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A review on 6G for space-air-ground integrated network: Key enablers, open challenges, and future direction

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ABSTRACT

Space-air-ground integrated network (SAGIN) is still in nascent stage of design. Despite of several key insights onto the augmentation of terrestrial, aerial and satellite systems, SAGIN ecosystem is yet not mature enough to survive into the realty. More agility, robustness, flexibility, and scalability are required to conform to optimum standard of abstraction. As 5G is at the verge of technology domain, this is high time when we should keep our focus on the next-generation advanced 6G technology to cater the issues of existing SAGIN ecosystem. In this article, we envisage a clear vision on how 6G can improve the current scenario of the SAGIN infrastructure will some value-added services. We firstly, present basics behind the SAGIN and discuss key concepts of the 6G. Secondly, we review key technologies related to the unmanned aerial vehicle (UAV) and satellite-based communications. Thirdly, we describe key enablers of the 6G-enbled SAGIN i.e., 6G-SAGIN. Fourthly, we present the UAV-as-a-service to augment the comprehension of 6G-SAGIN. Fifthly, we extend the orientation of 6G-SAGIN toward elemental design aspects. Finally, we depict key open research challenges and prescribe some future direction.

Contents

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1. Introduction

With the ever-increasing number of smart devices and exponential growth in network traffic, huge and worldwide connectivity has come up as a significant technological requirement (6G Flagship, 2020). Moreover, a large range of applications with the distinct necessities should be accommodated in the current context. Especially, the sophisticated networking services need to be incorporated into the futuristic use cases such as, the smart transportation, remote connectivity, maritime surveillance, intergalactic communication, smart city, and disaster rescue (Ray et al., 2021). With these overwhelming service aware demands, terrestrial networks alone cannot provide the huge traffic solutions in an efficient manner. It is thus envisaged that terrestrial networks along with the space and airborne communication infrastructures can act together for facilitation of delay mitigating network services (Ray, 2021). We can perceive that low and medium range satellite constellation can be augmented with the unmanned aerial vehicles (UAVs) or drones can leverage efficient services anywhere considering the three-dimensional (3D) network assimilation. In this context, we can foresee the opportunity of the SAGINs to provision a fully functional pervasive communication, computation, and caching capabilities, to attain high network data rate, minimal delay, and high reliability (Saad et al.). Most of such applications are related to national security and monitoring of disastrous place and events. One can easily think of going ahead with technology enablers like internet of things (IoT) to extend the coverage of sensing and actuator tasks in miniature level. Edge and cloud conglomeration have brought another level of delay mitigating aspect that can be augmented with the UAVs (Tang et al., 2020). With the involvement of IoT into the smart city and industry 4.0, importance of UAVs is gradually increasing. Not only for a service provider but also a service mitigator node i.e., network element. A need of amalgamating UAVs with rest of the network elements has arisen to further enhance and enrich the network coverage and user equipment servicing. We expect that the world shall face a new genre of ground breaking and remarkable networking alternations with increased speed, capacity, and service-aware behavior entitlement (Letaief et al., 2019). It is investigated that 5G is better than existing cellular technologies in numerous ways, but it may not be enough to justify the rigorous demand of SAGIN-based service spectrum. Especially, the backhaul and fronthaul integration, mobility management, extended security, user privacy, ultra-low latency and extreme reliability. One should think of a multidimensional SAGIN-aware design perspective for mitigation of ultra-low edge and fully-cognitive network invasion (De Lima et al., 2021).

6G is can be envisaged to formulate the necessity of the SAGIN-based user service orientation while inculcating UAVs, ground station and satellite communications to the next higher level. 6G aims at superseding the prospective convention of 5G in following terms, such as peak data rate with >1 Tbps, extremely mobility support with >1200 km/h, and end-to-end reliability with 99.99999%. Frequency range and bandwidth usage pattern for 6G is quite impressive over 5G. It may use sub-6 GHz, mmWave (mobile access), non-radio frequency, visible light communication, and higher than 300 GHz bands (Nawaz et al., 2019). It can leverage innovative cell-free smart surface architecture with high frequency support modules. On top of it, 6G would provide temporary hotspots and tine THz cells with the help of UAVs. Haptic communication and connection density shall extend beyond $10x10^6/km^2$. Complete artificial intelligence (AI) support shall enable SAGIN related tasks far from easy and manageable. Satellite bandwidth utilization and seamless spectral efficiency are perceived to have an overwhelming impact on the SAGIN ecosystem. Thus, we can comprehend those multi-dimensional aspects of 6G can highly enrich existing SAGIN infrastructure to the on-demand value added extension. Ubiquitous 3D coverage (space, aerial, terrestrial and undersea network) is the key of proposed 6G technology. With inherent distributed AI, real-time intelligent edge and cognitive radio would harness the intelligent connection of the SAGIN framework (Viswanathan and Mogensen, 2020). Further, enhanced stratification while covering a list of network point of views would inculcate the integration of SAGIN with 6G. New types of dynamic spectrum utilization along with the content driven routing schemes are best suitable for the SAGIN scenario.

1.1. Motivation

Numerous services and applications have dissimilar quality of service (QoS) necessities e.g., (i) latency, (ii) security, (iii) reliability, (iv) throughput, and (v) user experience (Gui et al., 2020). To accommodate such diverse services, SAGINs require to feat the corresponding recompences of individual segment considering (i) flexibility, (ii) availability, (iii) coverage, and (iv) accessibility. We know that each slice of the requirements has its own pros and cons. For example, satellite networks can leverage greater network coverage with higher network latency. We can also take the terrestrial networks which can accomplish minimal delay but with the possibility of envisaged notion of the service coverage (Chen et al., 2020). Moreover, the overall cost of deployment in attaining optimal utilization of the caching and computing resources are certainly increase along with the ever-growing magnitude. Thus, completing with the required service-oriented networking for the SAGIN is essentially imperative to encounter the necessities of dissimilar services competently, taking into account the advantages and disadvantages of each segment. However, it is a very thought-provoking task due to the following reasons such as, (i) effectual amalgamation of dissimilar segments is hard, since the scale and intricacy of the system, (ii) multi-dimensional heterogeneity in resources and diverse QOS necessities pose prodigious challenges to large network management and its operation, (iii) the envisaged SAGIN systems should be adaptive to the high dimensional segments of application specific environments, and (iv) constant monitoring of the spatial–temporal dynamics of the SAGIN systems covering topology, network traffic loads, and heterogeneous resource availability, due to extensive mobility and time-varying context.

1.2. Contributions

In this article, we envisage a vivid vision on the prospects of 6G for the upliftment of the SAGIN orientation. Our contributions to this work can be summarized as follows:

- To devise the basics behind SAGIN and 6G to understand the relative correlation
- To showcase key satellite and mobile communication technologies that can upgrade the future of the SAGIN
- Depiction of key enablers behind the vision of 6G-enabled SAGIN
- Inspection of UAV-as-a-service notion for suitability into the 6G-SAGIN
- Investigation of element-wise design aspects of the 6G-SAGIN
- Devising key open research challenges and possible future direction towards realization of 6G-SAGIN
- Potential applications and their limitations

1.3. Uniqueness

The comparison between related works demonstrates that none of the articles focuses on the aspect of 6G-enabled SAGIN. Further, we contribute in many verticals to counter the SAGIN on top of 6G technology. We present a number of well-structured key enablers namely, physical layer, task scheduling, task offloading, super IoT, stringent authentication, network fixed point, service function chaining, mobile crowd sensing, and mobility management. We also discuss on the UAV-as-a-Service paradigm to improve the 6G-SAGIN ecosystem to alleviate the holistic network service provisioning. We incorporate the elementary system design aspect which advocates the significance of following: a) ground center design, (b) aerial center design, (c) satellite center design, (d) communication and control center design for the design and implementation of 6G-SAGIN. We cover a number of sub-fields of interest in this study that includes cognitive spectrum design, routing in the air, under-sea communication, dew computing, HetNet design, on-the-fly data center, cross-layer performance, intelligent handoff, and role of network operators. Most significantly, this work presents a clear vision and pathways to achieve the full-fledged SAGIN ecosystem with help of 6G-based technologies in near future.

The rest of the paper is organized as follows. Section II presents background in the SAGIN and 6G. Section III discusses satellite and mobile technologies. Section IV deals with the key enablers of 6G-SAGIN. Section V shows how UAV can be used as a service ingredient. Section VI discusses about the prospective element-wise design schemes in the 6G-SAGIN ecosystem. Section VII depict crucial open research challenges that would hinder the vision of 6G-enabled SAGIN and their possible future road map. Table 1 presents abbreviations used in this paper.

2. Background of SAGIN and 6G

2.1. Basics on SAGIN

The vision of SAGIN for 6G is a purely conceptual approach with a list of justifiable arguments. However, such a holistic integrated network has become a much-needed factor in upcoming advanced technology improvement (Elmeadawy and Shubair, 2019). As investigated till now, we find few key aspects behind the SAGIN. Overall, the SAGIN is an integrated network framework that consists of space, aerial, and ground network elements into it. For example, satellites and space stations are expected to take vital part in future communication systems. Aerial networks are gradually getting popular after the disruption of the employment of drones of various forms and factors. For instance, wing-based or rotor centric drones are getting used in multiple industrial, mission critical, and emergency applications. Miniaturized balloons and fixed-wing high altitude flying machines can assist in creation of an effective aerial ad-hoc network on-the-fly. Ground networks may be further extended with invasion of the undersea network against existing standard platforms.

2.1.1. Satellites

It is highly expected that various geostationary, medium earth orbit, and low earth orbit satellites shall use free-space optical communication signals to interact with each other and the aerial layer of the network sometimes (Wild et al., 2021). With the advent of the forthcoming 6G network, futuristic SAGIN would imply the reuse of frequency bandwidth along with multiple spot beams featuring deployments. Improved radio access networking tools can be associated with the satellites to empower those to serve as spatial data centers. Instead of just using them as generic data centers, core networking capabilities could be introduced into themselves. This will help to extend existing satellite communication (SatCom) to penetrate deep space as well as aerial and ground networks simultaneously. Microwave, and mmWave communications seem to be highly devised in the SAGIN centric use cases. Multi-layer satellite communication would improve the availability of the SatCom-based services, thus resilience to the SAGIN. However, the problem with the pointing, acquisition and tracking (PAT) into the aerial network should be resolved beforehand. SatCom linkages must be self-aware, robust and highly reliable in nature so that negative aspects of PAT could be largely diminished.

2.1.2. Aerial

Mainly high-altitude platforms (HAPs) shall take the lead role in the creation of the middle layer of the SAGIN i.e., aerial network. It should be investigated to see how HAPs can seamlessly work in continuous collaboration with the low-altitude platforms (LAPs) such as generic drones. High end gas

balloons and fixed-wing HAPs could be placed on the higher end of the aerial network. One can also think of using airships to be utilized as a key HAP enabler in this regard. Importance should be to employ broadband wireless access points into the HAPs and LAPs whenever required. Besides, a novel flying ad-hoc network (FANET) framework could be designed with the help of such aerial elements. Hierarchical sub-data center (SDC) designing can be very useful in accordance with the FANET and drone-aware communication systems (Saad et al., 2020). This would provide the end users and the requesting APIs to get instantaneous access over the data in real-time fashion. Much attention should be given to the energy efficiency, battery designing, payload distribution and SDC servicing aspects.

2.1.3. Ground

Ground communication (GCom) system relies over the WiMAX, wireless local area network (WLAN), 2G, 3G, 4G, 5G and prospective 6G technology. MEC and ultra-dense network (UDN) collaboratively ascertain efficient task execution in the SAGIN platform. Device-to-device (D2D) connectivity and peer-to-peer networking are the basis of GCom. Furthermore, the user plane and control plane assist in the network function virtualization of GCom. Cloud platforms and traditional ground stations interact with the user

Table 1
Abbreviations used in this work.

Abbreviations	Full Form	Abbreviations	Full Form
6G	Sixth-generation communication technology	MMIU	Micro inertial unit
A2A	Air-to-air	mmWave	Millimeter wave
A2G	Air-to-ground	MSS	Mobile satellite service
APT	Acquisition pointing tracking	MSS	Mobile station
CCC	Caching, computing and communication	MVCC	Multi-version concurrency control
CCSDS	Consultative committee for space data systems	NEN	Near earth network
CDU	Command decoding unit	NFV	Network function virtualization
CLCW	Command link control words	OBC	On-board computer
cmWave	Centimeter wave	OFDM	Orthogonal frequency division multiplexing
CN	Core network	OPASC	Optical PAyload for space communication
CoMP	Coordinated multiple point	OSDL	Optical satellite data link
CP	Cyclic prefix	P2MP	Point-to-multi-point
CR	Cognitive radio	PHY	Physical layer
CRAN	Cloud radio access network	PISLIKR	Position and ISL information knowledge repository
CSTS	Cross support transfer service	PTMP	Parallel transmission network protocol
D2D	Device-to-Device	RAN	Radio access network
DSOC	Deep space optical communication	RAT	Radio access technology
DSSS	Direct sequence spread spectrum	ROT	Redundant, obsolete and trivial
DTN	Delay tolerant network	S2E	Space-to-earth
DVB	Digital video broadcasting	S2G	Space-to-ground
E2E	Earth-to-earth	S2S	Space-to-space
eeMBB	Extremely enhanced mobile broadband	SAGIN	Space-air-ground integrated network
EHF	Extremely high frequency	SatCom	Satellite Communication
eRLLC	Extremely reliable low-latency communication	SDC	Sub data center
FANET	Flying ad-hoc network	SDN	Software defined network
FCR	Full cognitive radio	SFC	Service function chaining
FSO	Free space optics	SHF	Super high frequency
FSS	Fixed satellite service	SIA	Satellite internet access
G2SM	Ground-to-submarine	SLE	Space link extension
GCom	Ground communication	SOE	Sequence of events
GEO	Geostationary earth orbit	SON	Self-optimizing network
GN	Ground network	S-RAN	Satellite radio access network
gNB	gNodeB	TDRSS	Tracking data and relay service
HAP	High-altitude platform	TM/TC	Telemetry and tele-command
HARQ	Hybrid automatic repeat request	U2G	UAV-to-ground
HetNet	Heterogeneous network	U2S	UAV-to-space
HGHR	Hybrid time–space hierarchical routing	U2U	UAV-to-UAV
IoT	Internet of things	UAV	Unmanned aerial vehicle
KPI	Key performance indicator	UAVaaS	UAV-as-a-service
LAP	Low-altitude platform	UAVWN	UAV-based wireless network
LEO	Low earth orbit	UDN	Ultra-dense network
LoS	Line-of-sight	UE	User equipment
MAC	Media access control	UHF	Ultra-high frequency
MAL	Message abstraction layer	umMTC	Ultra-massive machine type communication
MBMG	Multi-beam multi-gateway	USLP	Universal space link protocol
MEO	Medium earth orbit	VLC	Visible light communication
MILP	Mixed integer linear program	VNF	Virtual network function

equipment via conventional TCP/IP communication suite. Internet of Things (IoT)-based sensors, actuators and networking device pools are simultaneously getting associated with the GCom to improve SAGIN activity. Non-orthogonal and orthogonal multiple access schemes are used heavily to enable the GCom performance (Sodnik et al., 2017). Side by side, cognitive spectrum utilization, joint interference and resource management services are provisioned herein. Significant efforts are made to carry out user equipment handover flawlessly in the GCom periphery (Giordani et al., 2020). GCom also plays a vital role to establish a stringent service abstraction layer to the aerial and satellite layers while involving the delay-tolerant routing scheme.

2.2. Vision on the 6G-SAGIN

6G is envisaged to supersede existing generations of network capabilities with better order of quality services. We can expect that 6G will leverage super-flexible and great performance in coming days. Starting from 1981 till date, the world has seen a gradual evolution of mobile and communication technologies. Beginning with 1G, 2G, and 3G, currently we are enjoying various communication-centric benefits from the 4G (Moon et al., 2020). 5G is at the verge of deployment. It is assumed that by the end of 2022 the world will start experiencing 5G. With such growth of communication technologies, data transmission rate is significantly increased. During 1G, we used only 2 Kbps of data rate which got increased to 64 Kbps in 2G, 8 Mbps at 3G, 50 Mbps at 4G and expected 10 Gbps during 5G. 6G shall provide near about 100 Tbps with the actual implementation. Thus, the frequency spectrum has seamlessly increased since 1G. With just a simple set of analog tools, 5G shall experience around 30–300 GHz bandwidth. 6G shall supersede this and go beyond GHz range. On the accessories side, the IoT is being used as a smart enabler of device-to-device communication presently with 4G. We expect that 6G shall incorporate future radio access technology, OFDM-cmW, OFDM-mmWave, THz communication, ultra URLLC and seamless integration of the SAGIN-based communication and enabling technologies. Instead of depending solely on the narrow band as in earlier generations, 6G is envisaged to face terrestrial wide band coverage on top of regular broadband, ultra-broad band, and wireless WWW technologies (Piran and Suh, 2019).

We expect that 6G shall empower numerous key performance indicators (KPI) such as, speed, reliability, low-cost, capacity, connectivity, low-latency, availability, coverage, cognition, sensing, trust, and security. Thus, 6G would allow the users and network service providers to work closely for mutual benefit of deployable

Table 2
Comparison of spectrum bands for 6G.

Band	0.3–30 GHz	3–30 GHz	30–300 GHz	0.3–3 THz	3–30 THz
Dominant Propagation Scheme	LOS, Scattering, Penetration, Reflection, Diffraction	LOS, Scattering, Diffraction, Reflection	LOS, Reflection	LOS, Reflection	LOS, Reflection
Link Distance Support	10000 m	1000 m	100 m	<10 m	<1m
Wavelength	100–10 cm	10–1 cm	10–1 mm	1000–100 μm	100–10 μm
Dominant Attenuation Factor	Free Space Loss	Free Space Loss, Transmission Loss High at Upper Band	Free Space Loss, Molecular Absorption, O_2 @ 60 GHz, H_2O @ >24 GHz	Free Space Loss, Molecular Absorption, H_2O @ >30 GHz	Free Space Loss, Molecular Absorption, H_2O @ >30 GHz
Transmission Power Limiting Factor	Regulation	Regulation	Technology	Technology	Technology
System Bandwidth	≤100 MHz	400–800 MHz	≤30 GHz	≤300 GHz	>100 GHz

applications (Huang et al., 2019). We also expect that various innovative use cases may emerge during the 6G era. Especially in the application domain of the SAGIN. For example, automated human-transport public and private UAVs shall fly with help of self-command and control framework. Undersea communication can be established with the traveler who is flying with a gas balloon (Guan et al.). Even an astronaut will be able to play a real-time ultra-high-definition (UHD) video game with her children while travelling from earth to Pluto. We can dream of a number of use cases which seem to be hypothetical science fiction at the current time period (Qi et al., 2020). Thus, we can expect that 6G-SAGIN amalgamation would supersede all the barriers being faced presently. Implication of haptics, cognition, AI and tactical information processing, 6G would improve the SAGIN infrastructure to a higher level of experience. Table 2 presents spectrum comparison in 6G.

However, achieving such 6G-SAGIN orientation, we must include some key requirements such as, upgradation of existing machine type communication, ultra-reliable communication, low latency connectivity, and enhanced mobile broadband. Guaranteed quality of service with 99.999999% reliability would be a necessity. New spectrum bands must be exploited while using >100 Gbps peak data-rate. Extreme coverage of spectrum in air, space and under the sea. Energy consumption must be minimized in such a level so as to allow affordability of mmWave/THz nanowatt expenses. Minimal intervention should be given to depend on the battery charging scheme. Ultra-massive device connectivity (>100 M/km^2) range should be achieved. High-precision positioning (mm/cm-order) with enriched sensing ability needs to be augmented (Popoola et al., 2020). Fig. 1 presents 6G-SAGIN architecture.

2.3. Related work

At present no article is available on the public domain that focuses on the possibility of integration between 6G and SAGIN, Thus, no directly related work exists. However, a handful of articles are available that considers various angles of SAGIN for example, UAV implication, 5G integration, and architectural presentation. We discuss those articles briefly to present a holistic view about current research progress on the SAGIN based on the next-generation communication technologies.

In (Guan et al., 2020), an in-depth discussion on UAVs with relation to the 5G is elaborated where UAVs are assumed to be the main backbone of the proposed SAGIN infrastructure. It mainly focuses on the physical and network layer design aspects of UAV-5G amalgamation with associated research challenges and possible way outs. We also find some architectural views of prospective SAGIN that considers the SAGECELL, FANET and satellite-communication aware SAGIN. In all these architectures both the aerial and spatial flying objects are given the most importance. Elemental design aspects are discussed in the (Guan et al., 2020) to showcase the operation center elements design. Four key design frameworks are envisaged, including (a) ground center design, (b) aerial center design, (c) satellite center design, and (d) communication and control center design. UAVs are also tested as a service enabler in the SAGIN while allowing to comprehend the UaaS (Zhao et al., 2018). A more intuitive study (Liu et al., 2018) reveals the requirement of satellite and mobile communication technologies to achieve the SAGIN in accordance with 5G plethora. Main focus is given on the vision of the SAGIN with various implied challenges. An overview of the SAGIN is presented in (Knopp et al., 2020) where emphasis is given on the mobility-aware management schemes. A perspective has been waived in alliance with performance analytical tools of the SAGIN. A number of routing techniques has been proposed in (Qi et al., 2016; Huang, et al., 2017) to perceive how SAGIN can achieve efficient and low-latency communication with the help of multi-path QoS routing, placement routing and unified routing approaches.

On the other side, FSO and optical communication are investigated to see their applicability in the SAGIN infrastructure development (Alimi et al., 2019; Zhou et al., 2019). A novel design augmentation on the SAGIN is prescribed in (Dai et al., 2019). It discusses how network fixed point notion could be used along with the SAGIN ecosystem.

We notice that the service and accessory development related particulars are investigated in (Zhou, et al., 2019) to find the efficient offloading algorithm (Liu et al., 2015), task scheduling technique (Wang et al., 2020), software defined networking-based (Kato et al., 2019) service delivery, and service function chaining process (Qu et al., 2019). Table 3 presents comparison between related works where we classify the works based on the year of publication, inclusion of 6G in the study, relevance to SAGIN, applications, major contributions of the article, and challenge as well as the future directions paved in the paper. The offloading process discussed in the related work aims to distributed the tasks which are not feasible for processing at the SAGIN nodes. Similarly, the task scheduling approach performs scheduling algorithm to allow the priority invoked tasks in a demand basis manner. Software defined network aware service delivery and service function chaining processes can significantly improve the SAGIN environment where virtualized service provisioning algorithms can provide necessary chaining aspects of various tasks.

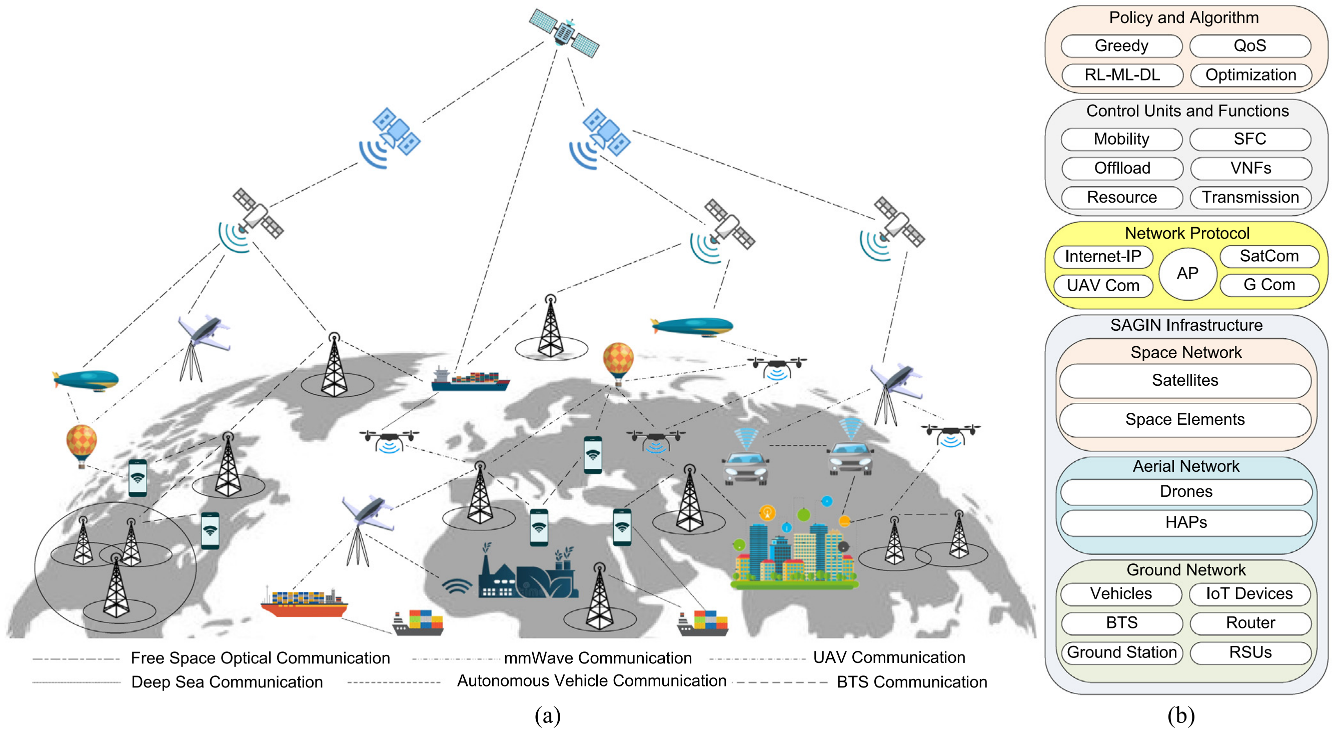

Fig. 1. 6G-SAGIN architecture. (a) Overall vision of 6G-based SAGIN, (b) 6G-SAGIN layered architecture.

3. Space and Mobile Networking in 6G-SAGIN

3.1. Space communication technology

3.1.1. Space access network

Space access network (SAN) addresses full-fledged tracking and relaying of satellite and spatial data transmission devices. The SAN can be used in 6G-SAGIN for establishing communication between various communicating elements. Usually, the geostationary satellites are used for providing network access support while covering the Ku band. The data transmission rate is about 506 Mbps. It can cover 100–6000 km of spatial region. The same could be integrated with the modem and dish antennas placed both at indoor and outdoor locations. Recent involvements are trying the medium and low earth orbit satellites for facilitation of communication (David and Berndt, 2018). It is observed that low and medium earth orbit satellites provide 64 Kbps and 1 Gbps, respectively. Satellite internet access (SIA) is also sometimes associated with the SAN where two-way only satellite communication is normal.

However, portable satellite modem and use of the internet via satellite phone has evolved recently. On the other hand, one-way receivers with terrestrial transmit solutions are being leveraged with slight modification into the broadcast mode. Such systems can empower 100–4000 end users at any point of time. This range can be extended with suitable changes into the software and time division multiple access schemes. This technique faces some key challenges that include signal latency, placement of geostationary orbits, interference with atmosphere, Fresnel zone and line of sight. Though, it is expected that 6G-SAGIN would be benefited by utilizing SAN and SIA together.

3.1.2. Satellite communication

Satellite communication would be seamlessly integrated with the 6G ecosystem. Due to high range coverage and extreme accurate communication aspects, satellite communication would become an inseparable part of 6G. Basically three types of satellites participate in digital communications, such as, (i) low earth orbit (LEO), (ii) medium earth orbit (MEO) and (iii) geostationary earth orbit (GEO). LEO satellites orbit earth between 160 and 2000 km above earth. MEO satellites orbit earth between 2000 and 36000 km above earth. GEO satellites have a stationary orbit of 22236 km above earth surface. Different types of satellite communication techniques are used to provision a number of applications, for example, fixed satellite service (FSS) is meant for broadcasting feeds to TV stations, radio channels and broadcast networks (Li et al.). Earth to space services is generally imposed by the FSS. We find that 14–14.25 GHz and 14.25–14.3 GHz bands are used for radio navigation and space research. Broadcasting of TV channels can be done by using 12–18 GHz with a small dish antenna having <0.5 m radius. Digital video broadcasting (DVB) standards including DVB-T, S, C and H are very useful for data transmission via the set-top boxes. Mobile satellite service (MSS) is achieved by using a variety of frequency bands such as, 137–136.025 MHz, 137.025–137.175/137.825 MHz, for space-to-earth (S2E) and 148–149.9/150.05 MHz, and 156.7625–156.8375 MHz for earth-to-earth (E2E) communication. Thus, 6G can utilize satellites for performing applications related to mobile data service, TV broadcasting service, radio broadcasting, military and internet broadband services. Satellite RAN (SARN) technique may be investigated for accessing radio service from the satellites directly. Table 4 presents space communication scenarios.

3.1.3. Laser space communication

Communication in the free-space with the help of a laser is an established method of networking. Optical telescopes can be used as the bridge creator between the terrestrial and space elements for facilitation of long-range communication. Several research projects are going on that try to implement laser space communication using various environments. Low earth orbit, medium earth orbit and geostationary earth orbit-based laser communication are mostly common. However, stratosphere and troposphere centric schemes are being investigated. Usually, four types of scenarios

Table 3
Comparison between related works.

Paper	Year	Inclusion of 6G	Relevance to SAGIN	Application	Major Contributions of the Article	Challenge and Future Direction
(Guan, 2020)	2020	No	Low	LEO satellite-based SAGIN	LEO satellite to ground connection, utilization of optical links from earth orbiting spacecraft, space element design	Discusses about LEO satellite for space-to-ground communication, no other satellite communication present, no future direction present
(Zhao et al., 2018)	2019	No	No	UAV in 5G with SAGIN	UAV with 5G, comprehensive survey on UAV communication, SAGIN architecture and research challenges	Survey of 5G-based SAGIN discusses no futuristic beamforming techniques, no future direction present
(Liu et al., 2018)	2018	No	Yes	SAGIN in 5G	SAGIN in 5G, trends in mobile and satellite communications, key enabling technologies, standardization initiatives, industrial research projects, 3GPP activities, open research issues	Lack of 6G integration techniques, no future direction present
(Knopp et al., 2020)	2020	No	Yes	Survey on SAGIN	Detailed survey on SAGIN about recent progress in research, network design aspects, resource allocation strategies, performance analysis, optimization schemes, open issues and future direction	Survey doesn't present how SAGIN can be improved in future network design, generic approach taken
(Qi et al., 2016)	2016	No	Partial	VM for SAGIN	Placement of virtual machine (VM) in the SAGIN, trade-off discussion of optimization algorithms, routing, service placement, and service migration	VM placement doesn't show improvement strategies for next generation computing, future direction present
(Huang et al., 2017)	2017	No	Partial	Routing in SAGIN	Unified routing framework for SAGIN, UAV-wise hybrid time–space graph design, contact time and contact probability mitigation	No explicit mention of ground-based SAGIN routing, no future direction present
(Zhou et al., 2018)	2018	No	Partial	Optical design for SAGIN	Hybrid optical wireless network design, free space optics, visible light interconnection design, on–off keying based OFDM transmission	No mention of ground connectivity with the OFDM scheme, no future direction present
(Alimi et al., 2019)	2019	No	Partial	Air-to-air channel for SAGIN	Arbitrary correlated multivariate FSO channel, FSO implementation, air-to-air linkage, gamma-gamma distribution	FSO communication with ground station is not presented, no future direction present
(Zhou et al., 2019)	2019	No	Partial	FSO channel for SAGIN	Impact analysis on multivariate FSO channel, outage performance estimation	No in-depth analysis of overall optimization scheme for FSO, no future direction present
(Dai et al., 2019)	2019	No	Yes	NFV for SAGIN	Bidirectional mission offloading, NFV and SFC integration with SAGIN	Only discusses offloading of NFV but no discussion with SDN, no future direction present
(Zhou et al., 2019)	2019	No	Partial	Task scheduling in SAGIN	Coordinated task scheduling, UAV connection with SAGIN, resource allocation, particle swarm optimization, local search capabilities	Ground station connectivity is less oriented with UAV, no future direction present
(Liu et al., 2015)	2015	No	Partial	IoT task in SAGIN	IoT task scheduling, delay aware SAGIN, Markov decision process, UAV trajectory, computation offloading analysis	IoT task offloading is not explicitly mentioned, no future direction present
(Wang et al., 2020)	2020	No	Low	Energy optimization in SAGIN	Energy optimization, secure protection, rule-based dynamic programming	Edge-centric energy aware discussion not expressed properly, no future direction present
(Kato et al., 2019)	2019	No	Partial	SFC in SAGIN	Service function chaining, aggregation ratio, near-optimal performance, service provisioning framework, heuristic greedy search, resource consumption	SFC is not aligned against the next generation computing, no future direction present
(Qu et al., 2019)	2019	No	Partial	AI in SAGIN	Optimization of SAGIN using AI, deep learning integration	Futuristic integration with quantum intelligence is missing, no future direction present

Table 4
Comparison between laser space communication scenarios.

Environment	Scenario	Data Rate	Project/Characteristics
LEO	S2G	1 Gbps	BridgeComm
	S2G	1 Gbps	Cloud Constellation
	S2G	1 Gbps	LeoSat
	S2G	1 Gbps	Starlink
	S2G	1 Gbps	Telesat LEO Constellation
	S2G	1 Gbps	Analytical Space
MEO	S2S, S2G	100 Gbps	Laser light communication
GEO	S2S,	1.8 Gbps	European data relay system
Stratosphere	A2A	0.15 Gbps	Google Loon
	A2A, A2G	10 Gbps	Facebook Aquila
Troposphere	A2A	10 Gbps	Airborne Wireless Network

are being tested: space-to-ground (S2G), space-to-space (S2S), air-to-air (A2A) and air-to-ground (A2G). On an average 1 Gbps data rate is achieved while transmitting a signal. However, it can vary and lower down to a minimum 0.15 Gbps with maximum limit till 10 Gbps. The objectives behind such implementations lies as follows, (a) global telecommunication backbone creation, (b) satellite mega-constellation, (c) hybrid radio-frequency enabled data relay network design, (d) rural and remote area network coverage (Liang et al.), and (e) in-flight communication.

3.1.4. Deep space optical communication

Another type of space communication i.e., deep space optical communication (DSOC) can be considered as a key enabler of the 6G-SAGIN. The DSOC can improve existing communication performance up to 100 times. It is estimated that DSOC would leverage very high bandwidth for downlink operations. Originated by the NASA JPL laboratory, DSOC is expected to employ near-infrared (NIR) i.e., 1.55 μm wavelength while transmitting optical signals. As envisaged, the DSOC method will be integrated with the *Psyche mission* by NASA in 2022. The system shall consist of two units (a) flight laser transmitter and (b) ground station. The satellite laser unit would focus a laser of 4 W power from a telescope of 22 cm aperture. With<100 W of overall transmitter module uplink and downlink operations shall be aligned at the ground station (Zhang et al.). Ground station would use 1.064 μm while in uplink mode. It is expected that the average data rate shall be 292 Kbps. We envisage that 6G-SAGIN could be improved with the intervention of the DSOC in coming days.

3.1.5. Optical PAyload for space communication

With the aim of maintenance of an optical link between space and ground station, optical PAyload for space communication (OPASC) was conceived. However, we find it suitable for possible use case development in the 6G-SAGIN scenario. OPASC is capable of processing distorted signals in space communication (Huang et al., 2019). It is very useful for designing procedural portions with the given optical links. Usual data rate is kept around 50 Mbps. 6G-SAGIN would use the OPASC for leveraging of the mission operation and application use cases. With help of tracking data and relay services systems (TDRSS) the OPASC would start collaborating between the satellite and ground station. In this aspect, 6G-SAGIN might integrate near earth network (NEN) or ground network (GN)-based approaches for formulating better downlink.

3.2. Mobile technology

3.2.1. Mobile backhaul technology

Mobile backhaul (MBH) refers to connecting future generation cell sites with the wireline networks via air interfaces (Nawaz et al., 2019). The aim of MBH is to provide ultimate data and content centric service provisioning to the mobile users of the network. As the gradual demand of bandwidth is increasing day by day, MBH needs to connect radio access networks (RAN) for integration of small and macro cell sites with the rest of the wired backhaul infrastructure. MBH should hold key characteristics for inclusion into the 6G era those are, (i) capacity increment to serve fast users, (ii) operation and administration to enterprises, (iii) maintenance and mobile operation service provisioning, (iv) network timing and synchronization management, and (v) allowing high network availability to the mobile users (Fadlullah and Kato). To achieve this, MBH should focus on integrating software function virtualization and software defined networking upgradation into the existing infrastructure. Heterogeneous network (HetNet) service automation is the most important aspect of MBH where it aims at combining a range of microcell, picocells, femtocells and small cells with macrocells with wireless communication media.

RAN implements radio access technology within wireless networks. RAN provides connections between mobile devices with a core network (CN). A silicon chip technology is deployed in the form of RAN both in the CN and the user equipment (UE) or mobile station (MS). Recent advancements of RAN can talk with cloud infrastructure i.e., Cloud RAN (CRAN). CRAN can facilitate long range connection for example 40–80 km for 3G and>20 km for 4G. Effective data speed is around 10 Gbps with very low latency (10 μs). Being associated with the cloud, CRAN can provide real-time virtualization capability to HetNet platforms. Internet protocol-based CRAN (IP-CRAN) could be assimilated with the MBH for emphasizing mobile user service mitigation in the 6G technology domain in future.

3.2.2. mmWave

mmWave spectrum lies within 30–300 GHz. mmWave frequency bands are useful for providing instantaneous action specifics, everything-aware communication and immersive experience in the 6G domain. mmWave allows short transmission path and propagation loss mitigation by limiting loss between adjacent cells (Kato et al.). Very small size antennas can be empowered with highly focused beam making for gain amplification. The mmWave bands can be used in three ways such as, 57–64 GHz unlicensed, 28/38 GHz underutilized 7 GHz, and 71/81/92 GHz with 12.9 GHz, 3 GHz light-licensed. Such bands are useful for developing cell-less 6G architecture, virtualization of 6G network, disaggregation of 6G frameworks, energy harvesting techniques into 6G and advanced network skeleton design. Further, indoor hotspot creation, mission-critical application deployment and fixed wireless internet access strategies can be evolved based on the mmWave in 6G. 6G-SAGIN may be benefited with the eight different bands that includes, 24.25–27.5 GHz, 31.8–33.4 GHz, 37.40.5 GHz, 40.5–42.5 GHz, 45.5–50.2 GHz, 50.4–52.6 GHz, 66–76 GHz and 81–86 GHz.

3.2.3. THz communication

THz communication lies within 0.3–10 THz. It can be very helpful for demystifying 6G-SAGIN perspectives with utilization of unused bandwidth. A recent test carried out in a shopping mall by Aalto University demonstrated the use of 140 GHz D-band signal propagation. Similarly, the NYU wireless research programme has investigated the use of 140 GHz and higher channel communication systems for long-range signal measurement and propagation. With minimal path loss the signal is successfully transmitted. Prototype development for real-time, over-the-air deployments are also under the investigation (Mao et al.). Thus, 6G-SAGIN can benefit with several key aspects of THz communication that includes, hybrid THz-optical wireless communication channels, THz for highly dynamic applications, improved data center service availability, mobile HetNet deploy-ability, and THz-3D

Table 5
Comparison between electronic THz design and communication systems

Type	Technology	Fmax	IC (Pout)	IC (Noise Figure)	Note
Compound Semiconductor	InP HEMT/HBT	> 1.5 THz	−2 dBm @ 850 GHz	12.7 dBm @ 850 GHz	Highest Fmax
	GaN HEMT	> 230 GHz	33 dBm @ 100 GHz	–	Highest Pout
	GaAs HEMT	> 3 THz	−14 dBm @ 2 THz	14 dBm @ 2 THz	Highest Frequency operation
Silicon	SiGe HBT	> 700 GHz	9.6 dBm @ 215 GHz	11 dBm @ 245 GHz	Medium volume
	CMOS FET	> 450 GHz	−4.6 dBm @ 210 GHz 5.4 dBm @ 300 GHz	9 dBm @ 200 GHz 14 dBm @ 280 GHz	Large volume

HBT: Hetrojunction bipolar transistor, Fmax: frequency of transistor unity power gain, FET: Field Effect Transistor, HEMT: high electron mobility transistor

beamforming. THz communication could be used in the establishment of tera-wi-fi, tera-IoT, tera-integrated access backhauls and tera-space communication making it a better avenue for 6G-SAGIN deployments. Despite several key strengths, more investigations should be made to see how massive antenna arrays could be used in the SAGIN, bidirectional antenna design should be formulated, and delay-critical applications need to be mitigated. Table 5 presents THz design comparison.

3.2.4. IEEE 802.11 standards

IEEE 802.11 refers to the local area network (LAN)-based communication protocols that correlates with some physical (PHY) and media access control (MAC). It works on different frequency bands such as 2.4/5/6/60 GHz (Sun et al.). It consists of many families of sub-protocol sets that follow various stream data rates, bandwidths, modulation schemes and ranges for communication. IEEE 802.11b follows direct sequence spread spectrum (DSSS) whereas IEEE 802.11a/p/y/g uses orthogonal frequency division multiplexing (OFDM). An extended version of OFDM i.e., multiple input multiple output (MIMO) is used by the IEEE 802.11n/ac/ax/af/ah. OFDM with single carrier and low power is used by the IEEE 802.11ad/aj/ay. Multi carrier on–off keying scheme is used by the IEEE 802.11ba. IEEE 802.11ax is also referred to as Wi-Fi 6 that uses binary phase shift queuing (BPSK), quadrature phase shift keying (QPSK), 16/64/256/1024 quadrature amplitude modulation (QAM) modulation techniques. It is an improvement over the IEEE 802.11ac in terms of single network allocation vector (NAV) and 0.4–0.8 μs guard interval duration. Gigabit wireless (Gi-Fi) is another variation of this standard that allows data transfer at 5 Gbps in the 57–64 GHz unlicensed band. Also, the WiGig or 60 GHz Wi-Fi is capable of operating in 2.4/5/60 GHz bands with 7 Gbps data transmission rate. Thus, IEEE 802.11 can improve communication range in the 6G-SAGIN spectrum.

3.2.5. 5G-Nr

Radio access technology (RAT) refers to the underlying physical communication strategies used in the radio-based network systems (Manogaran et al.). 5G-new radio (NR) is such an example of RAT that is a globally recognized aerial communication paradigm. It can be used in the 6G-SAGIN infrastructure too as an upgradation of the air interfacing tool. Two types of frequency ranges (FRs) can be utilized in the 6G-SAGIN plethora that comprises sub-6 GHz and mmWave (24–100 GHz) frequency band for FR1 and FR2, respectively. 5G-NR is capable of being associated with the 6G-SAGIN in terms of dynamic, standalone and non-standalone modes. DSS sharing scheme is used in the dynamic mode. 5G packet code (PC) is used in the standalone mode. Non-standalone mode uses 4G long term evolution (LTE). The cyclic prefix (CP) is related to the sub-carrier spacings of 5G-NR. We find 4.7 μs sub-carrier spacing for 0.015 GHz. A range of duplex modes are used in the 5G-NR in various downlink and uplink frequency bands making it a good choice for 6G-SAGIN communication Empowerment. Table 6 presents comparison between 5G-NR spacings.

Table 6
Comparison between 5G-NR carrier spacings.

Sub-carrier Spacing	Slot Interval (ms)	FR Bands	Characteristics
0.15 GHz	1	FR1	LTE
0.030 GHz	0.5	FR1	LTE
0.060 GHz	0.25	FR1, FR2	Cyclic prefix
0.120 KHz	0.125	FR2	Highest sub-carrier
0.240 GHz	0.0625	FR2	Synchronization signal block

3.2.6. Microwave

Microwave is a form of radiation that ranges between 0.3 and 300 GHz. It runs over the ultra-high frequency (UHF), extremely high frequency (EHF) and super high frequency (SHF) bands. As microwaves travel line-of-sight (LoS), it is good for visual horizon up to 64 km terrestrial communication applications. Thus, 6G-SAGIN can be highly benefited by microwaves to provide point-to-point connectivity between UAVs and satellites. Microwave technology offers a vivid range of frequency named after alphabets for formulating specific use cases. For example, 6G-SAGIN may be benefited by using microwave bands like L, S, C, X, K, Q and W. Satellite and UAV communication would be highly reliable by using microwave bands of choice. Table 7 presents a comparison between microwave bands.

3.2.7. Wireless regional area network (WRAN)

The WRAN uses underutilized portions of radio frequency for facilitation of internet connectivity to designated parts of application. Typical frequency range of the WRAN is between 0.4 and 0.7 GHz that is a good option to penetrate obstacles on the

Table 7
Comparison of microwave frequency bands.

Band	Frequency Range (GHz)	Wavelength Range	Use Cases
L	1–2	15–30 cm	Military, GPS, GSM
S	2–4	7.5–15 cm	Weather radar, some communication satellites
C	4–8	3.75–7.5 cm	Long range radio communications
X	8–12	25–37.5 mm	Satellite communication, radar, space communication
K_u	12–18	16.7–25 mm	Satellite communication
K	18–26.5	11.3–16.7 mm	Radar, satellite communication
K_a	26.5–40	5–11.3 mm	Satellite communication
Q	33–50	6–9 mm	Satellite communication, terrestrial microwave communication
V	50–75	4–6 mm	mmWave radar search
W	75–110	2.7–4 mm	Satellite communication, mmWave radar search, military radar targeting, automotive radar
F	90–140	2.1–3.3 mm	SHF transmission, WLAN, microwave communications
D	110–170	1.8–2.7 mm	EHF transmission, microwave remote sensing, mmWave scanner

pathways. It works on top of the cognitive radio (CR) aspect of the network which is dynamically configurable and programmable over-the-air. Thus, congestion and interference conflicts can be resolved in a better way. In 6G-SAGIN, both the full CR (FCR) and spectrum-sensing CR (SSCR) can be deployed under licensed and unlicensed bands. Moreover, use of intelligent antennas can substantially improve the open spectrum sharing capacity under a given spatial rate of action.

As the WRAN can use unused i.e., white space of a radio configuration, so it can use unutilized television (TV) signal at the range of 0.054–0.862 GHz UAV, satellite and other SAGIN-enabled devices can communicate with each other while operating on the point-to-multi point basis (P2MP). Selected 6G-SAGIN elements can be converted into the base stations and others as customer equipment. With help of cognitive sensing unused frequency bands could be leveraged over such devices to make the communication (Baiqing et al., 2018). Moreover, stringent PHY, MAC, and authentication schemes would empower the 6G-SAGIN.

3.3. FSO-based optical communication

We present a free-space optics (FSO)-based 6G-SAGIN architecture while implying hybrid optical wireless framework (HOWF). The HOWF is envisaged to serve in the congested 6G spectrum. Use of FSO in the HOWF inherently improves security of the 6G-SAGIN ecosystem. The HOWF combines FSO-based communication and visible light communication (VLC) paradigm to pave RF-sensitive service scenarios. 6G-SAGIN would require long distance and high bandwidth for establishing applications (White Paper, 2019). Thus, HOWF would benefit similar aspects with the inclusion of acquisition pointing tracking (APT) scheme. As the VLC-based cabins are in dynamic state, they must be integrated with the APT modules to disseminate seamless connectivity to the cabin-wise computing objects. Each of the VLC-based cabins is equipped with high-speed wireless communication protocols that work best in short-range and line of sight situations. Use of light emitting diodes (LEDs) in the VLC cabins allow various heterogeneous networking terminals, such as smart phones, robots, vehicles, and computers to access the 6G-SAGIN in a completely bi-direction manner. VLC-based embedded controllers can be placed at the ceiling and terminals inside the cabins for communication. All downlinked data is broadcasted inside each cabin by using time division multiplexing (TDM) and time division multiple access (TDMA) schemes. One can use VLC-based device-to-device links to connect all the terminals inside a cabin. Second type of larger bandwidth link is between the terminal of one VLC cabin. Two bi-directional up/downlink modules can be used in different cells of a cabin. The heterogeneous network (HetNet) controller would alleviate the communication spectrum between the VLC terminals inside a cabin. We need to think of setting linkage between terminals of multiple VLC cabins with the help of the FSO-VLC HetNet module. This would allow two bi-directional FSL channels to talk with one bi-direction FSO channel. HetNet controller is the most important layer in this framework that performs (a) signal interaction, (b) signal interaction, (c) signal distribution, and (d) resource scheduling and optimization. Fig. 2 presents HOWF architecture. Table 8 presents comparison between wireless communication technologies.

4. Key Enablers for 6G-SAGIN

4.1. Physical layer

The physical layer of the envisaged 6G-SAGIN must conform to specific parameters to make the system sustainable. Firstly, the frequency band utilization: it should be used in an optimal manner to apply different frequency bands in multiple applications (Emu and Choudhury, 2021). Ku, Ka Q/V bands are estimated to be effectively deployed. Secondly, the propagation channel modeling: 6G-SAGIN must work within such a communication channel that offers very low bit error rate and extremely high interruption mitigation approaches. Propagation delay is another option that must be satisfied in the estimated channel. System capacity

could be enhanced while developing such a channel. Thirdly, the cross-layer design aspects: as 6G-SAGIN shall operate in physical, data link and network layers simultaneously, overall monitoring of delay, throughput, reliability and energy efficiency must be dissolved. In Particular, multi-carrier modulation, antenna design, network coding, path loss and channel condition measurement need to be handled cautiously. Lastly, the spectrum allocation could be effectively done so that issues like Bayesian equilibrium can be suppressed. Multi-layer UAV deployment along with utilization of sub-bands might be very helpful in this regard.

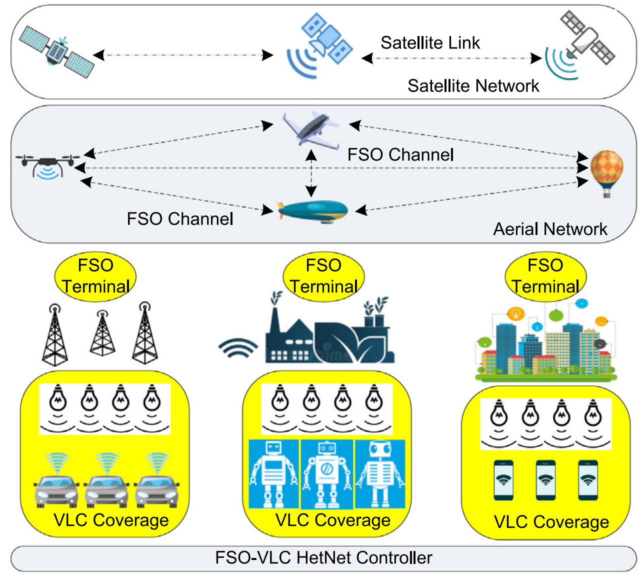

Fig. 2. HOWF: an optical network architecture in 6G-SAGIN.

4.2. Mobility management

6G-SAGIN is expected to be a hybrid approach of highly dynamic elements which need to be under the same communication channel all the time. Thus, a significant design and envision of the mobility management scheme is immensely important (Corre et al., 2019). The key aims of the mobility manager should be as follows, (a) user equipment condition monitoring, (b) implementation of location management aspect, and (c) handover management. Moreover, a plane-specific mobility management policy must be developed. For example, satellite networks and spatial communication must be carefully monitored to safeguard them against various errors in the system level. Different network scenarios could be thought of beforehand to mitigate the mobility management issues. For instance, we can assume the mobility manager to keep track of space-to-ground, space-to-space, air-to-ground, ground-to-space, and space-air-ground as a whole. Important depictions like multipath fading, shadowing effect mitigation, estimator error minimization, phased array antenna design, packet routing, and small-scale fading must be resolved. Use of game-theoretic approach and dynamic spectrum power allocation

Table 8
Comparison between wireless communication technologies.

Technology	mmWave	THz Band	Infrared	VLC	UV
Frequency Range	30–300 GHz	0.1–10 THz	1–430 THz	430–790 THz	790–30 PHz
Range	Short rage	Short/ medium range	Short/long range	Short range	Short range
Power Consumption	Medium	Medium	Relatively Low	Relatively Low	Expected to be Low
Network Topology	Pont-to-Multi point	Pont-to-Multi point	Point-to-Point	Point-to-Point	Point-to-Multi point
Noise Source	Thermal	Thermal	Sun/Ambient	Sun/Ambient	Sun/Ambient
Weather Condition	Robust	Robust	Sensitive	Not Known	Sensitive
Security	Medium	High	High	High	Not decided yet

Table 9
Comparison of resource management in 6G-SAGIN.

Resource	Reconfiguration Trigger Policy	Time Period	Scheduling Notions
Storage	Content wise requests	Minutes and Hours	Content update
Backhaul	Baseband function splitting	Minutes	Cache co-design
Satellite orbit	Position changing	NA	Link scheduling
Pilots	User mobility	Seconds to minutes	NA
Computation	New task arrivals	Minutes	Task offloading
Time-frequency ratio	Channel status variations	Seconds to minutes	Interference-aware

schemes could improve the current situation. Table 9 presents comparison of resource management in 6G-SAGIN.

4.3. Mobile crowd sensing

Traditional UAV and SAGIN centric approaches seem to be suffering from the issues like network densification, caching capacity and edge computational ability (Fang et al.). Thus, an improved mobile crowd sensed technique may be provisioned to safeguard 6G-SAGIN from possible edge caching related problems. Thus, an improved mobile edge network (MEN) needs to be formulated that can address the solutions to the earlier issues. The way out could be developed around the multi-access radio access network associated with the UAV-based cellular designs. In this approach, UAVs can act as base stations for providing HetNet-based services to aligned UAVs or ground/satellite stations. Herein, the mmWave and beamforming policies might improve the computational and caching capacity of the 6G-SAGIN. We can think of an interaction between four key pillars such a cross-layer interactive manager, crowd sensing module, publisher/subscriber module and a decision-making tool. Convolutional deep neural networks may be used as the decision maker. Software defined networks (SDN) may be imposed into the satellites, UAVs and ground stations to keep up with designated flow charts. Those flow charts could be referred to whenever any managerial issue arises. All types of UAV-based cells, backhaul interface and ad-hoc interfaces would be served by the 6G-SAGIN cooperation gateway upon receiving an exact decision by the underlying caching engine. However, this approach should mitigate the issues including cognitive behavior, prediction-aware facilitation capacity and optimization of communication links. Improved 6G-SAGIN centric scheduling and predictive modeling could minimize the routing problems inside the 6G-SAGIN.

4.4. Offloading

Important factors like agility make a networking system strong to perform efficient computation and rich spectrum sharing. 6G-SAGIN infrastructure also seeks such criteria to be fulfilled in due course of action (Al-Eryani and Hossain, 2019). Offloading of tasks in purely bi-directional fashion could be envisaged with the intervention of VNF and SFC together. Such offloading always enables the SAGIN type of network to support high-altitude platforms (HAPs) considering the UAVs. Mission offloading service in the 6G-SAGIN may be provisioned as follows. We can include a satellite cooperative sensing mission to ascertain the offloading of services from space to the ground station. For example, raw images captured by the satellites can be sent to the mobile and static ground elements via HAPs. MEC-enabled 6G-SAGIN user equipment can perform the image processing task and then feedback the analytical result to the satellite. HAP-based relaying option may be imposed herein to improve the offloading service. Software defined network (SDN) controllers can integrate all the three layers of 6G-SAGIN framework to share physical resources via virtual and data flow embodiment. In continuation to the design, the groundwork can be offloaded to the aerial network while allowing access to a 3D network framework. We can envisage to improve coverage, capacity, mobility, wireless backhauling and robustness in the 6G-SAGIN. With an enriched sustainable design and improved intelligent layer, space-air tasks can be offloaded to the ground station too (Zhu et al., 2019). Reconfiguration of agility aware resource scheduling needs to be investigated to abstract and virtualize the heterogeneous resource sharing in the 6G-SAGIN.

4.5. Task scheduling

Task scheduling in 6G-SAGIN is an immensely important service that must be carefully catered for efficient bandwidth utilization. Two key techniques can be used for task scheduling in the 6G-SAGIN framework namely intelligent coordinated task scheduling and delay-aware task scheduling. Intelligent task scheduling algorithms may involve particle swarm optimization (PSO) technique so that the transmission and storage scheduling could be jointly considered for overall resource interaction. Task priority and deadline centric conflict mitigation schemes are expected to outperform alternative scheduling approaches. Usually such a policy can start with a task sequence initialization command for further valid time settlement (Shawon et al., 2021). Tasks like resource allocation and scheduling operations would be performed based on the current metric values related to the global extremum, particle velocities, particle positioning, time window and particle fitness values. Delay-aware task scheduling presents an opportunity to dynamically schedule task offloading processes by using the Markov decision process. Efficient linear programming models can be tested to find the significance of stochastic channel conditions in the 6G-SAGIN. This domain of study may further be developed to seek for the possibility of the MEC deployment into the unknown as well as unfixed task arrival and particle trajectory follow-up.

4.6. Super IoT

Internet of Things (IoT) refers to paving a horizontal layer of heterogeneous elements to communicate with each other. Such

IoT platforms are being heavily used in different application domains. We expect 6G-SAGIN would be empowered with the super IoT version of implication. Super IoT refers to extending the current IoT-based scenario into asset tracking, monitoring and controlling features. 6G-SAGIN could be ingested with the super IoT concept for better facilitation of fixed and mobile asset tracking aspect. At the same time super IoT would mitigate the issues like security, service platform and dependency over centralized support system in the 6G-SAGIN. Things are an integral part of IoT thus super IoT would enhance its periphery while covering people under its scan. Thus, industry 4.0 would become immensely strategic with the involvement of super IoT along with 6G-SAGIN platforms. Energy monitoring, sales data generation, logistic operation handling and good quality service leverage will be harnessed from it. The amalgamation of super IoT in the envision of SAGIN might improve the safety and security of people and their systems with utmost emergency fashion.

4.7. Stringent authentication

Stringent authentication in the 6G-SAGIN era shall act as the main key enabler behind its success. It is important to safeguard the system against data tampering, identity forgery, interception and so on (Dong et al.). Hash-based chains could be used to mitigate this issue. In this architecture, 6G-SAGIN centric user elements such as smart city, smart phone, smart industry and people would be connected via the security drones in a localized manner. Overall drone-based communication system shall be solely dependent on the hash-based authentication framework. Key aspect of this authentication is the dynamic handshake transmission scheme. It works as follows; drone-assisted security manager (SM) allows to formulate the handshaking via authenticating the border crossing activity. All the 6G-SAGIN served communicating objects start establishing bi-directional signaling with help of the SMs. Designated SM collects transactions in this regard and creates blocks of the hash chain. The hash chain infrastructure supports the SMs and to encrypt and decrypt the identity of the materials. Wireless signal features are expected to be used for detection and identification of SMs and overall 6G things. Not only authentication, the Markle tree in the implied hash chain would support non-repudiation and confidentiality. Fig. 3 presents hash-based authentication architecture.

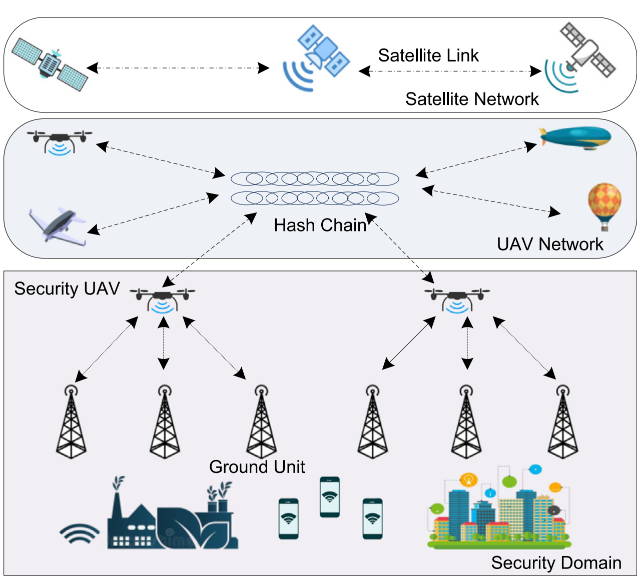

Fig. 3. Hash-based chain authentication architecture.

4.8. Network fixed point

Network fixed point (NTFP) theory could be helpful to realize the correlation of 6G-SAGIN nodes. Thus, a physical correlation characteristic of the 6G-SAGIN framework may be understood (Rajatheva et al.). As the 6G-SAGIN could be framed as the *Banach space*, the nodes into it can be iteratively utilized and analyzed. Such communication space can be better designed to implement the NTFP efficiently. Herein, the routing algorithm could be applied on the source nodes to get it mapped on to a target node that might correspond to a given network space. The NTFP theory would revolutionize the 6G-SAGIN scenario while controlling the packet generation rate of a node. We can use operator-based schemes to map the information of one node to correlate with another. As the theory suggests, mathematical formulation of the network space E can be defined as rows of node-wise information. Thus, a row of network space E can be assumed as a result of apriori information about routing prediction that may result in a global impact between the nodes of 6G-SAGIN. Such impact could be ascertained as the outcome of localized interaction between the nodes. It is expected the 6G-SAGIN network shall be large in scale, making it a good place to apply the NTFP to see that network information is stable. Thus, a sequence of node convergence might provide more significant information about the correlation of the networking elements.

4.9. Service function chaining

Coordination of heterogeneous objects in the 6G era would be a challenging task, especially in the SAGIN framework, where large scale infrastructure is deployed. Thus, amalgamation of virtual network function (VNF) with the service data routing could be a possible way out. Such type of service function chaining (SFC) is normally a NP-hard problem, but could be achieved with heuristic greedy approach. Aggregation ration (AR) can be used on top of the SFC to find the computation-communication trade-off. AR is a ratio between the difference of total VNS and required VNFs to total the VNFs. SFC could mitigate the resource blockage possibility in the 6G-SAGIN and result in improved near-optimal performance.

SFC with 6G-SAGIN can be envisaged in the form of a combined architecture. All the three layers of SAGIN can be virtualized with the help of VNFs where virtual link mapping and VNFs embedding concepts may be realized. SFC is able to solve the appropriate placement of VNFs in the physical network of 6G-SAGIN and route the data flow via proper way. SFC is capable of solving multiple intersection 6G-SAGIN traffic scheduling with an improved AR ratio. Fig. 4 presents SFC architecture in 6G-SAGIN.

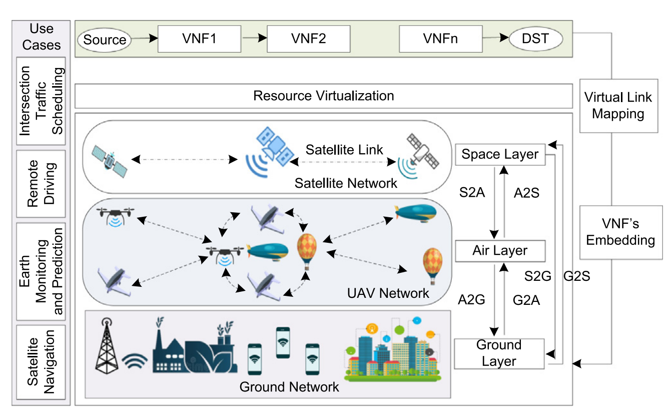

Fig. 4. Service function Chaining in 6G-SAGIN.

4.10. Ultra-dense cell free massive MIMO

6G-SAGIN is envisaged to have been highly supported by the ultra-dense cell-free massive MIMO orientation. It aims at merging the massive MIMO and cloud-RAN. Such cell-free notion alleviates the existing cellular-edge centric problem and leverages macro level of diversity (Li et al., 2019). It also results in minimal channel hardening. Cell-free network approach is capable of providing excellent features like mobile-edge computing (MEC) ready aspect, extremely low latency, energy efficient, ultra-reliability, extremely high capacity and low-power high data rate. In 6G-SAGIN, cell-free networking can be deployed among the UAVs to leverage a holistic central processing unit (CPU) enabled service mitigation on-the-fly. Lots of antennas will be surrounding the user elements in the SAGIN era. As there are no cells in the network, a massive number of distributed antennas are connected to the CPU to provide coherence in uplink and downlink. The connection to cloud-RAN enables distribution of processing in various antenna-nodes or access points (AP). Fig. 5 presents cell-free design in 6G.

5. UAV-as-a-Service in 6G-SAGIN

6G is expected to enable hyper-connectivity and mobility towards billions of things. UAVs shall play the most crucial role to aid support to achieve this target (Inomata et al., 2020). However, three key challenges are placed ahead that must be resolved before indulging into the fulfillment of 6G visions of the SAGIN, that includes, large-scale network complexity, ubiquitous intelligence framework and temporal-spatial dynamic behavior. 6G-SAGIN should empower high user-experience data rate >1 Tb.s and extreme low-latency <1–10 μs. More computation intensive applications including augmented reality (AR), virtual reality (VR) and mixed reality (MR) should be provisioned in the coming days. On top of these, automated traffic monitoring, smart city-based applications and autonomous driving shall become true and feasibly accessible. Such applications would be inferred with effective usage of UAV-based augmentation in the 6G-SAGIN infrastructure. UAV-as-a-service (UAVaaS) might be applied into the 6G-SAGIN while solving earlier issues through the mitigation of on-demand services by machine learning techniques, wide coverage network exploration, and flexible cum powerful computational ability on the fly (Figs. 6–10).

5.1. UAVaaS for wireless communication

Providing wireless communication to other 6G-SAGIN components is a main task of the UAVs. UAVs can act as (a) pervasive aerial ad-hoc communication ecosystem and (b) intelligent network broker (Inomata et al., 2021). In earlier mode, UAVs needed to predict demand of communication bandwidth and capacity of other

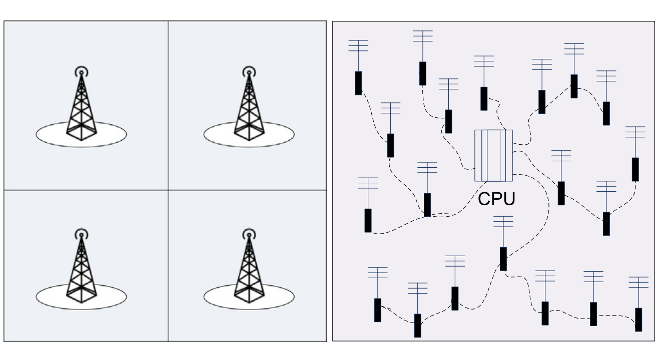

Fig. 5. Cellular versus cell-free network.

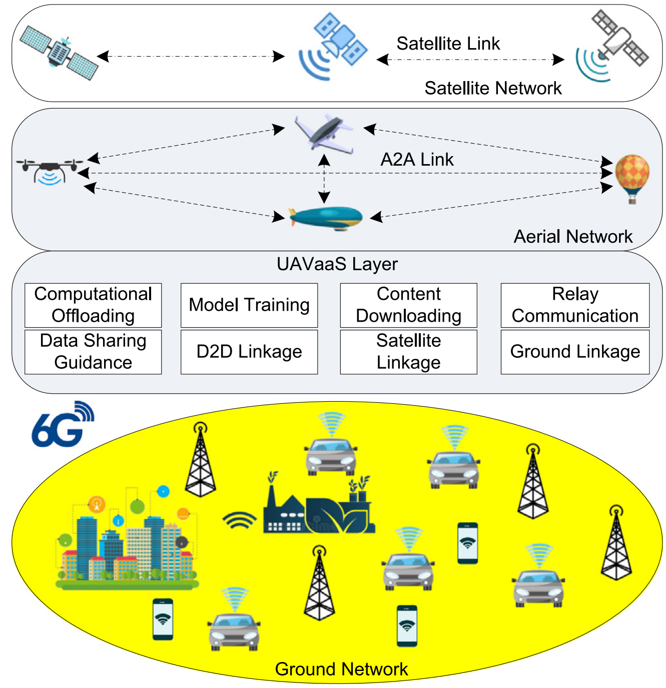

Fig. 6. UAVaaS architecture.

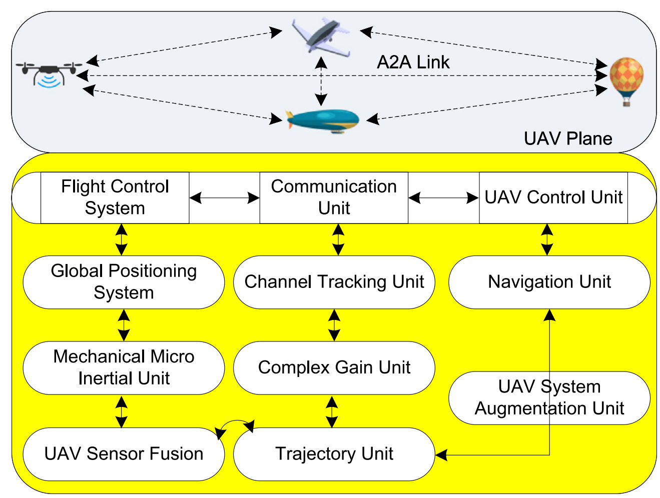

Fig. 7. Communication and control unit for UAVaaS.

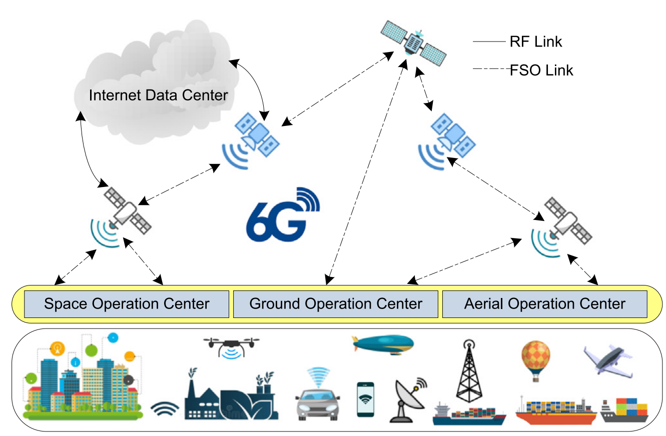

Fig. 8. SAGIN elements interaction in 6G.

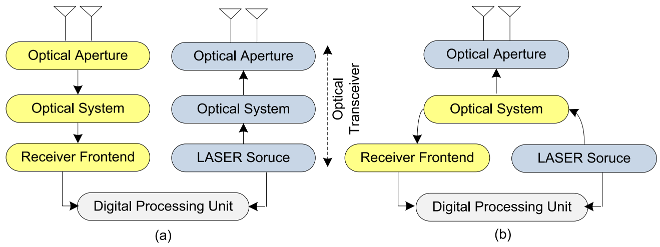

Fig. 9. Laser terminal design. (a) at ground station, (b) at space station.

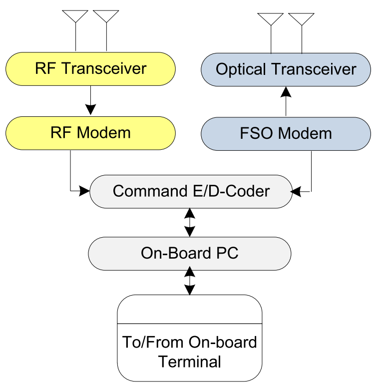

Fig. 10. Data handling elements design at the on-board satellite.

networking planes. Trajectory planning of UAVs in the 6G-SAGIN is an important task where movement trajectory and request rates are first analyzed. The outcome of this analysis produces communication demand distribution for the SAGIN infrastructure. In this aspect, UAVs need to accommodate extension of wireless coverage, cellular communication, relay communication and internet access facilities. Aerial data centers should be served to result in the appropriate responses. Mostly aerial-to-aerial (A2A) links are used to convey the information within the UAV plane. Alternatively, UAVs can host intelligent network brokerage services to assist in learning-based monitoring of 6G-SAGIN. In this mode, UAVs firstly use five core modules namely, ink utility, QOS necessity, mobility management, SAGIN-based node allocation and overall resource presence. Combination of all such modules results in a state of action which is ready for a learning-based approach. UAV-based learning agents perform several tasks to aid in access decision and resource mitigation among the components. Based on the response, reward or punishment is paved into the 6G-SAGIN. Heterogeneous linkages and communication protocols work together to facilitate low-latency provisioning, packet loss minimization, QoS enhancement and throughput maximization. Table 10 presents a comparison of UAVs for 6G (Fig. 11–13).

5.2. UAVaaS for Fog-Edge computing

UAVs shall play a major role in the 6G-SAGIN scenario while providing a highly dynamic fog-edge centric computing platform and leveraging smart intelligence services towards ground or satellite connectives (Tang et al., 2021). In earlier aspects, learning techniques may be utilized to use service request history logs for computing computational demand in the ground and spatial requirements. Service placements are carefully provisioned to allow A2A links to facilitate maximum network coverage to the ground connectives. At the same time, navigation, video streaming, network gaming, and AR/VR applications could be served on top of UAV-centric resource allocators and associator modules. UAVs are capable of enriching fog-edge intelligence while staying on-the-fly mode. A set of UAV-based parameters are posted on the learning server where UAV can act both as forwarding node and training node. Based on a localized model, a global model could be formulated to extend the UAV coverage. While doing so, the packet loss rate could be drastically minimized and QoS could be highly improved while allowing extreme low-latency aware throughput mitigation in real-life applications. Table 11 presents a comparison of UAV designs.

5.3. UAVaaS for intelligent caching

6G-SAGIN can argue with the ability of UAV-based intelligent caching to minimize overall energy consumption and minimization of model training and fitting aspects (Sun et al., 2021). UAVs can be loaded with the content popularity distribution prediction schemes to use historical logs for empowering the liquid AI-based model. As a result, an effective content popularity distribution pattern would be generated. The same popularity-based content can be later on distributed within the UAVs via A2A links. In this case, mobility, mission scheduling and policy optimization tasks could be largely extended to improve the efficiency of possible UAV-based airport work capacity and ground-spatial level service augmentation. Caching service and user moving pathways are immensely important to allow spatial interaction with the UAV-based data centers. Simultaneously, big data analytics schemes could be involved herein to use content popularity information to gather time and region wise data against strong correlation with the content popularity (Jiang et al., 2021). Thus, a 3D model can be superimposed over the A2A links to enable data mining policies. Three key types of links, such cellular, device-to-device (D2D) and control links are seamlessly observed to enhance overall caching activity (Table 12).

Although such UAVaaS is promising in the 6G-SAGIN scenario, three main issues must be catered beforehand. They are, (a) hyper-flexible switching within caching, computing and communication (CCC) services, (b) strong collaborative platform mitigation and (c) extremely efficient learning techniques usage. Federated learning (FL) and generic deep learning (DL) schemes could be tested against framing solutions to these problems. Moreover, dynamic spectrum resolution aspects need to be thought of so that effectiveness of the 6G-SAGIN ecosystem is perfectly utilized.

5.4. Control and communications for UAVaaS

UAVs are highly dynamic in nature which is expected to reach a new higher level in coming decades. Here, an opportunity is being

Table 10
Comparison of mainstream UAV for 6G.

Technology	Height	Speed	Mobility	Hovering	Energy Resources	Endurance	Maximum Payload
Balloon	>20 Km	Slow	Low	Supported	Solar Cell, LiPo, Petrol	Longest	Large (>1000 Kg)
Fixed-wing UAV	Sea level – 16 Km	Fast (Horizontally) Medium (Vertically)	Medium	Not Supported	Petrol, Solar cell, LiPo	Medium	Medium (<1000 Kg)
Rotary-wing UAV	Sea level – 6 Km	Medium (Horizontally) Fast (Vertically)	High	Supported	LiPo, Petrol, Solar Cell	Low	Law (<100 Kg)

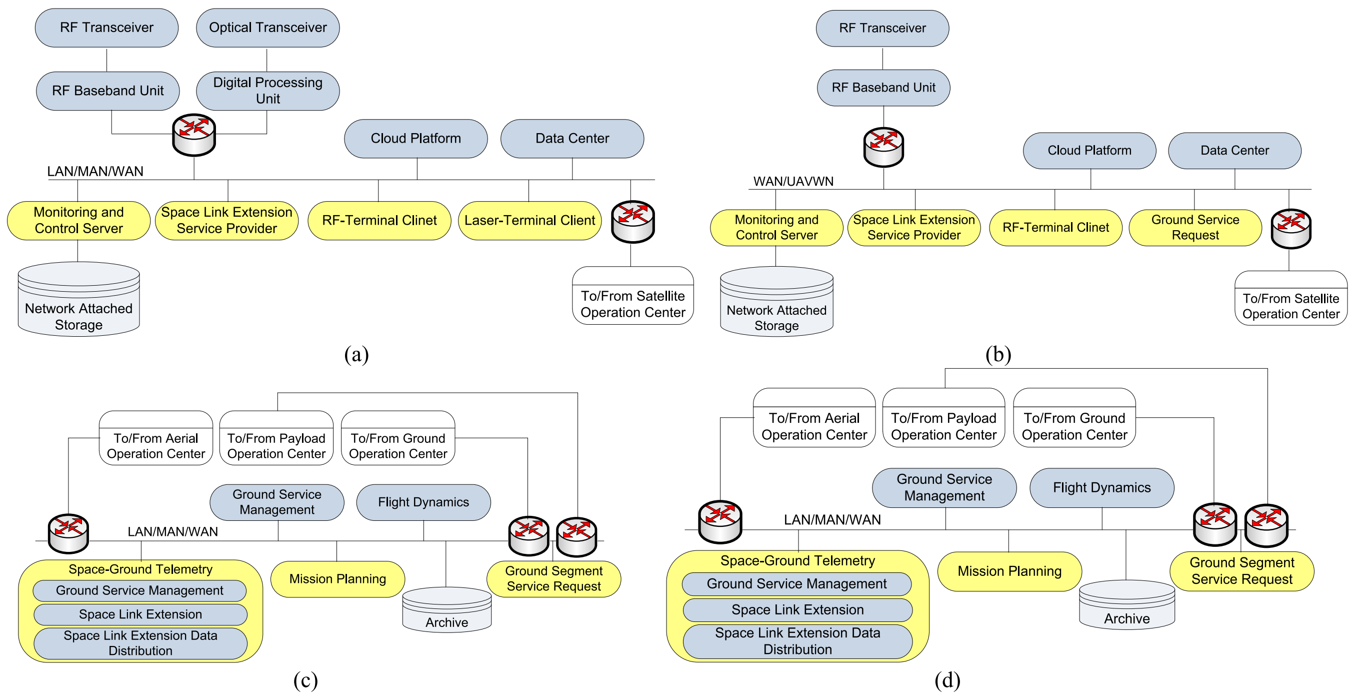

Fig. 11. Operation center elements design. (a) ground center design, (b) aerial center design, (c) satellite center design, (d) communication and control center design.

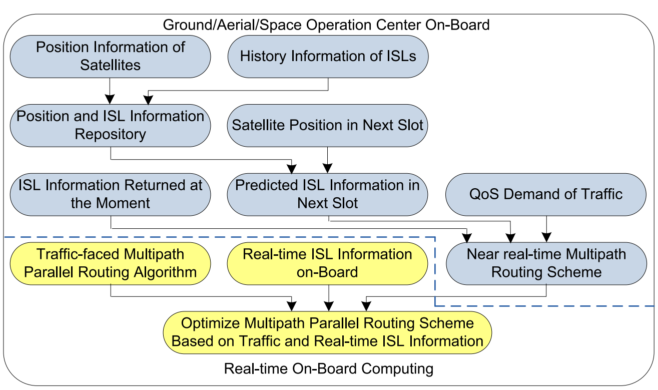

Fig. 12. Multipath QoS routing workflow.

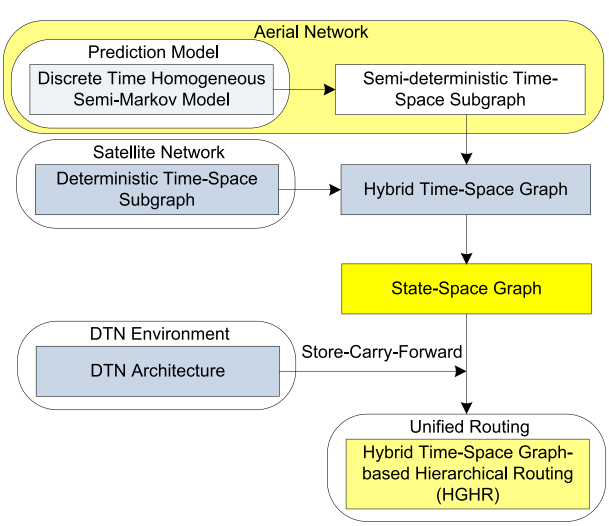

Fig. 13. Unified routing workflow.

envisaged within the UAV-based plethora i.e., communication and control. We can depict six parameters that can be highly useful to enact better communication and control services in 6G-SAGIN, such as, (a) UAV-satellite communication, (b) UAV-based relay communication, (c) multiple-UAV communication, (d) hotspot coverage extension, (e) swarm networking and (f) UAV-based network range extension. Intelligent flight control systems (FCS) may be put in place to augment communication and controlling features into the UAVs. The coordinated multiple point techniques (CoMPs) are assumed to perform good results in this regard. Whole communication and control unit can be partitioned into two layers, (a) UAV and (b) service layer. The UAV layer consists of A2A connections within the flying objects. Main focus is given to the service layer, where FCS, control and communication units pave a connected scenario for provisioning of channel tracking, trajectory navigation, complex system gain and sensor fusion services. Mechanical and micro inertial unit (MMIU) plays an important role to result into the sensor fused controlling framework for 6G-SAGIN (Lee et al., 2021). Control and communication activity of UAVaaS can be further subdivided into two ways i.e., singular and multiple UAV centric approaches. We discuss key points herein.

5.4.1. Singular UAV based communication and control

Altitude and attitude of a single UAV varies during the flight, resulting in the variation of beam direction and intensity. Thus, three key techniques should be addressed to make the beam formation in an optimized manner with optimal energy consumption. Firstly, an improved channel modeling scheme should be designed to minimize bit error rate while transmitting signals in line of sight (LoS) fashion. Adoption of 3 GHz-3THz frequency band would help formulating wireless backbone in 6G-SAGIN. mmWave and microwave both should be used simultaneously to enhance wideband transmission while complying with the M $\times$ N planar array structures. Frequency and time duplex division schemes should be employed to estimate downlink channel gain. Secondly, FCS-based channel tracking methods must be enabled with the singular UAV oriented 6G-SAGIN design frameworks. This is important

Table 11
Comparison between UAV designs.

Configuration	Takeoff/Landing	Hover	Payload (kg)	Endurance	Autonomy	Speed (s)
Fixed-wing	Conventional	No	≤14	≤ 60min	Full/Partial	≤22
Multi-rotor	Vertical	Yes	≤2.5	≤15 min	Full	≤11
Electric Helicopter	Vertical	Yes	≤5	≤15 min	Full/Partial	≤12
Gas Helicopter	Vertical	Yes	≤20	≤15 min	Full/Partial	≤ 20
Blimp	Vertical	Yes	≤4.5	≤60 min	Full/Partial	≤ 2.5

Table 12
Comparison between space and aerial elements.

Platform Type	Satellite			UAV
	GEO	MEO	LEO	
Altitude	35,786 km	7–25 K km	300–1.5 km	8–50 km
Motion	Stationary	4.9 km/s	7.5 km/s	15 m/s
Cell Size	0.2–1 km	100–500 km	100–500 km	5–200 km
RTT	~0.270 s	~0.095 s	~0.013 s	~0.003 s
Differ Delay	0.016 s	0.0134 s	0.0044 s	0.007 s
Doppler Shift	± 18.5KHz	± 150KHz	± 480.5KHz	± 100KHz
Doppler Freq	20 GHz	20 GHz	20 GHz	2 GHz
UE Speed	1000 km/h	1000 km/h	1000 km/h	100 km/h

when continuous navigation becomes immensely important for handling by the massive MIMO antenna models. Doppler shit, distance and azimuth angle computations must be aligned with the elevation angle. Such analysis can be obtained from the perturbation analytics with given inertial navigation factors. Kalman filter can help in modeling precisions into the channel tracking aspects. Lastly, the bream tracking approach with support from electrical cum mechanical adjustments would improve singular UAV centric service orientation. The concept here is to empower beam tracking schemes by the MIMO, global positioning system and motorized controls. Regular UAV navigation could be harnessed by using altitude on-board sensors. Electrical and mechanical adjustments are necessary to stabilize beam and dynamic isolation of sensory data with a given angular rate of the UAV (Hong et al., 2021). Use of phase shifter may be helpful in beam pointing towards 6G-SAGIN components placed over the ground or spatial regions.

5.4.2. Multiple UAVs based communication and control

Using a greater number of UAVs instead of just one is always better in terms of efficient beam formation and coverage aspects. However, with inherent benefits, such deployments bring new issues i.e. management of complex dynamics of the UAVs and accomplishment of mission critical applications (She et al., 2021). To resolve such problems three options could be paved that includes, cooperative communication, 3D coverage, and trajectory centric resource allocation. Cooperative communication concept interplays with the self-positioning aspect in multiple UAV deployment in the 6G-SAGIN scenario. It generates a number of advantages namely, independence on the number of antenna arrays, forming of spatial resolution, directed 3D beamforming, full utilization of mobility support, enhanced spatial gain, and robustness in the A2A communication. Herein, we can think of using two types of channels such as UAV-to-UAV (U2U), UAV-to-Space (U2S) and UAV-to-Ground (U2G). Such channels can be decomposed as per the direction of arrival of signal. Overall cooperation could be harnessed by involving sensor fusion, learning techniques, optimization control and rand reduction (RARE) techniques. Distance between the UAVs and trajectory can be autonomously computed to alleviate the performance level. Game theoretic solutions can be amalgamated with the caching and smart virtual antenna array abstraction. Thus, a concrete 3D coverage spectrum could be envisaged where amorphous cells could be deployed with the dynamic structure of UAV-based topology. Doing so would improve the scheduling probability of the user's plane. Suppression of signal blockage in this aspect is expected to be nominal (Guo et al.). Learning models can use pre-collected shelter locations along with the channel statistics and user's distribution in the application layer for lowering blockage probability. Finally, we can consider UAV trajectory centric resource allocation to reduce the distance of possible interference. Resulting into swarm formation of UAVs to allow exploitation of following features such as, caching, dynamic UAV topology, power consumption and multiuser communication scheduling. Resource allocation in this context imparts two time–cost parameters namely, FCS time–cost and wireless transmission time–cost. The cumulative time–cost impacts the power allocation and spatial distribution in the 6G-SAGIN. So, formulation of optimal multiple UAV deployment should cater the time–cost estimation on-the-fly. The bang bang control theory could be investigated for possible time–cost optimization. Further, the grey wolf optimizer algorithm may provide an opportunity to deal with optimized spectrum efficiency with a given time–cost constraint.

5.5. Prospects of UAVaaS

It is well known that UAVs shall undoubtedly enrich the user's network experience in the 6G-SAGIN era. We list four such key prospects that would be immensely obliged during the UAVaaS amalgamation with the 6G-SAGIN ecosystem, they are as follows. Firstly, communication protocols shall see new features to improve networking and data streaming design. Innovative protocols shall replace existing gerund-level communication schemes to allow flexible and dynamic UAV-based services. Synchronization and maneuverability among the flocks of UAVs would be certainly upgraded. Both navigation and information security need to be combined to enhance the overall security of the UAVaaS. Communication and controlling units of UAVs must be well equipped with the advanced security algorithms to guarantee integrity and confidentiality to the system. Integration of heterogeneous protocols, design frameworks and knowledge abstractions would surely result in a heterogenous situation in the UAVaaS. One should think of the 3D-heterogeneous deployment aspects to manage coverage ability, load mitigation and cellular service dissemination in proper fashion (Wang et al.). Lastly, the cost of design, testing and implementation of the UAVaaS must be carefully inspected before going for real-life application development. Time-cost tradeoff should be solved beforehand to minimize the error into the operator centric business amalgamation.

6. Element design aspects in 6G-based SAGIN

SAGIN elements need to designed in stringent manner to allow them establish and communicate in seamless fashion. Thus, we can enlist following key elements as the most important design aspects in 6G-SAGIN scenario, that includes laser terminal element design at the optical ground control unit, space terminal design at the space link, and data handling schema design for on-board satellite communication (Malik et al.). We also discuss the design considerations of the overall ground operation center and aerial operation center in conjunction to control dynamics.

6G-based SAGIN design should involve FSO along with RF links. All types of satellites (e.g., Geo, Meo, and Leo satellites) would communicate with each other to leverage a seamless communication paradigm towards SAGIN deployment. Internet data centers should be based on ad-hoc aspects within the satellites' periphery. Smart city, transportation, industry, and people shall be served with necessary actions as asked via the SAGIN elements (Varasteh, et al., 2019). Mainly, space, ground and aerial operation centers would integrate SAGIN under 6G networking scenario to enable multitude of heterogeneous services while involving innovative channel model and telemetry and tele-command (TM/TC). All the elements of SAGIN must cooperate to empower ground to satellite or vice versa signaling on the go. Besides, importance should be given to the automated repeat request (ARQ) and interleaving (IL) techniques to make SAGIN effective. Spread of fading-outages must be resolved by integrating forward error correction (FEC) tools. It is suggested to use at least 1 kHz tracking signal and 1Mbps data modulation signal (Alimi et al.). Thus, data bandwidth could be positioned beyond the tracking spectral boundary where utilization of line-coding schemes might improve overall service.

6.1. Terminal design aspects

6.1.1. Laser terminal

Reliable data transmission between ground to satellite stations could be provided by designing key elements like laser terminal and on-bard data terminal design. In the laser terminal design, two approaches could be considered such as, (a) ground station and (b) space station design. Careful consideration should be paved while framing both the elements so that optical transmission and reception are perfectly fitted against the need (Network (SAGIN), 2018). Ground station element consists of an optical aperture which is mainly made with a 40–80 cm diameter reflective telescope. An optical system consists of filters, relay assembly and optical beam splitter. Receiver front end is used to convert the optical signal to equivalent electrical signal. Received data is decoded at the digital processing unit. Moreover, link status update and information sharing are also paved by this unit. On the transmission side, a low-power seed form factor laser could be used whose radiation needs to be amplified by the following optical system in the line. The output optical signal is later transmitted by the optical aperture. On the other hand, an optical aperture is used to split the receiving and transmitting signals on the go. The optical system also performs the job of optical filters by changing the wavelengths be it uplink or downlink. Receiver frontend converts optical to electrical signal for further processing by the digital unit. Laser source in this element is used to transmit the digital signal.

6.1.2. On-board data terminal design

Satellites should be able to value RF-based sub-system that are capable of using packet utilization stands (PUS) as key sub-element in the data handling element on-board (Torrea-Duran et al., 2018). The RF transceiver acts as the interface between air and satellites that comprises antenna, signal amplifier up converter, down converter and modulator/demodulator (MODEM). Upon arrival of the valid signal of the consultative committee for space data systems (CCSDS)-type, it is converted into an equivalent bit-stream. The converted bit-stream is later piped to a command decoding unit (CDU). The header of the CCSDS signal is unpacked inside the CDU which is followed by possible error detection as well as correction. The Tele-command (TC) frame is then sent to the on-board computer (OBC). OBC then distributes the command packet to the designated PUS terminal for possible execution. TCs must be executed in an appropriate and pre-defined manner.

Consequently, such information may be downlinked along with telemetry and payload data for feeding the transmission side (Zhang et al.). In this case, two scenarios could be thought of, (a) wrapping of telemetry frame in accordance to the PUS guideline with added header or (b) combining the command link control words (CLCW) with the upcoming telemetry frame to allow it downlink, thus resulting into a faster feedback system for the tele-command packets. Automation could be placed if any problem arises during the up/downlinking phase. Thus, more reliable element might be provisioned however, following rules could be imparted into it such as, (a) incorporation of FSO channel uplink along with the OBC and TM/TC when TC-cable is certainly used for uploading from ground to satellite terminal, (b) telecommands are routed to the command decoder when automatic repeat-request (ARQ) scheme is failed or (c) upon inclusion of commands, command lists could be uploaded to the OBC for avoidance of possible command queueing conflicts.

6.2. Operation center design

6.2.1. Ground center design

Integrated ground operation center design relies on effective augmentation with the FSO and RF station (Li et al., 2020). Laser terminal units should be aligned with the network and application monitoring elements to keep track of the center's state of operation. Optical transceiver and RF transceiver units are connected via local area network (LAN), metropolitan area network (MAN) or wide area network (WAN). Standard communication protocols including user datagram protocol (UDP) and transmission control protocol (TCP) could be actively used for information sharing. Uplink and downlink data stream sharing and allied functionalities need to be paved by the RF terminal with help of network switches. Advanced 5G communication techniques might be involved with the monitoring and control server where a network storage device is attached. Such storage facility empowers ground stations to perform faster caching thus minimizing delay in information processing. Otherwise, networked cloud platforms and data centers can serve space link extension (SLE) service providers to get and send operation control information with the satellite centers.

6.2.2. Aerial center design

UAVs are expected to play the most vital role in the 6G-SAGIN ecosystem, thus envisioning aerial operation center design could improve overall network availability to a higher level (Li et al., 2019). We envision that 5G enabled UAV-based wireless networks would impart significant contributions to establish a seamless connectivity between various types of UAVs. In such cases, RF transceivers can be solely used to uplink and downlink signaling tasks. As in ground center, aerial center also integrates cloud and data centers within the design spectrum. Besides the use of SLEs, aerial center design gives main importance to the RF terminal unit that allows ground service requests to act accordingly. Attached networked storage facility improves data caching and servicing jobs on the fly.

6.2.3. Satellite center design

Satellite centers shall involve a larger scale of design metrics than the earlier mentioned schemes. We envision both RF and optical transceiver to take charge of signaling events. Two key types of data are handled by the ground segment of space centers, they are, (a) operational data and (b) management data. Operational data processing is down in two modes, namely on-bard real-time and offline. In real-time actions, payload telemetry and space center house-keeping related commands are executed. Spatial ranging, doppler effects and angular specifics are measured during offline mode (Li et al., 2019). Further history is logged for future processing. Management data type is used to aid support to the station TM and TC activities during real-time mode. Otherwise, service management, task scheduling, orbital tracking and station configuration jobs are done offline.

6.2.4. Command and control center design

Mission critical applications are planned and monitored by the space center (Singhal et al., 2015). Thus, it should maintain command-ready file systems in the time stamped fashion. Such files need to be executed based on the given TC within OBC. Simultaneously, sequence of events (SOE) should be monitored closely to pave effective task scheduling in order to produce appropriate results. In addition, flight dynamic, offline working facilities and data archival techniques are integrated. The ground segment service requests are considered to work with aerial and ground centers. Main aim of this center is to control the payload related operations in all the earlier mentioned centers. Innovative space-ground telemetry element is hereby augmented to provide three key features, such as, (a) ground service management, (b) SLE distribution and (c) SLE orientation. Moreover, on-board simulation tools may be used to visualize real-time command-control functioning within selected SLE user distribution TM/TC paradigm.

6.3. Link disturbance mitigation in designs

As the 6G-SAGIN is expected to host all possible types of design elements in various layers of spatial spectrum, it must be capable to do the same in completely fail-proof mode. To cater to this need, 6G-SAGIN would rely on two vital control-loops such as, (a) direct feedback and (b) indirect feedback. In the direct feedback method, channel fading specific actions are served by using acknowledgement and ARQ via optical terminal (Wu et al., 2019). Whereas, indirect feedback scheme allows space, ground and aerial centers to personal OBCs to trigger telemetry commands to safeguard single point of failure. AQR might be investigated to seek fail-safe communication between the ground, aerial, space and command-control centers. Triggering of retransmission of payload data streams should be served when requested. Optical satellite data link (OSDL) can act as a return-channel during the uplink process. Further, 6G-SAGIN could use a packet counter module to uniquely identify lost data packets during transmission. Thus, optical channeling would help in integrity-aware system design. In such a case, the whole SAGIN infrastructure could work independent of operators.

6.4. Data stream standardization in designs

6G-SAGIN must involve standardization policies to evolve existing protocols to work with futuristic designs. Such as, SLE protocol should be revisited to improve communication within the space, ground and aerial centers (Li et al., 2020). Internet protocol (IP) can be used as the base of SLE while allowing encapsulation of telemetry commands in alignment with space link protocol (SLP). Further, improvement should be made in the existing frames of TM/TC so that command link transmission units pave optimal services. Thus, three main services could be enhanced, such as (a) forwarding of data frames from the communication link transmission units, (b) returning channel frames and (c) renewal of all frames. Both SLP and SLE allow accuracy in data delivery between other centers in existence. 6G-SASIN would require cross support transfer service (CSTS) to enhance capabilities of all operation centers. Control service augmentation must be included to encompass real-time TM/TC among the operation centers. Further investigation should be made to improve universal space link protocol (USLP) to facilitate symmetrical link, telemetry formats and achieve a very high data rate. Message abstraction layer (MAL) needs to be used for encapsulation of transfer of file header between operation centers to satellite centers. New research should be done to leverage integration of CCSDS with the delay tolerant networking (DTN) and file delivery protocol (FDP) for establishing large volume data between satellite operation centers to other SAGIN centers on the earth.

6.5. Routing techniques of designs

6.5.1. Multipath QoS routing

Despite using a single transmission performance index, multipath quality of service (QoS) aware routing improves information sharing in the SAGIN ecosystem (Bassoli and Granelli, 2019). Inter satellite links (ISLs) are involved to utilize near real-time and historical data about ISLs. Such routing can be computed either at ground or aerial operation centers. Pre-computed routing policy is reconsidered later on to adjust QoS requirements as per the need of SAGIN. 6G-SAGIN must allow multi-path routing between two operation centers for enhancement of high arrival rate as well as extreme low latency aware data transmission. Load balancing among various operation centers is carried away by utilizing multiple link resources. In 6G-SAGIN, multipath QoS routing should be divided into two phases, such as (a) pre-computing on-board systems residing at ground, aerial or satellite centers and (b) real-time computing on board. Pre-computation involves three key steps such as, (a) establishing the position and ISL information knowledge repository (PISLIK) depending on the position information available and log of ISLs, (b) prediction of satellite position in next slot (e.g., bandwidth availability, delay etc.), and (c) combination of near real-time feedback ISL with the possible QoS demand and traffic persistence. Later, the pre-loaded near real-time multipath routing scheme is integrated with the traffic-faced parallel routing and real-time ISL information to leverage optimized multi-path parallel routing policy.

We envisage that 6G-SAGIN would utilize dynamic topology of satellite as well as UAV network to pre-compute multi-path routing (Sodnik et al., 2017). Simultaneously, multi-path parallel routing depends on four key aspects such as, (a) link bandwidth allocation, (b) link bandwidth pre-emption, (c) high-end data streaming, and (d) parallel transmission network protocol (PTMP). The PTMP is based on standard UDP packet structure that includes, data, routes, acknowledgement number, sequence number, start position at initial, association identity, checksum, length, source port, and destination port. Thus, this scheme would ensure high availability of data traffic and enhance link resource pool and balanced SAGIN.

6.5.2. Joint service placement routing

Careful determination of path to routing services improves QoS in SAGIN. Thus, 6G-SAGIN would aim at solving such challenges where air-to-ground (A2G) and direct-A2G (DA2G) links are present. Cost, bandwidth and latency are three main factors that vary in A2G or DA2G links (Cornwell, 2017). The problem increases with higher mobility of aerial as well as satellite operation centers. We discuss a newly introduced method called mixed integer linear program (MILP) that targets to infer better quality from the joint service placement and routing (JSPR) schemes. It is observed that long-term cost due to the mobility of UAVs and satellites impacts the service quality in the SAGIN. Costs of routing of information from aerial and satellites to the ground centers heavily adds on the service instance and service mitigation aspects in SAGIN. The JSPR can significantly improve the total cost by allowing two types of modes such as static and mobility-aware i.e., dynamic. 6G-SAGIN should be aligned in accordance to the combination of DA2G links between the ground and aerial and satellite networks. Static JSPR works as follows: firstly, a set of SAGIN-based services are floated in different time slots. Then, they are placed as per the requirement of aimed service instances in the given data centers. Lastly, finding the best route such that overall costs due to network service mitigation and service instances is minimized. Dynamic JSPR adds a new parameter into the earlier scheme i.e., time of the mobile elements. It aims at leveraging three key considerations such as, (a) number of service instances to be used in future i.e., placement, (b) routing path determination, and (c) service migration control. A European-based SAGIN infrastructure is tested to investigate the cost reduction so that trade-off between routing and service migration could be effectively determined.

The technique is further improved by using the placement of virtual machines (VMs) in the problem space (Biswas et al., 2017). VM-aware SAGIN addresses four issues namely, (a) number of VMs to be placed in each data center service per time slot, (b) VM to SAGIN communication path selection, (c) testing the necessity of VM migration, and (d) minimization of cost of services by combination of earlier issues. Thus, it is envisaged that 6G-SAGIN would be able to lower down the network servicing cost with improved data center and VM mitigation.

6.5.3. Unified routing

6G-SAGIN would be benefited by involving the hierarchical routing (HR) algorithm. In such a scenario, recent work has proposed a hybrid time–space graph centric HR (HGHR) for solving challenges associated with the mobility and time-varying topology management (Heese et al., 2017). The HGHR works on top of a hybrid time–space search technique while alleviating deterministic and semi-deterministic networks. Earlier one applies for satellite networks and the latter is meant for the aerial network with an added semi-Markov modular approach. A message forwarding rule-based engine then caters the hybrid time–space under the provision of store-carry-forward scheme. The aim behind the HGHR is to adopt improved results in terms of overall power consumption. Further, end-to-end delay mitigation and message delivery ratio are achieved with higher success rate. It is found that HGHR outperforms traditional DTN, topology characterization and predicted node movement mechanisms. The HGHR is capable of predicting the UAV position, contact time, contact probability, sojourn time probability, and state transition probability.

7. Open challenges

7.1. Cognitive spectrum utilization

6G-SAGIN is envisaged on top of the utilization of spectrums which are not being used presently. Thus, involvement of cognition into the spectrum utilization perspective shall become a difficult task (Hauschildt et al., 2017). It is expected that FSO and higher bands may be used to find a way out of this spectrum crunch. Spectrum sensing-based technologies might become very useful in this aspect. Not only sensing, spectrum sharing should be achieved to fulfill the dream of 6G-SAGIN. Overall cellular core networks could be segregated into various layers such as macro-cell, dedicated cognitive small-cell and cognitive M2M layer. Such cells can be connected via backhaul connection ecosystem, thus resulting in the utilization of smart users' environment with the help of SAGIN-centric cellular stations. Cognitive radio needs to assess TV white space for application deployment in the SAGIN use cases.

Investigations may be performed to check the applicability of both narrowband and wideband sensing schemes. Importance may be given to the Nyquist-based wideband and compressive wideband sensing so that non-blind compressive sensing and filter band detection techniques could be involved. Further, multi-band joint detection and wavelet-based detection would be leveraged along with the blind compressive sensing for realization of the spectrum utilization (Zhu et al., 2020). We can also look for the cyclostationary detection, matched filter detection, covariance-based detection and machine learning-based detection toward cognitive spectrum dissemination in the 6G-SAGIN. However, focus can be imposed on the orientation of high sampling rates, analog-to-digital conversion, and signal processing while working with the wideband spectrum policies. Selection and estimating of sparsity level would require prior knowledge, thus resulting in handling of noise uncertainty. 6G-SAGIN would need very low SNR where compressive sensing is very inaccurate. To solve this, one can use software defined radio units with low-complexity and computation cost ability. Further, the effect of shadowing and fading effects must be mitigated before proper use of cognitive spectrum utilization in 6G-SAGIN.

7.2. Cooperative implications

6G would require advanced multiple beamforming capability to improve high power density and super-flexible multiplexing during data transmission. SAGIN would require such cooperative beamforming techniques for satellite communications where MIMO-based array multibeam formation could be facilitated. We can deploy a phased antenna array to provide simultaneous large area beamforming coverage with extremely narrow inter-beam interference. Using a lens and reflector, a multibeam centric multibeam antenna could be used to harness cooperative beamforming. Such technology can be used along with the 6G-SAGIN communication system while using distributed antenna assembly to minimize the power consumption during the beamforming process. However, such design can be hindered with disturbances into the line-of-sight alignment between satellite and ground connectivity. So, a virtual MIMO system needs to be intervened where multiple satellites can cooperatively serve the users' needs (Moon et al., 2020). Here, a single antenna can help both the satellite and terminal station to improve the disturbances for deviation of line-of-sight alignment. 6G-SAGIN may also face the problem of uniquely identifying the user on a terrestrial domain when users are placed in close proximity to each other. Thus, multi-group beamforming can be involved to minimize the correlation between the user centric channels. One can think of using clusters of satellites moving on different orbits or the UAVs on the fly to relay the data via cooperative beamforming. One can also think of a multi-group multicast system for improving the QoS during cooperative beamforming. More work should be done to investigate the possibility of joint beamforming to enrich the 6G-SAGIN system.

7.3. Handover

6G-SAGIN would involve a number of dynamic objects including UAVs, satellites and other terrestrial transportation elements. It will make the task of handover management very difficult, especially the user equipment handover. It is also possible that handover from one SAGIN element to another (for example satellite to UAV) might create havoc. We should find efficient handover algorithms to optimize the SAGIN-based infrastructure. Firstly, the user equipment handover can be broadly divided into two categories such as network-layer and link-layer handover. Terminal IP addresses are frequently changed during the network-layer handover. Mobile IP (MIP) approach can be tested further to check its efficiency in the 6G-SAGIN ecosystem (Inoue, 2020). Although it is suitable for a centralized service-oriented domain i.e., ground station. To connect the handover process to other elements of Sathe GIN, a distributed IP (DIP) approach can be implemented. Herein, distributed anchors need to be placed across the users' plane to allow a smooth handover process. Secondly, link-layer handover can be used to transfer the operation from one active connection to another newly created UAV or satellite beam spot. But this might result in excessive complexity over the mobility management module. To resolve this issue, we may determine the footprint of every beam. Then, we can act according to the location of the related beam or cell. SDN could be an excellent option to minimize all such issues while providing QoS-aware handover between UAVs and satellite beams.

We should also think of gateway handover issue dissemination while covering both the UAV and satellite enabled gateways. A user connected to the UAVs gateway needs to access the satellite gateway for changing the beam location. To resolve this issue, one can use the multi-beam multi-gateway (MBMG) system whereby using Ka band spectrums. The feeder links can be augmented with the gateway diversity modules to reduce the packet loss and improve time-adaptive performance analytic services. New simulation tools and open test-bed design should be the next jobs to do.

7.4. Routing in air and space

6G-SAGAIN might work on top of various time-varying topology models that would make the mapping process from physical to routing addressing a difficult task. One should attend this task otherwise it can lead to significant packet loss or huge delay in the SAGIN ecosystem. Minimization of allied risks could be apprehended by utilization of following, (a) flying-objects' trajectory information, (b) link state prediction and (c) ephemeris data about the satellites. One can think of both virtual node and topology aware routing algorithms to be deployed before the flight of UAVs or satellites. But such design can only be optimally applicable to the single-layered flying-objects' framework. A multi-layered design of SAGIN must be accommodated with the master–slave mode of routing agenda. For each layer of SAGIN, a higher layer would act as the master. For example, MEO shall act as master of LEO satellites. LEO satellites can act as master of the balloons or fixed-wing drones (Hefele and Costa-Requena, 2020). However, depending solely on the layered approach might not give expected reliability of the 6G-SAGIN. Multiple factors, including dynamicity of topology, failure of UAVs or intermittent radio link obstruction can be safeguarded with the delay tolerant routing protocol. We need to use stochastic, enriched and deterministic DTN routing algorithms for both the UAVs and satellites. Over computation load on one UAV can be further lowered with help from the inter HAP routing algorithm.

7.5. Security

Security in 6G-SAGIN must be highly sophisticated to safeguard the interest of user equipment and all the SAGIN-based elements like UAVs, satellites and ground stations from external attacks. A new set of space data security protocols should be paved to improve end-to-end confidentiality. SAGIN might be required to improve the security of three key layers of architecture such as network, link and physical. Network layer security shall involve more secure satellite and UAV data stream protocols. Also, performance enhancing proxy systems need to be encompassed. Conventional key management schemes should reduce the complexity of underlying implications while in action. Also, intrusion detection algorithms need to be readdressed to act under the limited computational capacity in the 6G-SAGIN. Link layer security shall face new challenges during the era of 6G-SAGIN. We must look into the reutilization of revised packet data convergence protocol for effectiveness of on-board gNodeB (gNB). Also, user equipment security must be addressed during the handoff and channel fading scenarios. We need to employ hierarchical security deployment policies in the 6G-SAGIN to leverage improved service augmentation while covering context exchange and re-authentication of various access networks. Physical layer security algorithms are mainly computationally expensive; thus, it is not feasible to deploy in UAVs. Thus, modified security options should be chosen based on the intrinsic channel characteristics. In such a case, we can think of deploying the zero-forcing technique to provide security to the UAVs and satellites computing stations. One should think of various novel secure ideas to mitigate the issues like line-of-sight communication error rate burst, and propagation delay. UAVs and satellite channels are vulnerable to the denial-of-service attacks and radio jamming attacks. Thus, advanced non-terrestrial security tools must be accommodated into the 6G-SAGIN ecosystem.

7.6. Standardization

6G is currently at the discussion level of many standardization bodies. Thus, specifying exact details about the use cases, technical issues, and prospective way outs are not finalized yet. The 3rd Generation Partnership Project (3GPP) has initiated working groups (e.g., SA1, SA2, RAN1, RAN2, RAN3) to find action map of satellite access network design in next generation communication technologies, integration of satellites with the 5G and devising architecture of 5G-enabled satellite access networks (Hasegawa et al., 2020). Similarly, the European Telecommunications Standards Institute (ETSI) has launched a work group named SCN TC-SES that is working on the way out over the integration of UAVs and satellites together. More emphasis is being given to the development of edge delivery models and VNF integration with the satellites via multicast approach. ITU-R is engaged in devising key elements for satellite and NTN integration with 5G. We find that many organizations are bust with provisioning of SAGIN for 5G or next generation technologies, they are silent for 6G. It is high time that we should move on with the 6G for requirement analysis of SAGIN.

7.7. Layered architecture

SAGIN architecture is best described by the layered-approach. 6G can help to achieve the layered orientation of the SAGIN after resolving certain challenges. Any layered architecture of SAGIN should comprise of granular levels of various elements. Thus, interaction or intermediate layers should be precisely leveraged within the architectures. Intercommunication between the layers of the 6G-SAGIN architecture needs to be done with immense involvement of bottom-top approach. In this aspect, physical devices can be placed at the lowest layer and the service or applications can be positioned at the top (Banerjee et al., 2020). However, an opposite design can also be imparted with invasion of the top–bottom structure, Herein, all physical elements considering the IoT, sensors, actuators, power supply and peripheral objects should be placed. Gradually, next deeper layers shall comprise height-wise elements of various UAVs and then the satellites. Such positioning can improve the actual dissemination of the 6G-SAGIN perspectives. Security and privacy aware implications need to be mitigated throughout all the layers irrespective of the design style. One should emphasize on the architectural augmentation of the SAGIN infrastructure with the possible involvement of the 6G-based protocol suite.

7.8. HetNet design

6G is expected to include various types of tools, technologies and communication protocols. It would result in a complex scenario of heterogeneous (HetNet) networking structure. With extensive use of microcell, picocell and femtocells, 6G-SAGIN would emerge as a great example of the HetNet. As the HetNet characteristics would increase, 6G-SAGIN would become very difficult to get managed by traditional command-control centers usually positioned with the service providers and network operators. Such dependency over the network operators would incur huge cost to run the business. So, one should focus on estimation of wireless coverage zones and the placement of the SAGIN element (e.g., indoor or outdoor). Such HetNet designs might come with challenges like mobility, aggregation, interference between the RATs, and capacity determination of the heterogeneous wireless networks (HWNs). We can achieve a better HetNet centric 6G-SAGIN once certain issues are resolved. For example, cell-free MIMO designs can be seen as an alternative to traditional cellular networks while developing a HetNet ecosystem. We can include a massive number of highly distributed antennas across the 6G-SAGIN to establish connection with the distributed RAN. One can also investigate the appropriateness of the access points in such a scenario to serve a number of users while estimating many channels. Such channels can be used along with the beamforming capacities of the fronthaul related users. Thus, a self-optimizing network (SON) functionality can be imposed into the SAGIN infrastructure to empower the network densification. Plug-n-play type SON can be accommodated with the significant reduction of time and cost of the SAGIN deployment.

7.9. Gateway design

Appropriate selection of gateway in the 6G-SAGIN could certainly improve the overall functioning of the system. Thus, proper comprehension about the gateway design is a must (Ding et al., 2020). One should oblige the notions of the transfer gateways in the SAGIN use cases. Optimal design of gateways can impart a significant role into the enhancement of the manageability of the routing algorithms implemented herein. For example, ground stations should use stationary gateways which are responsible for monitoring of traffic delivery from ground to the aerial or satellites. While designing such gateways, factors like meteorological conditions and geographical placements must be well catered. UAV-based gateway designs need to consider the establishment of direct S2A and A2G linkages. Satellite gateways need to enable inter-spatial communication as well as ground/UAV communication on the go. Thus, one may find the selecting optimal number of gateways for all-plane communication is very difficult due to spatial positioning of the earth. Following issues should be resolved: (a) higher velocity of SAGIN elements need to accommodate with the dynamically changing topology and handover schemes, (b) inclination of UAVs for fitting line of sight linkage and (c) edge AI aware authorization on-the-fly.

7.10. Energy efficiency

All the SAGIN elements and underlying backhaul network should be designed cautiously to minimize the overall power consumption (Hadi et al., 2020). Limited power supply in the low height rotating-wing UAVs require the greatest attraction of all. Battery-free designs can be investigated in harnessing energy efficiency. Special attention should be given while designing the communication channels so that associated protocols can mostly consume very less energy. Payload distribution of such UAVs and the higher altitude SAGIN elements must be well monitored and continuously managed. Self-aware movement and trajectory selection schemes could be investigated to further optimize the performance of the system. Task offloading and peak-to-average power ratio should be maintained all the time. A y change into the protocol suite of dynamic topology must conform to the specific requirement of the energy constraints. Edge-computation can increase the power consumption of an UAV or satellite, so use of photonic as well as triboelectric nano-generator (TENG) could be best fitted in 6G-SAGIN design. Energy harvesting techniques from the environment is a good option herein situation.

7.11. On-the-fly data center

6G-SAGIN shall enable some of its elements to act as the on-the-fly data center (OFDC). The aim of such OFDC is to leverage a significant amount of data storage and highly distributed data servicing to other SAGIN elements. Mainly fixed-wing UAVs and gas balloons can be used as the OFDC units due to their capacity to carry large payload and more energy utilization. A set of geo satellites can be converted into the OFDC to enable seamless data aggregation and dissemination point in space. There remain some key challenges while making such provision of OFDC in the 6G-SAGIN scenario. For example, implications of huge ad-hoc and wireless storage area network (SAN) design. It would require distributed but synchronized availability and synchronization services. Also, periodic improvement of capacity of OFDC would require the rearrangement of power, cooling and spatial constraints. Threat management of the SAGIN-based OFDC needs to be well handled so that SAGIN elements could be facilitated with the efficient data service measures. Also, new algorithms must be devised to cater the zero-day payload issues in the OFDC. It is seen that 33% of data in data centers are unused most of the time. In OFDC, we need to deploy a distributed redundant, obsolete and trivial (ROT) algorithm to deal with such data. At the same time, we need to think of scheduling of equipment upgrades to keep the OFDC lifecycle active. Most importantly, optimization of energy and cost expenditure per OFDC should be of great focus.

8. Future direction

8.1. Synergy of 6G-SAGIN

We expect that prospective utilization of the SAGIN could be highly enriched when combined with the 6G technology. A synergy between these two is highly required to emphasize over the conglomeration of the service spectrum. Possible way outs should be investigated to find the feasibility of amalgamating SAGIN with 6G. Feasibility analysis must incorporate the cost-benefit tradeoff for the network operators (Zhang et al., 2020). Synergy is required in following aspects such as, high altitude adaptability, moving networks, large beam footprint and constrained payload mitigation. Impact analysis is to be done over the delay shift, delay variation, propagation delay, doppler shift, differ delay, processing capability, architecture and limited protection. Potential solutions in these aspects could be perceived as the hybrid automatic repeat request (HARQ) feedback, customized power control, reconfigurable design, smart gateway diversity, frequency shift compensation, and prediction-based adaptation. Further investigations can be performed to seek the doppler pre-compensation, time offset, payload size reduction, and anti-jamming strategies.

8.2. Under-sea communication

6G will revolutionize the connectivity of all spheres, especially undersea communication or underwater communication. 6G-SAGIN may require seamless communication with the undersea network. Thus, one should think of using very low frequency (VLF) signals in the range of 3–30 kHz that can penetrate the seawater till 20 m (Bsebsu et al., 2020). We should extend existing submarines' communication range for VLF signaling. The broadcasting antenna should be large enough to catch the VLF signals from the undersea. Ground-to-submarine (G2SM) channels should be one-way broadcast, however ascending to periscopic depth, one can make such a connection bidirectional. We can perceive only 300 bps by using VLF, so only text messages and simple voice could be sent at a low data rate. 6G would leverage a wider extension of coverage area and it is expected that proper combination with the VLF may be put into the appropriate place. Some military applications use extremely low frequency (ELF) with 3–300 Hz to penetrate seawater of hundreds of meters. We can use a dipole antenna array with the UAVs to establish a feasible communication with the submarines. One can use NATO-based Ramon god of gateways to establish communication with the undersea modems with as small as 60–900 Hz frequency. However, options are open to enable the use of acoustic and combination of radio-acoustics with the 6G-SAGIN.

8.3. Intelligent offloading

Invasion of the intelligent offloading may improve the existing situation of terrestrial workload distribution to higher levels in the 6G-SAGIN. We should impose QoS and quality of experience (QoE) centric offloading approaches for the SAGIN ecosystem (Ahmad et al., 2020). Doing so would help the SAGIN to act efficiently while improving overall task load distribution. We can include machine learning-based traffic monitoring with support from the edge analytics in this regard. Use of SDN might enact the opportunity in a more specific manner. One should consider key factors while dealing with the intelligent offloading practices in the 6G-SAGIN such as, link stability, link cost and link capacity. Real-time delay tolerant task management modules are responsible for leveraging optimum offloading strategy.

8.4. Dew computing

Dew computing is an emerging computing paradigm that aims at facilitation of purely user experience centric edge services with the help of innovative dew services. Dew computing could be seen as a prospective option for 6G-SAGIN deployment that can improve user experience to a higher level (Ray, 2018). Dew-cloud architecture disseminates peer-to-peer communication between the cloud and dew device via single-super-hybrid link. It is possible with 6G to achieve direct device-to-device connectivity with sophisticated mode of plug-in services consisting of synchronization and computational domain of actions. Dew server can be placed inside the UAVs and satellites' on-board system to act as dew client. Thus, other local machines and related tools can be integrated with the dew client in the form of a dew cluster. Such clusters can provide real-time data service in cached format to which the dew client asks for. A privacy-preserving aspect can be seen in this approach that can leverage dew client programs run on top of dew database management systems. Such systems help the dew client to perform customized dew script with auto-update and network table storage facilities. As a whole a dew client can provide its user a complete experience of internet data services without or minimal intervention of real-time backhaul network connectivity (Ray, 2018). Thus, dependency over the 6G backhaul could be minimized and overall traffic and privacy aware SAGIN ecosystem can be formulated.

8.5. Cross-layer communication

6G-SAGIN is an expected function in various layers of abstraction. Thus, a cross-layer communication system is highly important for the success of the SAGIN ecosystem (Guan et al.). While resolving the cross-layer communication deeds, 6G-SAGIN should encompass to follow several way outs. For example, tracking fast fading channels in the 6G should be carefully placed into the SAGIN infrastructure. Downlink synchronization is another aspect that must be conformed to the cross-layer optimization (Zhang and Guo, 2019). Channel estimation and timing advancement are necessary actions to adopt cross-layer augmentation in the 6G-SAGIN. We should dynamically change the HARQ buffer size as per the necessity of channel representation. One should find new ways to update UAV and satellite location and the user equipment handover policies while working with cross-layer apprehension. Higher flexibility and energy efficient design may improve cross-layer facilitation with enhanced mode of QoS. Further, on-board protection of UAV and satellites may be sought for improvement of cross-layer interaction.

8.6. Blockchain

Blockchain is an emerging technology meant to provide high security, privacy-awareness and transparency to network use cases. Thus, 6G-SAGIN must include blockchain technology to retain network activity logs into the immutable blocks stored in a decentralized manner. UAVs, satellites and ground stations can host as the block storage medium while applying cryptographic hash. Based on the requirement, private, public or consortium-based blockchain can be used in the SAGIN ecosystem. Decentralized consensus algorithms could be deployed in the 6G-SAGIN nodes where authentication of a user can be collectively approved or rejected based on the consensus scheme. Such robust workflow helps to improve mass collaboration among the SAGIN elements. Malicious attacks on double spending and reproducibility get highly reduced (Pin Tan et al., 2021). Main usage of blockchain in the SAGIN infrastructure could be its decentralized behavior which can be largely utilized with enhanced data quality and best-effort computational trusts. One can think of multi-version concurrency control (MVCC) in the decentralized ledgers across the SAGIN platform. Investigation should be performed to seek the way out for smart contract deployments on-the-fly mode into the UAVs and satellites. New software development tools and SAGIN-based crypto-currency should be involved to reward the network operators.

8.7. Caching capacity

Caching in the distributed system needs special attention to the extension of local cache to the global scenario. Main aim is to store distributed and web-based session data into the cache elements. Instead of using a database server, one can use web servers to store the distributed data into the cache. This helps to involve information-centric networking. In 6G-SAGIN, cache coherence facility can be opted to provide uniformity of SAGIN data to share among the elements so that it ends at the UAV or satellites' local cache. In SAGIN, distributed write propagation and transaction serialization require special attention. However, the coherence mechanism should follow distributed snooping and distributed directory-based approaches. Combination of distributed snooping and directory-aware services might improve the coherence specifics into the 6G-SAGIN ecosystem. Investigations need to be performed for checking the distributed coherence into the on-board multi-processor assemblies in the UAVs and satellites (Hong et al.). Synchronized write-invalidate and write-update type snoopy protocols could be deployed into the SAGIN. Issues like scalability and inconsistency in the shared data protocols need to be resolved. Moreover, the distributed cache-transcendent algorithm can provide an optimal cache-oblivious algorithm to use asymptotic sensors for optimal cache performance in the 6G-SAGIN.

8.8. Network operator

6G-based network operators must conform to the seamless services as envisaged during the SAGIN integration. Extremely enhanced mobile broadband (eeMBB), extremely reliable low-latency communications (eRLLC) and ultra-massive machine type communication (umMTC) centric services need to be revisited. Virtual network slicing schemes should be developed to augment the performance profiling of various service needs (Elayan et al., 2018). Augmented reality and virtual reality aware disseminations must be coped up with the proactive content caching techniques. Network operators should allow multi-hop networking and device-to-device communication throughout the system. One global standard for seamless vertical handover should be provisioned by the network operators. Command and control aspects should be carefully depicted with the UAVs so that efficient service abstraction could be mitigated. Moreover, new types of network operations and remote work locations need to be optimized. Latency minimizing telecommuters can be seen as cost-effective and flexible alternatives to existing network operators.

9. Applications and limitations

9.1. Accident coverage

SAGINs have enormous role to improve existing car accident coverage scenarios. Most of the time, a car accident happens in highways where network facilities may not be appropriately available. Further, the information about the accident should be propagated to nearby hospitals and police stations immediately to increase the chance of saving lives of the victims. Existing network infrastructure is less aware to such needs. We envisage that SAGINs with help of 6G can improve the accident coverage by using UAVs. On the other hand, accidents can be vulnerable in the situations like ship sinking in the mid sea. In such contexts, 6G-based SAGIN is expected to provide significant network communications services to save lives.

9.2. Cybertwin in petroleum industry

Petroleum industry is one the major sources of economy and simultaneous daily livelihood via direct or indirect ways. Cybertwin is being sought as the key enabler of next generation industry where each segment of physical entity shall have its digital replica to augmentation of industry level dynamics and embedded digital twin. Such aspect in petroleum industry will impact tremendously in near future while covering all aspects of financial gain and risk minimization during the production. The whole supply chain management related to petroleum industry will come under the purview of cybertwin. SAGINs can integrate the IoT, edge, and cloud computing along with 6G to uplift the real-time monitoring and control of petroleum manufacturing processes. Cybertwins can be accommodated with connectivity, modularity, homogenization, reproducibility, and digital trace marking with the SAGINs.

9.3. Smart healthcare

Smart healthcare is still a myth in many parts of the world. It is only visible in some of the developed nations with sophisticated mindset citizen. Thus, an efficient design and remediation of technology enabled healthcare is a primary mandate of the time. Majority of the world population reside in the rural or remote locations where advanced medical facility is not always available. SAGINs can improve the health services by incorporating seamless connectivity with UAVs, satellite communications, and ground stations. For example, a dementia patient can be continuously tracked by the family members via drone-based ad-hoc network even if the cellular communication is not possible. 6G can certainly assimilate the real-time aware delay minimizing schemes to immediately leverage healthcare.

9.4. Medical drone delivery

In recent times, the world is facing several traumatic incidents, especially the COVID-19 virus spread and other war-like emergency. Medical drone delivery is being thought as a potential candidate to mitigate the life-saving and monitoring activities. For instance, a person who has just felt a heart attack can immediately ask the nearby hospital to send the defibrillator to be sent via UAVs for health support. Similarly, a patient who is being admitted to the hospital or being discharged from clinic can be guided by the UAVs both outdoor and indoors to find appropriate facilitation unit. 6G enabled SAGINs shall empower medical drone delivery with auto-guided systems and continuous command/control (CC) augmentation. Further, such drones can be useful to supply drugs, blood test kits, pathological agents, samples, and light-weight medical instruments to the needed ones.

9.5. Geo-spatial mapping

Remote sensing related activities are fundamentally dependent on the satellite aware services like serving images of earth surface. This process is purely confidential an/or authorized by the government agencies due to seriousness of handling of satellites. Such restrictions may sometimes provoke the users to get reluctant of using the satellite-based administrative services for getting a green signal to use the maps. To resolve the complexities in this process, 6G-based SAGINs can be utilized. SAGINs are expected to deploy numerous drones with different shapes and functionalities. Such drones that are connected with the backbone of SAGIN infrastructure can provide autonomous geo-spatial monitoring in any part of the earth. Even, the application can be extended to the outer space exploration. For example, instead of using robot cars on the surface of the Mars, 6G-SAGIN enabled drones can fly with miniature appropriate rocket engines to capture the images and analyze the maps in real-time.

9.6. Maritime monitoring

Marine world is almost void of standard cellular facilities. Some ships use satellite communications to establish networking with nearby harbor or ships. In past few decades, we have witnessed many mishaps in the sea where lots of lives were destroyed. Despite of many machinery issues, one can think of using SAGINs to inform other ships, boats, or harbors to send emergency life-saving supports to safeguard the people. We can expect that SAGINs upon integration with 6G can mitigate this problem and allow to save many lives in coming days. Further, SAGINs can be useful in deep-sea exploration and regular under sea research activities to enable real-time communication and control over the situation.

9.7. Smart city

In recent years, the world has been gradually adopting the concept of the smart city into the reality. Many provinces of the world are being converted into a smarter one with help of IoT and related ubiquitous technologies. SAGINs have very important role in revolutionizing the smart city movement around the globe. Instead of solely depending of IoT-based smart monitoring, SAGINs are expected to propagate the growth of technological advancements via the realization of smart city. Drones and satellite communications together can support day-to-day activities of the society such as, smart communication in the transportation and automatic traffic monitoring on a congested road.

9.8. Precision agriculture

Precision agriculture refers to the process of managing of available resources to improve the yield of crops in a sustainable and optimized manner. SAGINs can take part in making the agriculture more precise in nature. For example, drones and satellite imagery can be used together to identify the drought area of the fields. Further, a clear map of crops and their growths can be automated by suing SAGINs. We expect that individual farmer's data needs to be combined with the temporal and spatial information received from the SAGINs to estimate the crop's production or loss. It can surely improve the utilization of resources in more optimum manner so that efficiency, profitability, and quality can be assured to the farmers.

9.9. Open and remote internet

Free internet is still a dream among the world population. Although, many countries are now enabled with basic 4G or 4G LTE, the cost of network service is worth to note. We expect that upon realization of 6G-SAGIN open and remote internet connectivity will be easily possible. It can be solved by using a dense chain of SAGINs that will allow local drones or base stations to communicate via the SAGIN's backhaul for the seamless internetworking. Internet connection can be paved in the remoted part of the Himalayan belt and the deepest core of the Amazon.

9.10. Disaster monitoring

We can neither perceive nor control large size natural disasters. Be it cyclone, flood, volcanic eruption, or earthquake, human being can just face the grudge of the nature's devastating power. In such situations, 6G-SAGIN can facilitate the real-time and continuous monitoring of the devastated area. Search and rescue operations can be served by the SAGINs during natural disasters. Man made disasters such as, collapsing of building or terrorist attacks can also be monitored by the SAGINs. For example, a person who is stuck under the boulder due a bridge collapse, can be searched by an automated snake robot which sends to visuals of the scene to the controlling drone. The drone in turn further establishes connection to the nearby stations. In case, no base station signal is available, the drone can directly contact to the LEO satellites for immediate message propagation to the government agencies.

9.11. Military navigation

Defense operations are always life threatening and cause blood loss of many soldiers. 6G-SAGIN can enable the soldiers to keep the ubiquitous communication with the command center by using a combination of drone, military personnel's communicating device, and satellites. Instead of depending solely on the satellites which is not always feasible due to low battery power or less signal strength, a soldier can use the SAGIN infrastructure to keep himself updated. Further, an ad-hoc network facility can be provisioned without the intervention of satellites that can make the chance of survival of the soldier few times more.

9.12. Environment monitoring

Environment monitoring is an important job which is now-a-days are done by using IoT, cloud computing or satellites. However, we know that availability of the three factors is not always guaranteed. Thus, SAGIN can pave an alternative solution to the existing technologies where IoT, cloud, and satellites are amalgamated with ad-hoc and decentralized networking schemes. For example, monitoring the environment of the Himalayan glacier is not an easy task to do. So, 6G-SAGIN can leverage a seamless orientation of dense networking in the targeted Himalayan glacier region with help of satellites, ground stations, drones, and balloons.

9.13. Railways infrastructural monitoring

Now-a-days, the railways are expanded in thousands of miles on the world. Monitoring of such a huge geographic location is a monumental task. 6G-SAGIN can simplify the railways infrastructural monitoring with an added network coverage system installed on the trains. It can also be initially placed at discrete railways infrastructures. Later, a group of balloons can be positioned in those spatial locations that can constantly monitor the infrastructures. We know that SAGINs allow balloons to communicate with UAVs, satellites, and ground stations to keep seamless interaction. Any issue or emergency incident can be thus reported to the driver of the train or the nearby rail stations for taking real-time decisions.

9.14. Limitations

The major limitations of the applications can be presented as follows.

Security and trust: Any application or use case hat requires 6G-SAGIN should be first examined against a robust and holistic secure scheme. Trust must be invoked into the SAGINs prior communicating or propagating data.

Vulnerability of UAVs: Not all the existing drones are susceptive the possible vulnerability attack. For example, a medical delivery drone may be vulnerable to an unwanted physical attack by some mischiefs.

Reliability: All the applications should be reliable in terms of execution and facility alignment to the users

Emergency support protocol: It is most essential component of the SAGINs infrastructure. Any drone, balloons, or air borne vehicles should be incorporated with the emergency support protocol. For example, instantiation of new air borne vehicles must be immediately provided once a mishap occurs.

Rapid timeliness: All the components of the 6G-SAGIN must adhere to the rapid timeliness feature while getting deployed into the fields.

Agility: We foresee that agility will be a limitation at the time of physical application of SAGIN-based use cases. Focus should be given to design more agile systems by incorporating potential time-aware protocols.

9.15. Lessons learned

We find that a very few numbers of valued contributions are made in the field of the SAGIN by several literature as discussed in earlier sections. Most of the articles describe (a) design aspects, (b) communication technologies, (c) usage of UAVs, (d) implication of satellites, and (e) routing algorithms. We also find that all the articles are based on a similar generic form of SAGIN, however minimal intervention is given on the under-sea network connectivity. None of the article talks about the prospect of the 6G in accordance with the SAGIN. Thus, the literature is silent about the possible issues in the 6G-SAGIN era. We find this as a promising research gap that needs to be further envisaged and investigated to find the applicability of 6G with the SAGIN. In this paper we aim at integrating SAGIN with the vision of 6G as a conceptual level (O'Hara, 2019).

In this section, we learned that effective utilization of envisaged 6G-SAGIN relies on the successful integration of satellite communication with mobile technology. Both the technologies shall play the most crucial role in the realization of the 6G-SAGIN ecosystem. Mostly, the 5G and allied WRAN, RAT and THz communication tools would highly improve the service paradigm behind the 6G-SAGIN. We find that WRAN and FSO cloud are amalgamated together for realizing HetNet-aware SAGIN facilitation. Special attention is given on the usage of the IEEE 802.11 standards that can provide key mobile communication in a purely dynamic aspect. Mobile backhaul technology designs must be catered well to mitigate the stringent requirement of the 6G-SAGIN. We must say that mmWave and microwave communication should be efficiently utilized to augment the services allied with SAGIN (Seijo et al.).

UAVs are undoubtedly a main part of the 6G-SAGIN era. Thus, understanding its needs and design aspects remains a very crucial task. In this section, we learned that the notion of the UAVaaS could be tested against the possible uplifting of the envisaged 6G-SAGIN framework. For that, we must emphasize on the command, control and communication technologies that can harness the capacity of the UAVaaS. Intelligent caching could be aligned with the edge-fog-cloud computing to make the system more resilient in nature. Both singular and multiple UAVaaS must be investigated for sake of efficient service provisioning. Elements of 6G-SAGIN need a major redesign so that it can perform the required tasks. In this section, we learned that five key types of designs should be examined including (a) terminal, (b) operation center, (c) link disturbance mitigation, (d) data stream standardization, and (e) routing technique design. We find that ground, aerial, and space centric designs require highest priority over the command/control design aspects. Use of UAVWAN, WAN, LAN, MAN, and SoE such design related issues could be eradicated. Further, investigation is necessary to provide QoS aware routing with improved technique considering multi-path, joint service placement and unified routing.

10. Conclusion

This work signifies the approach towards 6G-enabled SAGIN while provisioning a clear vision. We envisaged needs and requirements behind the conversion of the current scenario of SAGIN to the improved and futuristic 6G-SAGIN. We discuss how UAVaaS and space communication with 6G can enrich the SAGIN infrastructure. We expect that upon solving a few open research challenges, 6G-SAGIN can be truly realized. This article presents a new insight on the SAGIN to provide a futuristic direction for sake of stringent correlation to the next generation networking technologies. We find that with support from 6G technologies SAGIN can become a true part of our society. We discuss key applications and the limitations associated with such prospective use cases. Futuristic technological augmentation with SAGIN shall pave a remarkable platform to improve overall societal aspects for humanity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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