

6G VISION: AN ULTRA-FLEXIBLE RADIO ACCESS TECHNOLOGY PERSPECTIVE

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Abstract – Radio access technologies (RATs) are the primary enablers of mobile communications systems. The upcoming sixth generation (6G) communications systems are expected to support an unprecedented variety of applications, pervading through every aspect of human life. It is clearly not possible, without realizing a plethora of flexible options pertaining to the RATs themselves. At that point, this work presents an overview of the potential 6G RATs from the flexibility perspective, categorizes them, and provides a general framework to incorporate them in the future networks. Furthermore, the role of artificial intelligence and integrated sensing and communications as enablers of the said framework is also discussed.

Keywords – 6G, artificial intelligence, cognitive radio, flexibility, radio access technology, sensing.

1. INTRODUCTION

Following successful deployments of the fifth generation (5G) networks worldwide, the academia and industry have turned their attention to the next generation of wireless communication networks [1]. At present, there are more than 100 research papers regarding the sixth generation (6G) of wireless communications. Majority of these works attempt to identify the future applications, possible service types and candidate technologies for 6G [1–21]. Furthermore, specific technologies are being pushed for 6G as well [22–41, 45]. There is no doubt that new visions and perspectives will continue to be developed in the coming years. However, despite all these efforts, the current literature lacks the provision of a distinguishing feature for 6G that differentiates it from the previous generations.

The introduction of various services with diverse requirements under 5G highlighted the need of a flexible network, where flexibility¹ is defined as the capability of choosing the best one out of available options depending on the internal and external changes. The evolution of cellular communications through the different generations from the radio access technology (RAT) perspective is shown in Table 1. In this context, 5G has gave a start for highly flexible wireless communications but it remains limited.

Fig. 2 provides a concise flexibility analysis for different generations of cellular communications. As shown, the first generation (1G) provided a very rigid standard. However, the evolution of network entities and user requirements has led to the development of highly flexible transceiver structures, especially for 5G. Similarly,

¹The other terms used interchangeably are shown in Fig. 1.

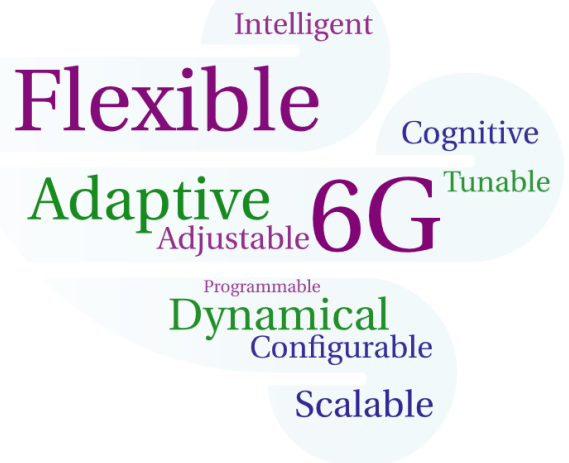


Fig. 1 – Flexibility terms.

a lot of effort has been made to control and mitigate the interference to ensure better Quality of Service (QoS) for the users. 6G extends the mitigation concept one step further by exploring ways of controlling the channel itself. Furthermore, awareness of the various aspects of the network and environment will be introduced in the communication paradigm via different sensing mechanisms. This awareness allows better utilization of the flexibility envisioned for 6G in this article. This motivates the consideration of flexibility as the primary design criterion for 6G networks. The candidate technologies should, therefore, be studied from the same (flexibility) perspective.

6G will redesign cellular communications to provide extreme flexibility in all of its building blocks. Correspondingly, this paper provides a unique categorization

Features/ Generations	1G		2G		3G		4G		5G			
Modulation Options	FM		GSM	GMSK	EDGE	8PSK	Wi-Fi	BPSK, QPSK, 16 QAM, 64 QAM		NR	BPSK, QPSK, 16QAM, 64QAM, 256QAM	
					CDMA 2000	QPSK, OQPSK		Wi-MAX	BPSK, QPSK, 16 QAM, 64 QAM			
			GPRS	GMSK	UMTS	QPSK	LTE		BPSK, QPSK, 16 QAM, 64 QAM			
					HSDPA	QPSK, 16 QAM						
Coding Options			Convolutional Coding		Turbo Coding		Turbo Coding		LDPC			
			Block Coding		Convolutional Coding		Convolutional Coding		Block Coding			
Modulation and Coding Scheme (MCS) Options			Fixed		Limited MCS Options		Medium MCS Options		High MCS Options			
Waveform Options			Fixed Lattice		Fixed Lattice		Fixed Lattice		Adaptive Lattice			
			Fixed Shape (GMSK)		Fixed Shape (RC)		Windowing and Filtering		Adaptive Windowing and Filtering			
			Fixed Type (The same for uplink and downlink)		Fixed Type (The same for uplink and downlink)		Uplink	SC-FDE	Uplink	OFDM, SC-FDE		
Multiple Accessing Options	FDMA		TDMA		CDMA		Uplink	SC-FDMA	Uplink	SC-FDMA		
							Downlink	OFDMA	Downlink	OFDMA		
Carrier Frequency Options	microWave		microWave		microWave		microWave		mmWave			
Architecture Options	SISO		SISO		SISO		MIMO		mMIMO			
Cell Planning	Frequency Reuse – 7		Frequency Reuse – 3, 4, 7, 12		Frequency Reuse – 1		Frequency Reuse – 1		Frequency Reuse – 1			
User-Cell Association Options			Mobile-assisted Hand-off		Soft Hand-off		ICIC		COMP			
							Attempt to COMP		CRAN			
Diversity Options			Freq.	Frequency Hopping	Freq.	FHSS	Freq.	Multi-User Diversity	Freq.	Multi-User Diversity		
							Space	MIMO	Space	MIMO		
							Space	Precoding	Space	Precoding		
			Time	Path Diversity	Time	DSSS	Space	Beamforming	Space	Beamforming		
							Space	Beamforming	Space	COMP		
Receiver Types			Multi-tap TDE		Rake Receiver		A Single Tap FDE		A Single Tap FDE			
Bandwidth Options	AMPS	30 kHz	GSM	200KHz (8 slots)	CDMA	1.25 MHz	1.25 MHz to 20 MHz		BWP			
			DAMPS	30KHz (3 slots)	WCDMA	5MHz			Carrier Aggregation			
			PDC	25KHz (3 slots)	TD-SCDMA	1.6MHz	100 MHz with Carrier Aggregation		Multi-numerology			
											Licence Assisted Access (LAA)	

Table 1 – Increasing number of the features for cellular generations.

of potential 6G RATs and elaborates the flexible aspects of these technologies. Moreover, a novel framework is proposed to make flexibility optimization of the said technologies.

The rest of the paper is organized as follows: Section 2 summarizes the previous works on 6G communications. Flexibility discussions on the potential RATs are provided with an inclusive categorization in Section 3. The proposed flexible framework is explained in Section 4. Finally, conclusions are drawn with several open issues in Section 5.

2. THE INITIAL FORECASTS FOR 6G

Identification of the future applications, requirements and possible service types is one of the primary objectives of the initial 6G research studies. Figure 3 illustrates the cyclic nature of the relationship between

these components. Mapping the potential future applications to the several requirements with different priorities is accepted as a first step in general. Next, these requirements are grouped under the service types in a reasonable manner. Service types should have unique requirement sets to take into consideration them while designing the service-aware subsystems. Additionally, application groups should be representable with one of the available requirement sets. The 5G service types namely, enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine-type communications (mMTC) [42] illustrate this point clearly. eMBB applications, as a group, prioritize high throughput, capacity and spectral efficiency; mMTC prioritizes energy efficiency and massive connectivity while URLLC requires high reliability and low latency. To this end, some of the initial 6G studies inherently analyze the relations between the 1) future applications, 2) prioritized requirements, and 3) possible service types in [3–6].

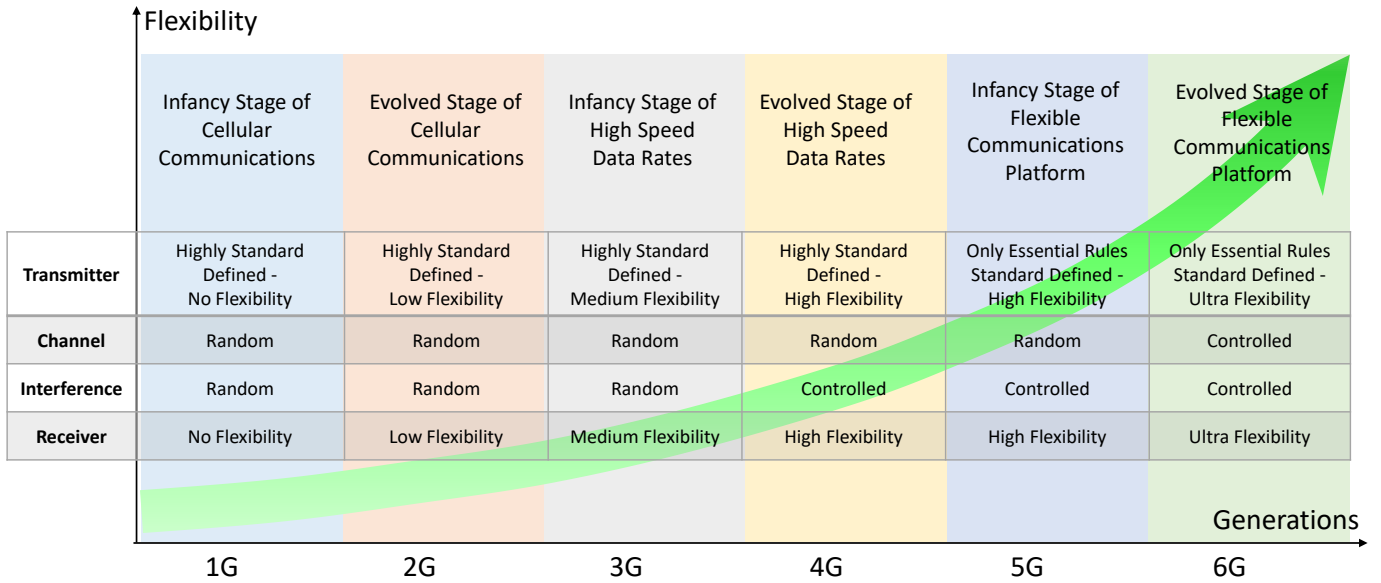


Fig. 2 – Flexibility analysis of the previous generations and 6G communications.

The following list exemplifies potential 6G applications: drone and unmanned aerial vehicle (UAV) networks, drone taxi, fully automated vehicle-to-everything (V2X), remote surgery, health monitoring, e-health, fully sensory virtual reality (VR) and augmented reality (AR), holographic conferencing, virtual education, virtual tourism, smart city, smart home, smart clothes, disaster and emergency management, and remote working. This list can be longer with more applications in the next years. Most of the aforementioned applications were originally envisioned for 5G, however, they could not be practically realized. Therefore, it makes sense to address them first while developing the 6G networks.

General wireless communications requirements for the given application examples can be defined as: high data rate, high throughput, high capacity, high reliability, low latency, high mobility, high security, low complexity, high connectivity, long battery life, low

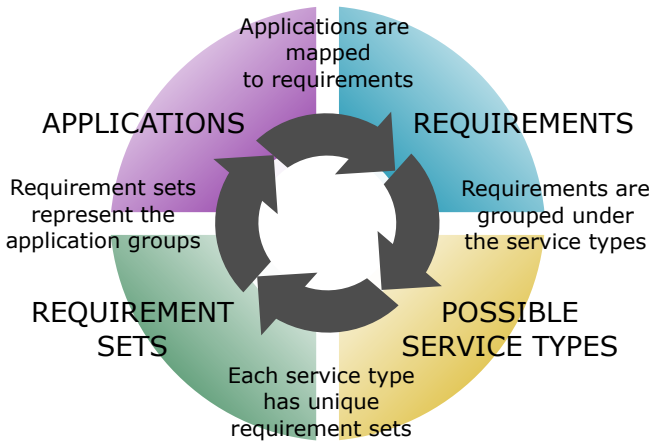


Fig. 3 – Constitution mechanism of the service types.

cost, wide coverage, and more. The importance and priority of the requirements may change under different cases. Moreover, higher levels of performances need to be obtained in next generation systems while meeting the related requirements.

Since the diversity of requirements is continuously increasing, more sophisticated service types are expected for 6G. Candidate service types are constituted by grouping together the applications with similar requirements. Some examples can be given as big communications (BigCom), secure uRLLC (SuRLLC), three-dimensional integrated communications (3D-InteCom), unconventional data communications (UCDC) in [6]; ultrahigh-speed-with-low-latency communications (uHSLLC) in [3]; long-distance and high-mobility communications (LDHMC), extremely low-power communications (ELPC) in [4]; reliable eMBB; mobile broadband reliable low latency communication (MBRLLC), massive URLLC (mURLLC), human-centric services (HCS), multi-purpose services (MPS) in [5].

The aforementioned applications/services envisioned for 6G illustrates the expected richness of its requirements. These diverse requirements necessitate the incorporation of flexible RATs, described below, in future networks.

3. A VISION FOR ULTRA-FLEXIBLE RATs

In this section, an inclusive categorization of promising RATs is presented for 6G communications and their flexibility aspects are discussed in detail. The seven main RAT categories and the related subcategories are shown in Fig. 4. Many of these technologies are

either superficially treated or not studied during 5G standardizations, such as integrated sensing and communications (ISAC) and intelligent communications. Although technologies placed in different categories can have an intersection region, the given categorization differentiates these technologies regarding their flexibility aspects.

Table 2 provides a summary of the potential flexible options achieved by the different technologies. It is worthy to emphasize that the different RATs have their own impact on the overall flexibility of the system. Ultimately all of them combine together to provide the complete infrastructure capable of realizing the flexible 6G vision that we aspire to achieve.

3.1 Flexible Multi-Band Utilization

The inclination of communications technologies towards high-frequency bands becomes more appealing due to the increased system capacity and throughput demands of cellular users. Flexible usage of available frequency bands, depending on the user and service requirements, is envisioned to be an inherent characteristic of the future wireless networks.

Millimeter wave (mmWave) spectrum is starting to be exploited in 5G. It provides new benefits, such as multi-giga bit data rates and reduced interference, however, the use of mmWave bands in 5G is limited by the current International Mobile Telecommunications (IMT) standards. In World Radiocommunication Conference 2019 (WRC-19), additional 17.25 GHz of spectrum is identified for IMT, where only 1.9 GHz of bandwidth was available before [43]. Therefore, it is expected that spectrum availability in these bands and consequently its flexible utilization will increase during the upcoming years. Moreover, beyond 52.6 GHz communications is one of the agenda items for 3GPP Release 17 [44].

Frequency bands from 100 GHz to 3 THz are envisioned as a candidate spectrum for 6G communications [23]. If THz communications is employed in 6G, it promises a way of dealing with the spectrum scarcity issue by providing an additional degree of flexibility in assigning the most suitable frequency resources for given scenarios.

Apart from mmWave and THz communications, visible light communications (VLC) also provides spectrum flexibility as a candidate RAT for 6G networks [39]. Besides, a new degree of freedom that is information source flexibility is exploited using visible light sources.

Spectrum coexistence is another important issue in need of flexible spectrum utilization [45,46]. Indeed, the coexistence of cellular communications, Wi-Fi, satellite net-

works, and radar systems is inevitable in the future due to both scarce resources and increasing growth in user demands. To exemplify, the coexistence of radar and cellular communication in mmWave frequency bands becomes more popular nowadays [47]. Moreover, the idea of dynamic spectrum access (DSA) relies on the spectrum coexistence.

3.2 Ultra-Flexible PHY and MAC

One of the unique features of 5G, specifically in the context of PHY design, is the introduction of numerology concept where different configurations of the time-frequency lattice are used to address the varying requirements [51]. While the numerology concept paves the way for flexibility in beyond 5G networks, it is rather limited considering the competing nature of requirements expected for future 6G networks [40]. In addition to the standardized activities, the use of flexible cyclic prefix (CP) configurations (e.g., individual CP, common CP, etc.) is explored to enhance the multi-numerology systems for 6G [52].

Taking one step beyond the use of different realizations of the same parent waveform as in 5G, multiple waveforms can be accommodated in a single frame for achieving 6G goals [53]. In line with this, multi-numerology structures can be designed for promising alternative waveforms, that are more suitable for providing additional parameterization options. Having these options enhances flexibility in the PHY layer via increased adaptation capability for meeting a large number of requirements. Moreover, waveform coexistence in the same frame gives the opportunity to serve multiple networks such as radar sensing [54] and Wi-Fi communications together with 6G communications in a flexible manner. There are also several waveform-domain NOMA studies that exploit different resource utilization aspects in the literature [55–58]. Besides, partial and full overlapping through available resources can also be employed while designing new generation NOMA techniques [24, 59]. The waveform-domain NOMA concept provides an important flexibility by increasing the resource allocation possibilities in 6G networks. Another flexibility aspect that can arise with 6G is the use of alternate waveform domain rather than the conventional time-frequency lattice employed by 5G and older generations.

In addition to the waveform itself, there is a large number of new generation modulation options in the literature [48] and only a small set of them have appeared in the 5G standards. 6G can be enriched with the flexibility provided by these options, particularly index modulation (IM) based solutions [6]. This concept can even be extended to multiple domains to provide additional degree of freedom [49]. Moreover, modulation techniques are adaptively designed consid-

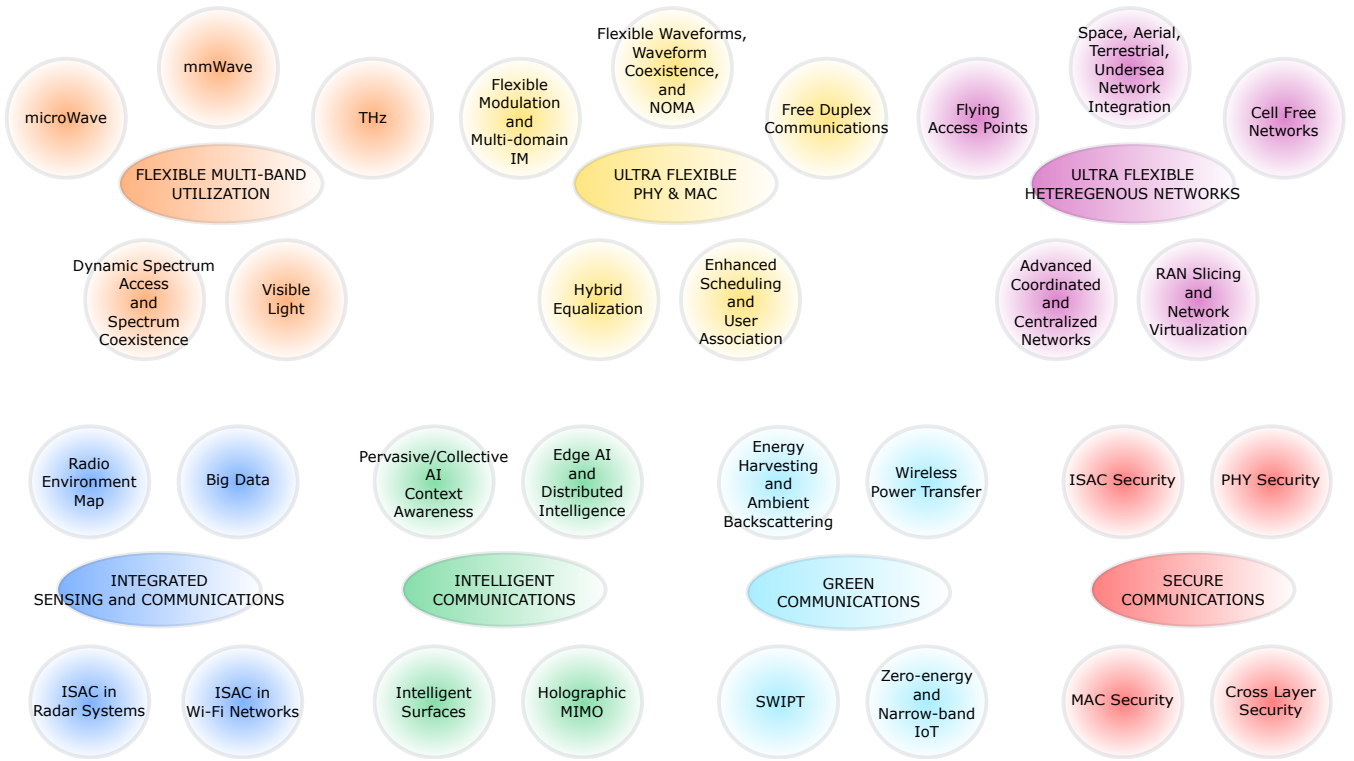


Fig. 4 – Categorization of ultra-flexible RAT concepts.

ering the other RATs such as non-orthogonal multiple access (NOMA) [50] and reconfigurable intelligent surface (RIS) [30] for 6G systems.

Since the configuration of the PHY parameters is, to a large extent, controlled by the medium access control (MAC) layer, it is imperative to develop the flexibility and adaptation capabilities of both layers simultaneously. Two important issues that requires flexibility in PHY and MAC would be the “waveform parameter assignment” or “numerology scheduling” paradigm under the context of 5G multi-numerology systems [40, 60], where the MAC layer is responsible for assignment of parameters of the PHY signal. Similarly, adaptive guard utilization methods have been developed for MAC layer [61–63] to control the new type of interferences in 5G systems. On this basis, it is expected that highly intelligent UE capabilities, and configurable network parameters, and flexible and efficient MAC designs will play a key role in 6G networks due to the expected increased diversity in service types and consequently requirements.

3.3 Ultra-Flexible Heterogeneous Networks

Flying access points (FAPs) provide enhanced flexibility for network deployment by allowing dynamic (3-D) positioning of the nodes or even optimized trajectory planning for different objective functions. The push in this direction occurred around the turn of the

century [64], and was further empowered by projects, such as: 1) Google Loon project, 2) Facebook Aquila project, 3) ABSOLUTE project, 4) Matternet project, and 5) Thales Stratobus project. The integration of FAPs with the terrestrial network can be leveraged to provide coverage in disaster/emergency scenarios, connectivity for rural/isolated areas and capacity enhancement for temporarily crowded places (such as stadiums/concert venues). FAP-based networks are expected to be an important part of 6G not only for achieving deployment flexibility but also for having better wireless propagation provided by a high probability of line of sight (LOS) communications.

In addition to the aerial and terrestrial networks, the integration of space (satellite) networks is another aspect of the flexible heterogeneous networks. Space networks are also promising solution for rural area communications [31]. They are employed for wireless backhaul communications in the previous cellular networks. However, space networks can also serve aerial user equipment such as drones and UAVs to increase coverage flexibility in 6G systems. Moreover, undersea network integration with the other networks will be useful while serving naval platforms.

Although, the integration of different networks is ensured, the cell structures of these networks are changing. Cell-less or cell-free networks are one of the potential 6G concepts considering the network architec-

RAT Categorization	Flexibility Perspective	Example Details
Flexible Multi-Band Utilization	Multi-band flexibility	microWave, mmWave, THz, visible light
	Information source flexibility	Radio signals, visible light
	Spectrum coexistence flexibility	DSA, CR, and coexistence of cellular networks, Wi-Fi networks and radar systems
Ultra-Flexible PHY and MAC	Modulation-option flexibility	BPSK, QPSK, 16QAM, 64QAM, 256QAM, 1024QAM, etc.
	Multi-domain modulation flexibility	IM (shape, interval, position, etc.), space, time, frequency, etc.
	Multi-type coding	New types of LDPC, block coding, polar coding, etc.
	MCS option flexibility	Ultra adaptive MCS
	Multi-option waveform flexibility	Multiple numerologies for any specific waveform
	Waveform processing flexibility	Adaptive windowing/filtering and the related configurable parameters
	CP utilization flexibility	Individual and common CP utilizations
	Adaptive guard utilization flexibility	Flexible guards for multi-waveform and multi-numerology designs
	Multi-waveform flexibility	Waveform coexistence in the same frame
	Multi-network multi-waveform flexibility	Waveform coexistence for cellular and Wi-Fi networks with radar sensing
	Multi-domain NOMA flexibility	Partial and fully overlapped resources with waveform-domain NOMA
	Multi-domain waveform flexibility	Alternative lattice flexibility together with the time-frequency lattice
	Multiple access flexibility	Fully flexible, both orthogonal and non-orthogonal
	Receiver-type flexibility	Fully flexible, hybrid equalization
	Bandwidth option flexibility	BWP, carrier aggregation, LAA, DSA, etc.
	User association flexibility	Multiple options under heterogenous networks, flexible user parameter assignment
	Channel access flexibility	GB transmission, GF transmission, and their coexistence over a resource pool
Ultra-Flexible Heterogenous Networks	Positioning flexibility of the access points	Flying access points can be positioned flexibly in the sky
	Connection link and relaying flexibility	User equipment can connect to different type of access points
	Altitude-based multi-network flexibility	Coexistence of space, HAP, terrestrial and undersea networks
	Coverage flexibility	Rural area coverage with space and HAP networks
	Network architecture flexibility	Ultra massive MIMO, small cell, D2D, relaying via different networks, etc.
	Cell-free network flexibility	User-centric network designs, handover-free communications
	Multi-cell flexibility	Network MIMO solutions, multi-cell NOMA, etc.
Integrated Sensing and Communications	Network slice flexibility	Network slices for each user equipment, user-specific virtual networks
	Multi-system flexibility	All systems can collaborate with the wireless communications in different ways
Intelligent Communications	Awareness flexibility	Awareness in spectrum, location, mobility, context, user, channel, interference, etc.
	Alternative solution flexibility	No need to get stuck on conventional algorithm designs
	Edge computing flexibility	Signal and data processing at the edge nodes
	Channel control flexibility	Different types of intelligent surfaces
	Interference management flexibility	Interference management with the channel control
Green Communications	Softwarization flexibility	Programmable architecture options for holographic MIMO systems
	Battery-free implementation flexibility	Removing battery limitations and constraints
Secure Communications	Interference exploitation flexibility	Interference can be useful for the energy harvesting
	Multi-domain security flexibility	No need to get stuck on key sharing security mechanisms, complementary solutions
	Wireless channel exploitation flexibility	PHY security methods exploit the characteristics of wireless channel

Table 2 – Flexibility perspectives under the RAT categories.

ture richness [65, 66]. User equipment connects to the network via multiple small cells in the cell-less networks. Cell-centric design is transformed into the user-centric system. Hence, it provides both handover-free communications and zero inter-cell interference. Cell-less networks may exploit a new dimension of network multi-input multi-output (MIMO) flexibility in 6G. As another network MIMO example, advanced coordinated and centralized networks [67] are addressed together

with NOMA schemes for 6G communications [68, 69]. These networks are called multi-cell NOMA. Flexibility comes with the number of the cells and architecture richness while exploiting other dimensions with NOMA.

From the network virtualization perspective, network slices are used in 5G to customize and optimize the network for service types or any other requirement sets [70–72]. Hence, the overall performance is increased by

meeting different requirement sets with virtually privatized networks. Network slicing brings an important flexibility in 5G since it enables different network options under the same umbrella. The number of network slices can increase for 6G and there may be network slices for each user equipment. This user-centric network slicing architecture can provide full flexibility in the network layer.

3.4 Integrated Sensing and Communications

With the emphasis on use cases such as V2X communications in recent years, sensing has attained increased importance leading to the integration of these two applications. However, the use of sensing is not limited to V2X or autonomous driving. Rather, if there is any observable data that can be utilized for the optimization or enhancement of the communications systems, it should be leveraged in 6G [73]. The information pertaining to the radio environment can be utilized in improving the network deployment, optimizing user association, providing secure communication and so on.

While it might sound like a novel idea to some, integrated sensing and communications (ISAC) has been studied in different domains in the past. Cognitive radio (CR) applications triggered the integrated sensing and communications (ISAC) research at the beginning of the 21st century. Spectrum sensing and awareness is one of the first application areas in the ISAC research [74]. Location awareness is exploited to improve the wireless communication system design in [75]. Satellite and drone images can be used to predict channel parameters [76]. Context-awareness is used to optimize network architectures in wireless communications [77]. ISAC systems are studied for radar sensing [54, 78] and Wi-Fi network coexistence [79] in the literature. However, the complete list of sensing information that can be useful for the next generation cellular communications systems from the ISAC perspective has not yet been comprehensively studied.

Radio environment map (REM) is a realization of the ISAC concept [80]. It is mainly used to obtain environmental information in the literature, however, for the next generation systems REM concept will be generalized from environmental-awareness to complete-awareness. REM may include all sensing information in a multi-dimensional manner for wireless communications networks. To exemplify, REM can be a specialized database for the ISAC. Therefore, the flexibility level of the ISAC systems can be determined by the dimensions in REMs. Each dimension in a REM increase the awareness, allowing better resource utilization. Moreover, control of the configurable options and parameters in different communications layers of 6G can be enhanced by more granular REM information.

The complete information and awareness of the environment comes at the cost of high volume of data, variety of sources and significant processing. This necessitates the use of big-data processing techniques [81]. A significant challenge, however, in this regard is the overhead of data exchange between the sensing and processing nodes. A centralized solution might not be suitable in such scenarios, rendering the use of edge-computing imperative, particularly for low-latency use cases.

3.5 Intelligent Communications

The usage of artificial intelligence (AI) in the communications society has increased in recent years. Several survey and tutorial papers are published on the usage of machine learning (ML) for wireless communications [82–89]. AI-aided design and optimization has even been leveraged for the flexible implementation options provided in 5G [40]. In many of the studies, AI is put at the center of 6G visions [8, 9, 14, 18, 28, 90] to complement the classical methods. Indeed, the use of AI is inevitable to incorporate intelligence in the future networks. AI-aided methods can propose fast and efficient solutions in case enough data is available.

AI and ML also find a range of applications in ISAC and REM paradigms to extract information regarding the environment from sensed data. A flexible system needs to benefit from the advantages of popular ML approaches such as reinforcement learning, deep learning, and edge computing. Especially distributed intelligence (edge AI) with edge computing is a promising paradigm for 6G communications. The management of multi-band utilization, MAC layer control, heterogeneous and cell-less networks, and the ISAC systems cannot be done in an all centralized manner. Edge computing will play an important role at that point with the help of distributed intelligence so 6G big data can be processed at the edge nodes without collected at a centralized network.

Intelligent networks are not limited to AI-aided concepts. For example, RIS technology is one of the most popular research topics nowadays [94, 95]. Intelligent surfaces bring a new flexibility on the control of channel parameters. In the past, wireless channel was just an observable medium. However, it can be controlled at some level with new generation wireless systems. Interference management flexibility is increased by controlling capabilities of the wireless channel. These flexibility aspects also affect the RAT designs in different communications layers. To exemplify, having control capability in multipath propagation, such as controlling delay spread, Doppler spread and the number of multipath alleviates the constraints related to waveform design. RIS technology can also be considered as passive holographic MIMO surfaces if it is located closer to the

transmitter and receiver antennas [41]. Additionally, it is possible to employ holographic MIMO surfaces as active elements. The active holographic MIMO surfaces work similar to massive MIMO but their softwarization flexibility is higher than the conventional MIMO systems [41].

3.6 Green Communications

While candidate 6G RATs are increasing the flexibility in different domains, new architectural changes of 6G should support energy efficiency and green communications [27]. Zero-energy Internet of Things (IoT) is one of the most important concepts since ultra low-power wireless communications is necessary for 6G connectivity. In this context, radio frequency (RF) energy harvesting is studied with ambient backscatter technology for 6G communications [96, 97]. Thus, low-power wireless systems can obtain their energy from the available high-power radio waves. Backscatter communications enables energy harvesting, simplifying the implementation of zero-energy IoT designs. Provision of different options for energy-efficiency promises fulfillment of different variations of energy requirements belonging to different applications.

It is also possible to benefit from wireless power transfer (WPT) while designing zero-energy IoT systems [98]. Under the WPT concept, simultaneous wireless information and power transfer (SWIPT) is the most popular technology that may be a candidate for 6G networks [100]. SWIPT designs are also used for interference exploitation purposes [99] since interference can be useful for energy harvesting. Transformation of interference into energy source introduces another flexibility perspective.

3.7 Secure Communications

With applications such as eHealth, online banking, and autonomous driving etc., wireless communication promises to be an enabler of innumerable sensitive applications utilizing private data. PHY security (PLS) is an emerging solution that has the capability to complement the conventional cryptography-based security techniques. In fact, PLS is more suited for the increased heterogeneity and power/processing restrictions of future wireless networks since it exploits the characteristics of the wireless channel and PHY properties associated with the link rather than utilize key sharing [103]. It is also possible to increase this flexibility by designing cross-layer security algorithms with PHY and MAC layer [104]. In several 6G vision papers, secure communications is discussed as one of the main topics [14, 28]. PHY and cross-layer security concepts are expected to play a critical role in 6G communications.

As discussed in the previous subsections, ISAC and REM concepts will be important enablers in 6G communications. However, a new security problem arises since there may be a large amount of confidential data for ISAC and REM concepts. In the literature, this problem is treated in [101] for ISAC security, and in [102] for REM security. Thus, there is a need for more secure communications options in 6G networks to meet new types of security requirements, especially for ISAC and REM concepts.

4. ULTRA-FLEXIBLE 6G FRAMEWORK

This section brings the abovementioned flexible RATs under the umbrella of a single ultra-flexible framework for 6G. Here it is important to realize that the presence of flexible options in itself is not enough to render a network intelligent. Rather, it needs the capability to make best use of the available options. Therefore, some sort of intelligence or cognition is imperative in future wireless networks. Keeping this in mind, the proposed framework has the following primary components: a) Flexible RAT platform (like an advanced Mitola radio), b) flexible cognitive engine, and c) flexibility performance indicators. Fig. 5 illustrates how these different components are interconnected within the framework. The key points of this framework can be summarized as follows:

1. New technologies should be integrated into communications standards via **flexible RAT platform** without waiting for ten years.
2. RATs should work together in an optimal flexibility to meet different requirements. Therefore, a **flexible cognitive engine** can make an optimization between different flexibility perspectives.
3. The amount of flexibility needs to be measured while making an optimization. Hence, developing new **flexibility performance indicators** is important and necessary.

The previous cellular communications generations were standardized approximately ten years apart. From a different point of view, it took about a decade for the available technologies to be included in the cellular standards. Waiting up to ten years to benefit from an available technology does not make sense if it is possible to develop a platform that hosts different technologies flexibly. For now, we need to tolerate the limited flexibility of 5G technologies for the next decade. However, an advanced Mitola radio can work like a smart phone that has installable and updateable software. We call this radio as a **flexible RAT platform**. In this concept, the platform has ability to have new RATs by a softwarization. Thus, flexibility level of the wireless communications system can be enhanced with new technologies and the related updates.

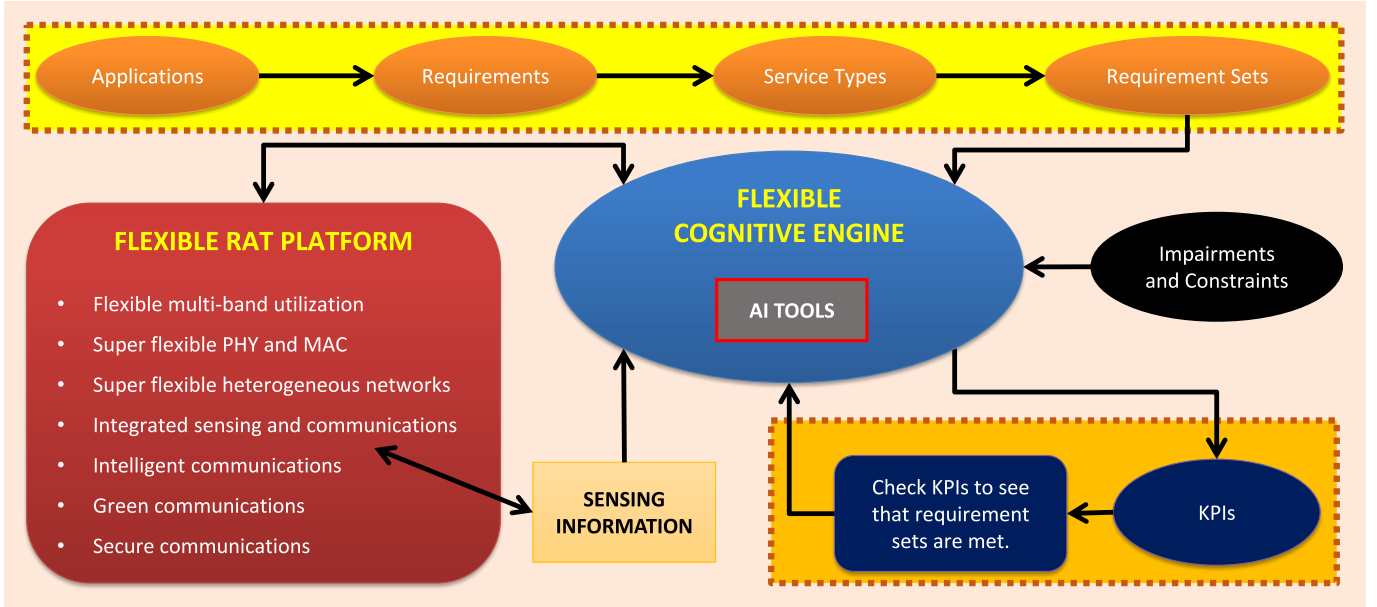


Fig. 5 – The proposed framework includes 1) flexible RAT platform, 2) flexible cognitive engine, and 3) flexibility performance indicators with the other KPIs. The flexible cognitive engine can be defined as a bridge between the requirements and potential technology options with the related configurations.

As it is shown in Fig. 5, each technology can bring different perspectives to the overall flexibility. There is a need for an multi-objective optimization unit to control all configurable and flexible aspects of the defined technologies in the flexible RAT platform. This engine can be designed in an AI-aided manner to optimize the RAT flexibilities jointly. An optimum work distribution should be done for the flexible configurations of RATs to meet all the system requirements in a most efficient way. At the end, all system requirements should be met optimally. The **flexible cognitive engine** will guarantee this optimization by the help of key performance indicators (KPIs) that show the success while meeting requirements.

ISAC technologies will be an important part of 6G technologies as discussed in the previous section. Any sensing information can be exploited to make the wireless communications more effective. The flexible cognitive engine can give decisions with more available information while meeting different requirements and handling with several impairments and constraints. Sensing information increases the awareness and controlling capabilities of the system. To provide these capabilities, AI tools in the flexible cognitive engine provide useful and unnoticeable relationships without heuristic designs and theoretical analysis. Hence, the flexible cognitive engine needs three important elements while optimizing the flexibility level with RATs: 1) Sensing information to increase awareness and controlling capabilities, 2) AI tools to increase the functionality of sensing information, and 3) key performance indicators to monitor the overall system.

KPIs are needed to measure several performances of the communications system. One of these KPIs can be the **flexibility performance indicator** so that the achieved flexibility can be quantified. It is difficult to decide on a specific flexibility performance indicator because there are many different flexibility perspectives as shown in Table 2. This indicator can be technology-specific and require separate metrics for different technology categories. 6G networks will need flexibility indicators similar to the other KPIs such as spectral efficiency and reliability. Generally, the current RATs are not designed to be called as a flexible technology. Flexibility aspects of these RATs are described mostly based on the inferences. In ideal conditions, 6G technologies need to be designed considering the flexibility perspective as one of the key criteria. At that point, flexibility performance indicators should be employed to quantify the advantages and disadvantages of new designs in both PHY and MAC layer.

5. CONCLUSION

5G systems were characterized by diverse applications and requirements. 6G is expected to continue in the same vein by enriching the application fabric even further. Fulfilling such a wide variety of use cases is not possible unless similar diversity and flexibility is incorporated in the enabling RATs for the future networks. Driven by this, we have presented the various potential RATs from a flexibility perspective.

We believe that 6G should be approached with flexibility at its primary design criterion. To this end we have presented a general framework comprising of

mentioned flexible RATs, empowered by flexible cognitive engine and supported by different aspects of sensing and AI. We believe that the presence of flexible options is imperative but only that is not enough to support the future applications. Rather, the ability to extract information regarding the operating environment, make intelligent decisions based on them regarding best-possible utilization of the flexibility offered by the RATs is the way forward in the wireless communication domain.

The realization of a flexible RAT platform like the one mentioned above is, however, not straight forward. It requires the methods capable of performing efficient multi-objective optimization to address the various competing applications requirements. Furthermore, quantifying the flexibility by proposing novel performance indicators also remains a significant challenge on the way to ensuring a fully-functional flexible, cognitive wireless communication network.

ACKNOWLEDGEMENT

The authors would like to thank Muhammad Sohaib J. Solaija for his valuable comments and suggestions to improve the quality of the paper.

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