On the Road to 6G: Visions, Requirements, Key Technologies, and Testbeds

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Agenda

- Introduction
- 6G vision and objectives
- Network architecture and key technologies
- Testbeds and verification platforms
- Future research directions and challenges
- Final Words

Limitations and challenges of 5G

- **Global coverage:** Maritime and high-latitude regions
- **Ultra-High data rates:** Cannot achieve the Tbps data rates for applications like ultra-high-definition video and adv. telemedicine
- **Ultra-Low latency:** End-to-end latency under 1millisecond at low speeds and microseconds at high speeds.
- **Ultra-Dense connection:** Cannot accommodate connection densities beyond a certain threshold e.g. in 6G require support upto 10^8devices per square kilometer for dense crowd and IIoT networks
- **High precision positioning:** Insufficient for certain application and requires to improve accuracy in cm outdoors and sub-cm indoors
- **Ultra-Reliable and safe connections:** Requires reliability and safety requirements for emerging applications like tactile internet, V2X among others
- **Energy efficiency:** Requires to reduce power consumption and increase energy efficiency by a factor of 100
- **Ubiquitous intelligence:** Not enough intelligent to support the growing number of intelligent applications. Needs advance levels of intelligence into communication systems

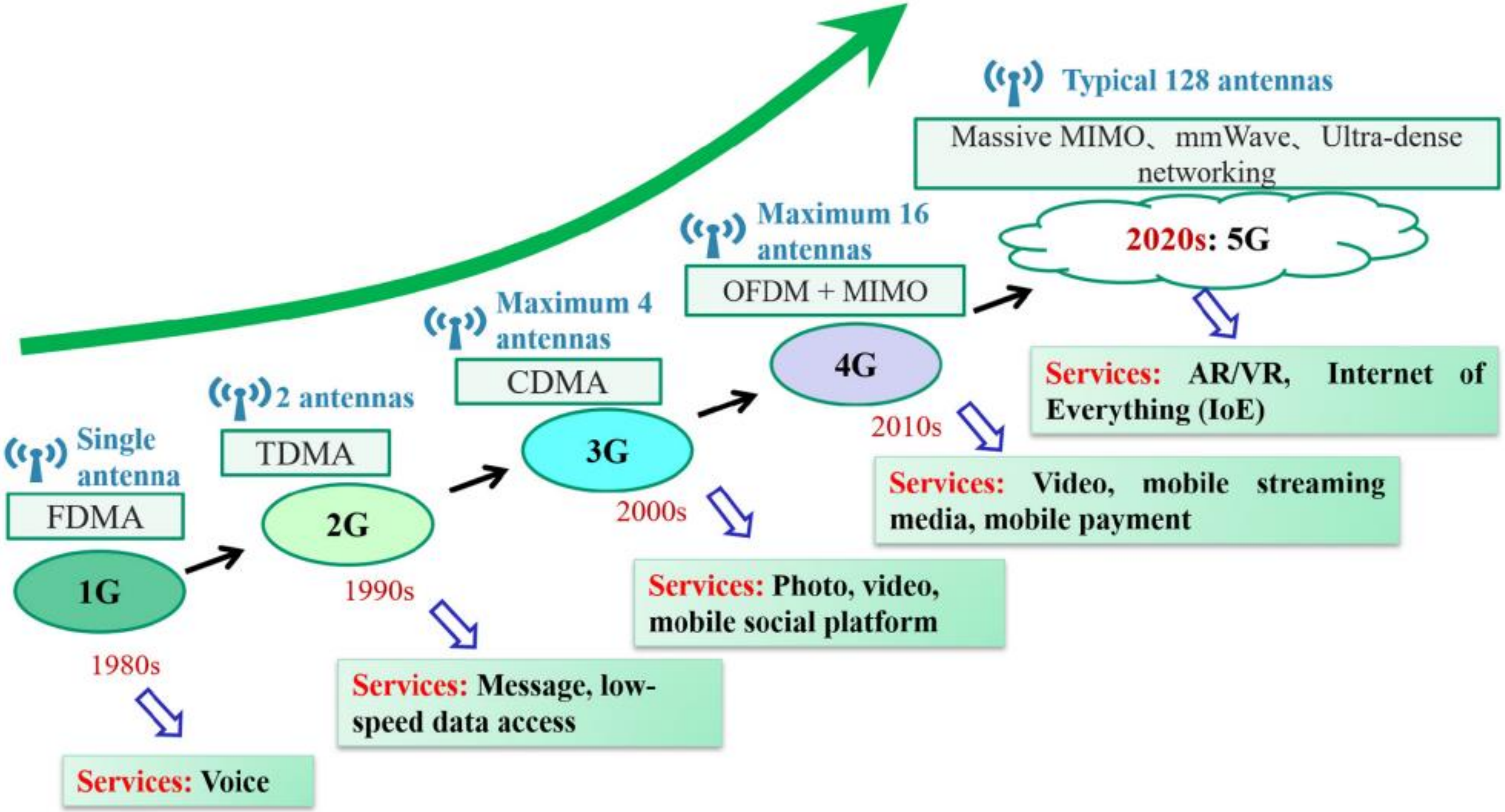

Fig. 1. 1G-5G: Antennas, multiple access technologies, and services.

6G early stage research

Global initiatives:

Finland: large scale 6G research program in 2018

US: FCC opened THz spectrum for 6G “mmWave + THz + Satellite” framework in march 2019

China: Initiated 6G research in Nov 2019

Japan: 6G strategic plan in April 2020

South Korea: 6G timeline in Jan 2020

Germany: 6G research hub and platform in April 2021

Europe: 6G smart networks and services industry association (6G-IA)

6G early stage research

Standardization and Research Bodies:

ITU: ITU released an initial 6G research schedule in Feb 2020 to finalize the 6G vision and technical propositions by mid-2023.

6G early stage research

Key Research and Publications:

Finland's 6G Flagship Organization: Released 6G White Paper in Sept 2019. Covering various aspects of 6G and gave a vision of "Ubiquitous Wireless Intelligence"

Rohde & Schwarz: A white paper exploring transition from 5G to 6G and forecasting key technologies

Ericsson: AI in 6G and identified key challenges

China center for information industry development (CCID): 6G progress investigations by releasing a white paper on 6G in March 2020

NTT DOCOMO: Ten years tech cycle with 5G evolution and 6G requirements

Samsung: Envisioned 6G with user experiences via hyper connectivity

NGMN Alliance: A journey from 5G to 6G

5GIA: Release a white paper on 6G's driving forces, key tech and architecture

6GANA: Explored network AI and intelligent 6G networks

Major Contributions

Critical appraisal: Evaluation of global vision for 6G with key performance indicators and potential application scenarios.

Development trends and network architecture: A promising 6G network architecture is proposed reflecting the latest insights and advancements in the field

Review of 6G Testbeds and verification platforms: Detailed review of existing 6G testbeds, including those designed for 6G wireless channels, crucial 6G components, verification platforms to validate 6G technologies

Research directions and key challenges: Concludes evaluations of the existing literature and potential pitfalls in 6G development**.**

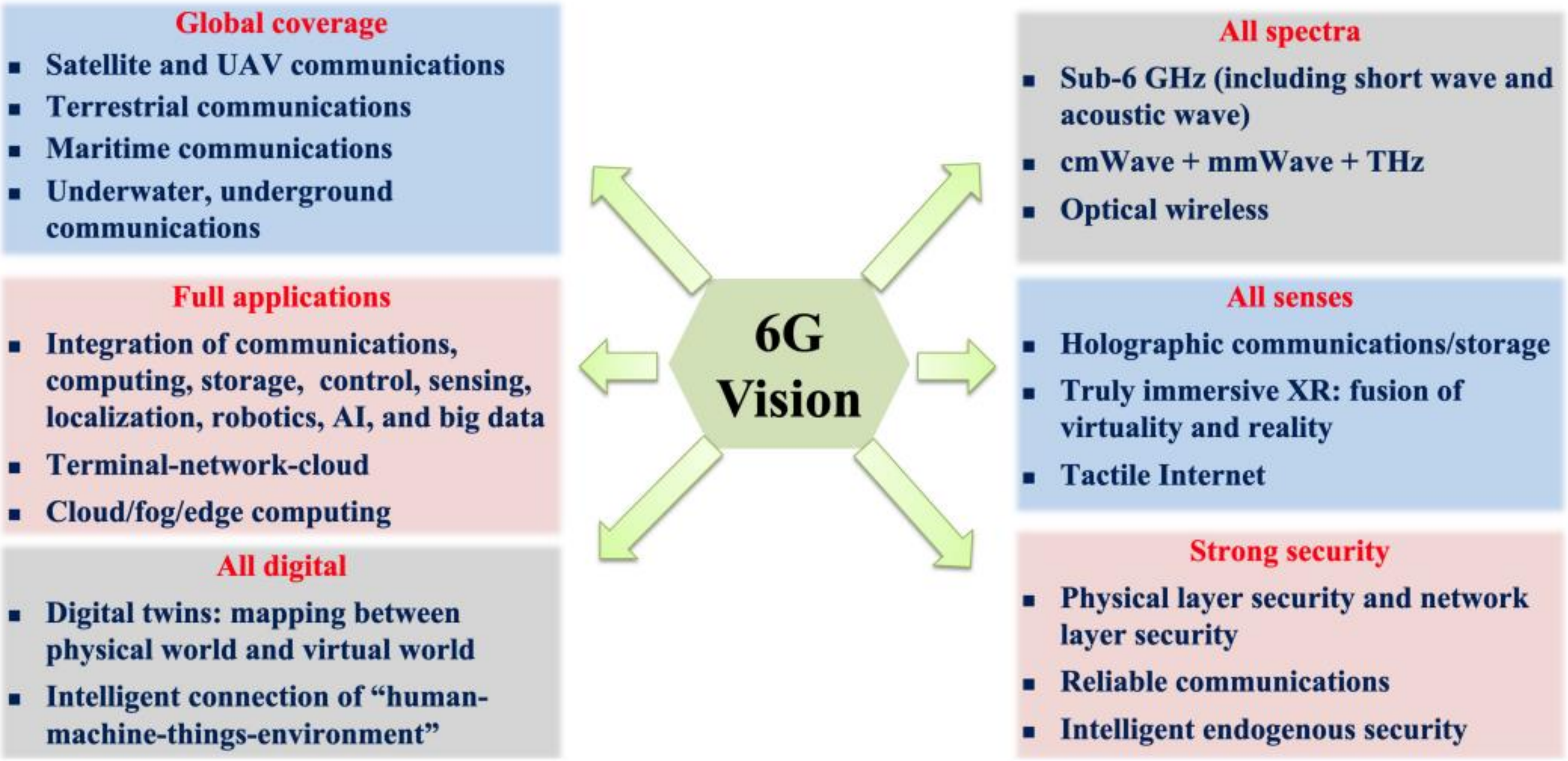

Fig. 3. 6G vision: Global coverage, all spectra, full applications, all senses, all digital, and strong security.

6G Technical Requirements

5G KPI's: The eight KPI's established by ITU-R for IMT-2020 (5G) are still relevant but need updates and new KPI's to evaluate 6G services, like positioning, sensing, security and intelligence among others

Proposed 6G KPI's: This paper proposes 17 KPIs for 6G with new indicators not covered by 5G standards.

Data Rate and Delay

1. Peak Data Rate: In 6G it is projected to reach 1Tbps which is 50 times compare to 5G, it rely on advanced technologies such as THz frequencies and OWCs

2. User Experience Date Rate: Measure max data rate which is almost 95% when needed in 6G this is rate is expected to be 10 Gbps.

3. Latency: Requires minimum delay for air interface access to technologies including intelligent driving, tele-surgery, industrial control, it is expected to be 0.1ms

4. Delay Jitter: 6G aims to achieve a delay jitter of 1microsec.

Capacity and Coverage

5. Air Traffic Capacity: 6G networks is expected to reach 10Gbps/square meter which may be crucial for supporting next gen scenarios like smart factories and smart cities

6. Connection Density: To achieve 10^8devices/square kilometer connected in future application.

7. Coverage: Unlike 5G provides 2D, 6G aims to offer 3D global coverage. 5G networks cover around 20% of land and 5% of ocean areas, amounting 10% of the earth's surface. In 6G it is expected to achieve more than 99% coverage of the Earth's surface.

Service Efficiency

8. Spectrum: For 6G systems is project to reach 90 bps/Hz, which 3 times than 5G. It is due to increasing data demands of 5G

9. Network Energy: Energy consumption of a base station is 1-2kW for an avg of 10Gbps with energy efficiency of 10^7bit/J for 5G. The goal is to increase network energy efficiency by about 100 times aim 10^9bit/J for 6G.

10. Economic: It evaluates the trade-off between cost of providing service and benefits to users. In 5G, cost efficiency is approx. 10Gb/$ which is expected to improve to 500Gb/$/

Diversified Service Evaluation

11. Mobility: Expected to support high mobility, with transceivers capable of speeds over 1000km/h

12. Battery Life: Extended upto 20 years for IoT.

13. Reliability: For uRLLC, the system must ensure that only one erroneous bit is allowed per 10million transmitted bits

14. Positioning: 6G networks aims to achieve positioning accuracy of 1m for outdoor and 10cm for indoor environments

15. Sensing/imaging resolution: Resolution for sensing and imaging is expected to reach 1mm precise data collection and analysis

16. Security capacity: 6G systems requires advanced security technologies like Quantum communication and blockchain

17. Intelligent level: AI integration is required to enhance 6G systems

6G KPIs

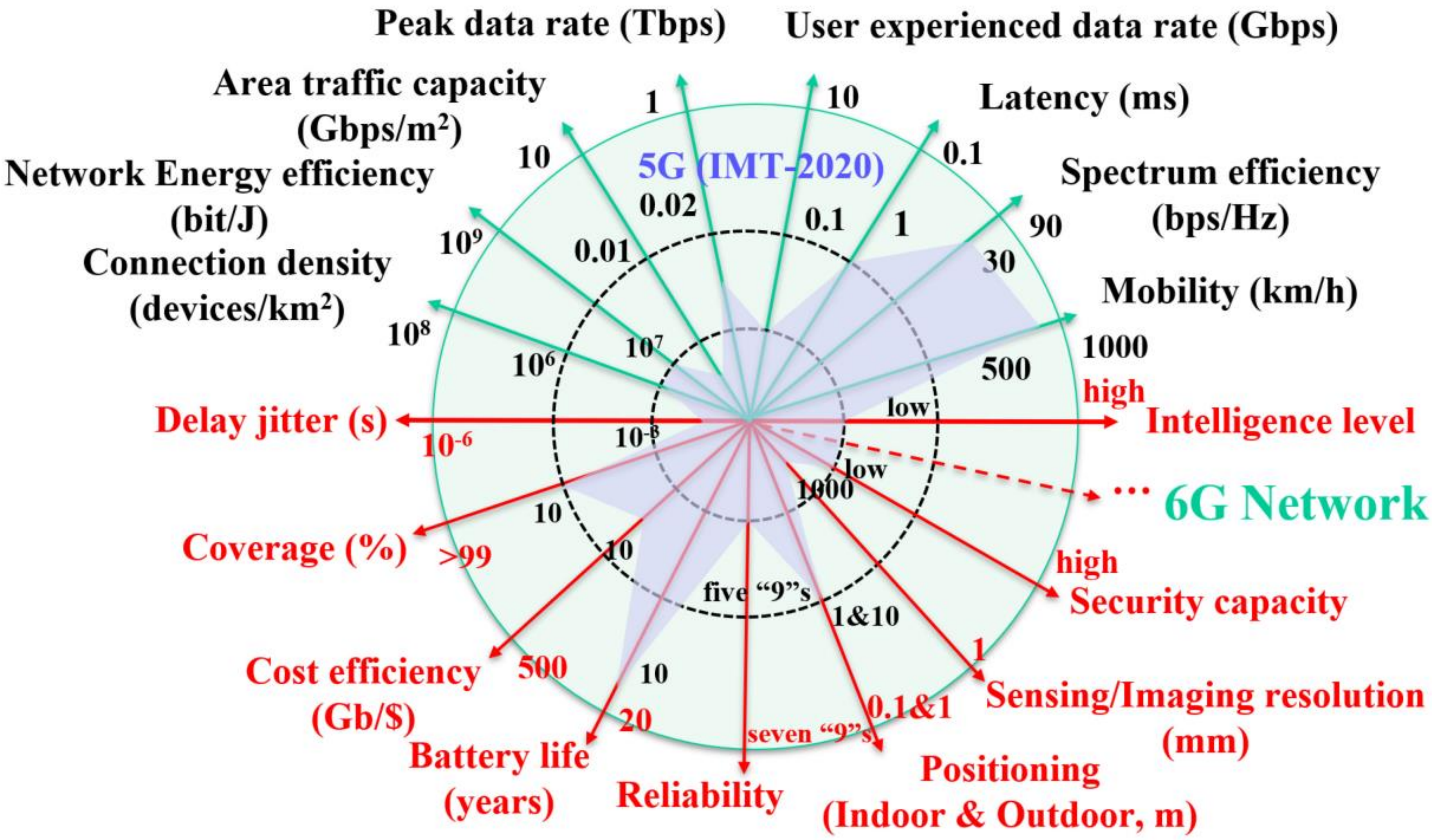

Fig. 4. 6G KPIs.

Potential 6G applications

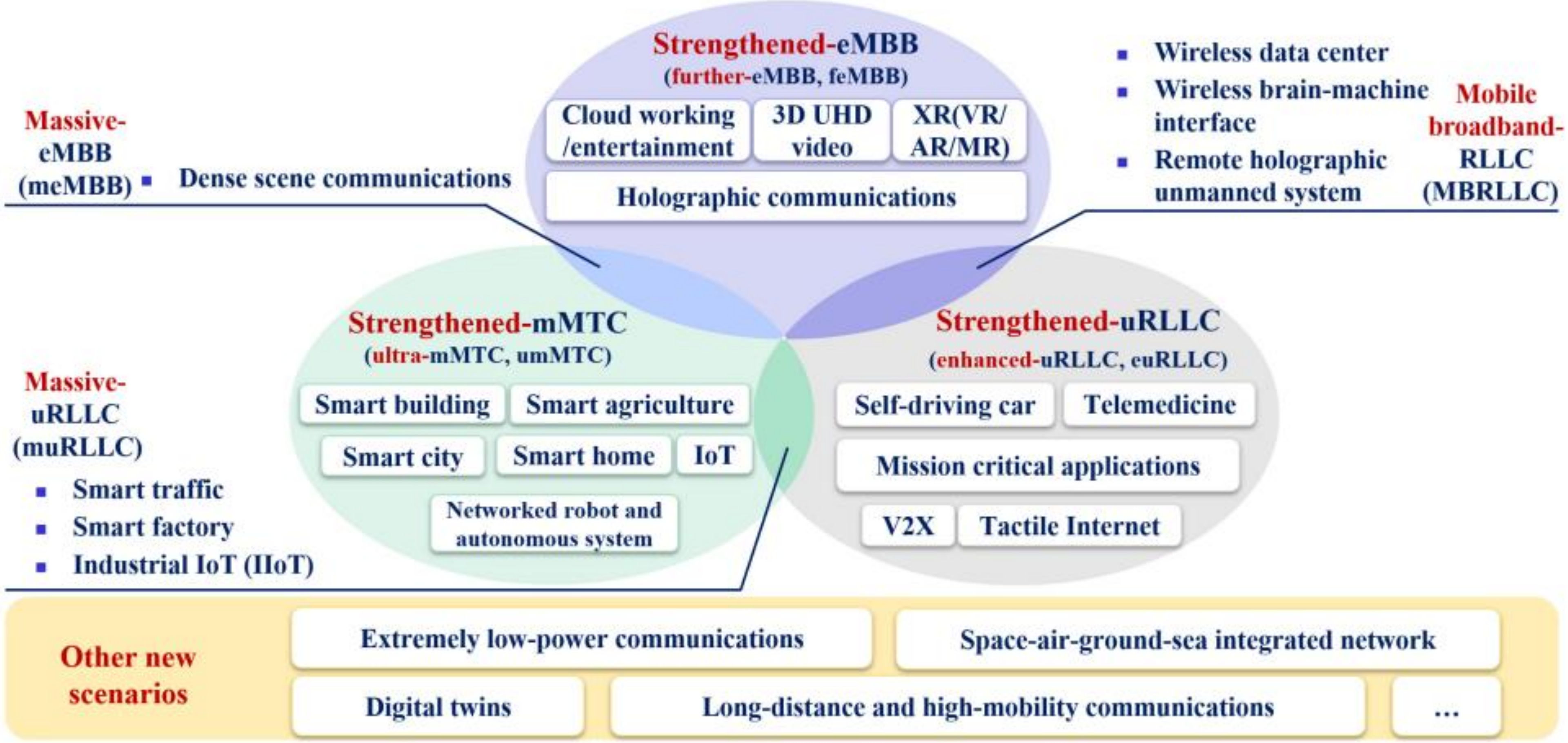

Fig. 6. Potential 6G application scenarios.

Trade-offs Between KPIs

6G is expected to surpass 5G in system performance across various metrics including network transmission, access performance, efficiency and QoS. 6G will support broader range of services, like digital twins, AI, computing, localization and sensing.

1. Simultaneous KPI improvements: Optimal performance achievement across all 17 KPIs is challenging due to hardware limitations, environmental factors and other constraints. So not all KPIs can be improved simultaneously.

2. Energy: Consumption is expected to be rise in 6G.

3. App specific requirements: Extended reality (XR) emphasizes high data rates, low latency and high resolution. Ultra-Low power communications focuses on energy efficiency and connection density.

6G Network Architecture

6G is expected to enhance eMBB, uRLLC and mMTC and introduce new scenarios such as digital twins, integration of communication, computing and sensing.

1. Evolution from 5G to 6G Network Architecture: Modularization, softwareization, virtualization, cloudification with key components network slicing, NFV, SDN, SBA.

2. 6G Network Architecture Directions: 3D multi-network integration, secure and trustworthy, integration of communications, sensing, and computing, and green, flexible, lightweight, natively intelligent.

3. Proposed Approach: review of 5G architecture, 6G development trends and proposed 6G architecture.

Network Function Virtualization

It’s a transformation from hardware to software based programmable networks by allowing virtual functions to run on shared physical resources. Including architecture components NFVI, VNF, NFV-MANO.

Performance Optimization: Acceleration technologies (low level hardware and high level software solution mitigate performance degradation in NFV), reinforcement learning (issues in heterogeneous environment with programmable accelerators), resource management (joint access control and resource allocation algorithms based on parallel VNF processes)

AI and ML Integration: To optimize NVFs in response to dynamic requirements and environments

Network Security: NFV based services protection and addressing security threats

Mapping and Routing: Mapping virtual networks to hardware, routing strategies and security defenses.

Challenges and Future Directions: System complexity, cloud-native NFV-MANO, network programming and automation, QoS and data privacy, edge cloud virtualization.

Software Defined Networking

Unlike NFV, which separates software from hardware, SDN focuses on decoupling the control plane (network control functions) from the forwarding plane (data forwarding functions).

Network implementation and enhancement: Transport network (challenging due to device heterogeneity and complexity), Networks integration (smart grids, underwater WSN, satellite networks, VN)

Innovation Applications: Edge computing and blockchain (integration with SDN can enhance wireless network virtualization's efficiency and security), Machine Learning (apply ML to SDN)

Algorithmic Studies: Controller Placement (to deal with latency, resiliency, energy efficiency and load balancing), Controller Synch (quantified and analyzed in distributed SDN contexts)

Security Issues: STRIDE threat model.

Challenges and Future Directions: Hybrid SDN (switch forwarding schemes in hybrid SDN environments), Energy efficiency improvement in SDN deployments, Handover Schemes (requires effective handover mechanisms for seamless connectivity).

Service Based Architecture

Adoption of SBA in 5G and its anticipated extension to 6G network is in demand

Evolution and extension to 6G: End 2 End (extending from the core to entire network including RAN and user plane), Service based RAN (applying SBA concepts to RAN where to focus on service module definitions and interfaces), Integrated Networks (SBA application to integrated air-space ground networks, to get comprehensive coverage)

Challenges and Future Directions: Fully integrated SBA is envisioned, capable of covering a wide range of applications and network functions to improve network efficiency and adaptability.

Network Slicing

It involves creating multiple virtual networks (slices) on top of a shared physical network infrastructure. Where each slice is tailored to meet the specific requirements of different applications or services, providing flexibility and efficiency

E2E Slicing (Multi level Slicing): Three levels (Cloud, RAN and Application level), Framework (propositions including RAN and Core NS in 5G VN where integrating RAN, transport network and core network slicing)

Specialized/Trailored Slicing: Cater Special Needs (advances in slicing and virtualization to lead to highly specialized slices), Soft customized RAN Slicing (to meet QoS needs in uRLLC and eMBB)

Intelligent Network Slicing: AI integration (to enhance efficiency and management includes AI-Assisted Architectures, digital twins and deep reinforcement learning)

Challenges and Future Directions: issues such as slice isolation, dynamic slice creation, and multi tenant management among others.

Integrated Networks

The 6G network will be a 3D full space network deeply integrated with the ultra-dense terrestrial heterogeneous communication network.

3D Full Space Integrated Network: Extends beyond terrestrial networks (space based, aerial, maritime, underwater, underground networks to enhance coverage and resilience)

Challenges and Future Directions: complexity due to diverse technologies, interoperability due to various types of networks and technologies, and resource management across multiple layers.

Ultra-Dense Heterogeneous Network: Integrating various network technologies (to meet demands for communication services, introduce multilayer network that improves overall QoS and reduces costs)

Challenges and Future Directions: self optimization, adaptive cell selection, coordinated handover schemes, intelligent methods based on deep learning.

Security

Addressing security and trustworthiness is essential due to the increased complexity and scope of the networks

6G security: Integration of tech (virtualization invites complex and less defined security boundary, increase of data exchange, storage and user data privacy is more crucial), risk associations (algorithms, software and systems)

Multilateral trust network: No more centralized models (bridge trust models are not well suited for the diverse security requirements)

Safe and reliable network architecture: Threats (RAN core convergence, intelligent network management, edge intelligence invites security challenges), Blockchain (decentralized and tamper proof records), Quantum communications (unbreakable encryption methods)

Integration of Communications, Computing and Sensing

Multi-Layer Ubiquitous Computing Network: Cloud Computing (resource centralization, on demand allocation and scalable service provisioning), Edge Computing (low latency, real time processing), Fog Computing (bridges gap between cloud and edge computing supports hierarchical structures)

Integration: Advanced App (high precision positioning, mapping, gesture recognition among others)

Applications: Intelligent Transportation (V2X and autonomous driving), UAV Networks (unmanned aerial vehicle), Metaverse (real time communication and sensing)

Green, Flexible and Lightweight

A network with characteristics like green (efficient), flexible (dynamic resource allocation) and lightweight (reduced operational costs) are desirable for 6G.

Cell Free/Less Architecture: Traditional NWs(Grid based structures, centralized control, leading to high costs and management complexity), Cell Free (instead of dividing network into cells, cell free architecture uses a distributed array of massive MIMO antennas and access points across a large area. Controlled by central processing units, offer seamless coverage and coordinated resource use), Challenges (Handling fronthaul links, CSI estimation, resource allocation in practical deployments)

RAN-Core Convergence: Combination (of high-level centralized RAN functions with core network elements to form a unified entity to simplify network architecture, reduce transmission costs and enhance scalability), Challenges (network decomposition division of functions between RAN and core network elements, coordination between various network protocols)

Fully-Decoupled RAN: Separation (control base stations handle control functions and data base stations manage data transmission which aims to enhance flexibility, spectral efficiency and reduce power consumption)

Natively Intelligent

Unlike 5G where AI support was limited, 6G aims to integrate AI natively, enable AI-driven network management and AI-enhanced application services.

AI for Network (AI4Net/Net4AI): Self Based Access (lead to self operation, self maintenance and self repair capabilities), Technology Based Learning (deep/reinforcement/federated learnings), Automated Tasks (network management, optimize resource allocation enhance fault tolerant detection, improve overall performance), AI application services for users (robust infrastructure for AI applications, enabling seamless AI service delivery and support complex AI workloads)

Cognitive Service Architecture: Dynamic Adaptability (real-time provide diverse services depending on user needs and business requirements, monitoring network status including traffic/resource availability/operational events, AI based real time reasoning, features matching and intelligent resource scheduling)

Deep Edge Nodes and Networks (DEN2): Deployment (communication services and intelligence at the network edge, enabling local data processing and pervasive intelligence)

Self-Sustaining Networks (SSNs): Autonomous Maintenance (Adapt highly dynamic and complex environments, self organizing network management)

Digital Twin-Based Network Architecture: Real Time Monitoring (a virtual representation of the physical network, allowing real-time monitoring, simulation and optimization)

Novel Promising 6G Architecture

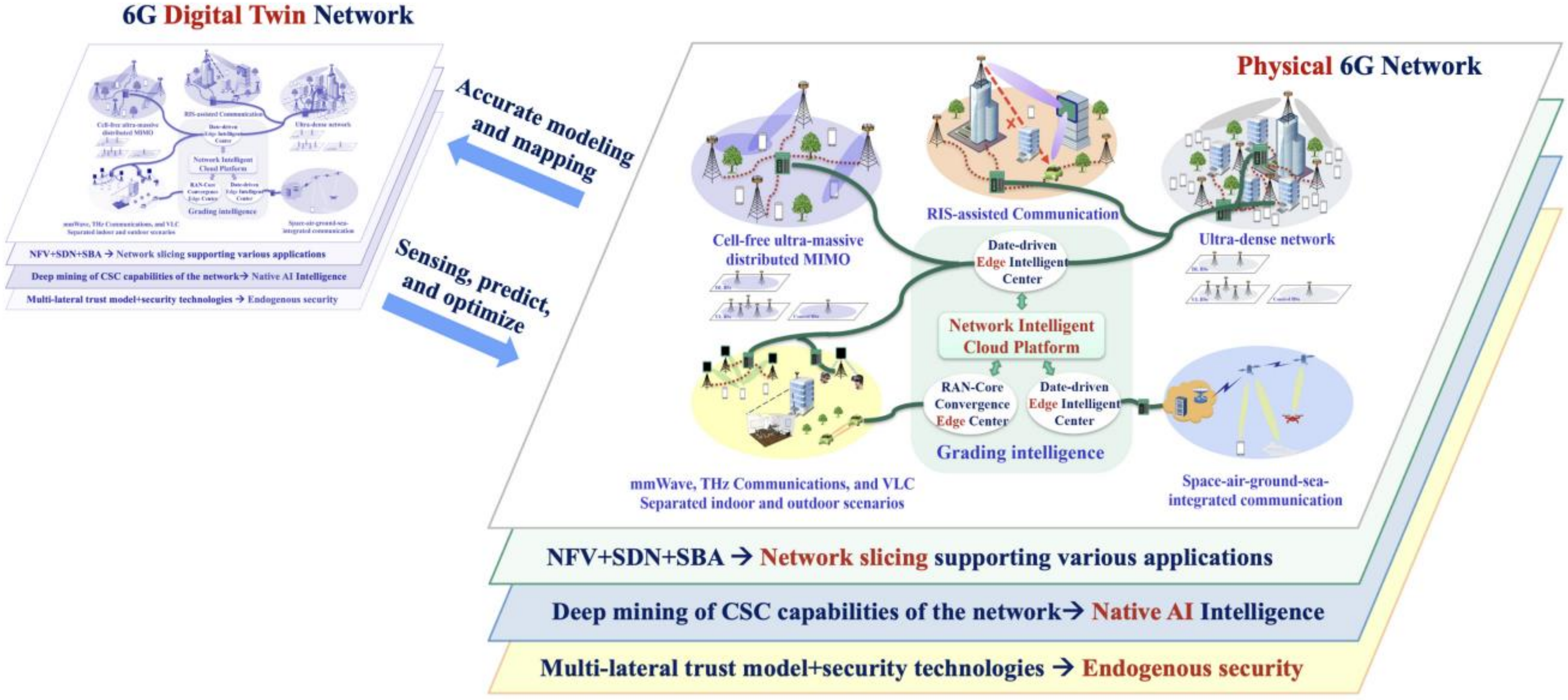

Fig. 8. A novel promising 6G network architecture (CSC: Communications, sensing, and computing).

Important Propositions

The vision of 6G networks involves significant evolution from 5G, driven by the need to support a diverse range of new applications and satisfy stringent KPIs.

Enhanced Intelligence and Flexibility: Cloud/Fog/Edge Computing Integration (such combination is in demand and desirable for real-time scheduling and efficient resource sharing), Hierarchical intelligent network (The integration will form a multi layer network featuring a network intelligent cloud platform and data driven edge intelligent centers. Where fog computing will serve as a bridge between centralized cloud resources and distributed edge networks)

Cell-Free Architecture and advanced technologies: Cell-Free Architecture (combined with massive MIMO antennas aims to overcome traditional cellular boundaries, improving spectral and energy efficiency), Reconfigurable Intelligent Surface (Control wireless channels and enhance coverage/capacity)

Decentralized and Low Latency: RAN-Core Convergence (integrate high level RAN functions with edge functions, reducing transmission delay and supporting low-latency applications like autonomous driving and telemedicine)

Advanced Network Functions and Security: NFV, SDN and SBA Evolution (support E2E network slicing, enabling additional computing and sensing capabilities in network elements), Cognitive and intelligent architectures (cognitive service architecture, DEN2 and Smart Sensor Networks (SSNs) will leverage distributed computing power and large training datasets to achieve native network intelligence)

Digital Twin Tech: Integration (DT will model the real 6G network, allowing real-time mapping and optimization including enable closed-loop simulation, performance prediction, guiding network deployment, management and operation)

Potential 6G Key Technologies

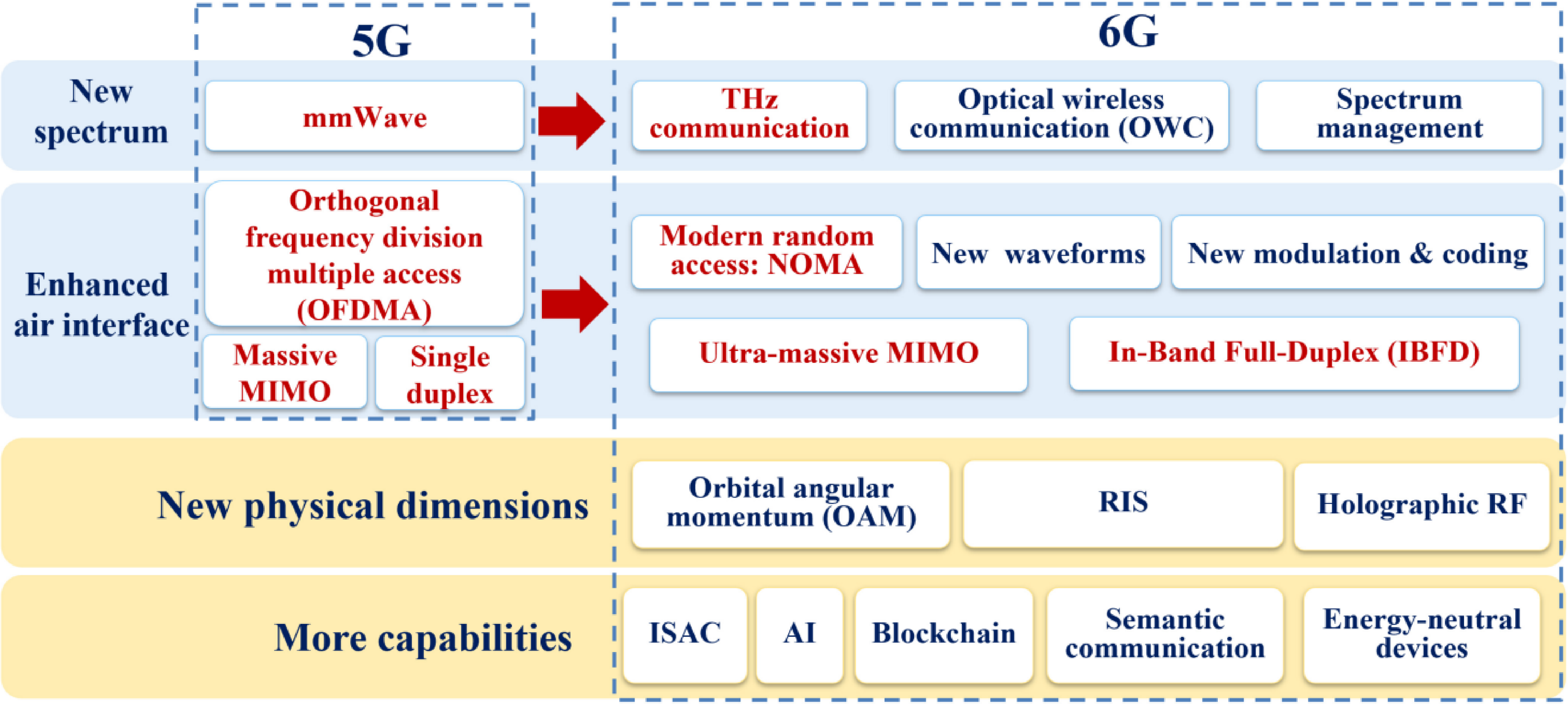

Fig. 9. Potential 6G key technologies.

My Research Interest

Technology	Ref.	Key points
THz	[285]	Standardization, scenarios, application, future research directions and open issues of THz
	[286]	THz generation methods, channel models, applications, standardization activities, and future outlook
	[72]	Challenges, novelties and standardization of THz
	[287]	THz sensing, imaging, and localization applications
	[288]	THz-specific signal processing
	[289]	THz Line-of-Sight MIMO communication
	[290]	MAC protocols for THz
OWCs	[78]	Different promising optical wireless technologies
	[291]	OWC channel research
	[73]	Optical wireless hybrid networks
	[292]	Concepts, architecture, and challenges of VLC
Spectrum management	[293]	Fundamentals, architecture, applications, and important issues of CR
	[294]	A systematic view for symbiotic radio
	[295]	Ongoing Initiatives, challenges, and a roadmap of dynamic spectrum sharing
New waveforms and modulation	[296]	Motivation, features, challenges, and applications of OTFS
	[297]	The history of SEFDM development
	[86]	ISAC-specific waveform design
	[298]	Advances and research directions for IM
New coding	[299]	Evolution of channel coding
	[300]	Decoder ASIC implementations of Turbo, LDPC, and Polar
Modern random access	[301]	Design, standardization progress and use cases of NOMA
	[302]	NOMA research, innovations, applications, and challenges
Ultra-massive MIMO	[303]	An overall research report on ultra-massive MIMO
	[304]	Benefit, signal processing techniques, and research challenges of cell-free massive MIMO
	[255]	Current status and future directions of user-centric cell-free massive MIMO network architecture
IBFD	[305]	Research status and future challenges of in-band full-duplex relaying
	[306]	Techniques and systems survey of IBFD
OAM	[307]	Generation, detection, and emerging applications of OAM waves
	[308]	The generation, detection techniques, and application of THz-OAM beams
	[309]	Insights and design guidelines of OAM-based sensing systems

RIS	[310]	Solutions, research issues, related communication-theoretic models, and performance limits of RIS
	[311]	Principles, performance evaluation, beamforming design and resource management of RIS
	[312]	Research, applications, and challenges of RIS-empowered smart radio environments
	[313]	The key differences and similarities between RISs and relays
	[314]	An overall research report on RIS
	[315]	Advantages, principles, applications, and research directions of RIS
Holographic radio	[316]	Realization and signal processing of holographic radio
AI	[317]	An overall research report on wireless AI
	[318]	AI-based 5G and B5G algorithm, implementation, and optimization
	[319]	Applications and open challenges of DL for the physical layer
	[320]	Techniques and challenges of ML for Internet congestion control
ISAC	[321]	An overall research report on ISAC
	[322]	Motivation, methodologies, challenges, and opportunities of realizing perceptive mobile network
	[323]	Signal processing techniques for joint communication and radar sensing
	[85]	Applications, trends, and challenges of ISAC for ubiquitous IoT
	[324]	Dual-function radar-communications strategies and their relevance to autonomous vehicles
	[325]	An overview research on integrated localization and communication
Blockchain	[326]	Fundamentals and recent efforts of Blockchain-enabled wireless communications
	[327]	The application of blockchain to radio spectrum management
	[328]	Blockchain solutions to address the challenges in data management
	[329]	Blockchain for IoT-based healthcare
	[330]	Blockchain for the IoV
	[331]	Blockchain for cybersecurity in smart grid
Semantic communication	[332]	The latest DL andE2E communication based semantic communications
Energy-neutral devices	[333]	A tutorial survey of backscatter modulation
	[334]	Resource allocation in backscatter communication networks

Need of Testbeds?

The development of 6G technologies are currently guided by ongoing standardization efforts and experimental research. Due to advancement in tech, at this stage, developing and finalizing 6G testbeds are crucial

Standardization Organization: 3GPP (R18-R19) (engaged in specifying requirements and technical standards for 6G networks), IEEE Standards (develop standards and methodologies based on technologies applicable to 6G), ETSI Tech Groups (Focused on tech areas and frameworks to 6G), ITU-T and ITU-R (provide international standards and recommendations for network technologies)

Importance of 6G Testbeds: Channels (new communication channels that 6G will utilize includes mmWave, THz, VLC), Key Tech (to validate and optimize critical tech like RIS, Ultra Massive MIMO and cell-free networks), System Verification (to evaluate the complete 6G system, including its architecture, integration of various technologies and overall system performance)

Testbeds for 6G Channels

Key aspects of channel research are large-scale fading (path loss, shadowing) and small-scale fading (multipath fading includes reflection, scattering). 6G introduces new frequency bands i.e. mmWave, THz, VLC under ultra dense environments, space-air-ground-sea integration, will lead to novel channel characteristics.

Software Channel Simulators: 6G Pervasive Channel Modeling Theory (key models i.e. geometry-based stochastic model (GBSM), Ray Tracing (RT) and AI/ML-based models), 6G Pervasive Channel Model (framework built on GBSM, cover all spectra and scenarios including sub-6GHz, mmWave, THz, IR and VLC). Where applications are ultra massive MIMO, IIOT and RIS channels

Hardware Channel Sounders: Key Properties (bandwidth, delay resolution, delay range, dynamic range), Types (Sub-6 GHz, mmWave, THz, OWC sounders with various frequency bands, UAV, Maritime, Mine environments such as aerial, sea and underground, Application Specific Sounders for massive MIMO, RIS, IIoT and ISAC),

Recent Developments: Sub-6GHz using omnidirectional antennas and planar arrays, mmWave with high speed channel sounders and rotating platforms for spatial characteristics, THz high frequency channel sounders for indoor and outdoor scenarios, LiFi IR channel sounders for indoor applications

Testbeds for 6G Key Technologies

Technology	Organization	Reference	Time	Testbed
mmWave	University of Leuven	[549]	2022	FORMAT (Flexible Organization and Reconfiguration of Millimeter-wave Antenna Tiles)
	Lund University	[550]	2021	LuMaMi28 (Real-time millimeter-wave massive MIMO testbed)
	PML	[551]	2022	Real-time photonics-assisted mm-Wave communication system
THz	Northeast University	[552]	2020	TeraNova (Integrated testbed for ultra-broadband wireless communications at THz-bands)
	PML	[340]	2022	Real-time transparent fiber-THz-fiber 2×2 MIMO transmission system
RIS	HUST	[553]	2021	Prototype for RIS-aided wireless communication
	Princeton University	[554], [555]	2022	Full-dimensional intelligent omni-surfaces
	Universit Paris-Saclay	[556]	2022	RIS prototype with continuous control of the reflection phase
	University of Surrey	[557]	2021	RIS prototype in the sub-6 GHz band
	Sungkyunkwan University	[558]	2021	1-bit RIS testbed
	Tsinghua University	[559]	2020	RIS-based wireless communication prototype
ISAC	HUAWEI	[560]	2022	5G-advanced ISAC technology demonstration of perceiving vehicles and people
	HUAWEI	[561]	2022	ISAC-OW prototype (ISAC with optical wireless)
	HUAWEI	[562]	2022	THz-ISAC prototype (ISAC at THz band)
	University College London	[563]	2022	OFDM-based MIMO SDR testbed

Testbeds for 6G Key Technologies

Cell-free	Ericsson	[564]	2019	Radio stripes
	Samsung	[565]	2022	D-FD-MIMO (Distributed-Full Duplex-MIMO system)
	HUAWEI	[566]	2021	User-centric 5G indoor distributed massive MIMO solution
	KU Leuven	[567]	2022	Techtile (Open 6G modular testbed)
	SEU	[568]	2020	Cloud-based cell-free distributed massive MIMO system
	SEU	[569]	2022	6G-TKμ cell-free massive MIMO testbed
OWC	University of Strathclyde	[570]	2020	Real-world hybrid LiFi/Wi-Fi network deployment
	Kyocera Soraalaser	[347]	2022	105 Gbps LiFi demonstration with WDM
	Mitsubishi Electric	[571]	2021	Demonstration of real-time 14 Tb/s 220 m FSO transmission
	Graz University of Technology	[572]	2019	Testbed for deep space FSO
	The University of Edinburgh	[573]	2019	Testbed for solar cell receiver OWC technology
	YunTech	[574]	2019	OCC testbed with DCO-OFDM
*HUST: Huazhong University of Science and Technology, YunTech: National Yunlin University of Science and Technology.				

6G Verified Platforms

6G addresses multi-band, multi-dimensional needs and integrate advanced technologies such as sensing, computing and AI. To effectively evaluate those systems, real-world data testbeds are essential. Few notable efforts and prototypes have been made aimed at advancing 6G technology.

Purple Mountain Laboratories Tkμ Platform: Validating Performance Metrics (peak data rates, spectral efficiency, delay and integrated intelligence), Key Measuring Components (Cell-Free Ultra-Massive Distributed MIMO, RIS-Assisted 6G Communication, Space-Air-Ground Integrate Communication, mmWave/THz Communication, Grading Intelligence)

China Mobile Research Institute and Beijing University of Posts and Telecommunications (Universal Prototype Platform): E2E Link Implementation (facilitates algorithm validation with improved efficiency through optimization techniques), Baseband heterogeneous acceleration (support open module capability for flexible expansion), Visible Light Communication (achieves joint processing and aggregation capabilities)

Huawei 6G Research Team SRC Prototype: Support (70GHz to deliver ultra-low power consumption, ultra-high throughput, ultra-low latency), Performance Metrics (throughput over 10Gbps, latency in sub millisecond, power consumption 560mW), Applications (supports upto 4k VR services in real-time)

Fundamental Theories

As 6G technology aims to fulfill the vision of "global coverage, full applications, strong security, all spectra, all senses and all digital" it faces a range of fundamental and practical challenges.

Novel Channel Research: Limitations (traditional methods for channel research involves channel measurement, parameter estimation, characteristic analysis and modeling these methods are passive, time-consuming and costly), Future directions (pervasive channel modeling is desirable which evolve passive to active channel recognition, AI to predict channel characteristics and scenarios, adaptive models to varying scenarios, incorporating RIS to enhance channel modeling)

EM & Information Theory: Challenges (integration of EM, information, antenna theory, and wireless propagation channel modeling is crucial, continuous space as network evolve from discrete to continuous spaces e.g. LEO satellites, UAVs acquiring CSI and calculating channel capacity continuously becomes essential, Ultra-Massive MIMO and Holographic MIMO antenna arrays demands new approaches to channel characterization and capacity calculations)

Unified Baseband Processing: Iterative and Joint Baseband Processing (Iterative receivers can improve system capacity and link reliability but may introduce latency and complexity), Unified Bayesian Network (it can improve efficiency for iterative modules), Hardware efficiency (unified architectures like VLSI-DSP can optimize baseband processing), Hardware auto-generation (EDA tools for auto-generating circuit designs can address diverse 6G applications)

Space-Air-Ground-Sea Integrated Networks

As 6G technology evolves, several key areas require focused research and innovation to meet the vision of global coverage and full spectrum integration

Challenges:

- Channel Measurement and Modeling: Integrating diverse channel characteristics across space, air, ground, and sea to address unique environmental and operational conditions.
- Architecture and Protocol Design: Designing a unified network architecture that accommodates the varied needs of these environments, while managing mobility and resource allocation, is complex.
- Mobility Management: Developing solutions for seamless mobility across heterogeneous networks (e.g., between satellites and ground stations) is crucial.
- Network Maintenance: Efficiently managing power supply and optimizing the energy consumption of devices such as UAVs and satellites.
- AI Integration: Leveraging AI for network optimization, including dynamic adaptation of network resources and architecture.

Research Directions:

- Unified Channel Models: Develop comprehensive models that integrate channel characteristics from all environments.
- Innovative Protocols: Create new network protocols and architectures that address the unique challenges of this integrated network.
- AI-Driven Optimization: Explore AI-based methods for real-time network management and optimization

RF-Optical Heterogeneous and Hybrid Networks

Challenges:

- Heterogeneous Network Issues: like mobility management, network synch and resource allocation
- Integration of RF and Optical Systems: overcoming the large freq gap between RF and OCS which complicates hardware integration and channel modeling
- Network Selection and Security: designing optimal network selection strategies and addressing security concerns in HN environments

Research Directions:

- Hybrid network integration: between RF and OCS including hardware and channel model fusion
- Optimal network selection: network selection and switching for various network types
- Security protocols: security mechanism for heterogeneous networks

AI-Enabled Wireless Communication Networks

Challenges:

- Data management: efficient collecting, sharing, usage of data for training AI models in WN
- AI performance optimization: for network configuration and resource allocation
- Energy efficiency: reducing energy consumption of AI models and reducing environmental impact
- Privacy and security: privacy concerns and ensuring secure data handling in AI-driven networks

Research Directions:

- Data collection: need to develop data collection and sharing AI application based framework
- Performance modeling: analysis of relationship between AI performance and network configuration

Integrated Communications, Sensing, and Computing Networks

Challenges:

- Integration Tech: developing technologies that seamlessly integrate comm, sensing, computing
- Resource allocation: managing resources across comm, sensing, computing func includes multi-layer computing and cloud edge terminal allocation
- Real time processing: handling real time data processing and coordination of distributed computing resources

Research Directions:

- ISAC Tech: requires enhanced network capabilities
- Multi-Layer Computing: for resource management and allocation
- Real-Time Data Processing: real time feature extraction and information fusion

Digital Twin Networks

Challenges:

- <u>Real Time Modeling</u>: of large scale networks and complex topologies
- <u>Compatibility and integration</u>: between equipment of various manufacturers and network components
- <u>Data management</u>: handing of massive amount of data required for network modeling and real-time updates

Research Directions:

- <u>Physical network</u>: accurate modeling for DT
- <u>Compatibility Solutions</u>: equipment and data compatibility
- <u>DM strategies</u>: efficient data collection, storage and processing in DT networks.

Outcomes

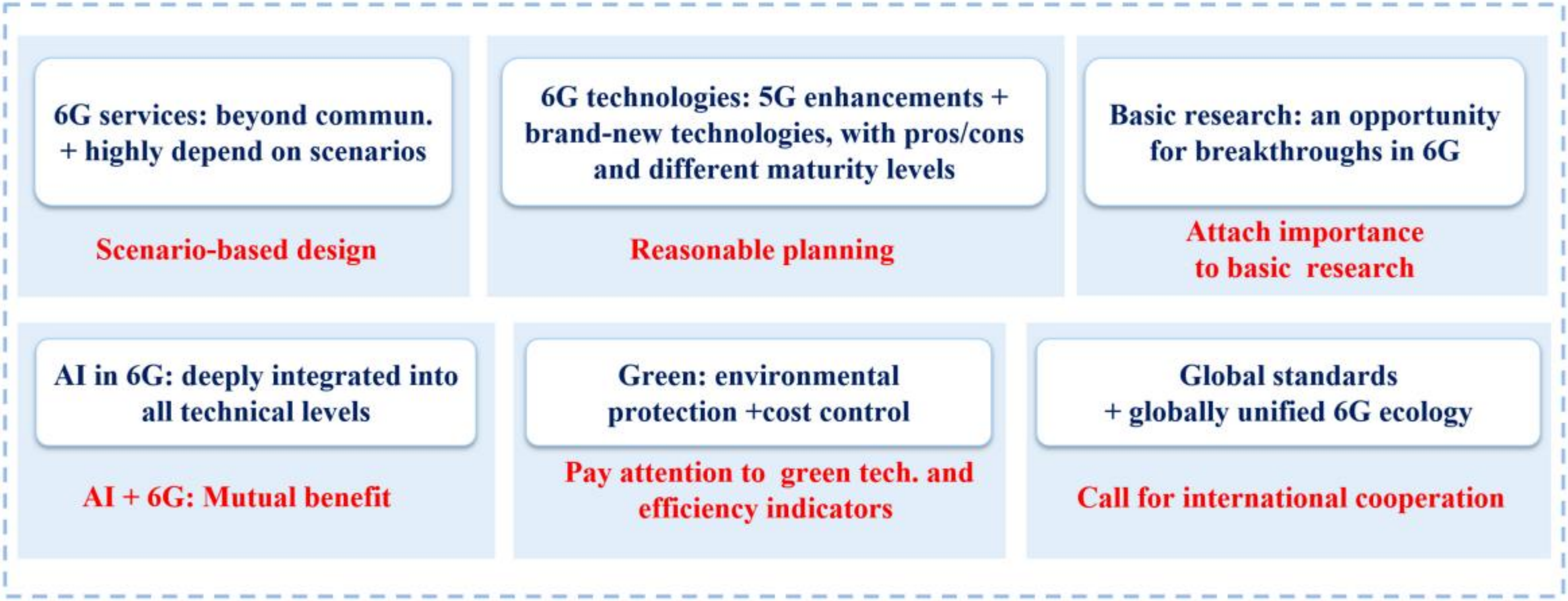

Fig. 13. Lessons Learned.