han, and C. S. Hong, ''Network slicing: Recent advances, taxonomy, requirements, and open research challenges,'' *IEEE Access*, vol. 8, pp. 36009–36028, 2020.
[123] Y. Li, Y. Zhao, J. Li, J. Zhang, X. Yu, and J. Zhang, ''Side channel attack-aware resource allocation for URLLC and eMBB slices in 5G RAN,'' *IEEE Access*, vol. 8, pp. 2090–2099, 2020.
[124] X. Li, C. Guo, L. Gupta, and R. Jain, ''Efficient and secure 5G core network slice provisioning based on VIKOR approach,'' *IEEE Access*, vol. 7, pp. 150517–150529, 2019.

[125] D. Schinianakis, R. Trapero, D. S. Michalopoulos, and B. G.-N. Crespo, "Security considerations in 5G networks: A slice-aware trust zone approach," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Marrakesh, Morocco, Apr. 2019, pp. 1–8.

[126] D. Sattar and A. Matrawy, "Towards secure slicing: Using slice isolation to mitigate DDoS attacks on 5G core network slices," in *Proc. IEEE Conf. Commun. Netw. Secur. (CNS)*, Washington, DC, USA, Jun. 2019, pp. 82–90.

[127] A. Rostami, "Private 5G networks for vertical industries: Deployment and operation models," in *Proc. IEEE 2nd 5G World Forum (5GWF)*, Dresden, Germany, Sep. 2019, pp. 433–439.

[128] P. Schneider, C. Mannweiler, and S. Kerboeuf, "Providing strong 5G mobile network slice isolation for highly sensitive third-party services," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Barcelona, Spain, Apr. 2018, pp. 1–6.

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

[130] *Multi-Access Edge Computing (MEC); Framework and Reference Architecture*, document ETSI GS MEC 003 V2.1.1, Etsi, Jan. 2019.

[131] S. Kekki, W. Featherstone, Y. Fang, P. Kuure, A. Li, A. Ranjan, D. Purkayastha, F. Jiangping, D. Frydman, G. Verin, and K. W. Wen, "MEC in 5G networks," ETSI, Sophia Antipolis, France, White paper 28, Jun. 2018.

[132] Ericsson. (Jan. 2017). *5G Systems: Enabling the Transformation of Industry and Society*. [Online]. Available: https://www.ericsson.com/49daeb/assets/local/reports-papers/white-papers/wp-5g-systems.pdf

[133] ETSI. *Network Functions Virtualisation (NFV)*. Accessed: Jan. 8, 2020. [Online]. Available: https://www.etsi.org/technologies/nfv

[134] *The Open Networking Foundation (ONF)*. Accessed: Sep. 2, 2020. [Online]. Available: https://www.opennetworking.org/

[135] *OpenStack*. Accessed: Sep. 2, 2020. [Online]. Available: https://www.openstack.org/

[136] *The OpenDaylight Foundation*. Accessed: Sep. 2, 2020. [Online]. Available: https://www.opendaylight.org/

[137] *The Open Platform for NFV*. Accessed: Sep. 2, 2020. [Online]. Available: https://www.opnfv.org/about

[138] *The O-RAN Alliance*. Accessed: Sep. 2, 2020. [Online]. Available: https://www.o-ran.org/

[139] GSMA Future Networks. (Oct. 2, 2019). *Common NFVI Telco TaskForce Terms of Reference*. [Online]. Available: https://www.gsma.com/futurenetworks/5g/common-nfvi-telco-taskforce-terms-of-reference/

[140] *Common Public Radio Interface*. Accessed: Sep. 2, 2020. [Online]. Available: http://www.cpri.info/

[141] The Linux Foundation. *Open Network Automation Platform*. Accessed: Sep. 2, 2020. [Online]. Available: https://www.onap.org/

[142] *Study on New Radio Access Technology: Radio Access Architecture and Interfaces (Release 14)*, document TR 38.801 V14.0.0, 3GPP, Mar. 2017.

[143] *5G Architecture Options—Full Set*, document RP-161266, Joint RAN/SA Meeting, Busan, South Korea, Jun. 2016. [Online]. Available: https://telecoms.com/wp-content/blogs.dir/1/files/2016/06/5G-architecture-options.pdf

[144] *5G Observatory Quarterly Report 6; Up to December 2019*, document 90013, IDATE Digiworld European Commission DG Communications Networks, Jan. 2020. [Online]. Available: http://5gobservatory.eu/wp-content/uploads/2020/01/90013-5G-Observatory-Quarterly-report6_v16-01-2020.pdf

[145] 5G Americas. (Feb. 2019). *5G Spectrum Vision*. [Online]. Available: https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Americas_5G_Spectrum_Vision_Whitepaper-1.pdf

[146] European Commission. (Apr. 28, 2016). *Commission Implementing Decision (EU) 2016/687 of 28 April 2016 on the Harmonisation of the 694-790 MHz Frequency Band for Terrestrial Systems Capable of Providing Wireless Broadband Electronic Communications Services and for Flexible National Use in the Union*. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.118.01.0004.01.ENG

[147] F. Pujol, C. Manero, and S. Remis. (Oct. 2019). *5G Observatory Quarterly Report 5: Up to September 2019*. IDADE DigiWorld. [Online]. Available: http://5gobservatory.eu/wp-content/uploads/2019/10/90013-5G-Observatory-Quarterly-report-5_final.pdf

[148] Global 5G. *NGPaaS: Mission Critical Push to Talk (MCPTT)*. Accessed: Sep. 10, 2020. [Online]. Available: https://www.global5g.org/ngpaas-mission-critical-push-talk-mcptt

[149] Global 5G. *SaT5G: 5G Cellular Backhauling in Rural Areas*. Accessed: Apr. 24, 2020. [Online]. Available: https://www.global5g.org/sat5g-5g-cellular-backhauling-rural-areas

[150] Global 5G. *METRO-HAUL: Network Slicing For Improving Public Safety*. Accessed: Sep. 10, 2020. [Online]. Available: http://global5g.org/metro-haul-network-slicing-improving-public-safety

[151] A. Dochhan, J. K. Fischer, B. Lent, A. Autenrieth, B. Shariati, P. W. Berenguer, and J.-P. Elbers, "Metro-haul project vertical service demo: Video surveillance real-time low-latency object tracking," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, San Diego, CA, USA, 2020, pp. 1–3.

[152] E. Lang *et al.* (Jul. 2019). *Final Evaluation and Integration, 5GXCast Deliverable D6.4, Version 2.0*. [Online]. Available: http://5g-xcast.eu/wp-content/uploads/2019/08/5G-Xcast_D6.4_v2.0_web.pdf

[153] T. Jokela, J. Kalliovaara, M. Bot, H. Kokkinen, B. Altman, C. Barjau, P. Sanders, D. Gomez-Barquero, and J. Paavola, "Multimedia public warning alert trials using eMBMS broadcast, dynamic spectrum allocation and connection bonding," *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 571–578, Jun. 2020.

[154] Global 5G. *MATILDA: 5G for Public Protection and Disaster Relief*. Accessed: Jan. 7, 2020. [Online]. Available: https://www.global5g.org/matilda-5g-public-protection-and-disaster-relief

[155] Global 5G. *5G ESSENCE: End-to-End Slicing for Mission Critical Applications*. Accessed: Jan. 7, 2020. [Online]. Available: https://www.global5g.org/5g-essence-end-end-slicing-mission-critical-applications

[156] E. Jimeno, J. Perez-Romero, I. V. Munoz, B. Blanco, A. Sanchoyerto, and J. F. Hidalgo, "5G framework for automated network adaptation in mission critical services," in *Proc. IEEE Conf. Netw. Function Virtualization Softw. Defined Netw. (NFV-SDN)*, Verona, Italy, Nov. 2018, pp. 1–5.

[157] J. Perez-Romero, I. Vila, O. Sallent, B. Blanco, A. Sanchoyerto, R. Solozabal, and F. Liberal, "Supporting mission critical services through radio access network slicing," in *Proc. Int. Conf. Inf. Commun. Technol. Disaster Manage. (ICT-DM)*, Paris, France, Dec. 2019, pp. 1–8.

[158] M. R. Spada, J. Perez-Romero, A. Sanchoyerto, R. Solozabal, M. A. Kourtis, and V. Riccobene, "Management of mission critical public safety applications: The 5G ESSENCE project," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Valencia, Spain, Jun. 2019, pp. 155–160.

[159] Q. Wang *et al.*, "Enable advanced QoS-aware network slicing in 5G networks for slice-based media use cases," *IEEE Trans. Broadcast.*, vol. 65, no. 2, pp. 444–453, Jun. 2019.

[160] T. Zahariadis, A. Voulkidis, P. Karkazis, and P. Trakadas, "Preventive maintenance of critical infrastructures using 5G networks & drones," in *Proc. 14th IEEE Int. Conf. Adv. Video Signal Based Surveill. (AVSS)*, Lecce, Italy, Sep. 2017, pp. 1–4.

[161] H. C. Leligou, T. Zahariadis, L. Sarakis, E. Tsampasis, A. Voulkidis, and T. E. Velivassaki, "Smart grid: A demanding use case for 5G technologies," in *Proc. IEEE Int. Conf. Pervas. Comput. Commun. Workshops (PerCom Workshops)*, Athens, Greece, Mar. 2018, pp. 215–220.

[162] H. Koumaras, D. Tsolkas, G. Gardikis, P. M. Gomez, V. Frascolla, D. Triantafyllopoulou, M. Emmelmann, V. Koumaras, M. L. G. Osma, D. Munaretto, E. Atxutegi, J. S. D. Puga, O. Alay, A. Brunstrom, and A. M. C. Bosneag, "5GENESIS: The genesis of a flexible 5G facility," in *Proc. IEEE 23rd Int. Workshop Comput. Aided Modeling Design Commun. Links Netw. (CAMAD)*, Barcelona, Spain, Sep. 2018, pp. 1–6.

[163] M. Gupta, R. Legouable, M. M. Rosello, M. Cecchi, J. R. Alonso, M. Lorenzo, E. Kosmatos, M. R. Boldi, and G. Carrozzo, "The 5G EVE end-to-end 5G facility for extensive trials," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, Shanghai, China, May 2019, pp. 1–5.

[164] K. Mahmood, P. Gronsund, A. Gavras, M. B. Weiss, D. Warren, C. Tranoris, A. F. Cattoni, and P. Muschamp, "Design of 5G end-to-end facility for performance evaluation and use case trials," in *Proc. IEEE 2nd 5G World Forum (5GWF)*, Dresden, Germany, Sep. 2019, pp. 341–346.

[165] 5G!Drones. *Description of 5G!Drones Use Cases*. Accessed: Jan. 7, 2020. [Online]. Available: https://5gdrones.eu/use-case-scenarios/

[166] LOCUS. *The 5G Infrastructure Public Private Partnership*. Accessed: Jan. 7, 2020. [Online]. Available: https://5g-ppp.eu/locus/

[167] PriMO-5G. *Project Outcomes*. Accessed: Jan. 7, 2020. [Online]. Available: https://primo-5g.eu/project-outcomes/use-cases/

[168] K. W. Sung, S. Sharma, G. Destino, Y. Deng, T. Mahmoodi, M. Ullmann, A. Nahler, Y. Kyung, S. Kim, S. Seo, S.-L. Kim, E. Mutafungwa, R. Jantti, M. Choi, J. Jeon, D. Kim, J. Kim, J. Costa-Requena, and A. Nordlow, "PriMO-5G: Making firefighting smarter with immersive videos through 5G," in *Proc. IEEE 2nd 5G World Forum (5GWF)*, Dresden, Germany, Sep. 2019, pp. 280–285.

[169] *Federation for Fire Plus (Fed4FIRE+)*. Accessed: Sep. 10, 2020. [Online]. Available: https://www.fed4fire.eu/
[170] *OneLab*. Accessed: Apr. 24, 2020. [Online]. Available: https://onelab.eu/services
[171] GENI. *GENI Maps*. Accessed: Sep. 11, 2020. [Online]. Available: https://www.geni.net/about-geni/geni-maps/
[172] 5Barcelona. *Labs*. Accessed: Sep. 11, 2020. [Online]. Available: https://5gbarcelona.org/en-labs/
[173] V. Marojevic, S. Kikamaze, R. Nealy, and C. Dietrich, "5G-CORNET: Platform as a service," in *Proc. IEEE 5G World Forum (5GWF)*, Silicon Valley, CA, USA, Jul. 2018, pp. 6–9.
[174] E. Coronado, S. N. Khan, and R. Riggio, "5G-EmPOWER: A software-defined networking platform for 5G radio access networks," *IEEE Trans. Netw. Service Manage.*, vol. 16, no. 2, pp. 715–728, Jun. 2019.
[175] A. S. Khatouni, M. Mellia, M. A. Marsan, S. Alfredsson, A. Lutu, J. Karlsson, A. Brunstrom, O. Alay, C. Midoglu, and V. Mancuso, "Speedtest-like measurements in 3G/4G networks: The MONROE experience," in *Proc. 29th Int. Teletraffic Congr. (ITC)*, Sep. 2017, Art. no. 169177.
[176] *AERPAW*. Accessed: Dec. 10, 2020. [Online]. Available: https://aerpaw.org/
[177] F. Silva, P. Rosa, H. Hrasnica, and A. Gravas, "5GINFIRE: Enabling an NFV based experimentation of vertical industries in the 5G context," in *Proc. Anais do X Workshop de Pesquisa Experim. da Internet do Futuro (WPEIF)*, May 2019, pp. 64–69. [Online]. Available: https://sol.sbc.org.br/index.php/wpeif/article/view/7700.
[178] European 5G Observatory. *Spectrum Ranges Used in 5G Trials*. Accessed: Dec. 20, 2019. [Online]. Available: https://5gobservatory.eu/5g-spectrum/spectrum-ranges-used-A. Lutuin-5g-trials/
[179] K. Clement *et al.*, *D1.1—Use Case Specifications and Requirements, 5G for Drone-based Vertical Applications (5G!Drones)*, document ID D1.1, Version 1.0, Dec. 2019. [Online]. Available: https://5gdrones.eu/wp-content/uploads/2020/05/D1.1-Use-case-specifications-and-requirements-v1.0.pdf
[180] M. Rugelj, M. Volk, U. Sedlar, J. Sterle, and A. Kos, "A novel user satisfaction prediction model for future network provisioning," *Telecommun. Syst.*, vol. 56, no. 3, pp. 417–425, Jul. 2014.
[181] *ETSI Kepler*. Accessed: Jan. 29, 2021. [Online]. Available: https://docbox.etsi.org/STQ/Open/Kepler
[182] 5G PPP. *5G-LOGINNOV: 5G Creating Opportunities for Logistics Supply Chain Innovation*. Accessed: Nov. 9, 2020. [Online]. Available: https://5g-ppp.eu/5g-loginnov/
[183] 5G PPP. *Int5Gent: Integrating 5G Enabling Technologies in a Holistic Service to Physical Layer 5G System Platform*. Accessed: Jan. 25, 2021. [Online]. Available: https://5g-ppp.eu/int5gent/
[184] 5G PPP. *5G-INDUCE: Open Cooperative 5G Experimentation Platforms for the Industrial Sector NetApps*. Accessed: Jan. 20, 2021. [Online]. Available: https://5g-ppp.eu/5g-induce/
[185] 5G PPP. *5GASP: 5G Application & Services Experimentation and Certification Platform*. Accessed: Jan. 29, 2021. [Online]. Available: https://5g-ppp.eu/5gasp/
[186] J. Sterle, U. Sedlar, M. Rugelj, A. Kos, and M. Volk, "Application-driven OAM framework for heterogeneous IoT environments," *Int. J. Distrib. Sensor Netw.*, vol. 2016, pp. 1–9, Jan. 2016.

MOJCA VOLK (Member, IEEE) received the B.Sc. and Ph.D. degrees in telecommunications from the University of Ljubljana, Slovenia, in 2004 and 2010, respectively.

She has been an Assistant Professor with the Laboratory for Telecommunications, Faculty of Electrical Engineering, University of Ljubljana, since 2016, and as a Senior Researcher and a Scientific Associate, from 2010. Her main areas of work are research and development and innovative infrastructure and business model development and prototyping in communication networks, services and applications, with a specific focus on 5G, the IoT, and cybersecurity in applied areas of technology development, prototyping and trials for security, critical infrastructures, and public protection and disaster relief (PPDR). She holds various national and U.S. patents in the field of communications systems (US 8483059; US 8260357; US 8213942; SI 24374; SI 24373). She has an established track record of research and development and production-grade projects in communications, safety and digital health sectors, including 5G safety, a recent national project on 5G PPDR supported by the European Union. She is a member of the EuCNC Steering Committee, and the IEEE and IEICE societies.

JANEZ STERLE received the M.Sc. and Ph.D. degrees in telecommunications from the University of Ljubljana, Slovenia, in 2012 and 2020, respectively.

He is currently a Co-Founder and the CEO of the Internet Institute. His main area of work concerns network design, planning, service management, testing and implementation in production networks for SDN, IPv6, QoS, and QoE, BGP peering and multicast services, wireless/mobile LTE/4G and 5G systems with SON support, NATO enabled tactical telecommunication system for Armed Forces, and test, measurement, and verification of state-of-the-art protocols and technologies. He holds Cisco certificates and various U.S. patents (US 8,885,511; US 8,699,341; US 8,483,059; US 8,472,334) in the field of mobile systems. He has an established track record of research and development and production-grade projects in communications, safety, and security sectors, including EC's H2020 projects 5GASP, Int5GENT, and 5G-LOGINNOV on the topic of 5G, and cooperates closely with the respective industries, practitioners, regulatory, and legislative bodies on strategic and technical levels (NRA consultancy in the areas of mobile technologies and PPDR, National 5G PPDR initiative member, strategic architecture and solution consultancy for vendors and telcos).