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6G

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1. 6G Technology Megatrends and Motivation on Driving Factors

The applications and services enabled by the wireless communication technologies of the future will connect not only humans and but also machines and various other objects together. Thanks to advances in new human–machine interfaces such as extended reality (XR) displays, haptic sensors and actuators, e–smell and e–taste, and brain interfaces, connected users can enjoy truly immersive experiences, which are virtually generated or happen in a remote place. On the other hand, connected machines are intelligent and automated so that they can move ultra–fast and ultra–precisely as desired, by virtue of advances in machine perception, robotics, and artificial intelligence (AI). These humans and machines will interact with each other continuously in the real physical world, as well as in a digital world that replicates the real world and is produced through the use of huge numbers of advanced sensors. Such a digital world not only replicates but also affects the real world, providing virtual experiences to humans and computerized control to machines in the real world. For this reason, it needs to be trustworthy, and allow a huge amount of computing to be split and distributed all over the network and devices. To interconnect this digital world with the physical world, 6G needs to play an important role as an infrastructure, by: 1) collecting huge amounts of real–time sensing data everywhere in the physical world, 2) computing real–time controls of automated machines and immersive senses for humans, and 3) delivers these back to the physical world so that humans and machines can continuously interact with each other, as summarized in Figure 1.

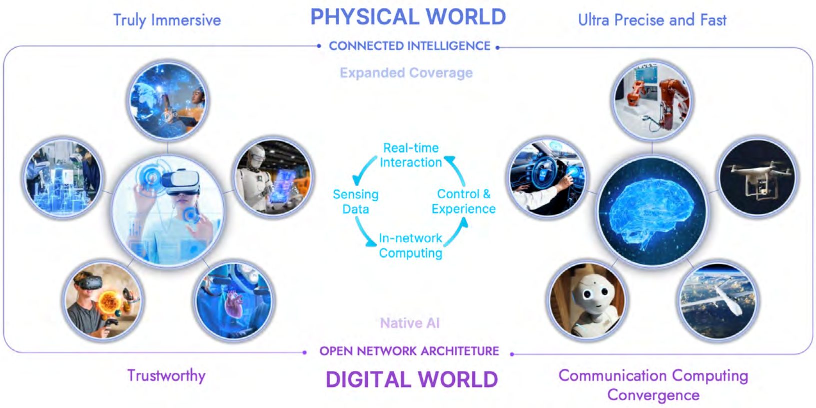

Figure 1. 6G Technical Megatrends.

2. 6G Technology Trends

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In order to substantiate the anticipated role of 6G, wireless communication and network technologies for 6G need to provide extended coverage all over the world to connect everything, everywhere (both on the macro- and micro-scale) while supporting enhanced mobility for fast-moving automated machines. At the same time, much better connectivity and service continuity need to be provided by advancing network topology beyond the existing cellular concept. This aspect of the enabling technology can be categorized as “coverage and network topology beyond cellular,” as shown in Figure 2.

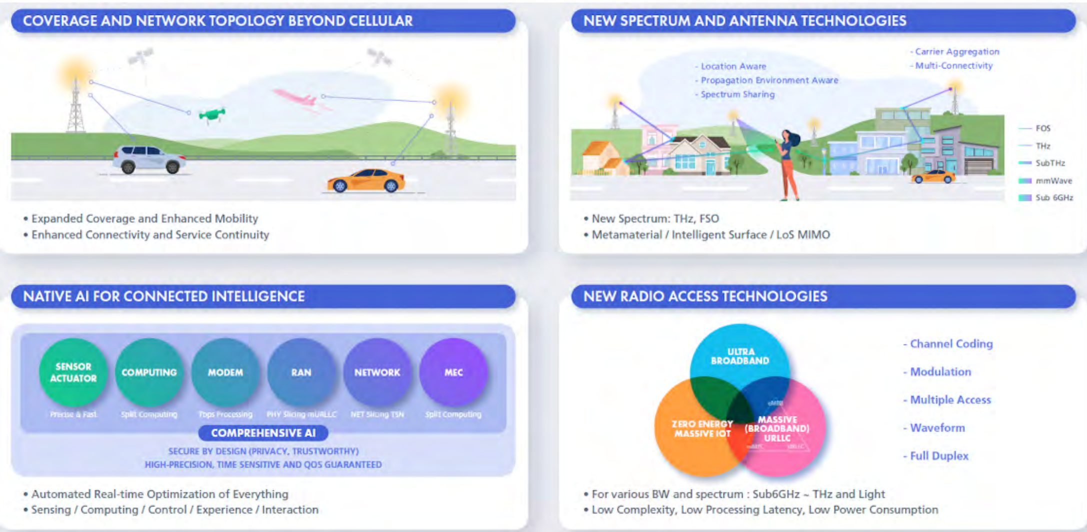

Figure 2. 6G Technology Trends.

The huge amount of sensing and computing data delivery between the physical and digital world requires that 6G should provide a much higher data rate (e.g., tens of Gbps) to each of the mobile devices, the number of which is reaching hundreds of billions. For this reason, it is essential to utilize a new and wider spectrum, such as in the terahertz bands and optical bands. Also, the use of a new spectrum always requires new antenna technologies and propagation methodology. At the same time, the time-geographical utilization efficiency of the existing spectrum (e.g., under 6GHz) needs to be significantly improved. This aspect of the enabling technology can be categorized as “new spectrum and antenna technologies.”

6G wireless networks need to provide a huge amount of computing capability distributed all over the network by appropriately delivering a huge amount of collected data. As such, every system resource (radio, network, computing, etc.) and network operation need to be real-time optimized to guarantee the performance and a system design based on comprehensive AI, which consists of local, joint, and e2e AI over all entities, including user equipment (UE), base stations (BSs), core network, and server. In addition, a 6G wireless network should be secured through a design that considers needs related to security and privacy. This aspect of the enabling technology can be categorized as “native AI for connected intelligence.”

Finally, the radio access technology for 6G should utilize hyper-wideband up to several GHz in the terahertz and optical bands to provide up to tera-bps (Tbps) data transmission. Furthermore, it should support ultra-massive connectivity and broadband ultra-reliable low-latency services, which implies that novel radio access technologies need to be developed including waveform, modulation, multiple-input multiple-output (MIMO), multiple access, duplexing, and channel coding. This aspect of the enabling technology can be categorized as “new radio access technologies.”

3. Enabling Technologies

3. Enabling Technologies

3.1. Coverage and Network Topology beyond Cellular

As described in the previous section, one category of enabling technologies is “coverage and network topology beyond cellular” and among the good candidates in this category are 3-dimensional (3D) coverage technology, network topology beyond cellular, satellite access, and in/around-entity wireless data transfer.

3.1.1. 3D Coverage

A technology that can provide communication coverage in a 3D space, transcending the limitations of ground-oriented mobile communications service, is required. It is expected that it will be possible to provide stable internet services to various moving vehicles in the air through integrated satellite and terrestrial network technologies. The integrated 3D network technologies will be developed in the form of the vertical integration of 3D mobile communication technology and 3D satellite communication technology, as shown in Figure 3.

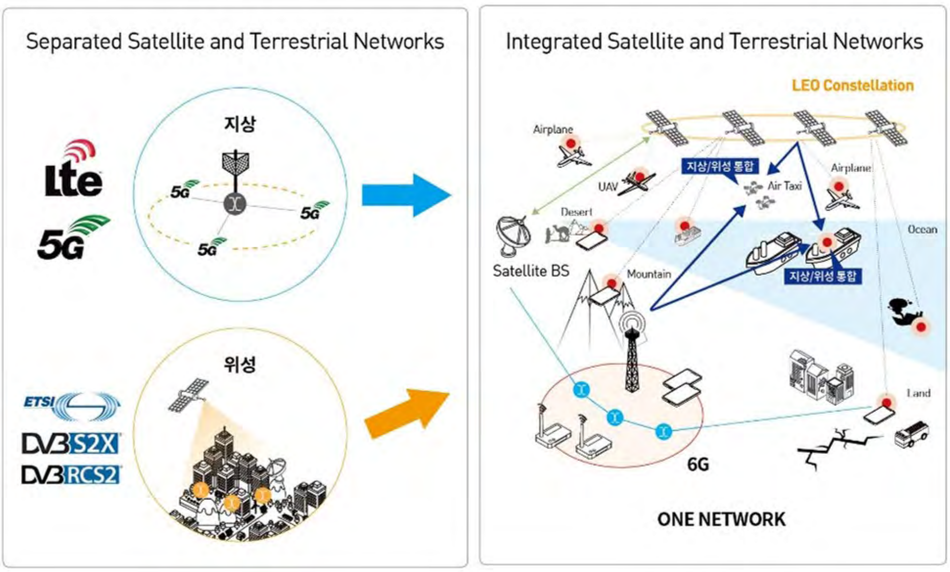

Figure 3. Concept map of the integrated satellite and terrestrial networks.

The global market for unmanned aerial vehicles such as smart airlines, flying taxis (air taxis), and drones is expected to grow rapidly. As such, the area of communication that provides Gbps class internet service will be expanded in 3D form not only on the ground, but also in the air and at sea, so that users will be able to receive Gbps-class internet service anytime, anywhere. This can also be used for disaster response, disaster monitoring, and disaster alert propagation services, even in areas where ground communication is not available.[1) 2)]

Satellite-terrestrial networks leverage a range of technologies and methodologies to achieve seamless service coverage, robust service supporting ability and high-efficiency performance via heterogeneous networks.[3)] Handover schemes should be developed to tackle frequent handover due to satellite movement. The improvement of beam management is required for mobility of satellites and aerial vehicles, long round-trip time (RTT), wide beam coverage, and various beam types.[4)] Challenging issues here include fast beam tracking/switching and beam interference mitigation with bandwidth part (BWP) and polarization. In addition, antenna technologies for LEO satellite payload are crucial. The hurdles to overcome here include multibeam flat antenna for user link, feeder link, ICs for analog/digital beamformer and front-end, and inter-satellite antenna for Gbps communications.

3.1.2. Network Topology beyond Cellular

Figure 4 shows the technical concept of future cellular network topology, which can be considered as "network topology beyond cellular," which in contrast to the classic cellular network has the characteristics of being 1) cell-free, 2) dynamic, and 3) space-terrestrial integrated.

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1) J. Kim, M. Y. Yoon, D. You, and M.-S. Lee, "5G Wireless Communication Technology for Non-Terrestrial Network," Electronics and Telecommunications Trends, vol. 34, no. 6, pp. 51-60, 2019.

2) M. Giordani and M. Zorzi, "Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities," December. 2019. (https://arxiv.org/pdf/1912.10226.pdf)

3) P. Wang et al, "Convergence of Satellite and Terrestrial Networks : Comprehensive Survey", Vol.8, Jan. 2020.

4) 3GPP TR 38.811, "Study on New Radio (NR) to support non-terrestrial networks(Rel-15), July 2020.

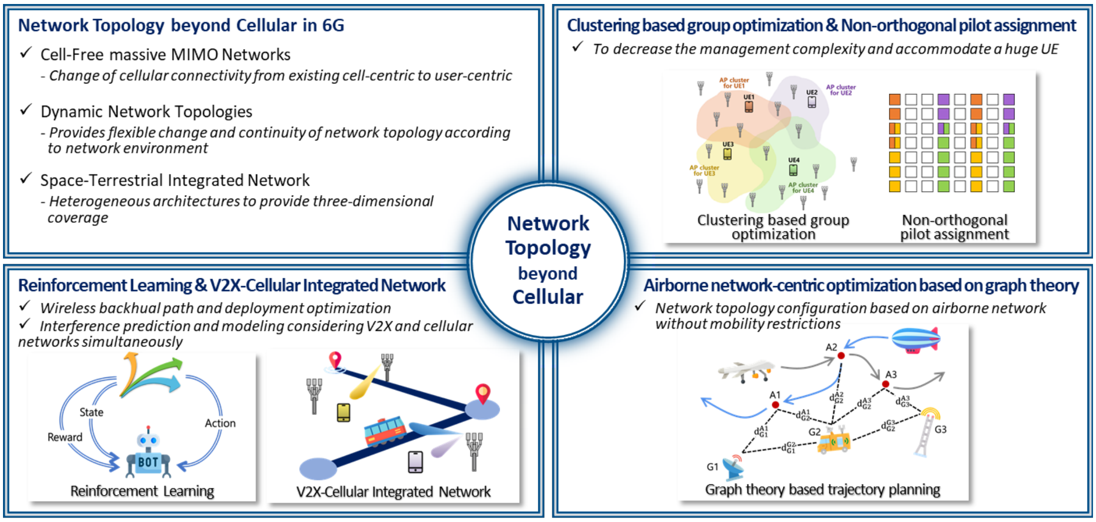

Figure 4. Technical Concept of Network Topology beyond Cellular

Cell-Free massive MIMO Networks: In the conventional cellular networks, including small-cell networks, mobile users are in general connected with the single nearest base station with the strongest signal strength; this may cause performance degradation, particularly in hot-spot environments without a direct link.[5] Recently, cell-free massive multiple-input multiple output (MIMO) networks, in which multiple base stations equipped with a large number of antennas cooperatively support a relatively small number of mobile users without considering cell-boundaries in order to improve network performances such as coverage probability and computation cost, have received much attention from both industry and academia.[6] The advantages of a cell-free massive MIMO network include high array gain, high energy efficiency, and reduction of inter-cell interference by achieving coherent cooperation between distributed base stations through a backhaul link.[7] But in cell-free massive MIMO networks, orthogonal downlink pilot assignment may not feasible, and thus channel estimation and

5) N. T. Nguyen and K. Lee, "Coverage and Cell-Edge Sum-Rate Analysis of mmWave Massive MIMO Systems With ORP Schemes and MMSE Receivers," *IEEE Trans. Signal Process.,* vol. 66, no. 20, pp. 5349–5363, Oct. 2018.

6) H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-Free Massive MIMO Versus Small Cells," *IEEE Trans. Wireless Commun.,* vol. 16, no. 3, pp. 1834–1850, Mar. 2017.

7) H. Q. Ngo, L. Tran, T. Q. Duong, M. Matthaiou, and E. G. Larsson, "On the Total Energy Efficiency of Cell-Free Massive MIMO," *IEEE Trans. Green Commun. Netw.,* vol. 2, no. 1, pp. 25–39, Mar. 2018.

network organization are challenges. Recently, the non-orthogonal downlink pilot structure in power-domain or code-domain and a group-wise network optimization technique based on base station cluster have been proposed as sub-optimal but cost-effective approaches.

Dynamic Network Topologies: Dynamic network topologies flexibly adapt mobile traffic in time and space according to the movement of mobile users, particularly in overcrowded areas, and these have several advantages, such as self-recovery and self-adaption.[8)] For example, integrated access and backhaul (IAB) provides an access link and wireless backhaul link based on multi-hop relay simultaneously, and thus it is more cost-efficient than optical fiber-based wired backhaul.[9)] For group mobility scenarios, in which multiple users move on the same vehicle such as a bus, high-speed train, or airplane, it is possible to efficiently improve high traffic capacity simply by placing multiple radio units on the track of a vehicle.[10)] Recently, reinforcement learning has been exploited for instantaneous path selection and user scheduling in managing dynamic network topologies.

Space-Terrestrial Integrated Network: Three-dimensional network topologies are expected to support unrestricted communication coverage for 6G mobile networks, and these include unmanned aerial vehicles (UAVs), high altitude platforms (HAPs), and low earth orbit (LEO) satellites as wireless communication nodes. A space-terrestrial integrated network can be divided by layer based on altitude into a ground-based network, an airborne network, and a spaceborne network.[11)] Each layer applies individual communication protocols, transmission techniques, and systems architecture for different communication environments. The OpenFlow routing protocol can facilitate inter-layer communication by solving the routing protocol compatibility problem.[12)] In addition, a self-organization satellite terrestrial integrated

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8) E. A. Kushko and N. Y. Parotkin, "The research of technologies for secure data communication in dynamic networks," *2017 Dynamics of Systems, Mechanisms and Machines (Dynamics)*, 2017.

9) M. Polese et al., "Integrated Access and Backhaul in 5G mmWave Networks: Potential and Challenges," *IEEE Commun. Mag.,* vol. 58, no. 3, pp. 62 - 68, Mar. 2020.

10) Samsung "The Next Hyper Connected Experience for All," White Paper, Jul. 2020.

11) H. Yao, L. Wang, X. Wang, Z. Lu, and Y. Liu, "The Space-Terrestrial Integrated Network: An Overview," *IEEE Commun. Mag.,* vol. 56, no. 9, pp. 178-185, Sept. 2018.

12) W. Chien et al., "Heterogeneous space and terrestrial integrated networks for IoT: Architecture and challenges," *IEEE Netw.,* vol. 33, no. 1, pp. 15 - 21, Jan./Feb. 2019.

system (SSTIS) has also been proposed to support self–organization network management, and performs network recognition, monitoring, and resource management in each layer, which are the perception layer, recognition layer, and intelligence layer, respectively.[8] Software defined network–based reference architectures and network function virtualization technologies are being considered as an approach to improving the performance of space–terrestrial integrated networks.[13] However, the optimization of node position and trajectory are extremely complex, and many studies only consider the centralized network optimization technique based on graph theory, which presumes an optimal candidate trajectory.

3.1.3. Satellite Access Technology

Primary services with satellites for 6G networks are expected to be direct satellite access using the same smart phones as those for terrestrial networks, backhauling service from gNBs, relay towers, and gateways, and global coverage for M2M and IoT, including in remote areas. Technologies and their corresponding requirements are 1) Very High Throughput Satellites (VHTS) for a downlink data rate higher than 500 Mbps for fixed access and higher than 10 Mbps for mobile access, 2) mega–constellation low earth orbit (LEO) satellites with on–board processing (OBP) with inter–satellite links (ISL) for coverage up to 10 km above the ground, 3) small satellites with end–to–end latency less than 10 ms, and 4) space–air–ground integrated network (SAGIN) for seamless 3D connectivity by extending 3GPP 5G Non–Terrestrial Network (NTN) specifications. Figure 5 illustrates the services and enabling technologies for satellite access.

13) S. Yao *et al.*, "SI–STIN: A smart identifier framework for space and terrestrial integrated network," IEEE Netw., vol. 33, no. 1, pp. 8 – 14, Jan./Feb. 2019.

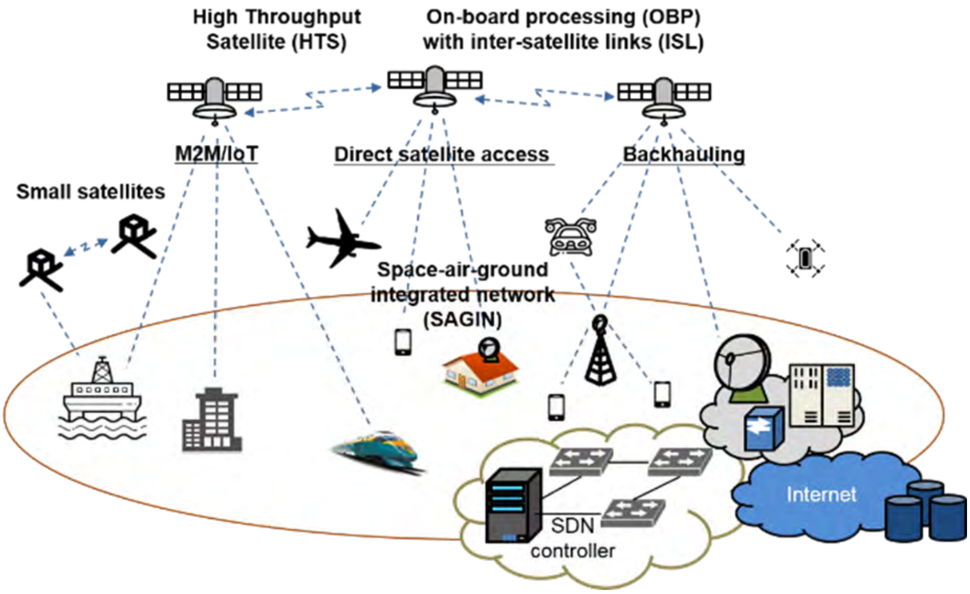

Figure 5. Future Satellite Access Technology.

For HTS, R. De Gaudenzi et al. emphasized the importance of active antennas and flexible OBPs for VHTS,[14)] while A. I. Pérez-Neira et al. investigated on-board signal processing techniques including precoding for HTS/VHTS with a focus on fixed satellite service (FSS).[15)] Large-scale multiple spotbeams and high-traffic on-board router/switch will be key technologies for further advancements of HTS. For OBP with ISL, A. Papa et al. addressed the dynamic control satellite placement in the LEO satellite network,[16)] and J. P. Choi et al. jointly optimized OBP switching/routing and beamforming for advanced phased array antenna.[17)] Future networks will need to support space laser crosslinks with high-precision antenna and

14) R. De Gaudenzi et. al., "Future Technologies for Very High Throughput Satellite Systems," Int. J. Satellite Communication and Networks, 2020.

15) A. I. Pérez-Neira et. al., "Signal Processing for High-Throughput Satellites: Challenges in new interference-limited scenarios," IEEE Signal Processing Magazine, 2019.

16) A. Papa, T. de Cola, P. Vizarreta, M. He, C. Mas-Machuca and W. Kellerer, "Design and Evaluation of Reconfigurable SDN LEO Constellations," IEEE Transactions on Network and Service Management, 2020.

17) J. P. Choi, S.-H. Chang*, and V. W. S. Chan, "Cross-Layer Routing and Scheduling for Onboard Processing Satellites with Phased Array Antenna," IEEE Transactions on Wireless Communications, 2017.

satellite position tracking under high satellite mobility. For small satellites, I.F. Akyildiz et al. proposed an "Internet of Space Things/CubeSats" by applying cyber-physical systems (CPS),[18] and R. Bassoli et al. designed a virtual baseband unit (BBU) of the cloud radio access network (C-RAN) based on cubesats and UAVs.[19] Small satellites can be a main item to be added to 3GPP NTN in the near future, and will require cost-efficient system design under SWaP (size, weight, and power) constraints. For space-air-ground integrated networks (SAGIN) M Bacco et al. proposed the integration of 4 network segments: UAVs, high altitude platforms (HAPs), LEO, and geostationary (GEO) satellites.[20] T. Hong et al. applied network slicing to SAGIN for IoT service with UAVs in mmWave bands.[21] With enhancements of 3GPP 5G NTN Study/Work Items, integration of satellites with terrestrial networks will need cross-layer optimization of heterogeneous algorithms/protocols, such as SDN/NFV, for seamless service coverage.

As enabling technologies for future satellite access, the main focus of OBP architecture will be on multibeam signal processing for a high throughput increase and the design of router/switch in the sky with optical ISLs for latency reduction. To make small satellites technically and economically feasible, the cost-efficient use of commercial off-the-shelf components, such as solid state power amplifiers, antennas, and processors, will be critical. Interconnections of small satellites with UAV, HAP, and orbital satellites can be a candidate item for new 3GPP NTN Study/Work. Finally, software-defined networking (SDN) and network function virtualization (NFV) can realize centralized network control and efficient resource management for 5G/6G networks. Differentiated and seamless services with 3D network slicing will be achievable with the full adaptation of SDN/NFV into the SAGIN.

18) I.F. Akyildiz et al. The Internet of Space Things/CubeSats: A Ubiquitous Cyber-Physical System for the Connected World, Computer Networks, 2019.

19) R. Bassoli et al., Cubesat-Based 5G Cloud Radio Access Networks, IEEE Vehicular Technology Magazine 2020.

20) M Bacco et al., IoT Applications and Services in Space Information Networks, IEEE Wireless Communications 2019.

21) T. Hong et al., Space-air-ground IoT Network and Related Key Technologies, IEEE Wireless Communications 2020.

3.1.4. In/around-Entity Wireless Data Transfer

As shown in Figure 6, in/around-entity wireless data transfer is a micro-scale high-speed and low-latency wireless network to interconnect peripheral devices. As vehicles, robots, and smart devices become more intelligent, the number of embedded modules supporting high-resolution and multiple functionalities increases. Accordingly, to reduce wiring harnesses and increase the degrees of freedom in network configuration, it is necessary to configure a micro-scale wireless network for each module in a wired network, and to provide connectivity to external cellular networks. In addition, to support high-resolution and multiple functionalities of multiple modules, high mobility for connected/autonomous vehicles (CAVs), high connectivity and real-time control for human-like behavior (brain, nervous reflex), and safety, advanced techniques satisfying 6G technical requirements are required.

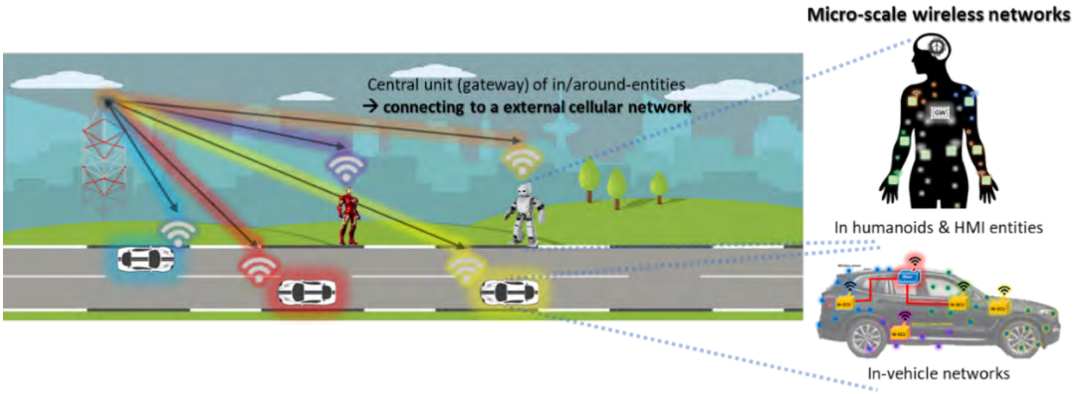

Figure 6. Technical Concept of in/around-entity Wireless Data Transfer.

For an in-vehicle network (IVN), controller area network (CAN), which is the de-facto standard of IVN and supports up to 1Mbps, has been widely used. To support massive data in autonomous vehicles, new wired technologies such as automotive Ethernet and automotive SerDes (serializer/deserializer) have been introduced, achieving a +1Gbps data rate. However, the use of a wired harness causes a significant burden on fuel/battery efficiency, poses a design limitation, and slows movement due to the increase[22) 23) 24)] in weight and volume that results. To relieve this burden, several studies have been conducted on the use of wireless technologies. For example, existing Zigbee, Bluetooth, and Wi-Fi systems were tested for wireless IVN and human-machine interface[25) 26)], but these have the limitation of low data rates and higher delay, only supporting low-end products of IVN and humanoids.

Therefore, for in/around-entity wireless data transfer such as CAVs and more intelligent humanoids, the application of future wireless techniques is essential to support massive multiple data, ultra-low latency, real-time controls for high mobility and high reliability for safety.

3.2. New Spectrum and Antenna Technologies

Another category described in the previous section is "new spectrum and antenna technologies" and the good candidates in this area include terahertz technology, free-space optics communication technology, programmable wireless environments, and spectrum sharing technology.

3.2.1. THz Technology

Holographic vision or future XR utilizing 6DoF, providing service consumers with true volumetric or immersive visual experience, require an immense bandwidth of up to several Tbps. Also, as machines equipped with AI have started to emerge as new principal data consumers and some of them need much higher resolution and wide angle vision than human sight, the data rate required will be unprecedentedly immense. The most fundamental three

22) M. Laifenfeld and T. Philosof, "Wireless Controller Area Network for In-Vehicle Communication," IEEE 28th Convention of Electrical & Electronics Engineers in Israel, pp. 1-5, Dec., 2014.

23) K. Hashimoto, "Mechanics of Humanoid Robot," Journal of Advanced Robotics, vol. 34, no. 21-22, pp. 1390-1397, Aug. 2020.

24) T. Asfour et al., "ARMAR-6: A Collaborative Humanoid Robot for Industrial Environments," IEEE International Conference on Humanoid Robots (Humanoids), pp. 447 - 454, Nov. 2018.

25) S. S. Kulkari and P. Y. Mali, "Use of Smart Wireless Node in Vehicle Networking," International Journal of Engineering Research and General Science, vol. 2, no. 4, pp. 635-640, Jun., 2014.

26) M. Ahmed et al., "Intra-vehicular Wireless Networks," IEEE Globecom Workshops, pp. 1-9, Nov. 2007.

strategies to satisfy the higher required data rate are: securing bandwidth, improving spectrum efficiency, and network densification. Since spectrum resources under 100 GHz are currently highly congested, to secure sufficient bandwidth, it is necessary for us to focus on THz frequency resources in the range from 100 GHz to 3 THz.

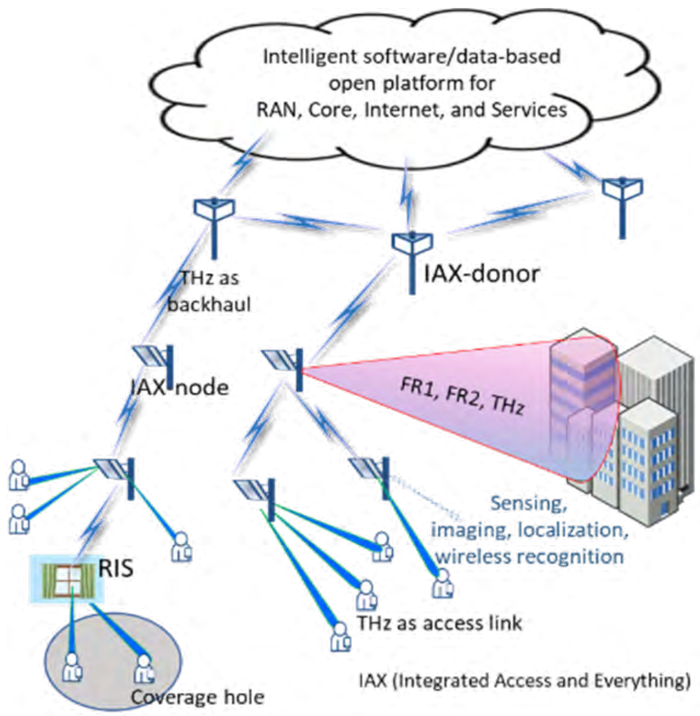

Figure 7. Concepts of Ultra-dense IAX network and extreme MU-MIMO.

Hurdles of exploiting THz: Thus far, there is no verified channel model for THz propagation. However, it is known that THz has a low link budget due to air absorption, leading to severe coverage limitations and frequent holes in coverage due to the pronounced shadowing. It has not yet been discovered whether there are deleterious effects on human health or risks in terms of biological safety related to THz wave exposure.[27] The availability of commercial off-the-shelf THz RF devices is not yet clear.[28] Given the extremely high data rate, the complexity and

27) Y. Xing and T. S. Rappaport, "Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz," IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1 - 6.

28) S.B. Hyun et al.,"RF Technology Trends for 6G Communications" IEEK Journal, 47(5), 53-63.

calescence of devices is also a problem to be solved.

Coverage extension and spectral efficiency improvement: Due to the shorter wavelength of THz, it is possible to constitute a much denser antenna array, leading to ultra-massive MIMO at the network side and massive MIMO at the terminal side. This not only provides a coverage extension by boosting beamforming gain, but also improves spectral efficiency by exploiting higher spatial resolution. High volume MU-MIMO through a higher spatial resolution facilitates spectrum reuse in a much more efficient and powerful way.

Ultra-dense IAX network: One of the definitions of UDN is its network deployment with small cells, in which the number of sites is higher than that of terminals. Currently, the concept of IAB is to integrate access and backhaul links by reusing the existing access link framework. In this way, IAB facilitates dense networks by reducing costs, as it does not require fiber optics as backhaul links. Also, IAB provides multi-hop capability, and is particularly useful to enhance coverage in mmWave deployment. In addition to communication, other applications of THz such as sensing, imaging, localization, and wireless recognition might have an impact on industry verticals.27 Taking these facts and poor THz propagation characteristics into account, the concept of an ultra-dense integrated access and everything (UD-IAX) network is considered inevitably necessary for the efficient use of the THz spectrum, as shown in Figure 7.

3.2.2. Free-space Optics Communication Technology

It is widely acknowledged that one of the key architectural enablers of extremely high data rate coverage in wireless networks is the dense deployment of small cells. But connecting the small cell base stations to the network requires a very expensive infrastructure when the conventional wired links are employed. In addition, the non-terrestrial network integrating the satellites and UAVs with the terrestrial network is one key enabler for 6G networks to provide the high data throughput with service ubiquity. Thanks to recent advances and the fact that there is no need for spectrum licensing in free space optics (FSO), backhaul/fronthaul traffic between the access and core networks for backhaul/fronthaul in both terrestrial and non-terrestrial environment is feasible in the near future.[29] [30] The possible link scenario by FSO is illustrated in Figure 8, where an FSO transceiver needs to be able to support the coverage from 1km for small cell links to 2000km for inter-satellite links.

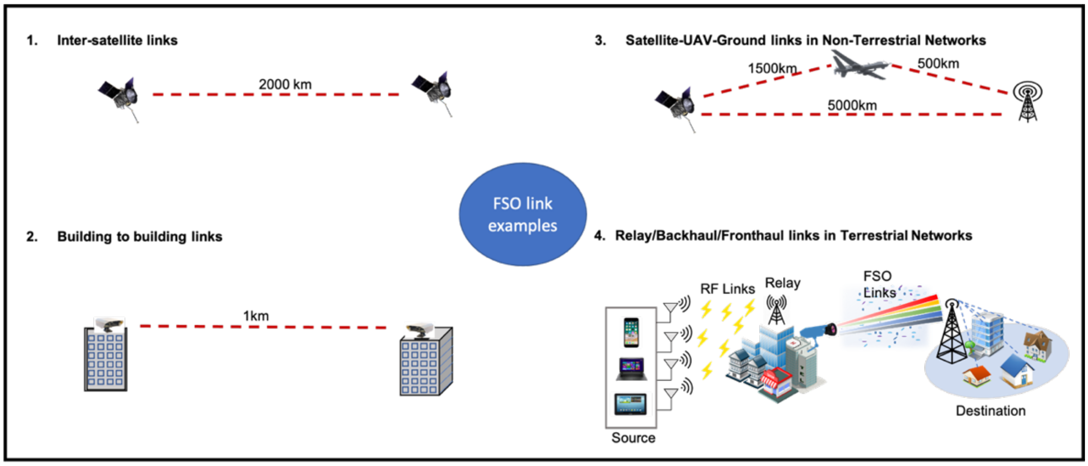

Figure 8. Possible FSO Links.

Power budget: As shown in the above figure, FSO needs to reliably provide a long-distance link. To this end, a laser source with sufficient power should be available. Although some recent industrial products assert that about 4W laser source for 4000 km inter-satellite link purpose is already developed,[31] it seems that those laser sources are not easily available.

Beam pointing and tracking: Due to the low divergence property of the laser beam, beam pointing between the transmitter and the receiver is critical for a reliable link. There are a number of suggested beam pointing techniques, such as a Gimbal-based mechanical scheme, RF pilot assisted scheme, pilot laser beam scheme, etc.[32] In addition, for moving devices such

29) M. Alzenad et.al., "FSO-Based Vertical Backhaul/Fronthaul Framework for 5G+ Wireless Networks," IEEE Communications Magazine, pp. 218-224, Jan. 2018.

30) A. Chaudhry and Yanikomeroglu, "Free Space Optics for Next-Generation Satellite Networks," IEEE Consumer Electronics Magazine, Early Access, 2020.

31) https://tesat.de.

32) Y. Kaymak et.al., "A Survey on Acquisition, Tracking, and Pointing Mechanisms for Mobile Free-Space Optical Communications," IEEE Tutorials & Surveys, Vol. 20, No. 2, pp. 1104-1123, 2nd Quarter, 2019.

as satellites, the laser beam needs to be tracked, along with movement.

Transmission scheme to overcome adverse weather environment: FSO can be applied to a terrestrial backhaul/fronthaul link, as depicted in the figure above. The propagating laser is affected by the air turbulence, earthquakes which can affect even a moving car, and weather conditions such as snow, fog, etc., and the received signal can be misaligned with the detector, severely impacting the performance. Transmission techniques that can overcome this harsh channel environment need to be investigated.

Multiplexing techniques: Although the vast frequency band is available in FSO without the need for licensing, narrow-band transmission is desirable where possible in the name of cost-effective hardware design. Accordingly, a multiplexing scheme with high degrees-of-freedom shall be investigated. So far, the orbital angular momentum (OAM), spatial mode multiplexing (SMM), and LoS-MIMO have been discussed,[33] but no certain proof by demonstrations in the real channel environment are known.

3.2.3. Programmable Wireless Environments

Programmable metasurface (reconfigurable intelligent surface, RIS), a man-made metasurface composed of passive reflecting elements that can adjust the amplitude and phase of the signal, is becoming one of the crucial technologies for utilizing 6G wireless networks with an ultra-massive multiple-input (UM-MIMO) communication system and Terahertz (THz) spectrum. It creates a new wave path and enables intelligent beam routing by manipulating electromagnetic (EM) waves, significantly reducing the path loss of 6G signals in the high spectrum range. Moreover, by reconfiguring and optimizing the MIMO architecture with passive elements, we can reduce the cost of RF hardware, with its enormous power consumption and computational complexity.

33) N. Zhao et. al., "Capacity Limits of Spatially Multiplexed Free-Space Communication," Nature Photonics, Vol.9, pp.822-826, Dec. 2015.

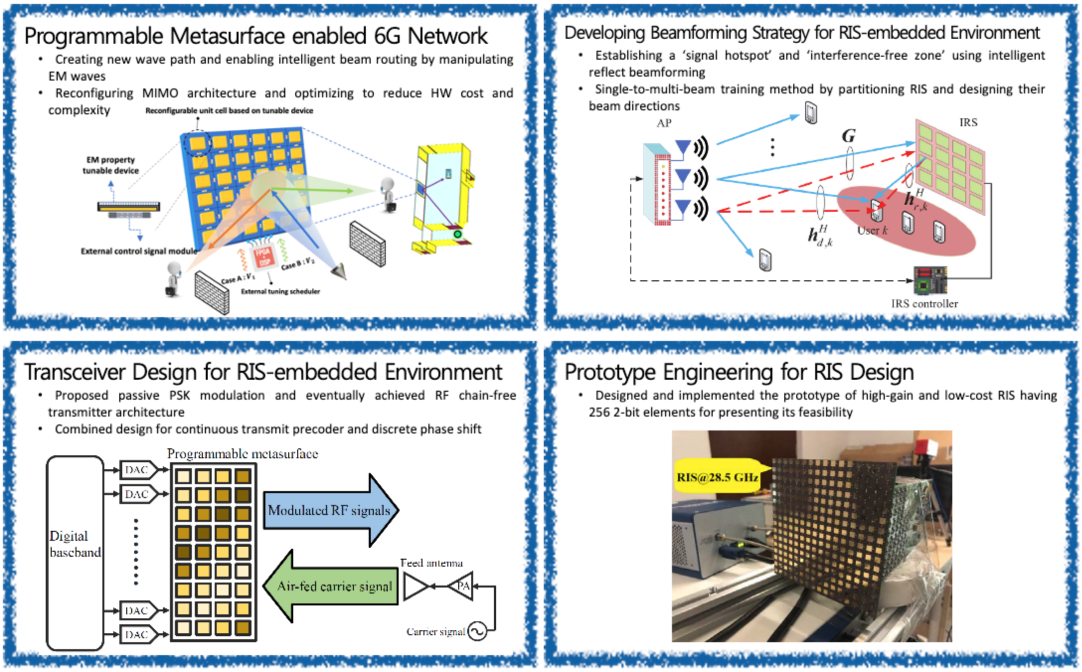

Figure 9. Technical Concept of Programmable Environments.

Several studies have been conducted on optimizing the system architecture and proposing a new communication scheme using RIS. Beamforming strategies for the RIS-embedded environment are proposed, including an intelligent reflect beamforming that utilizes a 'signal hotspot' and 'interference-free zone' and a single-to-multi-beam training method by partitioning RIS and designing their beam directions, both of which lead to improvements in overall network performance.[34) 35)] Various transceiver designs were proposed with passive phase-shift keying (PSK) that mapped the digital baseband signal directly to the RIS control signal to achieve an RF chain-free transmitter architecture and a combined design for

34) Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5394–5409, Nov. 2019.

35) C. You et al., "Fast beam training for IRS-assisted multiuser communications," IEEE Wireless Commun. Lett., vol. 9, no. 11, pp. 1845–1849, Nov. 2020.

continuous transmit precoder and discrete phase shift.[36)] [37)] A prototype of high-gain and low-cost RIS was designed and implemented with 256 2-bit elements, presenting the feasibility of RIS.[38)] They considered 2.3 GHz and 28.5 GHz signal and measured the antenna gain of 21.7 and 19.1 dBi, respectively, which implies that the prototype developed can significantly reduce the power consumption.

In addition to the above use cases, various applications such as edge computing, device-to-device (D2D) communications, and internet-of-things (IoT) backscattering are in progress in consideration of using smart radio technology with a programmable metasurface. Challenging issues related to RIS include the realistic transceiver design considering the structure of non-ideal RIS elements. Since the previous studies have mainly been limited to solving the optimization problem with ideal RIS location and elements, a development direction is needed that considers the non-ideal characteristics of RIS from designing devices to signal processing. Moreover, research comparing the RIS-aided environment with other relaying technologies, including amplifying-and-forward (AF) and decode-and-forward (DF), is still in its infancy. Therefore, comparative research of RIS-aided versus conventional-relay-aided systems should be ongoing.

3.2.4. Spectrum Sharing Technology

Although the new spectrum above 100GHz is attracting an increased amount of interest for 6G communication systems, spectrum resources under 6GHz are still very important due to their capacity to broadcast over a much wider coverage area than such a high-frequency spectrum. Under-6GHz, mmWave, and THz spectrum resources need to be utilized together to provide various kinds of wireless links with different bandwidth and beam-propagation characteristics to satisfy the extremely wide range of service requirements of 6G, and the temporal-geographical utilization of the under-6GHz spectrum needs to be substantially improved due to its scarcity. One of the most promising approaches is to share the spectrum

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36) W. Tang et al., "MIMO Transmission Through Reconfigurable Intelligent Surface: System Design, Analysis, and Implementation," *IEEE J.Sel. Areas Commun.,* vol. 38, no. 11, pp. 2683-2699, Nov. 2020.

37) Q. Wu and R. Zhang, "Beamforming optimization for wireless network aided by intelligent reflecting surface with discrete phase shifts," *IEEE Trans. Commun.* vol. 68, no. 3pp. 1838-1851, Mar. 2020.

38) L. Dai et al., "Reconfigurable intelligent surface-based wireless communications: Antenna design, prototyping, and experimental results," *IEEE Access,* vol. 8, pp. 45913-45923, 2020.

among service providers through the application of an intelligent spectrum access system (SAS) that can allocate frequency resources to its subsystems as desired in a highly dynamic way while preventing interference among nearby entities, as shown in Figure 10.

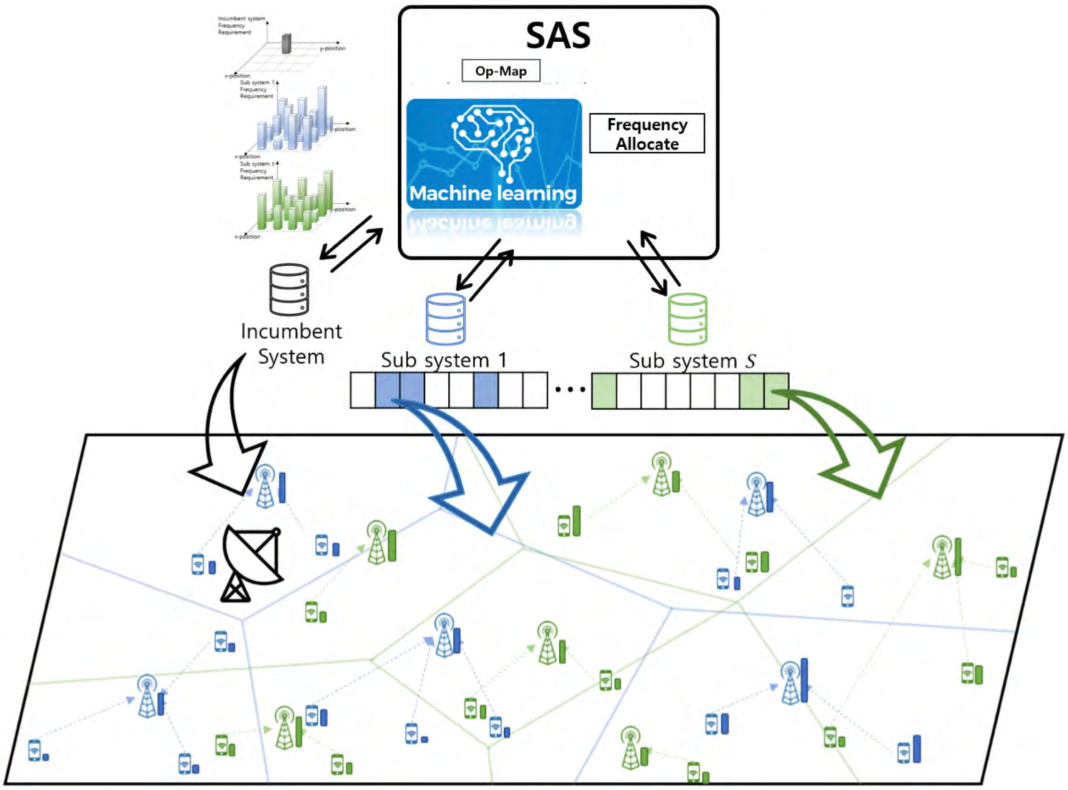


Figure 10. Spectrum Sharing System.

Dynamic Spectrum-Sharing Cellular Communication Systems: It is suggested in the literature that dynamic spectrum-sharing is a promising candidate enabling technology for 6G,[39] and that new spectrum management based on spectrum sharing will play an increasingly important role.[40] One of the most challenging issues in dynamic spectrum sharing is to avoid collision of spectrum usage among different entities. It is expected that this challenge can be handled

39) Samsung Research, 6G: The next hyper-connected experience for all, July 2020.

40) M. Matinmikko-Blue et al., "Spectrum Management in the 6G Era: The Role of Regulation and Spectrum Sharing ," Proc. 6G Wireless Summit, 2020.

by employing a distributed AI engine in devices, base stations, subsystem core networks, and SAS. Also, new regulation and licensing strategies suitable for dynamic spectrum sharing are required.

AI-based MAC & MAC for AI: New MAC designs based on spectrum-sensing or spectrum-sharing have been suggested in the literature.[41] However, if future cellular systems are evolved to have such a dynamic spectrum sharing nature, entire radio resource control (RRC) and radio access network (RAN) layer 2 (L2) designs need to be completely changed. In addition, the dynamic spectrum request of each subsystem is mainly expected to come from various computing needs in devices.[42] Thus, future MAC should be designed for computing and communication convergence.

3.3. Native AI for Connected Intelligence

A third category for enabling technologies is "native AI for connected intelligence" and included among the good candidates are AI-native 6G network architecture, programmable data plane for network security, performance guaranteed networking, and high-precision positioning technology.

3.3.1. AI-Native 6G Network Architecture

6G should support extremely reliable and performance-guaranteed services, and will introduce a multi-dimensional network topology, which will make the network management and operation more difficult and pose challenging problems. To address these problems, 6G will adopt AI technologies for automated and intelligent networking services. At the same time, to assist in computation intensive tasks in AI applications, 6G will evolve into an AI-native network architecture, as shown in Figure 11.

41) S. Kim, H. Cha, J. Kim, S.W. Ko, S.-L. Kim, "Sense-and-predict: harnessing spatial interference correlation for cognitive radio networks," IEEE Transactions on Wireless Communications 18 (5), 2777-2793, 2019.

42) E. Jeong et al., "Communication-Efficient On-Device Machine Learning: Federated Distillation and Augmentation under Non-IID Private Data," [Online]. ArXiv preprint: http://arxiv.org/abs/1811.11479, Nov. 2019.

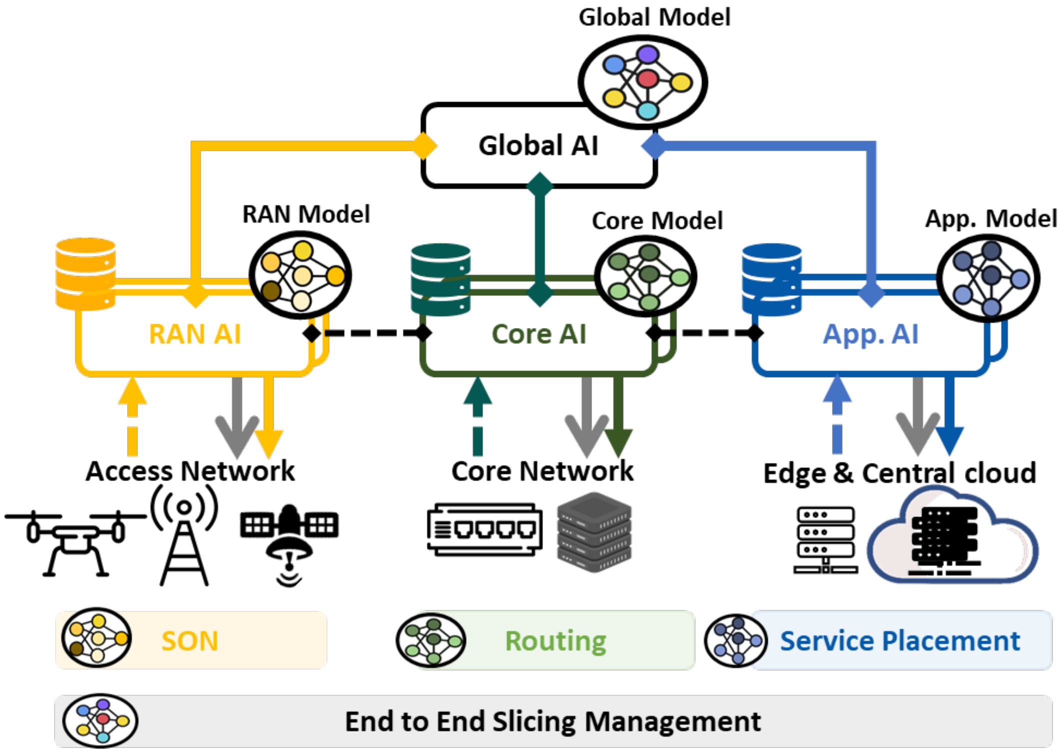


Figure 11. AI-native 6G Network Architecture.

R. Shafin et al.[43] presented different use cases of AI-empowered network automation, such as fault recovery/root cause analysis, AI-based energy optimization, optimal scheduling, network planning. Furthermore, they identified the five key challenges of training issues, lack of bounding performance, lack of explainability, uncertainty in generalization, and lack of interoperability to realize full network automation in 6G. Letaief *et al.*[44] classified four types of analytics in 6G: descriptive analytics, diagnostic analytics, predictive analytics, and prescriptive analytics, and introduced on-device distributed federated learning and on-device distributed inference via wireless MapReduce. The key to successful network automation in 6G is how rich and reliable network data, which are not typically open to other players other than network

43) R. Shafin et al., "Artificial Intelligence-Enabled Cellular Networks: A Critical Path to Beyond-5G and 6G," IEEE Wireless Communications, April 2020.

44) K. Letaief et al., "The Roadmap to 6G: AI Empowered Wireless Networks," IEEE Communications Magazine, August 2019.

operators, can be collected. To realize the vision of zero-touch network management, an open network dataset and open eco-system should be established.

In 6G, more computation nodes will be required to support highly computation-intensive services. Thus, computation nodes will be pervasive from core to edge and from network to device. To cope with this trend, the control and user planes of 6G need to be redesigned, and emerging technologies such as programmable switch and distributed/federated learning should be aggressively adopted. China Mobile Research Institute[45)] introduced two new planes – data collection plane and AI plane – to enable native AI support in 6G. Akyildiz et al.[46)] introduced the concept and open problems of pervasive AI and a high-level network architecture for self-driving networks with accurate intent definitions/automated real-time inference/in-band telemetry over fully programmable network substrate. When we consider the evolution from 5G to 6G, a radical change of network architecture cannot be expected. However, some notable directions (e.g., adoption of on-device AI, device-edge-cloud collaboration, in-network computing) towards AI-native 6G need to be discussed in 6G research.

3.3.2. Programmable Data Plane for Network Security

As networked services (e.g., Internet of Things, Connected Cars, wireless devices, mobile devices) become more popular, causing more traffic to be carried over the mobile communications network, the growth and increase of mobile infrastructure are very steep in terms of both scale and economics, and the confidentiality of services and data has also increased. As such, the number of malicious attempts in the network have also increased significantly, and security has become a major concern in the modern mobile communication network. However, in providing security services on the mobile network, the following characteristics should be considered.

45) G. Liu et al., "Vision, Requirements and Network Architecture of 6G Mobile Network beyond 2030," China Communications, Sep. 2020.

46) I. Akyildiz et al., "6G and Beyond: The Future of Wireless Communications Systems," IEEE Access, July 2020.

Frequent changes in the network environment:[47] The location of the end-hosts in the mobile network is no longer fixed, but can be frequently moved. Also, since recent networked-services are usually offered over short-lived lifecycle network flows and applications, service providers apply virtualization methods to offer a wider range of services, and objects/nodes, applications, or computing functions are easily added, deleted, or moved on a network. As a result, network environments that were almost static and stable in a traditional network can now change frequently over time.

Heavy network traffic:[48] As more services are connected to the mobile network, modern network infrastructure faces several Zettabytes of traffic per year, and as this amount gradually grows every year, the performance issues caused by these security services is a major bottleneck and the network is unable to sufficiently manage the large amount of traffic.

Low-latency:[49] Some services such as connected cars, healthcare IoT devices or multimedia streaming are time-sensitive or mission-critical. To safely operate and manage those services, ultra-reliable low-latency communication (URLLC) is a crucial requirement, which demands sub-millisecond latency with error rates lower than 1 packet loss per 100K packets.

However, it is challenging to sufficiently satisfy those characteristics with existing approaches.

Software-based security services: Software-based approaches provide high flexibility, in terms of being freely deployable and updatable in a network. However, due to the architectural limitation of the complicated processing stacks, these have low performance and a long processing time. In particular, such computing-intensive operations (e.g., IDS pattern matching) suffer huge performance degradation, and providing low-latency of under 1 ms is quite challenging with the software security services.

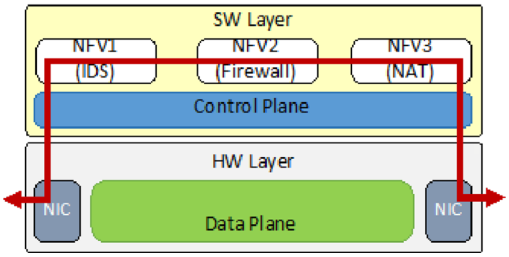
47) Popović, Krešimir, and Željko Hocenski. "Cloud computing security issues and challenges." The 33rd international convention mipro. IEEE, 2010.

48) Index, Cisco Global Cloud. "Forecast and Methodology, 2016 - 2021 White Paper." *Updated: February* 1 (2018).

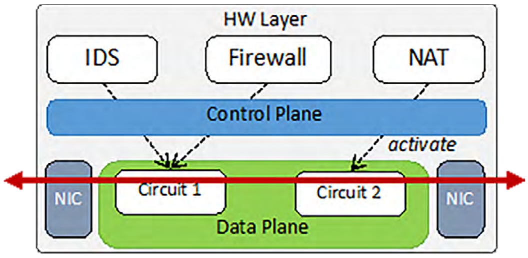
49) Series, M. "Minimum requirements related to technical performance for IMT-2020 radio interface (s)." *Report* (2017): 2410-0.

Hardware-based security services: On the other hand, hardware-based approaches provide high-performance and can achieve low-latency processing. But because of the rigidity, there is limited potential to enforce security services dynamically on demand. Therefore, hardware-based approaches cannot satisfy the changing network environment of the mobile infrastructure.

To address these challenges, modern mobile infrastructure adopts a high-performance and flexible security service platform. One method is a '*programmable data plane*' that migrates software programmability into hardware devices, as described in Figure 12.



Prior approach (Software/Hardware)



Programmable data plane

Figure 12. Concept of a Programmable Data Plane.

As a result, the processing of packets takes place at the hardware level, so high performance and low latency can be achieved. At the same time, with regard to programmability, in comparison to a software-based solution, a hardware-based solution has the flexibility to actively respond to network changes. The following are some of the reported trends for existing programmable data plane hardware.

Microsoft AccelNet:[50] Microsoft presents Azure Accelerated Networking (AccelNet), which offloads host networking to hardware using custom Azure SmartNICs based on FPGAs. It has a level of programmability that is comparable to software solutions, and a level of performance and efficiency comparable to hardware solutions. Azure SmartNICs implementing AccelNet have

50) Firestone, Daniel, et al. "Azure accelerated networking: SmartNICs in the public cloud." *15th USENIX Symposium on Networked Systems Design and Implementation (NSDI 18)*. 2018.

been deployed on all new Azure servers since late 2015 in a fleet of >1M hosts. The AccelNet service has been available for Azure customers since 2016, providing consistent <15μs VM-VM TCP latencies and 32Gbps throughput, representing the fastest network available to customers in the public cloud.

FlowBlaze:[51] FlowBlaze is an open abstraction for building stateful packet processing functions in hardware. The abstraction is based on Extended Finite State Machines and introduces the explicit definition of flow state, allowing FlowBlaze to leverage flow-level parallelism. FlowBlaze is expressive, supporting a wide range of complex network functions, and is easy to use, hiding low-level hardware implementation issues from the programmer. Its prototype implemented on a NetFPGA SmartNIC achieves very low latency (on the order of a few microseconds), consumes relatively little power, can hold per-flow state for hundreds of thousands of flows and yields speeds of 40 Gb/s, allowing for even higher speeds on newer FPGA models.

However, future programmable data plane hardware needs to solve further challenges including the followings.

Programmability range: Since it is virtually impossible to make all network features programmable into a hardware data plane, it is necessary to determine the programmability range through optimization. It should be possible to cover as wide a range of services as possible while taking into account the purpose, purpose, and service type of the device.

Security support: Programmability of the hardware data plane has been focused on packet processing (Switching), but this is inadequate for security processing. In particular, advanced security features such as DPI for network intrusion detection/prevention systems mostly rely on software procedures due to their complexity.

3.3.3. Performance Guaranteed Networking

In order to support real-time, hyper-immersive interactive services such as XR and hologram

51) Pontarelli, Salvatore, et al. "Flowblaze: Stateful packet processing in hardware." *16th USENIX Symposium on Networked Systems Design and Implementation (NSDI 19)*. 2019.

communications, or high-precision vertical services such as remote control of robots and drones, it is necessary to introduce end-to-end latency-deterministic networks which absolutely guarantee in-time and on-time packet delivery. In-time-guaranteed networking minimizes latency between application ends in order to improve real-time characteristics of interactive services, whereas on-time-guaranteed networking minimizes the variation in latency – manifested through jitter, for example – in order to enhance the precision characteristics of the remote-control services. The core of the time-deterministic packet-forwarding technology that guarantees both in-time and on-time delivery is precise control of each network system's egress queues based on synchronized time between network nodes with very high precision. The IEEE Time-Sensitive Networking (TSN) technology[52] is currently available for Ethernet LAN. On the other hand, Deterministic Networking (DetNet) technology,[53] which targets IP or MPLS-based enterprise networks under single administrative control, is being standardized in the IETF. To expand the scope of latency determinism to large-scale networks, those technologies must evolve in a direction applicable to complex, wide-area networks composed of multiple layers and domains. Real-time monitoring and control/management of network resources are expected to emerge as key issues in maintaining QoE of massive time-sensitive service flows in large-scale networks.

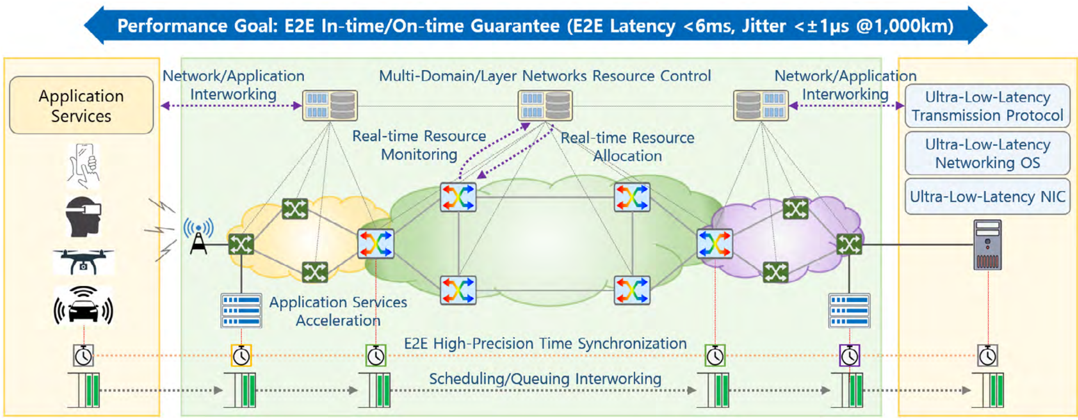


Figure 13. Performance Guaranteed Network.

52) IEEE Time-sensitive networking task group (https://www.ieee802.org/1/pages/tsn.html).

53) IETF Deterministic networking working group (https://datatracker.ietf.org/wg/detnet/about/).

Recent observations on low-latency video streaming[54] specify that a latency guarantee is only possible when the encoded data size matches the available end-to-end bandwidth, including the cellular hops. These observations are important, as they reveal that the quality of low-latency service is affected more by the latency of the decodable unit (i.e., object latency) than the latency of individual packets. To this end, performance guaranteed networking (PGN) extends the on-time-guaranteed networking toward a form of networking that takes application performance into account, as shown in Figure 13. Since PGN needs object latency to be guaranteed, PGN servers are asked to perform two unprecedented network operations: 1) encode objects adaptively (with prediction) in their size in order to closely match the sizes with the time-varying end-to-end bandwidth in the upper layer, 2) once the encoded objects are injected to the network, adjust the network resources (e.g., physical resource blocks in the cellular links) to match the bandwidth with the given size of objects in the lower layer when unexpected bandwidth fluctuations occur. To accomplish this, it is expected that existing TCP/UDP protocols will also evolve to satisfy the application service's performance requirements through tightly-coupled interworking between the upper and lower layers. Research directions for PGN may include the following. PGN should consider not only the delays caused by networks but also the delays generated inside of application ends. Packet processing/computation time in the application end needs to be minimized in order to provide ultra-low latency services between application ends. Furthermore, it is anticipated that low-latency operating system technologies, which adopt various techniques such as kernel-bypass and zero-copy to reduce the delays associated with network stacks and data processing, and network-based application service acceleration technologies, which utilize various offloading techniques such as proxy, caching and buffering, need to be studied in a package.[55]

3.3.4. High-precision Positioning Technology

Positioning information of an object such as its location, speed, and direction can be used for safety and productivity improvement, and shall be applied to services requiring high levels of real-time accuracy, such as unmanned aerial vehicle operations, augmented reality, movement

54) S. Fouladi, J. Emmons, E. Orbay, C. Wu, R. S. Wahby, and K. Winstein, "Salsify: Low-Latency Network Video through Tighter Integration between a Video Codec and a Transport Protocol," NSDI 2018.

55) 6G Insight – Vision and Technologies, ETRI, Nov. 2020.

of mobile trolleys in smart factories, and traffic monitoring & control.[56] Even though meter-level accuracy is sufficient in most cases, 6G positioning technologies should realize cm-level positioning accuracy with a latency within a few tens of milliseconds to provide new services and applications. In addition to the horizontal/vertical positioning accuracy and latency, other metrics such as power consumption, scalability/capacity, network deployment complexity, availability, and security/privacy can be considered as important design factors in positioning solutions.[57] [58]

Millimeter-level accurate positioning using satellites is possible with the aid of real-time kinematic techniques. However, it is difficult to provide positioning services through satellites in dense urban or indoor areas, which satellite signals have difficulty reaching. Also, when using communication radio waves such as 5G or Wi-Fi, the accuracy level is only a few meters.[55] Target requirements for NR positioning enhancements in release-17 are defined as horizontal position accuracy less than 0.2m and end-to-end latency less than 100ms for industrial internet of things use cases.[59]

To substantially improve timing measurement accuracy, line-of-sight/non-line-of-sight path detection and identification is the key component technology which will harness ultra-wide bandwidth and ultra-massive MIMO in millimeter-wave or terahertz band.[60] A sampling rate more than 3GHz at receiver-side and sub-nanosecond synchronization between reference nodes should be required for cm-level accuracy. In the absence of line-of-sight path, fingerprinting or ray-tracing with the help of deep learning can be considered as the most promising technologies. It is difficult to meet the diverse requirements and overcome all technical difficulties with one technology. For this reason, a combination of positioning technologies that utilizes visible light, satellite signals, sensors, and communication signals as well may be required, as shown in Figure 14. Ultra-dense networks deployed to shorten the

56) 3GPP, "3GPP TR 22.872: Study on positioning use cases; Stage 1 (Release 16)," ETSI, Tech. Rep., Sept. 2018.

57) 3GPP, "3GPP TS 22.071: Location Services (LCS); Service description; Stage1 (Release 16)," ETSI, Tech. Rep., July 2020.

58) 3GPP, "3GPP TR 38.855: Study on NR positioning support (Release 16)," ETSI, Tech. Rep., March 2019.

59) 3GPP, "3GG TR 38.857: Study on NR positioning enhancements (Release 17)," ETSI, Tech. Rep., Dec. 2020.

60) Andre Bourdoux et al., "6G White Paper on Localization and Sensing," eprint arXiv: 2006.01779v1, Jun. 2020.

measurement distance and secure the line-of-sight path make it easier to attain the target accuracy. However, interference and mobility managements are critical to provide stable and seamless services. In addition, if the theoretical limits for estimating the achievable accuracy level are more clearly identified, it will be of great help in the development of positioning technology.[61)]

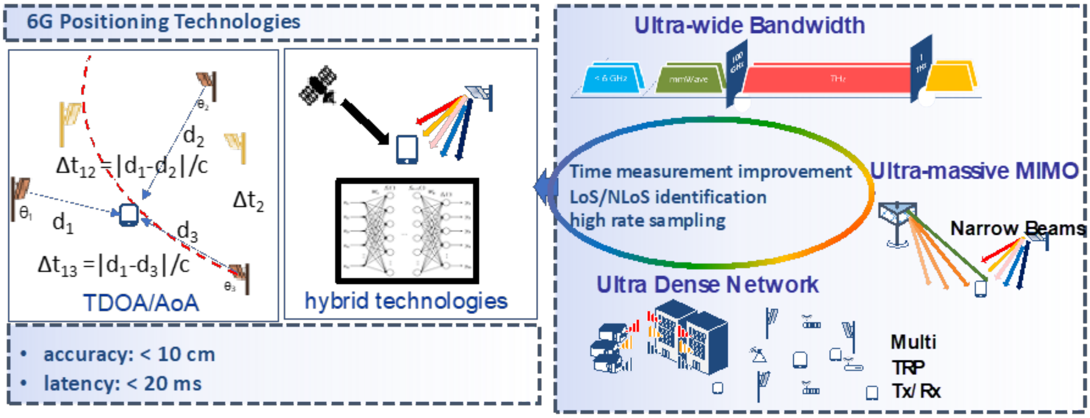


Figure 14. High-precision Positioning.

3.4. New Radio Access Technologies

The last category described in Section 2 for enabling technologies is "new radio access technology," and the good candidates in this area include massive (broadband) URLLC radio access network, Tbps wireless modem technologies, zero-energy IoT technologies, and AI-based physical-layer (PHY) technologies.

3.4.1. Massive (Broadband) URLLC RAN

The three 5G service categories by ITU-R are enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable and low-latency communications (URLLC). However, a truly immersive XR experience using 5 senses or ultra-precise and fast-

61) J. del Peral-Rosado et al., "Whitepaper on New Localization Methods for 5G Wireless Systems and the Internet-of-Things," COST Action CA15104, 2018.

moving autonomous vehicles and robots, which are expected as the most typical use-cases for 6G, require both broadband and URLLC characteristics, as a huge amount of data delivery with very low latency and high reliability is required. Also, it is expected that hundreds of billions of intelligent devices will be connected, and so a massive URLLC connectivity needs to be supported in 6G, as shown in Figure 15.

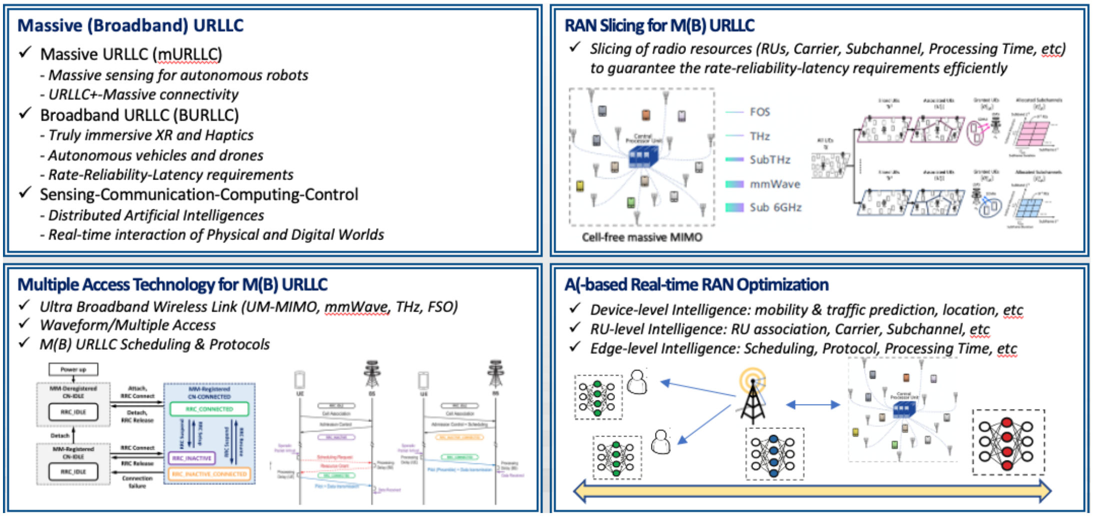


Figure 15. Massive (Broadband) URLLC RAN Technologies.

RAN slicing for M(B) URLLC: It is expected that 6G RAN will be a user-centric cell-free network[62] using various frequency bands, and every RAN resource, including radio unit association, frequency band, subchannels, processing time, needs to be flexibly partitioned (RAN slicing) to guarantee packet flows with similar QoS requirements.[63] [64] Such 6G RAN slicing should support 1) adaptive RAN slicing architecture for cell-free network using massive MIMO and various frequency bands, 2) MIMO/beamforming/power control/transmission technology to overcome fading channel and mobility, and 3) spectrally efficient channelization and scheduling to guarantee URLLC QoS considering mobility and traffic characteristics.

62) O.T. Demir, E. Bjornson, and L. Sanguinetti, "Foundations of User-centric Cell-free Massive MIMO," Foundations and Trends in Signal Processing, 2020.

63) H. Viswanathan and P.E. Mogensen, "Communications in the 6G Era," IEEE Access, Nov. 2019.

64) K.S. Kim, et al., "Ultrareliable and Low-Latency Communication Techniques for Tactile Internet Services," Proc. IEEE, Feb. 2019.

Multiple Access Technology for M(B) URLLC: It is reported in the literature that spectrally efficient URLLC multiple access, scheduling, and protocols need to be developed for broadband URLLC,[64] and grant-free based multiple access is required for massive URLLC.[65] However, it is further required that 1) ultra-broadband transmission techniques using new spectrum or antenna technology be considered, 2) spectrally efficient protocol, channelization and scheduling be further developed to guarantee URLLC QoS, and 3) multiple access schemes supporting both massive connectivity and ultra-low latency be developed.

AI-based Real-time RAN Optimization: In 6G, it is expected that edge AI is a key enabler for 6G, particularly for sensing-communication-computing-control.[66] On the other hand, a distributed deep learning architecture is considered for realizing URLLC in a 6G network.[67] Thus, 6G RAN should be flexibly and adaptively optimized with the aid of AI to guarantee QoS; here, the topics of interest include 1) adaptive RAN slicing architecture and the corresponding distributed intelligence architecture, 2) knowledge-assisted learning architecture and methods, and 3) fast training/federated learning methods.

3.4.2. Tbps Wireless MODEM Technologies

Embodied in the 6G vision there are emerging services, such as data kiosk, hologram, extended reality, etc., which require extremely large data bandwidth. To support such services over the air, wireless transceivers should be able to support Tbps level data transmission. To provide such extremely high data rate communication, new frequency bands such as subTHz, THz, and optical frequency should be utilized. Even if the development and advances of the analog receiver technologies for the new bands are expedited, there still are challenging issues in the realization of a wireless baseband modem, as shown in Figure 16. First, analog to digital converters operate under limited power, and the computational and hardware complexity for mobile application can be huge, which means there are two major technological challenges:

65) T. Kim and B.C. Jung, "Performance Analysis of Grant-Free Multiple Access for Supporting Sporadic Traffic in Massive IoT Networks," IEEE Access, October 2019.

66) W. Saad, M. Bennis, and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," IEEE Network, Oct. 2019.

67) C. She et al., "Deep Learning for Ultra-Reliable and Low-Latency Communications in 6G Networks," IEEE Network, Sep./Oct. 2020.

providing robust and energy efficient signal processing that fits the new bands, and supporting fast, reliable, and low complexity channel coding technologies.

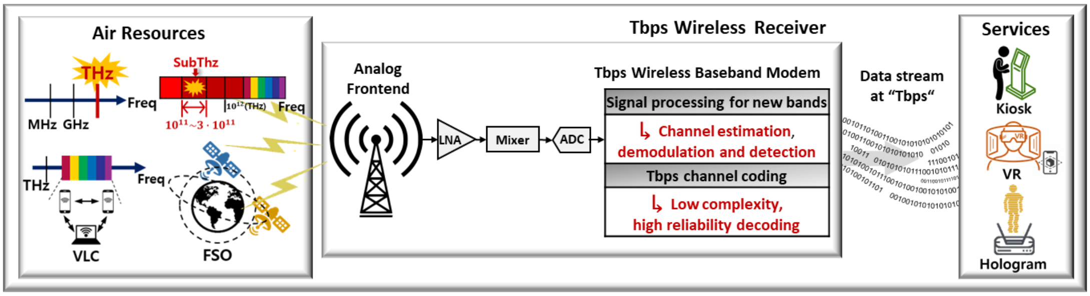


Figure 16. Challenging Issues in the Realization of Tbps Wireless MODEM.

As a wide band of tens to hundreds of GHz should be used to achieve Tbps transmission, the ADC resolution can be limited.[68] New waveforms, modulation schemes and antenna technologies are being studied and under development. As such, the baseband signal processing should adapt the new band's channel characteristics and new transmission schemes. In recent works, compressed sensing-based[69] and learning-based[70] low complexity channel estimation algorithms for massive MIMO systems have been studied. Also, data detection algorithms for low resolution ADC, THz noise characteristics have been recently investigated.[71] The realization of the ultra-fast decoder with Tbps throughput is another key issue. There have been a number of studies that tried to extend the range of the state of the art design in terms of throughput. Although over 500Gbps decoders have been implemented once

68) O. Orhan, E. Erkip, and S. Rangan, "Low power analog-to-digital conversion in millimeter wave systems: Impact of resolution and bandwidth on performance," in ITA 2015, Feb. 2015.

69) V. Schram, A. Bereyhi, J.-N. Zaech, R. R. Müller, and W. H. Gerstacker, "Approximate message passing for indoor THz channel Estimation," arXiv:1907.05126, 2019.

70) S. Nie and I. F. Akyildiz, "Deep kernel learning-based channel estimation in ultra-massive MIMO communications at 0.06-10 THz," in 2019 Globecom Workshops, Dec. 2019.

71) H. Sarieddeen, M.-S. Alouini, and T. Y. Al-Naffouri, "An Overview of Signal Processing Techniques for Terahertz Communications," *arXiv:2005.13176.*

for polar codes[72] and LDPC codes,[73] those designs were provided in limited code flexibility and with compromised performance.

For a practical Tbps baseband modem, the low complexity signal processing algorithms for new THz MIMO systems should be developed. Joint channel estimation detection and joint demodulation and decoding can be considered for low complexity and latency implementation. For Tbps channel coding, code design and decoding algorithms should be developed in consideration of parallelizability, implementation constraint, and new channel characteristics. New coded modulation schemes can be combined for better spectral efficiency. Deep-learning aided approaches may be applied to both baseband signal processing and channel coding algorithms.

3.4.3. Zero-energy IoT Technologies

One of the most significant emerging 6G technology trends is energy-efficient (EE) communications, which are also known as green networks. EE is the most important feature in IoT networks. In this section, we consider (near) zero-energy IoT networks. 6G IoT networks will require ultra-high energy efficiency, and if possible, battery-free communications are preferred. To realize this requirement, it is possible to utilize natural energy sources for energy harvesting, such as solar, wind, ocean waves, etc. However, we focus on the radio frequency (RF) signal-based technologies including ambient backscatter communication (AmBC), intelligent reflecting surface (IRS), and compressed sensing (CS)-based random access techniques, as shown in Figure 17.

72) P. Giard, G. Sarkis, . Thibeault and W. J. Gross, “Multi-Mode Unrolled Architectures for Polar Decoders,” IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 63, no. 9, pp. 1443-1453, 2016.

73) R. Ghanaatian, A. Balatsoukas-Stimming, T. C. Müller, M. Meidlinger, G. Matz, A. Teman and A. Burg, “A 588-Gb/s LDPC Decoder Based on Finite-Alphabet Message Passing,” IEEE Trans. VLSI Systems, vol. 26, no. 2, pp. 329 - 340, 2018.

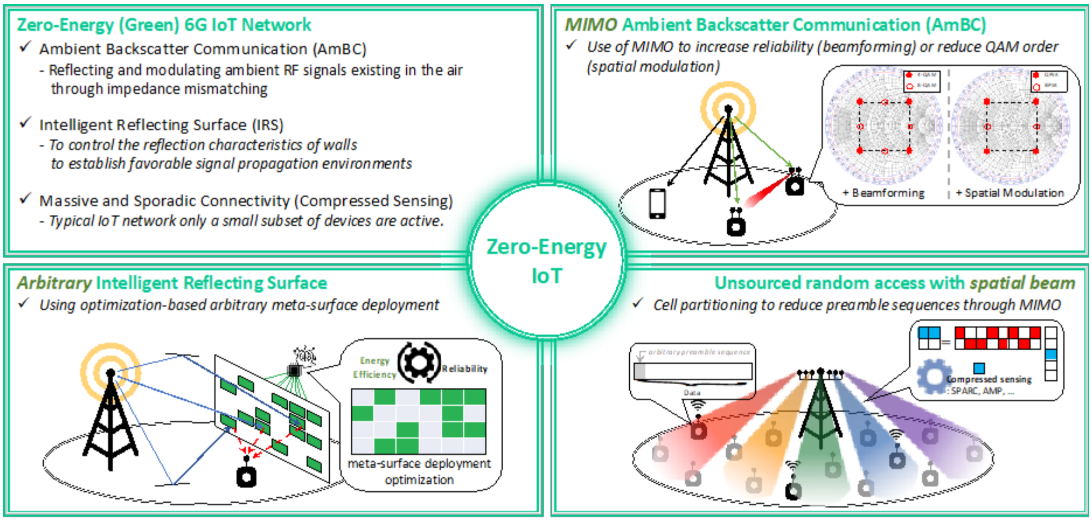


Figure 17. Zero-energy IoT Technologies.

Ambient Backscatter Communication (AmBC): AmBC is a technology that exploits ambient RF signals (symbiotic radio: SR) in the air to transmit information bits without active RF transmission. Specifically, it is implemented by modulating and reflecting the ambient signals through impedance mismatching.[74] Since the power consumption of this mechanism is in microwatt units, which are less than existing wireless technologies, and there is no power infrastructure or carrier emitter, AmBC provides ultra-low-power communication.[74] Furthermore, battery-free communication is enabled by utilizing other ambient RF signals as the energy sources through energy harvesting.[75]

However, studies on AmBC have highlighted some challenges. Backscatter propagation has reduced power, and backscatter signals may interfere with legacy receivers.[76] MIMO-based technologies can be applied as an effective way to overcome these problems. For example, beamforming through multiple antennas on the backscatter tag can increase the power

74) R. Duan et al., "Ambient backscatter communications for future ultra-low-power machine type communications: Challenges, solutions, opportunities, and future research trends," *IEEE Commun. Mag.,* vol. 58, no. 2, pp. 42-47, Feb. 2020.

75) T. Huang et al., "A survey on green 6G network: architecture and technologies," *IEEE Access,* vol. 7, pp. 175758-175768, Dec. 2019.

76) N. H. Mahmood et al., "White paper on critical and massive machine type communication towards 6G [white paper]," *6G Research Visions,* vol. 11, Jun. 2020.

and directivity, which can mitigate interference with legacy receivers. Alternatively, spatial modulation can be exploited to reduce the complexity by decreasing the modulation order of the backscatter signals.

Intelligent Reflecting Surface (IRS): IRS is an emerging hardware technology that also significantly reduces energy consumption. It controls the reflection characteristics of walls to establish favorable signal propagation environments (or desirable wireless channels) through meta-surfaces. Specifically, IRS consists of a large number of reflecting units that generate a favorable propagation environment via beamforming, and is controlled by a microcontroller.[77) 78)] In particular, since it operates through low-cost sensors and a cognitive microcontroller without RF chains, it allows for high energy-efficient communication.[79) 80)] However, IRS has several technical challenges, including passive beamforming optimization, channel acquisition, IRS deployment, and outdoor scenarios. It is expected that arbitrary IRS could be one of the solutions to address these issues. By sparsely consisting the meta-surfaces, the deployment area can be reduced, and the complexity required for beamforming optimization and channel acquisition can also be reduced.

Compressed Sensing (CS)-Based Random Access: Strictly speaking, the CS itself is not closely related to zero-energy IoT networks. Recently, however, it has re-emerged as the optimal signal processing technology for massive connectivity with grant-free or unsourced random access.[81) 82)] A typical IoT network involves sporadic traffic patterns, because only a small subset

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77) S. Hu, F. Rusek, and O. Edfors, "Beyond massive MIMO: The potential of data transmission with large intelligent surfaces," *IEEE Trans. Signal Process.,* vol. 66, no. 10, pp. 2746-2758, Mar. 2018.

78) C. Huang et al., "Reconfigurable intelligent surfaces for energy efficiency in wireless communication," *IEEE Trans. Wireless Commun.,* vol. 18, no. 8, pp. 4157-4170, Aug. 2019

79) Q. Wu, and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network," *IEEE Commun. Mag.,* vol. 58, no. 1, pp. 106-112, Jan. 2020.

80) X. Chen et al., "Massive access for 5G and beyond," *IEEE J. Sel. Areas Commun.,* Sept. 2020 (Early Access Article).

81) A. Fengler, P. Jung, and G. Caire, "SPARCs and AMP for unsourced random access," in *Proc. 2019 IEEE ISIT,* Paris, France, pp. 2843-2847, Jul. 2019.

82) S. S. Kowshik, K. Andreev, A. Frolov, and Y. Polyanskiy, "Energy efficient coded random access for the wireless uplink," *IEEE Trans. Commun.,* vol. 68, no. 8, pp. 4694-4708, Aug. 2020

of devices is activated at each time slot to save energy consumption. Considering that some active devices first send their unique preambles (metadata) to the BS and then transmit the data signals directly, CS can be effectively applied to detect the active devices, and estimates their channels from the metadata transmitted by IoT devices.[83)] It is also mentioned that the grant–free or unsourced random access can reduce the signaling overhead at the expense of high computational complexity at the BS, as well as improve energy–efficiency. Challenging issues in the CS studies include the need for efficient codebook (set of preamble sequences) design and an activity detection algorithm. These issues occur due to the insufficient number of preambles compared to the number of IoT devices in a cell, and will be further intensified in the massive connectivity scenarios of 6G IoT networks. Cell partitioning using spatial beams through multiple antennas offers a potential solution this problem. By dividing a cell, each beam can handle and process fewer IoT devices. In other words, the optimization complexity of the codebook design and activity detection algorithm can be reduced.

3.4.4. AI-based PHY Technologies

Recently, the concept of artificial intelligence (AI), such as machine learning, has been widely studied in relation to wireless communications. AI means any technique which resembles human behavior, such as vision. Machine learning (ML) is a subset of AI. ML uses statistical methods to enable machines to improve through experiences. ML consists of reinforcement learning (RL) and deep learning (DL). Mostly, DL can solve classification problems and non–linear optimization. AI–based 6G technology can be utilized for solving non–linear PHY technology. To apply AI to 6G, ML needs experience in the form of pre–collected data and reward as a metric. Data of real–time communication, such as ray–tracing, is required.

83) S. S. Kowshik, K. Andreev, A. Frolov, and Y. Polyanskiy, "Energy efficient coded random access for the wireless uplink," *IEEE Trans. Commun.,* vol. 68, no. 8, pp. 4694–4708, Aug. 2020

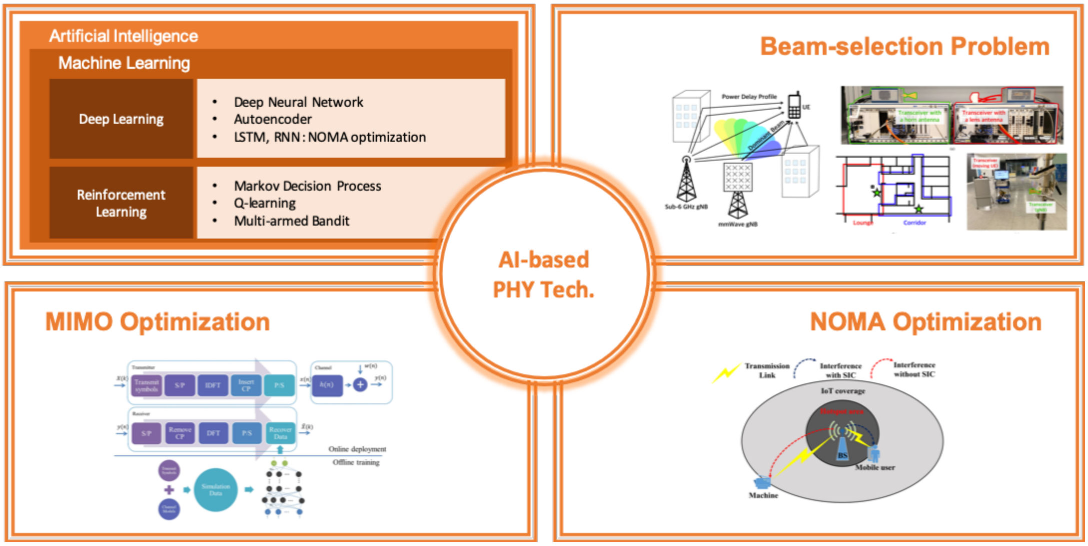

Figure 18. AI-based Physical-layer Technologies.

Beam Selection Problem: A representative example of solving the 6G communication problem through AI is the beam selection problem. In millimeter waves, beamforming technology is essential because it shows relatively high propagation loss. The beam selection problem is selecting one of several beams stored in the base station. Instead of doing a full search of beams in all directions, the goal is to use AI to reduce the search's complexity. Studies are attempting to solve this problem through AI, particularly the deep learning-based method. The main issue of handling the beam selection problem with AI is the choice of training data. In a V2X environment, LIDAR data can be used as training data. The collection of location and LIDAR data have no overhead, which is why they are also utilized for autonomous vehicles.[84] The sub-6GHz power delay profile (PDP) data is also a kind of training data.[85] In the beam selection problem, DL is mainly used because it is a classification learning problem. However, since compensation for selecting the wrong beam is another problem, it is expected to be necessary to develop a technique for post-processing the selected beam through reinforcement learning.

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84) A. Klautau, N. González-Prelcic, and R. W. Heath Jr, "LIDAR data for deep learning-based mmWave beam-selection," *IEEE Wireless Commun. Lett.,* vol. 8, no. 3, pp. 909 - 912, Jun. 2019.

85) M. S. Sim, Y. Lim, S. H. Park, L. Dai and C. -B. Chae, "Deep Learning-Based mmWave Beam Selection for 5G NR/6G With Sub-6 GHz Channel Information: Algorithms and Prototype Validation," *IEEE Access,* vol. 8, pp. 51634-51646, Mar. 2020.

MIMO Optimization: In a MIMO environment where there are relatively numerous optimization factors, such as the practical limitations of ADC converter and RF chain, research is also being conducted on sending and receiving a large amount of information with low transmission power. The encoder and decoder responsible for compressing and decoding information are viewed as one DNN and learned simultaneously. Combined with compressive sensing, compressing CSI is implemented through deep learning.[86)] However, a metric such as mean-squared error is used to evaluate image compression performance, so it is necessary to examine communications metrics. Also, the results of using deep learning for channel estimation and symbol detection were introduced in the MIMO-OFDM system.[87)] However, there is a limitation, in that the channel data used for learning is generated artificially.

NOMA Optimization: DL is also applied to optimize NOMA, which performs at a relatively high level of spectral efficiency, for multiple users. Since high computational complexity is needed to implement NOMA, transmission power distribution in the NOMA environment is solved through DL. A deep learning-based NOMA using long short term memory (LSTM) was proposed, and its performance was verified through block-error-rate.[88)] But since LSTM focuses only on time series data, it has the limitation of requiring data measured for a long time in advance. NOMA assuming incomplete successive interference cancelation (SIC) was optimized through DL.[89)] Since the entire NOMA transmission process is learned with one black box, it is necessary to obtain a decoding block or a transmission power distribution block as an individual model for actual implementation.

86) C. Wen, W. Shih, and S. Jin, "Deep Learning for Massive MIMO CSI Feedback," *IEEE Wireless Commun. Lett.,* vol. 7, no. 5, pp. 748 – 51, Oct. 2018.

87) H. Ye, G. Y. Li and B. Juang, "Power of Deep Learning for Channel Estimation and Signal Detection in OFDM Systems," *IEEE Wireless Commun. Lett.,* vol. 7, no. 1, pp. 114-117, Feb. 2018.

88) G. Gui, H. Huang, Y. Song and H. Sari, "Deep Learning for an Effective Nonorthogonal Multiple Access Scheme," *IEEE Trans. Vehicular Tech,* vol. 67, no. 9, pp. 8440-8450, Sept. 2018

89) M. Liu, T. Song and G. Gui, "Deep Cognitive Perspective: Resource Allocation for NOMA-Based Heterogeneous IoT With Imperfect SIC," *IEEE Internet of Things Journal,* vol. 6, no. 2, pp. 2885-2894, April 2019.

4. Conclusion

4. Conclusion

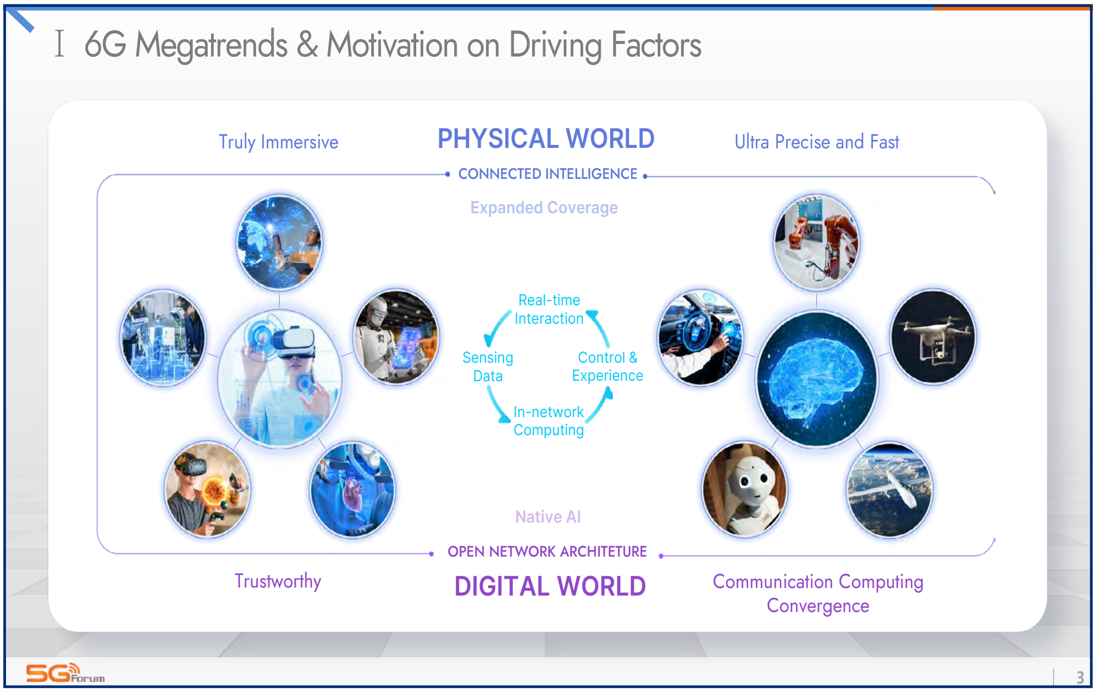
This report examines 6G technology trends that are applicable to mobile devices, radio access network, and core networks considering the time frame of 2030 and beyond. These technology trends, which have been discussed among members of the 6G working group of the 5G forum, Korea, during 2020, include 16 enabling technologies in the following four categories: 1) network topologies beyond cellular, 2) new spectrum and antenna technologies, 3) native-AI for connected intelligence, and 4) new radio access technologies.

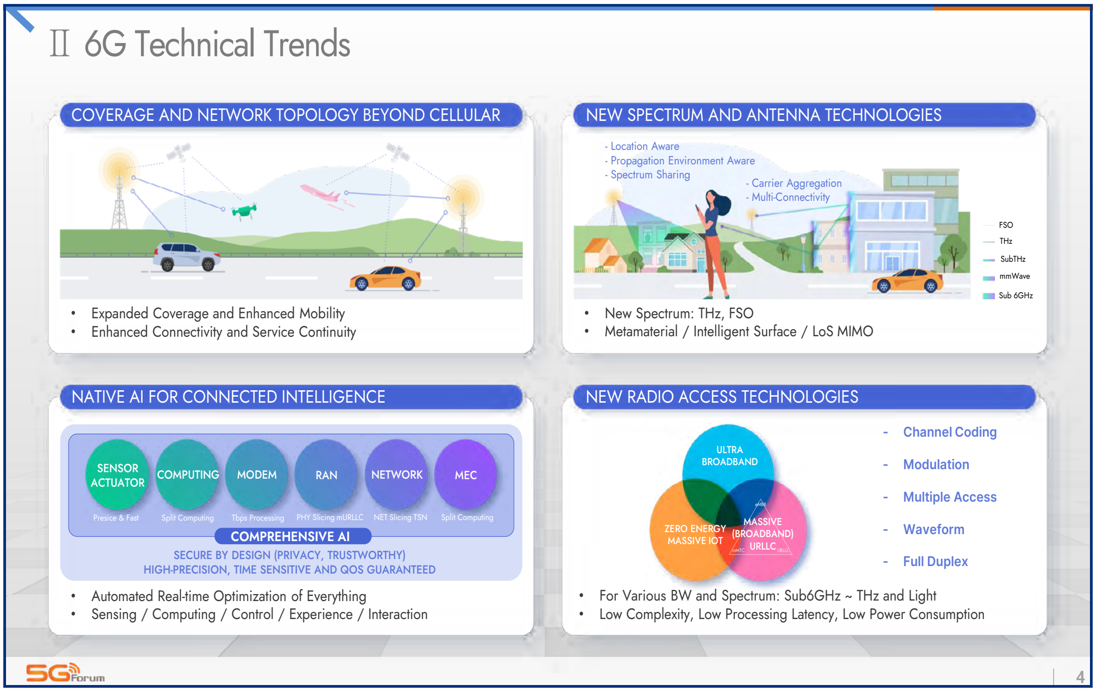
Appendix

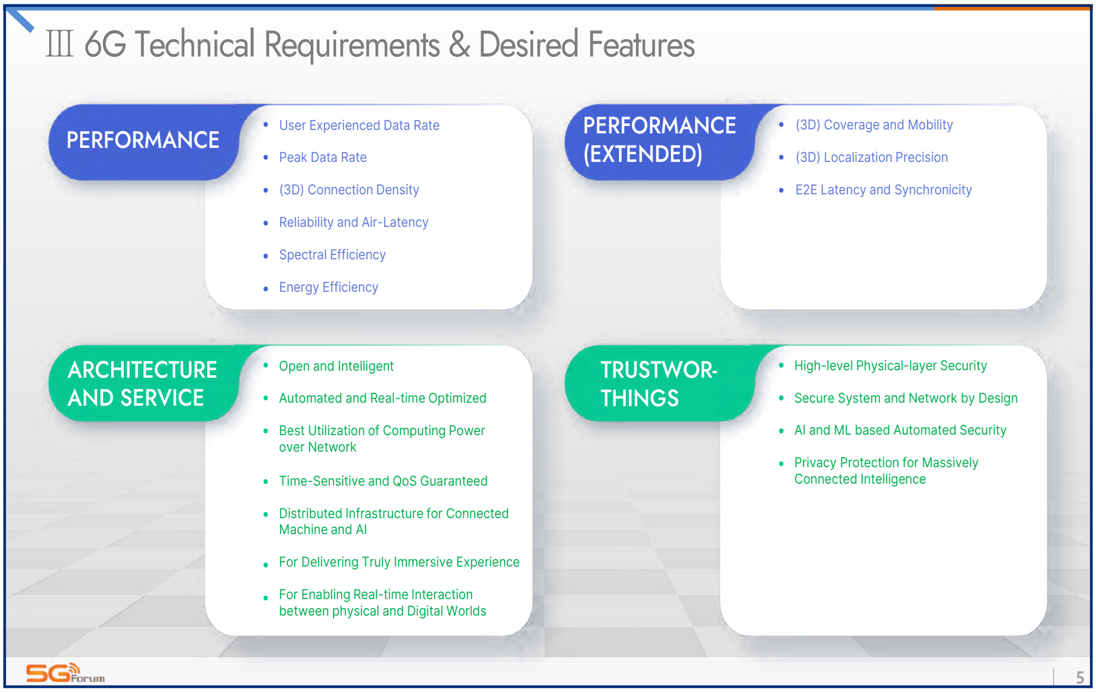
6G Technology Trends

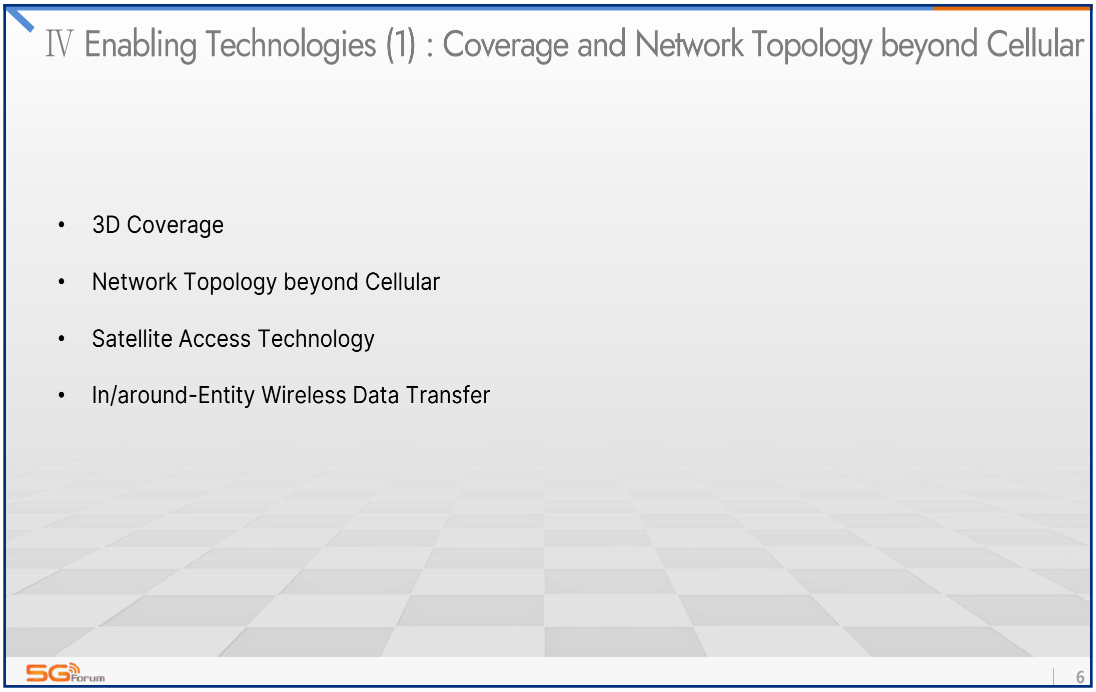
5G Forum Technology Committee 6G Working Group February, 2021

Table of Contents


Ⅰ 6G Megatrends & Motivation on Driving Factors
Truly Immersive
PHYSICAL WORLD
Ultra Precise and Fast
CONNECTED INTELLIGENCE
Expanded Coverage
Real-time Interaction
Sensing Data
Control & Experience
In-network Computing
Native AI
OPEN NETWORK ARCHITETURE
Trustworthy
DIGITAL WORLD
Communication Computing Convergence
3

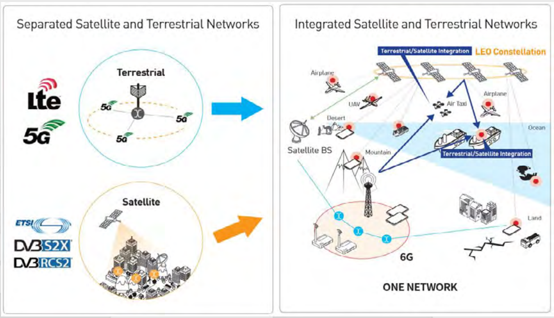

Ⅱ 6G Technical Trends
COVERAGE AND NETWORK TOPOLOGY BEYOND CELLULAR
Expanded Coverage and Enhanced Mobility
Enhanced Connectivity and Service Continuity
NEW SPECTRUM AND ANTENNA TECHNOLOGIES
- Location Aware
- Propagation Environment Aware
- Spectrum Sharing
- Carrier Aggregation
- Multi-Connectivity
FSO
THz
SubTHz
mmWave
Sub 6GHz
New Spectrum: THz, FSO
Metamaterial / Intelligent Surface / LoS MIMO
NATIVE AI FOR CONNECTED INTELLIGENCE
SENSOR ACTUATOR
COMPUTING
MODEM
RAN
NETWORK
MEC
Precise & Fast
Split Computing
Tbps Processing
PHY Slicing mURLLC
NET Slicing TSN
Split Computing
COMPREHENSIVE AI
SECURE BY DESIGN (PRIVACY, TRUSTWORTHY)
HIGH-PRECISION, TIME SENSITIVE AND QOS GUARANTEED
Automated Real-time Optimization of Everything
Sensing / Computing / Control / Experience / Interaction
NEW RADIO ACCESS TECHNOLOGIES
ULTRA BROADBAND
ZERO ENERGY MASSIVE IOT
MASSIVE (BROADBAND) URLLC
- Channel Coding
- Modulation
- Multiple Access
- Waveform
- Full Duplex
For Various BW and Spectrum: Sub6GHz ~ THz and Light
Low Complexity, Low Processing Latency, Low Power Consumption
4


Ⅲ 6G Technical Requirements & Desired Features
PERFORMANCE
User Experienced Data Rate
Peak Data Rate
(3D) Connection Density
Reliability and Air-Latency
Spectral Efficiency
Energy Efficiency
PERFORMANCE (EXTENDED)
(3D) Coverage and Mobility
(3D) Localization Precision
E2E Latency and Synchronicity
ARCHITECTURE AND SERVICE
Open and Intelligent
Automated and Real-time Optimized
Best Utilization of Computing Power over Network
Time-Sensitive and QoS Guaranteed
Distributed Infrastructure for Connected Machine and AI
For Delivering Truly Immersive Experience
For Enabling Real-time Interaction between physical and Digital Worlds
TRUSTWOR-THINGS
High-level Physical-layer Security
Secure System and Network by Design
AI and ML based Automated Security
Privacy Protection for Massively Connected Intelligence
5G Forum
5


Ⅳ Enabling Technologies (1) : Coverage and Network Topology beyond Cellular
3D Coverage
Network Topology beyond Cellular
Satellite Access Technology
In/around-Entity Wireless Data Transfer
5G Forum
6

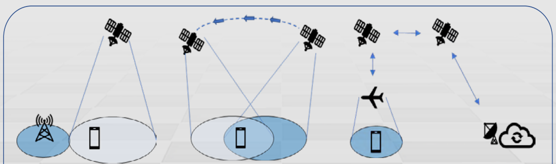
Coverage and Network Topology beyond Cellular : 3D Coverage

- Necessity of Integration of Satellite and Terrestrial Networks for 3D Coverage
  - The global market of unmanned aerial vehicles such as smart airlines, flying taxis (air taxis), and drones is expected to increase rapidly
  - In order to provide aerial mobile broadband services, it is necessary to develop technologies providing communication coverage beyond the ground-based mobile communication service limit
  - It is expected that it will be possible to provide stable internet services to various moving vehicles in the air through integrated satellite and terrestrial network technologies
  - The integrated 3D network technologies will be developed in the form of vertical integration of 3D mobile communication technology and 3D satellite communication technology



Coverage and Network Topology beyond Cellular : 3D Coverage

- (Enabling Technologies) Mobility for Integrated Satellite and Terrestrial Networks
  - Research Reports
    - ✓ Satellite-terrestrial networks leverage various technologies to concrete the methodology of heterogeneous networks as seamless service coverage, robust service supporting ability and high-efficiency performance[1]
      - Seamless service ability : offloading traffic for the same service coverage or reinforcing the reliability for the different service coverage
      - A fluent service area switch for the seamless service ability is to develop efficient handover schemes
    - ✓ Mobility Challenges for Integrated Satellite and Terrestrial Networks
      - Unlike the terrestrial networks, much smaller signal strength, higher propagation delay and frequent handover introduced by LEO satellite with fast movement [2]
      - Existing many satellite handover schemes make the decision based on multiple performance metric such as the radio quality link, QoS, BER and received signal strength. Most of them are centralized, the management structure exposes detects like scalability problems and long latency problems [1]
  - Challenging Issues : HO schemes to tackle frequent handover due to satellite movement

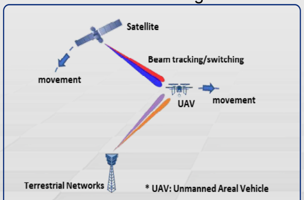


Various Handover scenarios for 3D coverage

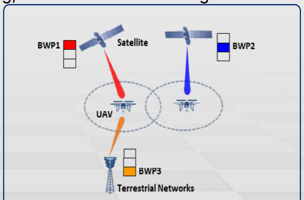
[1] P. Wang et al, "Convergence of Satellite and Terrestrial Networks : Comprehensive Survey", Vol.8, Jan. 2020.
[2] 3GPP TR 38.821, "Solutions for NR to support non-terrestrial networks (NTN) (Release 16)", Dec. 2019.

Coverage and Network Topology beyond Cellular : 3D Coverage

- (Enabling Technologies) Beam Management for Integrated Satellite and Terrestrial Networks
  - Research Reports
    - ✓ The improvement of beam management is required for mobility of satellites and aerial vehicles, long RTT, wide beam coverage, and various beam types [1]
      - ▪ Mobility: 7.6 km/h(@LEO), 1200 km/h(@airplane), RTT: 541.46 ms(@GEO),
      - ▪ Beam coverage: 3500 km(@GEO), Beam types: earth-fixed beam, moving beam
    - ✓ It is necessary to consider the effect of the beam pattern and beam interference according to the altitude
      - ▪ Due to the presence of possible nulls in the side lobes, an aerial UE may possibly see a stronger signal from a faraway BS than the one that is geographically closes according to the interlaced coverage pattern on different height due to the impact of beam pattern [2]
      - ▪ The system capacity may be better if frequency reuse greater than 1 is used depending on the beam interference [3]
  - Challenging Issues: Fast beam tracking and switching, Beam interference mitigation with BWP and polarization



Fast Beam Management



Beam Interference Mitigation

[1] 3GPP TR 38.811, "Study on New Radio (NR) to support non-terrestrial networks(Rel-15), July 2020.
[2] RP-192578, "Discussion on NR-UAV for Rel-17", 3GPP RAN#86, Dec. 2019.
[3] 3GPP TR 38.821, "Solutions for NR to support non-terrestrial networks (NTN) (Release 16)", Dec. 2019.

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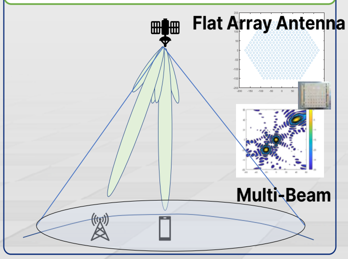
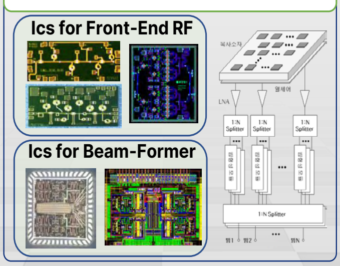
Coverage and Network Topology beyond Cellular : 3D Coverage

- (Enabling Technologies) Antenna for LEO Satellite Payload
  - Multibeam Flat Antenna for User Link & Feeder Link
    - ✓ Light Flat Phased Array Antenna (Earth-fixed Beam)
    - ✓ Fast beam tracking and scanning
  - ICs for Analog/Digital Beamformer & Front-end
    - ✓ Compact MMICs with High Performance for Front-end RF Module
    - ✓ Multi-Channel Analog/Digital Beamforming ICs
  - Inter-Satellite Antenna for Gbps Communications

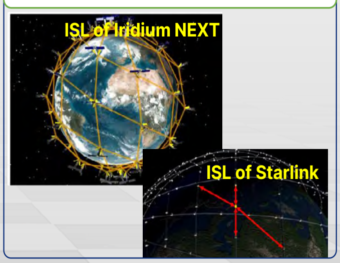
Multibeam Phased-Array Antenna



Ics for Analog/Digital Beamformer



Inter-Satellite Antenna



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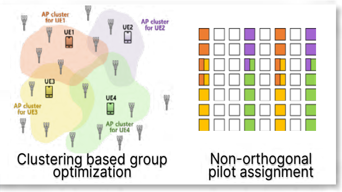
Network Topology beyond Cellular

Network Topology beyond Cellular in 6G

- ✓ Cell-Free massive MIMO Networks
  - Change of cellular connectivity from existing cell-centric to user-centric
- ✓ Dynamic Network Topologies
  - Provides flexible change and continuity of network topology according to network environment
- ✓ Space-Terrestrial Integrated Network
  - Heterogeneous architectures to provide three-dimensional coverage

Clustering based group optimization & Non-orthogonal pilot assignment

- ✓ To decrease the management complexity and accommodate a huge UE



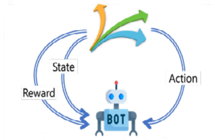
Clustering based group optimization

Non-orthogonal pilot assignment

Network Topology beyond Cellular

Reinforcement Learning & V2X-Cellular Integrated Network

- ✓ Wireless backhual path and deployment optimization
- ✓ Interference prediction and modeling considering V2X and cellular networks simultaneously

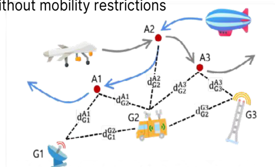


Reinforcement Learning

V2X-Cellular Integrated Network

Airborne network-centric optimization based on graph theory

- ✓ Network topology configuration based on airborne network without mobility restrictions

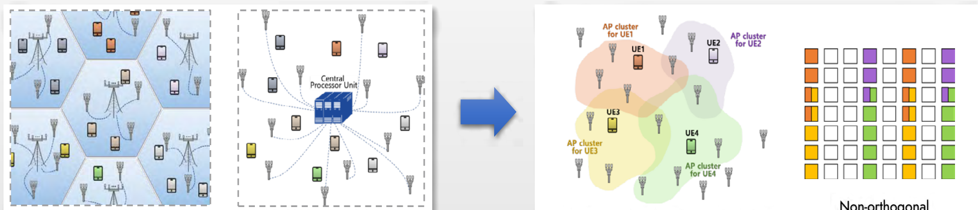


Graph theory based trajectory planning

Network Topology beyond Cellular : Cell-Free massive MIMO Network

Keyword : Multiple connection, distributed/cooperative AP system, user-centric network, macro diversity

- **Technical Concept**



Network MIMO Cell-free massive MIMO Clustering based group optimization Non-orthogonal pilot assignment

  - ✓ In this system, a large number of geographically distributed antennas in the network cooperate to jointly serve the users in a *user-centric fashion* without cell boundaries[1]
- **Technical Trends**
  - ✓ The centralized architecture improves energy efficiency by a high array gain and reduces inter-cell interference through coherent cooperation between distributed APs[1]
  - ✓ This topology can reduce obstacles between the AP and the UE by reducing the distance between them, and can generate many communication paths by increasing path selection candidates[2]
  - ✓ When the number of APs is 100 and the number of UEs is 40, 95% of UEs have fivefold the throughput performance compared to small cell networks[1]
- **Challenging Issues :** Fully characterizing cell-free massive MIMO systems, e.g, downlink pilot assignment and sophisticated power control algorithms

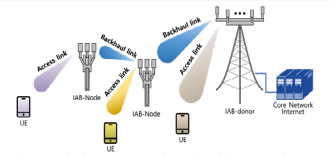
➔ ***Non-orthogonal pilot assignment, Clustering based group optimization***

[1] J. Zhang *et al.*, "Cell-Free Massive MIMO: A New Next-Generation Paradigm," *IEEE Access*, vol. 7, pp. 99878-99888, 2019.
[2] NTT DOCOMO, "5G Evolution and 6G," White Paper, Jan. 2020.

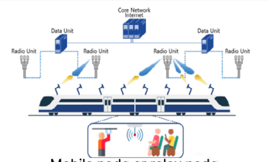
Network Topology beyond Cellular : Dynamic Network Topologies

Keyword : Dynamic network, integrated access and backhaul (IAB), mobile node, relay node, service continuity

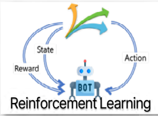
- **Technical Concept**



Integrated access and backhaul architecture



Mobile node or relay node



Reinforcement Learning

V2X-Cellular Integrated Network

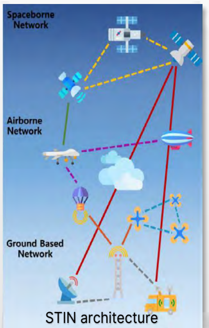
  - ✓ **The topology is dynamically adapted** for service continuity (e.g., when a backhaul link is degraded or lost) or for load balancing (e.g., to avoid congestion)
  - ✓ In order to enable **flexible network deployments**, a non-static moving object acts as a BS in a specific area
- **Research Reports**
  - ✓ The central unit updates the associations between the IAB-nodes based on information on the traffic load and backhaul link quality **to converge to an optimal configuration**[1]
  - ✓ One of the meaningful research for dynamic network topology is the concept of **group mobility** which efficiently supports mobile devices that are moving as a group on a bus, a train, or even an airplane[2]
    - Reduce the effort for network planning / enhance mobility support / enhance service continuity
- **Challenging Issues :** IAB – deployment, efficient path selection strategies, scheduling & retransmission ➔ **Reinforcement learning**
  Mobile node – interference dynamics modeling, vehicular penetration loss at mmWave
  ➔ **V2X-cellular integrated network**

[1] M. Polese *et al.*, "Integrated Access and Backhaul in 5G mmWave Networks: Potential and Challenges," *IEEE Commun. Mag.*, vol. 58, no. 3, pp. 62–68, Mar. 2020.
[2] Samsung "The Next Hyper Connected Experience for All," White Paper, Jul. 2020.

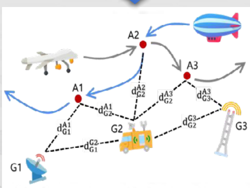
Network Topology beyond Cellular : Space-Terrestrial Integrated Network

Keyword : Satellite Network, ground-based network, heterogenous network, LEO satellite

- **Technical Concept**
  - STIN envision future 6G heterogeneous architectures to provide three-dimensional coverage, thereby complementing terrestrial infrastructures with non-terrestrial platforms
  - It organically combines the **ground based network**, the **airborne network**, and the **spaceborne network** divided into three network layers according to altitude
- **Research Reports**
  - A large scale routing problem solution for the integration of terrestrial network routing and SN routing can be implemented using the Openflow routing protocol[1]
  - In order to improve the management performance of STIN, **Self-organization Satellite Terrestrial Integrated System (SSTIS)** is proposed[2]
    - ✓ Perception Layer : Perceiving the network information
    - ✓ Cognition Layer : Monitoring network information, based on perceived data
    - ✓ Intelligence Layer : Integrating STIN route planning, resource management, and so on
  - Software defined networking (SDN)-based reference architectures and network functions virtualization (NFV) technologies are proposed for STIN[3]
- **Challenging Issues :** Topology and trajectory optimization, and energy efficiency
  ➔ ***Airborne network-centric optimization based on graph theory***



STIN architecture

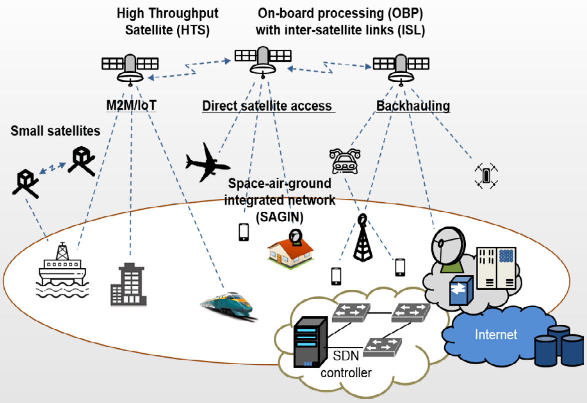


Graph theory based trajectory planning

[1] N. Rajatheva *et al.*, "White paper on broadband connectivity in 6g," *arXiv:2004.14247*, 2020.
[2] W. Chien *et al.*, "Heterogeneous space and terrestrial integrated networks for IoT: Architecture and challenges," *IEEE Netw.*, vol. 33, no. 1, pp. 15–21, Jan./Feb. 2019.
[3] S. Yao *et al.*, "SI-STIN: A smart identifier framework for space and terrestrial integrated network," *IEEE Netw.*, vol. 33, no. 1, pp. 8–14, Jan./Feb. 2019.

Satellite Access Technology

- Services
  - **Direct satellite access** using the same smart phones for terrestrial networks
  - **Backhauling** service from gNBs, relay towers, and gateways
  - Global coverage for **M2M and IoT** in remote areas



- Technologies and requirements
  - Very **high throughput satellite** (VHTS) for downlink data rate >500 Mbps for fixed access and >50 Mbps for mobile access
  - Mega-constellation low earth orbit (LEO) satellites with **on-board processing (OBP) with inter-satellite links (ISL)** for coverage up to 10 km above the ground
  - **Small satellites** with end-to-end latency <10 ms
  - **Space-air-ground integrated network (SAGIN)** for seamless 3D connectivity by extending 3GPP 5G Non-Terrestrial Network (NTN) specifications

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Satellite Access Technology – Technical Trends

- High Throughput Satellites (HTS)
  - emphasized the importance of active antennas and flexible OBPs for VHTS[1]
  - investigated on-board signal processing techniques including precoding for HTS/VHTS with focus on fixed satellite service (FSS) [2]

  → Will need large-scale multiple spotbeams and high-traffic on-board router/switch

- On-board processing (OBP) with inter-satellite links (ISL)
  - addressed the dynamic control satellite placement in the LEO satellite network[3]
  - jointly optimized OBP switching/routing, beamforming for advanced phased array antenna[4]

  → Will need to support space laser crosslinks with high-precision antenna and satellite position tracking under high satellite mobility

- Small satellites
  - proposed "Internet of Space Things/CubeSats" by applying cyber-physical systems (CPS) [5]
  - designed a virtual baseband unit (BBU) of the cloud radio access network (C-RAN) based on cubesats and UAVs[6]

  → Will need cost-efficient system design under SWaP (size, weight, and power) constraints; can be one main item to be added to 3GPP NT

- Space-air-ground integrated networks (SAGIN)
  - proposed an integration of 4 network segments: UAVs - high altitude platforms [HAPs] – LEO satellites – GEO satellites[7]
  - applied network slicing to SAGIN for IoT service with UAVs in mmWave bands[8]

  → Will need cross-layer optimization of heterogeneous algorithms/protocols, such as SDN/NFV, for seamless service coverage; will need enhancements of 3GPP 5G NTN Study/Work Items

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Satellite Access Technology – Technical Trends

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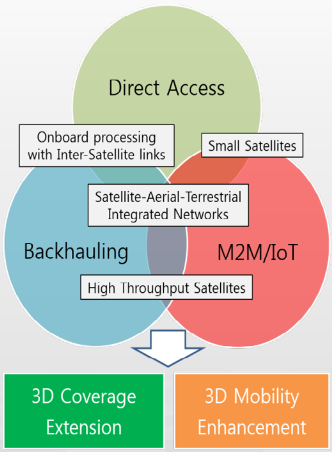
[1] R. De Gaudenzi et. al., “Future Technologies for Very High Throughput Satellite Systems,” Int. J. Satellite Communication and Networks, 2020.
[2] A. I. Pérez-Neira et. al., “Signal Processing for High-Throughput Satellites: Challenges in new interference-limited scenarios,” IEEE Signal Processing Magazine, 2019.
[3] A. Papa, T. de Cola, P. Vizarreta, M. He, C. Mas-Machuca and W. Kellerer, "Design and Evaluation of Reconfigurable SDN LEO Constellations," IEEE Transactions on Network and Service Management, 2020.
[4] J. P. Choi, S.-H. Chang*, and V. W. S. Chan, “Cross-Layer Routing and Scheduling for Onboard Processing Satellites with Phased Array Antenna,” IEEE Transactions on Wireless Communications, 2017.
[5] I.F. Akyildiz et al. The Internet of Space Things/CubeSats: A Ubiquitous Cyber-Physical System for the Connected World, Computer Networks, 2019.
[6] R. Bassoli et al., Cubesat-Based 5G Cloud Radio Access Networks, IEEE Vehicular Technology Magazine 2020.
[7] M Bacco et al., IoT Applications and Services in Space Information Networks, IEEE Wireless Communications 2019.
[8] T. Hong et al., Space-air-ground IoT Network and Related Key Technologies, IEEE Wireless Communications 2020.

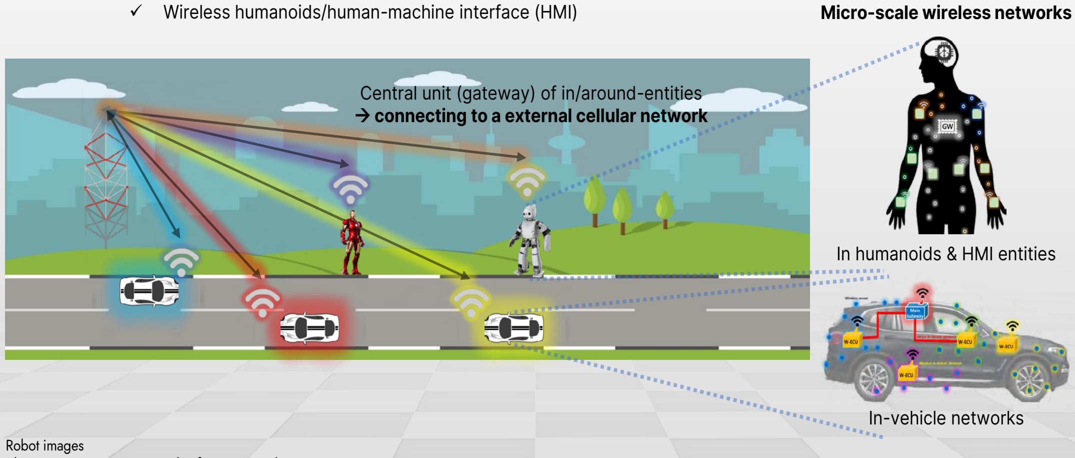
Satellite Access Technology – Enabling Technologies for the Future

- On-board processing
  - Multibeam signal processing for high throughput increase
  - Router/switch in the sky with optical ISLs for latency reduction
- Small satellites
  - Cost-efficient use of commercial off-the-shelf components: solid state power amps, antenna, and processors
  - Interconnection with UAV, HAP, and orbital satellites
  - Candidate for new 3GPP NTN Study/Work Items
- Software-defined networking (SDN) and network function virtualization (NFV)
  - Centralized network control and efficient resource management
  - Differentiated services with 3D network slicing for seamless SAGIN



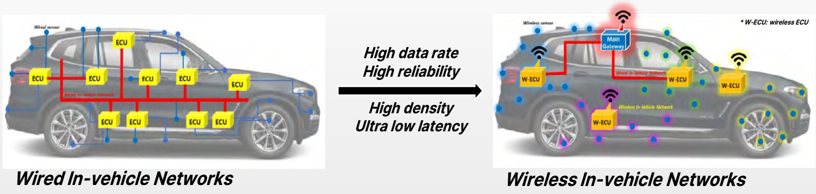
In/Around-Entity Wireless Data Transfer

- Technical Concept
  - A micro-scale high-speed/low-latency wireless network for an in/around-entity and connectivity with external cellular networks
    - ✓ Wireless in-vehicle networks (IVN)
    - ✓ Wireless humanoids/human-machine interface (HMI)



Robot images
: https://www.pngwing.com/ko/free-png-pvexk
: https://www.pngegg.com/ko/png-oogvh

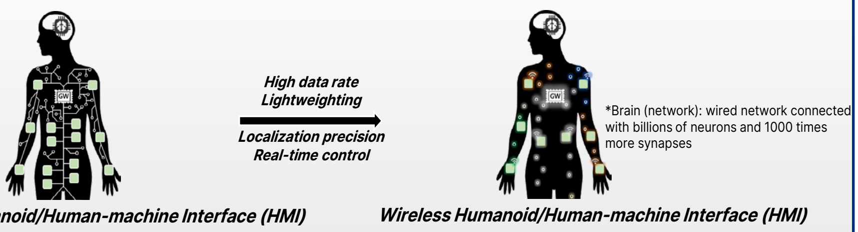
In/Around-Entity Wireless Data Transfer – Wireless In-vehicle Networks



- Wireless in-vehicle network (IVN) trends
  - ✓ Introducing wireless communication on a controller area network (CAN), which is a conventional IVN, to reduce wiring harnesses in vehicle[1]
  - ✓ Reducing wiring harnesses and proposing wireless IVNs to support flexible network topology by using Zigbee [2]
  - ✓ Proposing a wireless IVN using Zigbee and showing packet delivery performance depending on MAC protocol (CSMA/CA, slotted scheduled MAC) [3]
- Limitations
  - ✓ No considerations on an IVN channel environment and a high-speed IVN (such as automotive Ethernet/SerDes supporting up to 16Gbps)
    - ▪ Data rate demands and interference will rapidly grow with more modules (~100) and higher resolution of sensors such as camera/radar/lidar
  - ✓ Less considerations on latency requirements of IVNs (less than sub-ms)
- Considerations
  - ✓ High data rate: considering current wired-IVN data rate requirement (~tens of Gbps), wireless IVN should support higher data rate (+100Gbps?)
  - ✓ Reliability: error rate should be comparable with wired communication for real deployment
  - ✓ Connection density: more than 100 ECUs should be supported having different QoS (data rate, error rate, latency…)
  - ✓ Ultra-low latency: Low-latency is critical for fast control considering high mobility of the vehicle

[1] M. Laifenfeld and T. Philosof, "Wireless Controller Area Network for In-Vehicle Communication," *IEEE 28th Convention of Electrical & Electronics Engineers in Israel*, pp. 1-5, Dec., 2014.
[2] S. S. Kulkari and P. Y. Mali, "Use of Smart Wireless Node in Vehicle Networking," *International Journal of Engineering Research and General Science*, vol. 2, no. 4, pp. 635-640, Jun., 2014.
[3] M. Ahmed et al., "Intra-vehicular Wireless Networks," *IEEE Globecom Workshops*, pp. 1-9, Nov. 2007.

In/Around-Entity Wireless Data Transfer – Wireless Humanoid/HMI



- Wireless humanoid/HMI technical trends (Example: Iron man)
  - ✓ Requiring high data rate & robust-to-interferences communication according to increment of sensors and actuators
  - ✓ In addition to sensors and actuators which are connected by peripheral nerve, in future, brain* should be interconnected wirelessly
  - ✓ Proposing EtherCAT platform for humanoid [2] with performance analysis according to humanoid weight [1]
- Limitations
  - ✓ Performance degradation of humanoid dynamics according to increment of joint inertia due to humanoid weight[1]
  - ✓ Low speed movement (speed of proposed humanoid is 1m/s [2] is much slower than human) and insufficient data rate to support various sensors
- Considerations
  - ✓ Lightweighting: Weight reduction is critical to improve dynamic performance of humanoid
  - ✓ High data rate and low latency: A high-speed low-latency network is needed to improve joint control of actuators and to imitate human-like movement
  - ✓ Robust to interference: According to increment of sensors and actuators, wireless humanoid network needs to consider inter-node interference

[1] K. Hashimoto, "Mechanics of humanoid robot," Journal of Advanced Robotics, vol. 34, no. 21-22, pp. 1390-1397, Aug. 2020.
[2] T. Asfour et al., "ARMAR-6: A Collaborative Humanoid Robot for Industrial Environments," IEEE International Conference on Humanoid Robots (Humanoids), pp. 447–454, Nov. 2018.

V Enabling Technologies (2) : New Spectrum and Antenna Technologies

- THz/Sub-THz Technology
- Free-Space Optics Technology
- Programmable Wireless Environments
- Spectrum Sharing Technology

THz/Sub-THz Technology : Spectrum

- Extreme data-hungry applications (tens of Gbps – Tbps)
  - Display resolution: HD/FHD → UHD (4K/8K) → 16K
  - MPEG-I: Coded Representation of Immersive Media (over the MPEG-4 AVC)
    - ✓ Windowed-6DoF, Omnidirectional 6DoF, Dense Light Field Compression
  - LF: 3D image reconstructed by either light ray or wavefront (holography)
  - Ultra Wide Vision (UWV), 360-degree vision, or Stereoscopic vision
  - Machines requiring much more higher resolution and wider angle visions than human sight
  - Future XR: immersive, realistic, interactive, onsite, and real-time experience

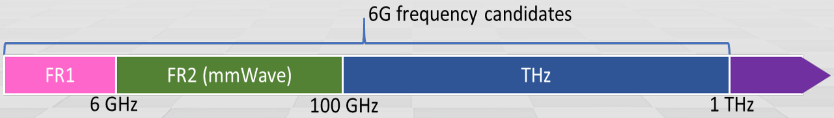
Band number	Symbols	Frequency range (lower limit exclusive, upper limit inclusive)	Corresponding metric subdivision
4	VLF	3 to 30 kHz	Myriametric waves
5	LF	30 to 300 kHz	Kilometric waves
6	MF	300 to 3 000 kHz	Hectometric waves
7	HF	3 to 30 MHz	Decametric waves
8	VHF	30 to 300 MHz	Metric waves
9	UHF	300 to 3 000 MHz	Decimetric waves
10	SHF	3 to 30 GHz	Centimetric waves
11	EHF	30 to 300 GHz	Millimetric waves
12		300 to 3 000 GHz	Decimillimetric waves

ITU-R naming

- Most fundamental issue: securing bandwidth
  - FR1 (Sub 6 GHz) + FR2 (mmWave) + THz
    - ✓ 3GPP FR1: 410-7125 MHz
    - ✓ 3GPP FR2: 24.25-52.6 GHz, upto 71 GHz
    - ✓ WRC-19 for IMT use: 24.25-27.5, 37-43.5, 45.5-47, 47.2-48.2, 66-71 GHz.
  - WRC-19 for land mobile & fixed service: 275-296, 306-313, 318-333, 356-450 GHz [1]

3GPP
- FR3: 7.125-24.25 GHz
- FR4: 52.6-114.25 GHz

FCC: Spectrum horizon (95G-3T)



[1] World Radio Communication Conference 2019 (WRC-19) Final Acts, 5.564A, ITU-R

THz/Sub-THz Technology : Challenges

- Little is known about THz propagation, however [1]
  - Severe additional path loss beyond free space propagation → short-range applications, close-in communications, whisper radio, information shower
  - Coverage holes at NLOS environments
  - Less additional path loss bands for longer-range mobile and fixed applications
- Concerns about biological safety?
- Feasibility [2]
  - Power consumption and heating especially at device side
  - Complexity and cost
  - THz RF devices availability
  - Need of new algorithms w.r.t.
    - ✓ New waveforms
    - ✓ New modulation and coding schemes
    - ✓ New multiple access schemes

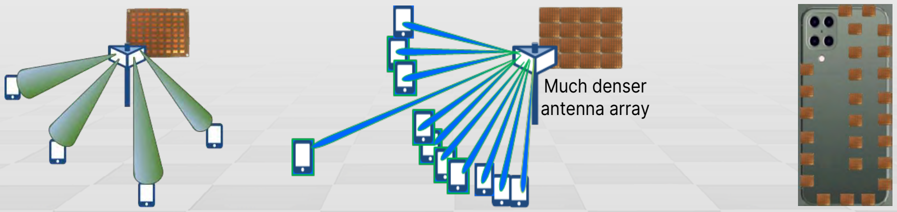
[1] Y. Xing and T. S. Rappaport, "Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz," IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.
[2] 현석봉 외 2인, 6G 통신에 대비한 RF 기술 동향, 전자공학회지 47(5), 53-63.

THz/Sub-THz Technology : Ultra Massive MIMO

- Coverage extension by exploiting very short wavelength
  - Massive MIMO (5G) → Ultra massive MIMO (6G)
  - Improved beamforming gain by exploiting much denser antenna array at BS
  - Massive MIMO configuration at UE
- Improved spectral efficiency
  - MU-MIMO (5G) → Extreme MU-MIMO (6G)
  - Much higher spatial resolution

5G [1]
- DL: Up to 12 orthogonal DMRS ports
- UL: Up to 4 orthogonal DMRS ports

6G
- # orthogonal DL/UL orthogonal ports >> 5G



MU-MIMO (5G) Ultra MU-MIMO (6G) Massive MIMO configuration at UE

[1] 3GPP TS 38.211

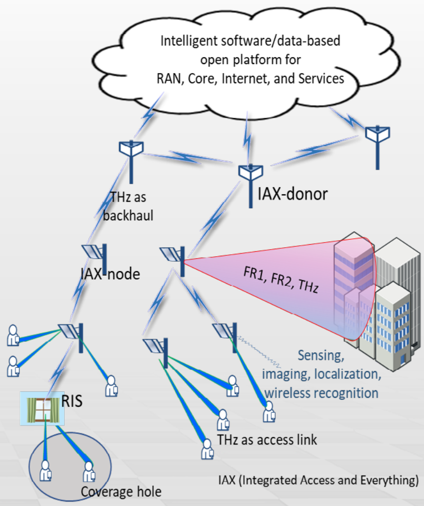
THz/Sub-THz Technology : Ultra Dense IAX Network

- 6G usage of mmWave/THz as ultra dense integration of;
  - Access links
  - Backhaul links
  - Sensing, imaging, localization, wireless cognition

✓ B5G UDN [1]
- 22.8 Mbps/m^2
- 2.2 bps/Hz (c.f. 5G 0.5 bps/Hz)

✓ 6G Ultra Dense IAX Network [2]
- 1 Gbps per space
- 3.3 bps/Hz @1000kmph

- For providing such user experiences as
  - Edgeless
  - Immersive, realistic, everywhere

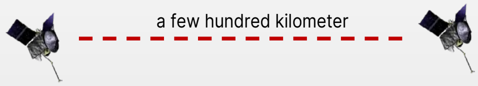


[1] Minhyun Kim, Kyoung Seok Lee, and Seung-Eun Hong, System-Level Evaluation on Non-Coherent Joint Transmission in Indoor Ultra-DFense Networks, ICTC 2020.
[2] 6G INSIGHT Vision and Technologies, https://library.etri.re.kr/service/rsch/issue-report/down.htm?view=open&id=810

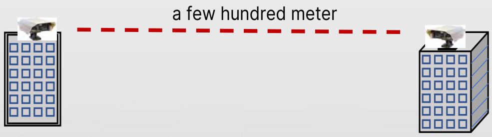
Free Space Optical Communications(FSOC) for 6G Backhaul/Fronthaul Link

Usage model of FSOC

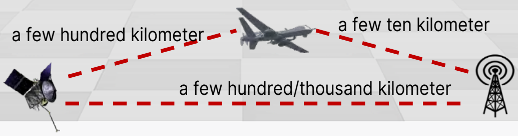
1. **Inter-satellite links**



2. **Relay/Backhaul/Fronthaul links in Terrestrial Networks**



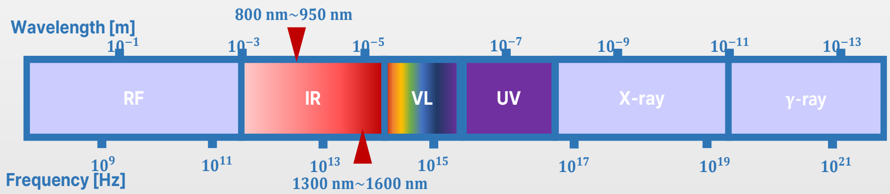
3. **Satellite-UAV-Ground links in Non-Terrestrial Networks**



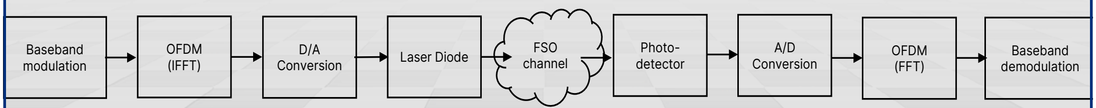
Free Space Optical Communications(FSOC) for 6G Backhaul/Fronthaul Link

Spectrum and TRX Structure

- For long-range FSOC, the wavelength of 750nm-1550nm is often adopted due to the eye and skin safety.



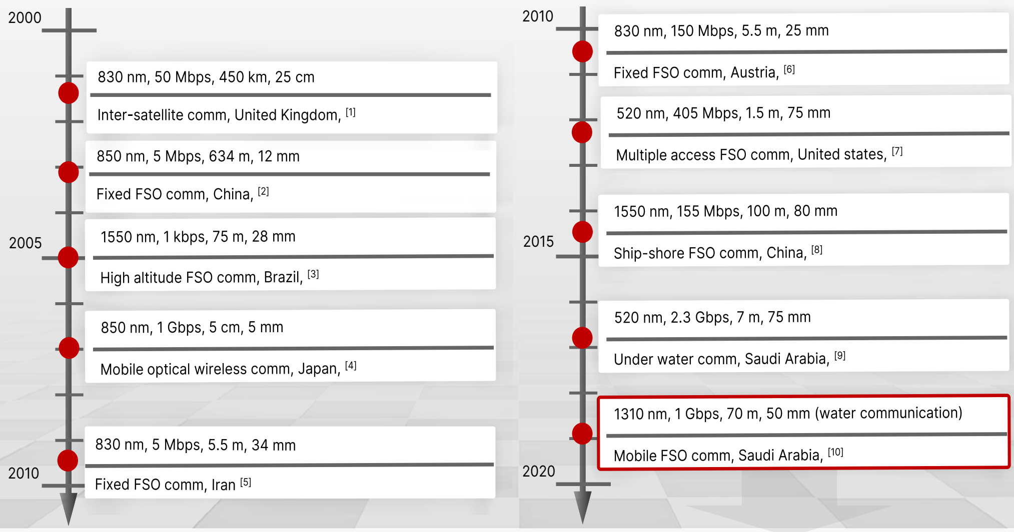
- Coherent or Non-coherent optical modulation can be possible.



Non-coherent OFDM FSOC is illustrated. For coherent FSOC, the laser diode is replaced by optical oscillator. There are some trade-offs between coherent and non-coherent in terms of cost and performance.

Free Space Optical Communications(FSOC) for 6G Backhaul/Fronthaul Link

Testbed Proven Systems



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Free Space Optical Communications(FSOC) for 6G Backhaul/Fronthaul Link

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[2] W. Lu, Z. Zhang, X. Yu, and M. Li, "Transmitting and receiving lens design in free space optics," Proc. SPIE 5284, 365–368 (2004).
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[4] T. Yazaki, M. Hattori and H. Tanaka, "Design and Demonstration of 1Gbit/s Optical Wireless Interface for Mobile Phones," IEEE GLOBECOM 2007 - IEEE Global Telecommunications Conference, Washington, DC, pp. 2226-2231. 2007.
[5] M. Ijaz et al., "Experimental investigation of the performance of different modulation techniques under controlled FSO turbulence channel," 2010 5th International Symposium on Telecommunications, Tehran, 2010, pp. 59-64.
[6] H. Le-Minh et al., "Experimental study of bit error rate of free space optics communications in laboratory controlled turbulence," 2010 IEEE Globecom Workshops, Miami, FL, 2010, pp. 1072-1076
[7] F. Aveta, H. H. Refai, and P. LoPresti, "Multiple access technique in a high-speed free-space optical communication link: Independent component analysis," Opt. Eng., vol. 58, no. 3, 2019, Art. no. 36111.
[8] Yi-xiang, AI Yong, SHAN Xin, LIU Hong-yang, "Experiment of ship-shore free-space optical communication," Journal of optoelectornics. Laser, Mar. 2014
[9] H. M. Oubei, "Underwater Wireless Optical Communications Systems: from System-Level Demonstrations to Channel Modeling," (2018).
[10] Wael G. Alheadary, Ki-Hong Park, Nasir Alfaraj, Yujian Guo, Edgars Stegenburgs, Tien Khee Ng, Boon S. Ooi, and Mohamed-Slim Alouini, "Free-space optical channel characterization and experimental validation in a coastal environment," Opt. Express 26, 6614-6628 (2018).

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Free Space Optical Communications(FSOC) for 6G Backhaul/Fronthaul Link

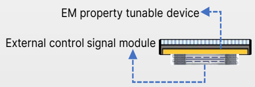
Issues and Challenges

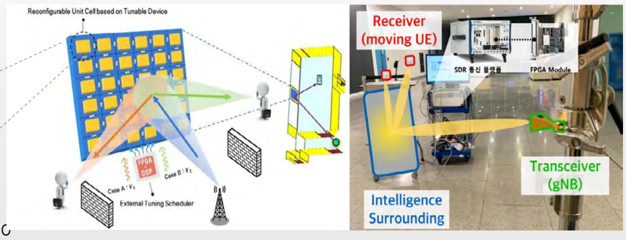
- Beam pointing-acquisition-tracking (PAT)
  - ✓ PAT is critical to establish the links. Besides mechanical beam alignment (conventional scheme), the algorithm based PAT scheme is necessary.
    [Kaymak, et. al. "A survey on acquisition, tracking, and pointing mechanisms for mobile free-space optical communications", IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 20, NO. 2, SECOND QUARTER 2018]
- Channel modeling and estimation
  - ✓ For terrestrial application, the channel model in various weather conditions need to be set up.
    [Esmail et.al., "Outdoor FSO communications under fog: Attenuation modeling and performance anlysis", IEEE Photonics, Vol. 8, 2016]
  - ✓ Channel estimation technique needs to be developed.
    [Safi et/al, "Adaptive channel coding and power control for practical FSO communication systems under channel estimation error", IEEE TVT, Vol. 68, 2019
- Some advanced transmission schemes
  - ✓ For multiplexing gain, the orbital angular momentum (OAM), the spatial mode multiplexing (SMM), LoS-MIMO, and WDM with optical channel coding shall be investigated to achieve high degree of freedom.
    [Zhao et. al, "Capacity limits of spatially multiplexed free-space communication", Nature Photonics, 16 Nov. 2015]
  - ✓ The conventional relay protocol such as AF or DF cannot be directly applied to FSOC. The optical relay protocol needs to be developed.
    [Dabiri et.al. "Performance analysis of all-optical amplify and forward relaying over log-normal FSO channels", JOCN Vol. 10, Feb. 2018]
- Link budget
  - ✓ For long-range links, the exact link budget needs to be calculated and the optical components corresponding to the link budget needs to be designed.
    [Quwaiee et. al. "On the asymptotic capacity of dual-aperture FSO systems with generalized pointing error model", IEEE TWC, Nov. 15, 2016

Programmable Wireless Environment

Wireless Communication with Reconfigurable Intelligence Surface

EM characteristics of the whole surface is dynamically adjustable by tunable elements in unit cell → making it "**programmable**"





*UM-MIMO: ultra massive MIMO

- In 6G mobile systems, *UM-MIMO and THz band are promising with challenges including extremely a large number of RF chains, high hardware cost and path loss [1]
- Programmable metasurface is a key technology for above 6G design
  - ✓ Creating new wave path and enabling intelligent beam routing by manipulating EM waves
  - ✓ Reconfiguring MIMO architecture and optimizing to reduce HW cost and complexity
- Promising technologies for 6G intelligent wireless environments
  - ✓ Can be combined with beamforming/LoS MIMO (flexible operation e.g., 100 beams ~ 25 beams x 4 LoS MIMO)
  - ✓ Beam routable RIS based on LoS MIMO, location/channel aware beam routing MAC

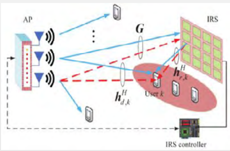
[1] Samsung Electronics., 6G Vision, 2020

Programmable Wireless Environment

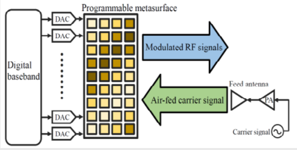
RF / Signal Processing Techniques for Communication System Performance Gain

- Theoretically, RIS makes wireless propagation environment controllable. Then, advanced RF and signal processing technologies such as beamforming optimization and novel modulation will be made possible.

[1]



[2]



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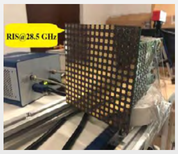

- [1] establish a 'signal hotspot' and 'interference-free zone' using intelligent reflect beamforming
  so that enhance SINR of users and minimize total transmit power in RIS coverage. Thereby improve the overall network performance.
  But they assume perfect CSI, so practical channel estimation technique using RIS becomes the next research step.
- [2] mapped digital baseband directly to RIS control signal for achieving modulation of reflected waves
  Then they propose passive PSK modulation scheme and eventually RF chain-free transmitter architecture
  However this research remain future works such as OFDM modulation scheme and considering practical hardware characteristics
- [3] design and implement prototype of high-gain and low-cost RIS having 256 2-bit elements for presenting feasibility of RIS
  - ✓ Research to **optimize system architecture**, propose a **new communication scheme** using the unprecedented properties of RIS are underway . Hereafter, a development direction **considering the non-ideal characteristics of RIS** from device design to signal processing is needed.

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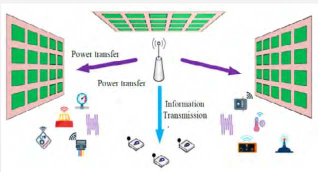
[2] Wankai Tang, et al. "Wireless communications with programmable metasurface: New paradigms, opportunities, and challenges on transceiver design." IEEE Wireless Communications (2020)
[3] Linglong Dai, et al. "Reconfigurable Intelligent Surface-based Wireless Communications: Antenna Design, Prototyping, and Experimental Results," IEEE Access (2020)

Programmable Wireless Environment

Promising Use cases for 6G Smart Radio Environment

- Advanced technologies by exploiting RIS have potential advantages for enhancing the 6G smart radio applications.

[1]



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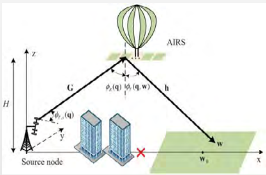
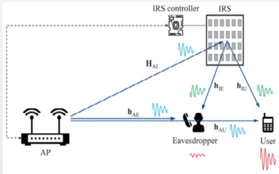


[3]



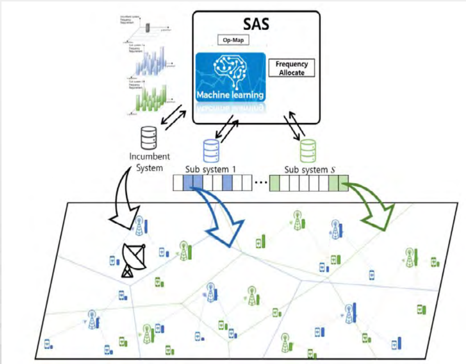
- [1] compensate the low energy efficiency and hardware cost of SWIPT using RIS's intelligent signal reflection.
  And they create an effective energy harvesting / charging zone with guarantee of QoS for both information/energy users.
- [2] consider UAV-carried RIS to achieve panoramic signal reflections from the sky.
  Thereby enhancing the performance of mmWave network and maximize transmission capacity.
- [3] propose secure communication in RIS-assisted network. The multi access points scheme exploiting RIS intelligent beamforming could serve legitimate users in the presence of eavesdroppers and maximize the system secrecy rate.

➢ In addition to above use cases, there are various future applications such as **edge computing**, **D2D communication**, and **IoT backscattering** using smart radio technology of RIS-aided network.
However, since these works mainly solved just the optimization problem, then **realistic transceiver design and simulation need to be made.**

[1] Rui Zhang, et al. "Joint active and passive beamforming optimization for intelligent reflecting surface assisted SWIPT under QoS constraints." IEEE Journal on Selected Areas in Communications (2020)
[2] Bennis Mehdi, et al. "Reflections in the sky: Millimeter wave communication with UAV-carried intelligent reflectors." IEEE Global Communications Conference (GLOBECOM) (2019)
[3] Robert Schober, et al. "Robust and secure wireless communications via intelligent reflecting surfaces." IEEE Journal on Selected Areas in Communications (2020)z

Spectrum Sharing

- Technical Concept
  - Scarce under 6GHz spectrum is shared among multiple service providers according to traffic and spectrum demand in a temporally and geographically dynamic way
  - Required amount of spectrum is allocated to each base station so that each user can be served as it wants
  - Temporal and geographical spectrum utilization can be maximized



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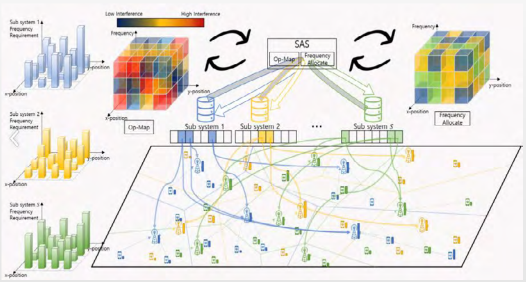
Spectrum Sharing

- **Spectrum-Sharing Cellular Communication System: architecture, protocol, and interference managements**



- **Technical Trends**
  - [1] suggests a dynamic spectrum-sharing is a candidate enabling technology for 6G. [1]
  - [2] claims that a new spectrum management based on spectrum sharing will play increasing role. [2]
- **Challenging Issues**
  - Dynamic spectrum sharing should avoid collision of spectrum usage among different entities, possibly by employing an AI engine
  - New regulation and licensing strategies suitable for dynamic spectrum sharing are required.

[1] Samsung Research, 6G: The next hyper-connected experience for all, July 2020.
[2] M. Matinmikko-Blue *et al.*, "Spectrum Management in the 6G Era: The Role of Regulation and Spectrum Sharing ," *Proc. 6G Wireless Summit*, 2020

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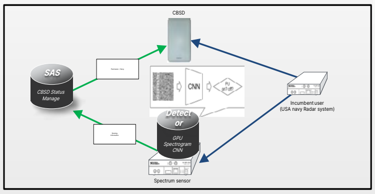
Spectrum Sharing

- **A novel AI-based MAC (MAC) & MAC for AI in a spectrum sharing celluar communication system**



	Conventional Distributed Learning	Federated Learning	Co-distillation
Users exchange:	Distributed training sample local data	Learning model exchange	Prediction results exchange
Pros & Cons:	Privacy leakage Comm. cost ↑as samples↑	Periodically upload : saving Comm. Cost Not available @ hetero Models	Available @ hetero. Models Comm. Cost : identical Training Dataset required.

- **Technical Trends**
  - [1] suggests a sensing and predict random MAC based on spectrum sensing. [1]
  - [2] showed the necessity of spectrum sharing for efficient on-device distributed learning. [2]

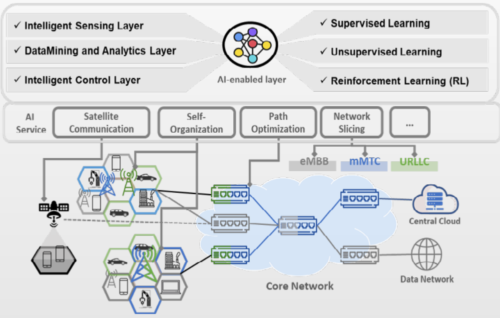
- **Challenging Issues**
  - A novel RRC and L2 design is required based on a dynamic spectrum sharing mobile communication systems.
  - A novel MAC design is required for communication and computing convergence and distributed learning.

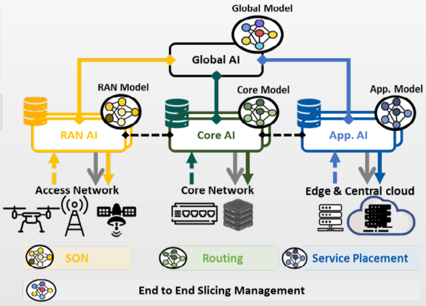
[1 S Kim, H Cha, J Kim, SW Ko, S.-L. Kim, "Sense-and-predict: harnessing spatial interference correlation for cognitive radio networks," IEEE Transactions on Wireless Communications 18 (5), 2777-2793, 2019.
[2] E. Jeong et al., "Communication-Efficient On-Device Machine Learning: Federated Distillation and Augmentation under Non-IID Private Data," [Online]. ArXiv preprint: http://arxiv.org/abs/1811.11479, Nov. 2019.

VI Enabling Technologies (3) : Native AI for Connected Intelligence

- AI-Native 6G Network Architecture
- Performance Guaranteed Networking
- High Precision Positioning
- Programmable date plane for high-performance network security services

AI-Native 6G Network Architecture

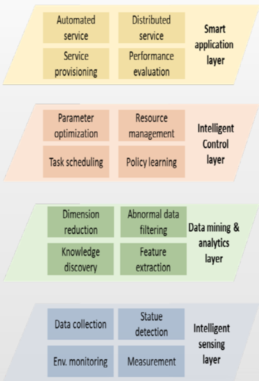




- Multi-dimensional network topology & extremely reliable and performance-guaranteed services
  - ➔ The network management and operation will be more challenging and a new network architecture for computation-intensive tasks is required
- **Adoption of AI technologies for automated and intelligent networking services**
  - ✓ (Tech #1) Fully automated 6G network management and operation
  - ✓ (Tech #2) AI-native control and user planes for 6G

AI-Native 6G Network Architecture

- **(Tech. #1) Fully automated 6G network management and operation**
  - Use cases of AI-empowered network automation [1]
    - ✓ Fault recovery/root cause analysis, energy optimization, optimal scheduling, network planning, etc.
    - ✓ Further issues: lack of bounding performance, lack of explainability, uncertainty in generalization, lack of interoperability to realize full network automation in 6G
  - Classification of 6G data analytics [2]
    - ✓ Descriptive analytics, diagnostic analytics, predictive analytics, and prescriptive analytics
- **The key for successful network automation in 6G**
  - How to collect rich and reliable network data which are not typically open to other players except network operators



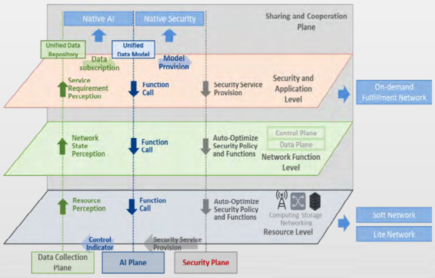
AI-enabled intelligent 6G [1]

To realize the vision of zero-touch network management in 6G, open network data set and open eco-system should be established!

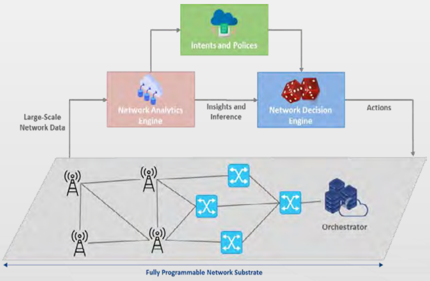
[1] R. Shafin et al., "Artificial Intelligence-Enabled Cellular Networks: A Critical Path to Beyond-5G and 6G," *IEEE Wireless Communications*, April 2020.
[2] K. Letaief et al., "The Roadmap to 6G: AI Empowered Wireless Networks," *IEEE Communications Magazine*, August 2019.

AI-Native 6G Network Architecture

- **(Tech. #2) AI-native control and user planes for 6G**
  - Data collection and AI planes to enable native AI support [1]
  - Pervasive AI and high-level network architecture for self-driving networks [2]
    - ✓ Accurate intent definitions/automated real-time inference/in-band telemetry over fully programmable network substrate



Data collection and AI planes [1]



Self-driving network architecture [2]

New directions and approaches (e.g., adoption of on-device AI, device-edge-cloud collaboration, in-network computing) towards AI-native 6G need to be discussed

[1] G. Liu et al., "Vision, Requirements and Network Architecture of 6G Mobile Network beyond 2030," *China Communications*, September 2020.
[2] I. Akyildiz et al., "6G and Beyond: The Future of Wireless Communications Systems," *IEEE Access*, July 2020.

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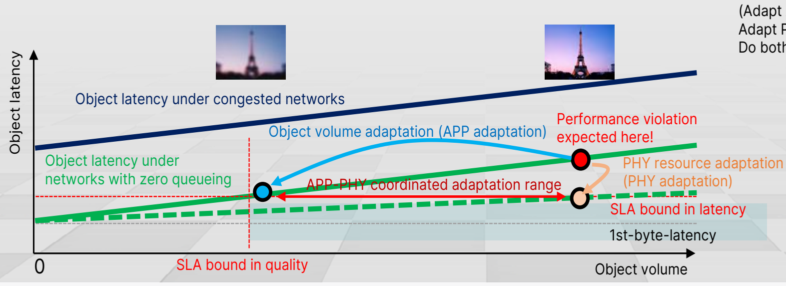
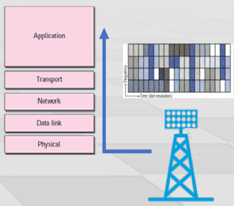
Performance Guaranteed Networking (PNG) is about Object Latency

Object Latency = 1st-byte-Latency + ObjectVolume/Throughput

- High quality immersive low-latency services are with decodable units (objects) whose size are large.
- Therefore, PGN needs to guarantee the latency of objects which is beyond the latency of packets.
- For this, objects should be encoded in their volumes matching with the available end-to-end bandwidth available at the moment. (**APP-PHY coordination**)
- **Time synchronization and E2E determistic packet delivery** are further required to guarantee on-time delivery of objects in PGNs.



APP-(Transport)-PHY coordination
(Adapt APP data to PHY/MAC resource + Adapt PHY/MAC resource to APP demand. Do both most efficiently.)



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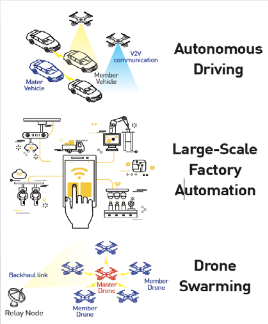
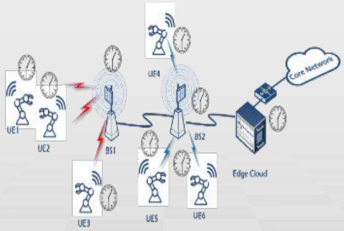
Performance Guaranteed Networking: Synchronization

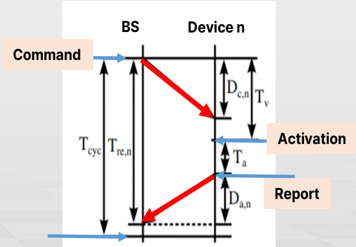
- Performance goal: absolute time synchronization(ATS) with nano-sec margin
  - Devices concurrently or sequentially need to be operated while meeting very tight jitter requirements in factory automation application.
  - Maintaining absolute time synchronization during connection status even in very low SNR
  - ATS procedure for big factory served by several BSs (IEEE 1588v2.1 White Rabbit) [1]



<Applications relating to ATS>



<Example of big factory with two BSs>



<Closed loop control cycle mechanism>

[1] IEEE 1588-2019 - IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, 2020-06-16

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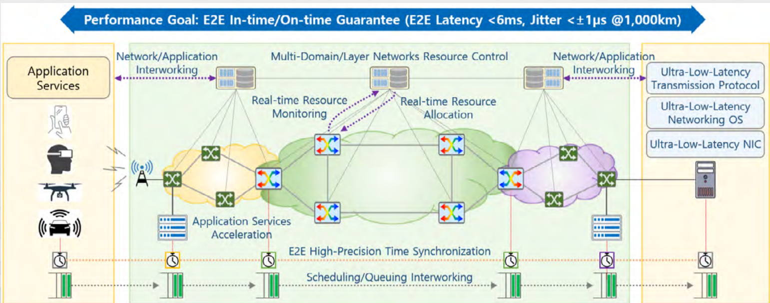
Performance Guaranteed Networking: E2E Deterministic Network

- Performance goal: in-time/on-time packet delivery in large-scale network
  - E2E latency-deterministic network is required for real-time, hyper-immersive interactive services or high-precision vertical services.
  - TSN is available for Ethernet LANs, and DetNet which targets IP or MPLS enterprise networks, is being standardizing in IETF. To expand the network scope, technologies would evolve in a direction applicable to complex, wide-area networks composed of multiple layers and domains.
  - Real-time monitoring and control/management of network resources are expected as key issues to maintain QoE of massive time-sensitive service flows in large-scale networks. [1]



[1] 6G Insight – Vision and Technologies, ETRI, Nov. 2020.

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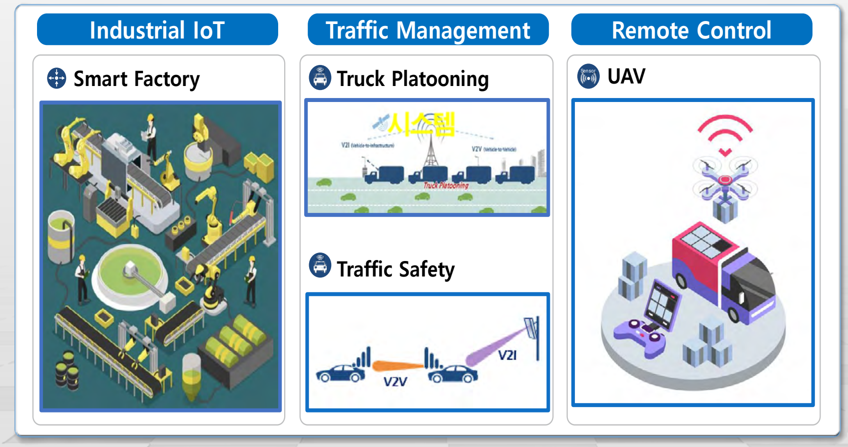
High Precision Positioning – Technical Concept

- cm-level positioning accuracy within a few tens of ms latency
  - is need for applications such as remote control for smart factory, traffic management/control, and UAVs[1].



[1] 3GPP, "3GPP TR 22.872: Study on positioning use cases; Stage 1 (Release 16)," ETSI, Tech. Rep., Sept. 2018.

High Precision Positioning – Trends

- state-of-the-art positioning accuracy[1]

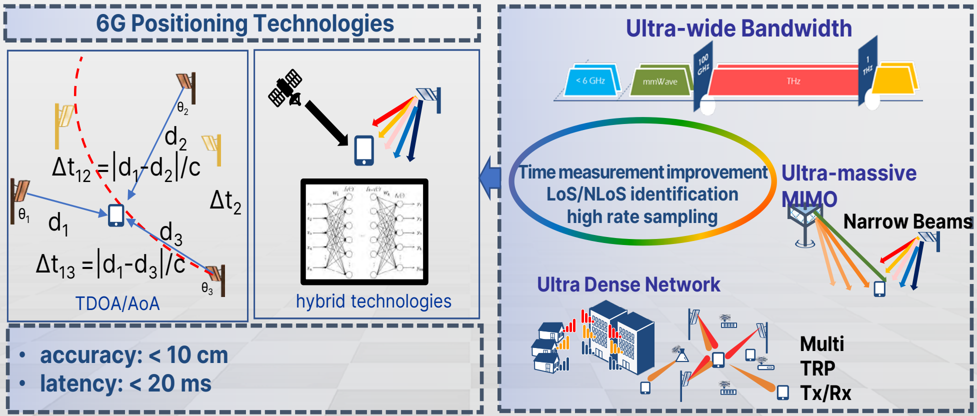
systems	cases	accuracy	comments
Terrestrial communication systems	5G NR	~ 3m	
	Wi-Fi/Bluetooth	~ 30m	
	UWB	~ 10cm	
Global navigation satellite systems	GNSS only	~ 5m	open areas only
	RTK	~ 1cm	open areas only

- target requirements in 3GPP Release-17 (IIoT use cases)[2]
  - Horizontal position accuracy: < 0.2m for 90% UEs
  - vertical position accuracy: < 0.2m for 90% UEs at least 3GHz sampling rate for 10cm-level accuracy
  - end-to-end latency for position estimation of UE: < 100ms
  - physical layer latency for position estimation of UE: < 10ms

[1] ETRI, "6G insight: vision and technologies," Nov, 2020.
[2] 3GPP, "3GG TR 38.857: Study on NR positioning enhancements (Release 17)," ETSI, Tech. Rep., Dec. 2020.

High Precision Positioning – Enabling Technology

- Most fundamental issue: multipath resolution and high-rate sampling
  - LoS/NLoS resolution with the help of ultra-wide bandwidth and ultra-massive MIMO in THz[1]
  - more than 3GHz sampling rate for cm-level accuracy
  - application of deep learning or hybrid positioning methods[2]

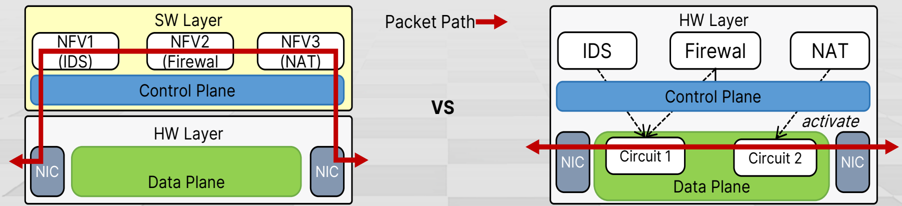


[1] J. del Peral-Rosado et al., "Whitepaper on New Localization Methods for 5G Wireless Systems and the Internet-of-Things," COST Action CA15104, 2018.
[2] Andre Bourdoux et al., "6G White Paper on Localization and Sensing," eprint arXiv: 2006.01779v1, Jun. 2020.

Programmable data plane for high-performance network security services

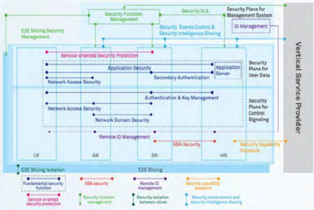
- A large number of **network threats** will occur in the future Mobile Communication Network (Due to IoT Devices) -> **The need for network security**
  - Characteristics of 5G: 1) Frequent Environment Changes, 2) Heavy Network Traffic 3) Low Latency .
- **SW based security services : Long Delay**
  - **Long processing time** due to the complex processing stacks
  - **Performance degradation** in compute-intensive operations (e.g., IDS *pattern matching*)
- **HW based security services : Poor Flexibility**
  - Limited to administrator enforced security functions
  - Lack of scalability
- **Need of hybrid(SW+HW) security service platform**

① Improve existing SW based security services → solution to improve existing SW based 5G security services
② Develop Programmable HW based security service platform → solution to improve existing HW based 5G security services
③ **Develop SW/HW co-desinged security service platform** → fundamental solution of next-generation Mobile Communication Network

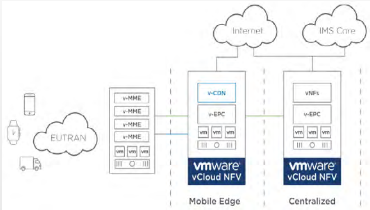


Programmable data plane for high-performance network security services

- **Technology Trend: Virtualization Infrastructure for 5G and security**



[1] 5G Security Architecture Framework



[2] vCloud NFV platform

- [1] Huawei 5G Security Architecture Framework
  - Huawei makes efforts in developing network virtualization technologies such as SDN / NFV for 5G network security enhancement, and developing a security framework architecture based on this
- [2] Vmware vCloud NFV platform for virtualized evolved packet core
  - VMware is proposing the vCloud NFV platform and DPI VNF as a 5G core and security technology.

- A large number of architectures are proposed for supporting programmability since it becomes important in ever-changing 5G network
- However, the software-based infrastructure has a performance limitation, especially critical for 5G ultra-low latency services.

=> Need a Programmable & High performance Structure -> Need to develop a HW-SW Integrated Architecture

[1] "5G Security Architecture White Paper", https://www-file.huawei.com/-/media/corporate/pdf/white%20paper/5g_security_architecture_white_paper_en-v2.pdf?la=en
[2] "VMWare vCloud NFV Platform for Virtualized Evoloved Packet Core", https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/solutions/industry/vmware-vepc-solution-whitepaper.pdf

Programmable data plane for high-performance network security services

- **Technology Trend: Data plane programming interface**

- [1] P4 / [2] Domino
  - Programming interface combines multiple Match-Action Tables to define the data plane functions
  - *Support limited states, cannot check payload of packets*

- [3] ClickNP / [4] Emu
  - Provide hardware programming abstraction for network functions
  - *Hardware programming skill is required for development (low Programmability)*

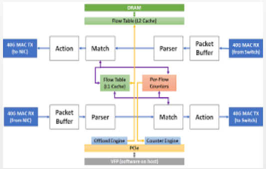
- They focus on the problem: "How to control the programmable hardware?"
  -> Data plane programming interface
- Nevertheless, limited functionality or low programmability due to the hardware structure
- Furthermore, not able to program pattern matching for payload inspection

=> Usable interface / Programmable pattern matching is needed

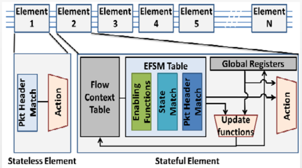
[1] Bosshart, Pat, et al. "P4: Programming protocol-independent packet processors." ACM SIGCOMM Computer Communication Review 44.3 (2014): 87-95.
[2] Sivaraman, Anirudh, et al. "Packet transactions: High-level programming for line-rate switches." Proceedings of the 2016 ACM SIGCOMM Conference. 2016.
[3] Li, Bojie, et al. "Clicknp: Highly flexible and high performance network processing with reconfigurable hardware." Proceedings of the 2016 ACM SIGCOMM Conference. 2016.
[4] Sultana, Nik, et al. "Emu: Rapid prototyping of networking services." 2017 {USENIX} Annual Technical Conference ({USENIX}{ATC} 17). 2017.

Programmable data plane for high-performance network security services

- **Technology Trend: Programmable data plane hardware**



[1] AccelNet



[2] FlowBlaze

- [1] Microsoft AccelNet
    - Propose a programmable SmartNIC can be used in data centers with centralized remote control
- [2] FlowBlaze
    - Propose an architecture support FPGA based SmartNIC with stateful packet processing

- Hardware data plane is essential for high performance and being introduced in the industry
- Programmability has been concentrated on packet processing (Switching), but inadequate for security processing

=> The need for a security function integrated, comprehensive, high-performance/dynamic network operation

[1] Firestone, Daniel, et al. "Azure accelerated networking: SmartNICs in the public cloud." 15th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 18). 2018.
[2] Pontarelli, Salvatore, et al. "Flowblaze: Stateful packet processing in hardware." 16th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 19). 2019.

Enabling Technologies (4) : New Radio Access Technology

- Massive (Broadband) URLLC RAN
- Tbps Wireless MODEM Technology
- Zero-Energy IoT technology
- AI-based PHY Technology

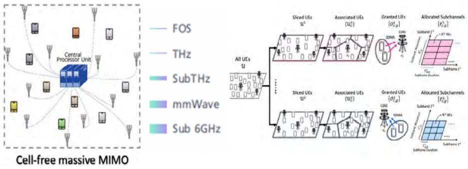
Massive (Broadband) URLLC RAN

Massive (Broadband) URLLC

- Massive URLLC (mURLLC)
  - Massive sensing for autonomous robots
  - URLLC+Massive connectivity
- Broadband URLLC (BURLLC)
  - Truly immersive XR and Haptics
  - Autonomous vehicles and drones
  - Rate-Reliability-Latency requirements
- Sensing-Communication-Computing-Control
  - Distributed Artificial Intelligences
  - Real-time interaction of Physical and Digital Worlds

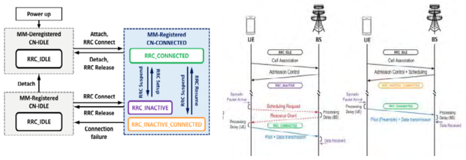
RAN Slicing for M(B) URLLC

- Slicing of radio resources (RUs, Carrier, Subchannel, Processing Time, etc) to guarantee the rate-reliability-latency requirements efficiently



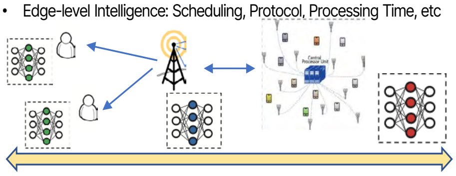
Multiple Access Technology for M(B) URLLC

- Ultra Broadband Wireless Link (UM-MIMO, mmWave, THz, FSO)
- Waveform/Multiple Access
- M(B) URLLC Scheduling & Protocols



A based Real-time RAN Optimization

- Device-level Intelligence: mobility & traffic prediction, location, etc
- RU-level Intelligence: RU association, Carrier, Subchannel, etc
- Edge-level Intelligence: Scheduling, Protocol, Processing Time, etc



Massive (Broadband) URLLC RAN

- **RAN Slicing for M(B) URLLC**
  - User-centric cell free network using various frequency bands (under 6GHz, mmWave, THs, FSO)
  - Every RAN resource, such as radio unit association, frequency band, subchannels, processing time, needs to be flexibly partitioned to guarantee packet flows with similar QoS requirements.
  - Each RAN slice should be very efficient (in terms of spectral efficiency or connectivity) while guaranteeing rate-reliability-latency requirements
  - Such a RAN slicing should be quite adaptive to track the changes in mobility and traffic characteristics
- Research Trends
  - [1] suggests an architectural framework and description for realizing RAN slicing in 5G
  - [2] proposes a user-centric cell-free massive MIMO network concept and suggests distributed/centralized DL/UL operations and the corresponding resource optimizations
  - [3] suggests hyper-specialized slicing and RAN-CORE convergence
  - [4] proposes RAN slicing for URLLC according to the QoS requirements and suggests a corresponding multiple access protocol and scheduling algorithm for URLLC
- Technical Challenges
  - Adaptive RAN slicing architecture for cell-free network using massive MIMO and various frequency bands
  - MIMO/beamforming/power control/transmission technology to overcome fading channel and mobility
  - Spectrally efficient channelization and scheduling for guaranteeing URLLC QoS considering mobility and traffic characteristics

[1] R. Ferrus, O. Sallent, J. Perezz-Romero, and R. Agusti, "On 5G Radio Access Network Slicing: Radio Interface Protocol Features and Configuration," *IEEE Commun. Magazine, May 2018.*
[2] O.T. Demir, E. Bjornson, and L. Sanguinetti, "Foundations of User-centric Cell-free Massive MIMO," *Foundations and Trends in Signal Processing*, 2020.
[2] H. Viswanathan and P.E. Mogensen, "Communications in the 6G Era," *IEEE Access*, Nov. 2019.
[4] K.S. Kim, et al., "Ultrareliable and Low-Latency Communication Techniques for Tactile Internet Services," *Proc. IEEE*, Feb. *2019.*

Massive (Broadband) URLLC RAN

- **Multiple Access Technology for M(B) URLLC**
  - Grant-free multiple access schemes for M(B) URLLC
  - Ultra-broadband wireless link needs to be considered for various frequency bands (under 6GHz, mmWave, THs, FSO)
  - Spectrally-efficient URLLC scheduling and protocols need to be developed
  - Grant-free multiple access scheme supporting both massive connectivity and ultra-low latency
- Research Trends
  - [1] evaluates UL grant-free (GF) transmission schemes to show that GF is promising for URLLC
  - [2] suggests massive MIMO and multi connectivity as key technologies for URLLC
  - [3] proposes spectrally efficient GF protocols and scheduling algorithm for BURLLC using massive MIMO
  - [4] analyzes the latency performance of GFMA for mURLLC
- Technical Challenges
  - Ultra-broadband transmission techniques using new spectrum or antenna technology need to be considered
  - Spectrally efficient protocol, channelization and scheduling for guaranteeing URLLC QoS
  - Multiple access schemes supporting both massive connectivity and ultra-low latency

[1] T. Jacobsen et al., "System Level Analysis of Uplink Grant-Free Transmission for URLLC," *Proc. IEEE Globecom, 2017.*
[2] P. Popovski et al., "Wireless Access in Ultra-Reliable Low-Latency Communication (URLLC)," *IEEE Trans. Commun., Aug.* 2019.
[3] K.S. Kim, et al., "Ultrareliable and Low-Latency Communication Techniques for Tactile Internet Services," *Proc. IEEE*, Feb. *2019.*
[4] T. Kim and B.C. Jung, "Performance Analysis of Grant-Free Multiple Access for Supporting Sporadic Traffic in Massive IoT Networks," *IEEE Access*, October 2019.

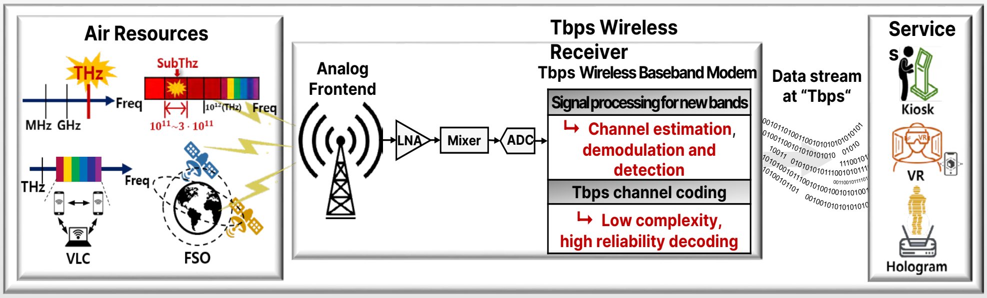
Massive (Broadband) URLLC RAN

- **AI-based real-time RAN optimization**
  - In order to guarantee E2E latency, a cross-layer design with high-complexity is required
  - On device ML + edge AI is a desired architecture for realizing E2E URLLC by optimizing every RAN resource
  - Architecture and training method need to be developed for facilitating fast training and real-time inference for resource optimization
- Research Trends
  - [1] suggests on-device ML and edge AI as one of the key enablers for URLLC
  - [2] suggests edge AI as a key enabler for 6G, especially for sensing-communication-computing-control
  - [3] proposes a distributed deep learning architecture for realizing URLLC in 6G network
  - [4] suggests to combine theoretical knowledge and deep learning to achieve URLLC in 6G network
- Technical Challenges
  - Adaptive RAN slicing architecture and the corresponding distributed intelligence architecture
  - Knowledge-assisted learning architecture and methods
  - Fast training/federated learning methods

[1] M. Bennis, M. Debbah, and H.V. Poor, "Ultra-Reliable and Low-Latency Wireless Communication: Tail, Risk and Scale," *Proc. IEEE*, Oct. *2018.*
[2] W. Saad, M. Bennis, and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," *IEEE Network, Oct. 2019.*
[3] C. She et al., "Deep Learning for Ultra-Reliable and Low-Latency Communications in 6G Networks," *IEEE Network, Sep./Oct. 2020.*
[4] C. She et al., "A Tutorial of Ultra-Reliable and Low-Latency Communications in 6G: Integrating Theoretical Knowledge into Deep Learning," *arXiv:2009.06010.*

Tbps Wireless Modem Technology

- Technical Concept

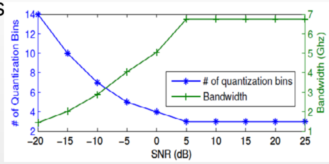


- For supporting BW hungry 6G applications, the implementation of a modem that is able to support Tbps data stream is required. Fast and energy efficient signal processing and channel coding are key components to realize the Tbps wireless baseband modem. Implementation aware design needs to be considered and communication performance compromise should be minimized.

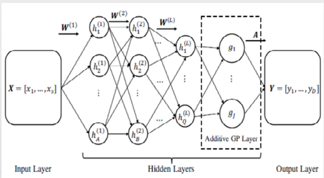
- To realize Tbps modem, two core enabling technologies are
  - Tech 1: Robust and energy efficient baseband signal processing for new bands
  - Tech 2: Tbps channel coding: super fast decoder with high reliability

Tbps Wireless Modem Technology

- Technology 1: Robust and energy efficient signal processing for new bands
  - To support Tbps transmission and reception, high frequencies (sub-THz, THz and optical bands) and their aggregation are needed. Baseband processing of a super wideband is complex and energy efficient transceiver implementation is thus important.
  - New signal processing techniques in regard of new band's channel characteristics, modulation, antenna technologies, and ADC resolution [1] are required.
- Technical trends
  - Channel estimation for low-resolution quantization, fast channel tracking method for low overhead have been studied.
  - Compressed sensing based [2] or learning-based [3] approaches for massive MIMO low complexity channel estimation.
  - Data detection for low resolution, for THz noise, and modulation and coding [4]
- Challenging issues
  - Deep learning-aided algorithms for channel estimation and detection of THz LOS-MIMO
  - Joint channel estimation and detection for the new frequency bands. Joint detection and decoding and their low precision realizations.



< Optimal bandwidth and ADC resolution under fixed ADC power [1] >

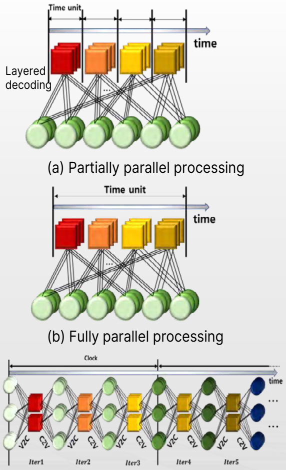


< deep kernel learning for Thz channel estimation [3] >

[1] O. Orhan, E. Erkip, and S. Rangan, "Low power analog-to-digital conversion in millimeter wave systems: Impact of resolution and bandwidth on performance," in ITA 2015, Feb. 2015
[2] V. Schram, A. Bereyhi, J.-N. Zaech, R. R. Müller, and W. H. Gerstacker, "Approximate message passing for indoor THz channel Estimation," arXiv:1907.05126, 2019.
[3] S. Nie and I. F. Akyildiz, "Deep kernel learning-based channel estimation in ultra-massive MIMO communications at 0.06-10 THz," in 2019 Globecom Workshops, Dec. 2019.
[4] H. Sarieddeen, M.-S. Alouini, and T. Y. Al-Naffouri, "An Overview of Signal Processing Techniques for Terahertz Communications," *arXiv:2005.13176.*

Tbps Wireless Modem Technology

- Technology 2: Tbps Channel coding
  - Channel coding is the most power consuming component of the baseband modem [1].
  - Realization of Tbps supporting channel coding is a key requirement for 6G. Extensive comparison of state of the art results was given [2].
- Technical trends
  - 588Gbps LDPC decoder based on finite alphabet message passing was implemented [3] where the unrolled architecture was used. An unrolled polar SC decoder achieved 512Gbps [4]. Such high-speed decoders have been attained under considerable sacrifice of decoding performance.
  - More bandwidth efficient coded modulation schemes are under study [5].
- Challenging issues
  - Code design and decoder implementation for low-level quantization or new noise characteristics
  - More efficient or reliable parallelizable decoding algorithms, latency minimizing coded modulation
  - Low complexity and parallel decoding combined with modulation shaping and multi-level coding



(a) Partially parallel processing

(b) Fully parallel processing

(c) Unrolled fully parallel processing (with pipelining)

<Architectures of LDPC decoders [2] >

[1] N. Rajatheva *et al.*, "Scoring the Terabit/s Goal:Broadband Connectivity in 6G," *arXiv:2008.07220 [eess]*, Aug. 2020.
[2] EPIC-D1.2-B5G-Wireless-Tbs-FEC-KPI-Requirement-and-Technology-Gap-Analysis-PU-M07
[3] R. Ghanaatian, A. Balatsoukas-Stimming, T. C. Müller, M. Meidlinger, G. Matz, A. Teman and A. Burg, "A 588-Gb/s LDPC Decoder Based on Finite-Alphabet Message Passing," IEEE Trans. VLSI Systems, vol. 26, no. 2, pp. 329–340, 2018.
[4] P. Giard, G. Sarkis, . Thibeault and W. J. Gross, "Multi-Mode Unrolled Architectures for Polar Decoders," IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 63, no. 9, pp. 1443-1453, 2016.
[5] O. İşcan and W. Xu, "Polar Codes with Integrated Probabilistic Shaping for 5G New Radio," *arXiv:1808.09360 [cs, math]*, Aug. 2018, Accessed: Dec. 15, 2020.

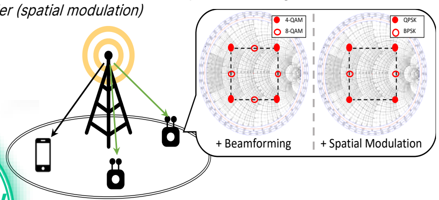
Enabling Technologies (4) : Zero-Energy IoT Technology

Zero-Energy (Green) 6G IoT Network

- Ambient Backscatter Communication (AmBC)
  - Reflecting and modulating ambient RF signals existing in the air through impedance mismatching
- Intelligent Reflecting Surface (IRS)
  - *To control the reflection characteristics of walls to establish favorable signal propagation environments*
- Massive and Sporadic Connectivity (Compressed Sensing)
  - *Typical IoT network only a small subset of devices are active.*

MIMO Ambient Backscatter Communication (AmBC)

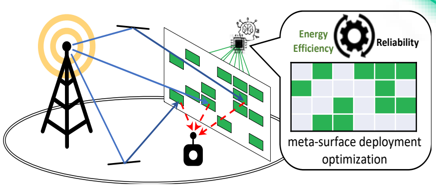
- *Use of MIMO to increase reliability (beamforming) or reduce QAM order (spatial modulation)*



Zero-Energy IoT

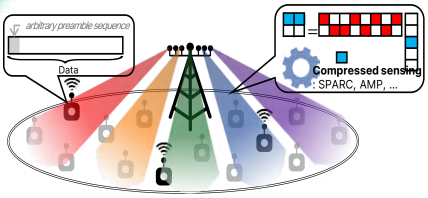
Arbitrary Intelligent Reflecting Surface

- *Using optimization-based arbitrary meta-surface deployment*



Unsourced random access with *spatial beam*

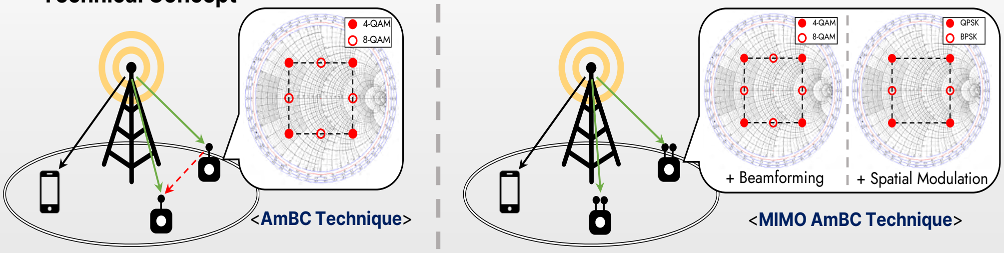
- *Cell partitioning to reduce preamble sequences through MIMO*



Zero-Energy IoT: Ambient Backscatter Communications (AmBC)

Keyword : Symbiotic radio(SR), ambient RF signal, impedance mismatching

- **Technical Concept**



<AmBC Technique> <MIMO AmBC Technique>

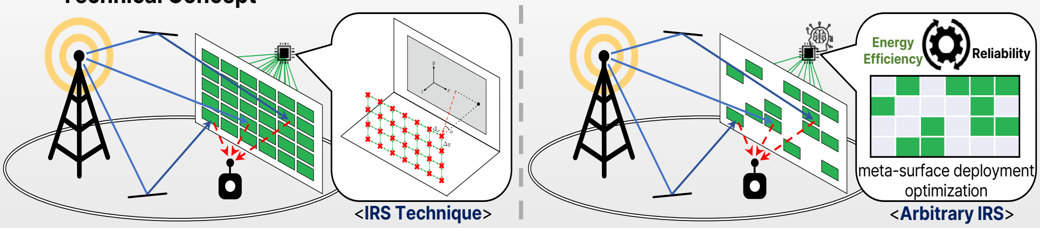
  - Exploiting **ambient RF signals** (symbiotic radio, SR) **existing in the air** to transmit information without active RF transmission
  - Modulating and reflecting the ambient RF signal via **Impedance mismatching**
- **Technical Trends**
  - The **power consumption of AmBC (microwatts) is 1,000 times less than conventional wireless technologies**, such as Wi-Fi (tens of milliwatts), Bluetooth/Bluetooth Low Energy (several milliwatts), and LTE (hundreds of milliwatts)[1].
  - **Battery-free communication** is possible by utilizing ambient RF signals as the energy source for energy harvesting[2].
  - Since there is **no power infrastructure** and **a carrier emitter**, AmBC provides **ultra-low-power** communication[3].
- **Challenging Issues :** Direct path interference, unknown and fast changes of the amplitude and phase of the ambient signal backscatter propagation, co-existence with the legacy receiver ➔ ***MIMO AmBC Technique***

[1] C. Xu, L. Yang, and P. Zhang, "Practical Backscatter Communication Systems for Battery-Free Internet of Things: A Tutorial and Survey of Recent Research," *IEEE Signal Process. Mag.*, vol. 35, no. 5, pp. 16-27, Sept. 2018.
[2] T. Huang *et al.*, "A Survey on Green 6G Network: Architecture and Technologies," *IEEE Access*, vol. 7, pp. 175758-175768, Dec. 2019.
[3] R. Duan *et al.*, "Ambient Backscatter Communications for Future Ultra-Low-Power Machine Type Communications: Challenges, Solutions, Opportunities, and Future Research Trends," *IEEE Commun. Mag.*, vol. 58, no. 2, pp. 42-47, Feb. 2020.
[4] N. H. Mahmood *et al.*, "White paper on critical and massive machine type communication towards 6G," *6G Flagship White Paper*, 6G Research Visions, no. 11, Jun. 2020.

Zero-Energy IoT: Intelligent Reflecting Surface (IRS)

Keyword : Reconfigurable Intelligent Surface (RIS), passive beamforming, reflected array, meta-surfaces

- **Technical Concept**



<IRS Technique> <Arbitrary IRS>

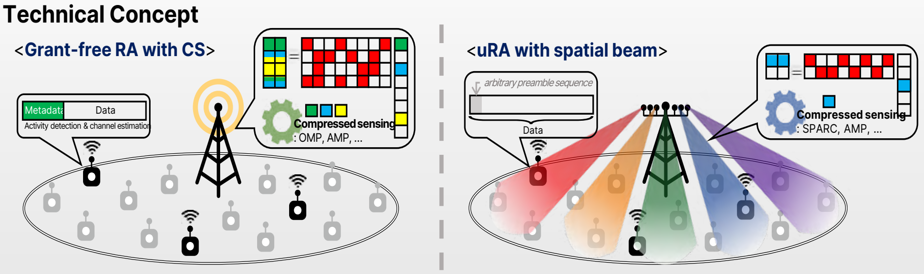
  - To control the reflection characteristics of walls to establish favorable signal propagation environments through meta-surface
  - Comprising a large number of reflecting units generates a favorable propagation environment via beamforming and is controlled by a microcontroller.
- **Technical Trends**
  - A recent emerging hardware technology with increased potential for **significant energy consumption reductions**[1].
  - Since no amplifier is used, **IRS will consume much less energy** than amplify-and-forward relay transceiver[1].
  - The IRS can operate with **low-energy consumption** by eliminating the use of the transmit RF chains[2].
  - The large IRS does **not require power-hungry RF chains** because the IRS entails lower cost and complexity[3].
- **Challenging Issues :** Passive beamforming optimization, IRS channel acquisition, IRS deployment, outdoor scenarios ➔ ***Arbitrary IRS***

[1] C. Huang *et al.*, "Reconfigurable Intelligent Surfaces for Energy Efficiency in Wireless Communication," *IEEE Trans. Wireless Commun.*, vol. 18, no. 8, pp. 4157-4170, Aug. 2019.
[2] Q. Wu, and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106-112, Jan. 2020.
[3] X. Chen *et al.*, "Massive Access for 5G and Beyond," *IEEE J. Sel. Areas Commun.*, Sept. 2020. (Early Access Article)
[4] S. Hu, F. Rusek and O. Edfors, "Beyond Massive MIMO: The Potential of Data Transmission With Large Intelligent Surfaces," *IEEE Trans. Signal Process.*, vol. 66, no. 10, pp. 2746-2758, Mar. 2018.

Zero-Energy IoT: Compressed Sensing (CS) for Massive Connectivity

Keyword : Sparse signal processing, orthogonal matching persuit, approximate message passing, unsourced random access

- **Technical Concept**

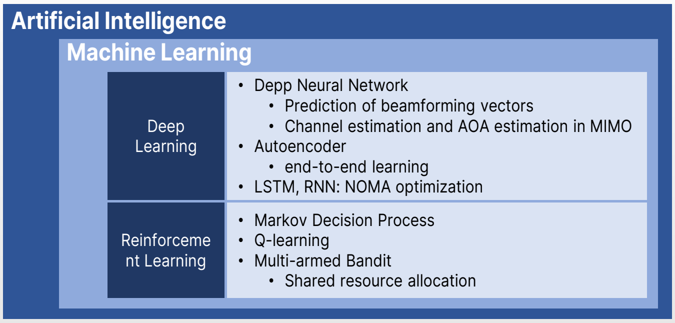


  - A typical IoT network only a small (unknown) subset of devices are active at each time slot. (The sporadic traffic pattern may be because devices are often in sleep mode to **conserve energy**[1])
  i. Active devices first send their ***unique preambles*** to the BS and then transmit the data signals **directly**.
  ii. The BS first **detects the active devices** by detecting which pilot sequences are used based on **compressed sensing (CS)**, next, the BS **estimates their channels** based on the received metadata.
- **Technical Trends**
  - In the interest of **improving energy consumption**, the conceptual paradigm shift is to move to the **grant-free access**[2].
  - Grant-free random access **reduces** the signaling overhead at the expense of **high computational complexity** at the BS[3].
- **Challenging Issues :** Efficient codebook (set of preamble sequences) design, activity detection algorithm

➔ ***Cell partitioning via spatial beam***

[1] L. Liu *et al.*, "Sparse Signal Processing for Grant-Free Massive Connectivity: A Future Paradigm for Random Access Protocols in the Internet of Things," *IEEE Signal Process. Mag.*, vol. 35, no. 5, pp. 88-99, Sept. 2018.
[2] S. S. Kowshik, K. Andreev, A. Frolov, and Y. Polyanskiy, "Energy Efficient Coded Random Access for the Wireless Uplink," *IEEE Trans. Commun.*, vol. 68, no. 8, pp. 4694-4708, Aug. 2020.
[3] X. Chen, et al., "Massive Access for 5G and Beyond," *IEEE J. Sel. Areas Commun.*, Sept. 2020. (Early Access Article)

AI-based PHY technology



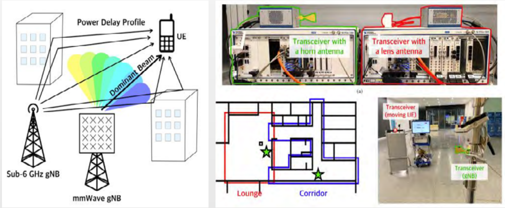
- Recently, the concept of AI such as machine learning has been widely studied for wireless communications
  - **Artificial Intelligence**: Any technique which resembles human behavior such as vision
  - **Machine Learning**: Using statistical methods to enable machines to improve with experiences
  - **Reinforcement Learning:** Take actions in an environment in order to maximize the notion of cumulative reward
  - **Deep Learning**: Make the computation of multi-layer neural networks
- Deep learning can be used for solving classification problem and non-linear optimization
  - Find optimal solution from pre-defined candidate set
  - Examine the correlation as function of multi block model

  ➔ AI-based 6G technology can be utilize for optimize non-linear PHY technology
- To apply AI to 6G, machine learning needs **"experience"** as pre-collected data and **"reward"** as metric
  - Real-time communication system data such as ray-tracing
  - Communication system friendly metrics such as channel gain and processing time

AI-based PHY technology

Beam Selection Problem: In millimeter waves, beamforming technology is essential because it shows relatively high propagation loss, and one must select one of several beams stored in the base station, which is called the beam selection problem. Instead of doing a full search of beams in all directions, the goal is to **reduce the complexity of the search with AI**. Studies are trying to solve this problem through AI, especially the deep learning-based method.

[2]



- As shown below, research is active on whether the performance is feasible when learning a deep neural network when which data is used.
- In [1], authors assumes a vehicle communication (V2X) environment and solves whether the channel is LOS and beam selection through location data and LIDAR data. However, since this is effective when communication is already in progress, it is not suitable for the initial beam selection problem.
- In [2], mmWave beam selection was solved using the Power Delay Profile (PDP) of the sub-6GHz channel, and its performance was verified through the implementation of an actual prototype. A solution to the initial beam selection problem was presented, but additional requirements for measurement of the PDP were presented.
- In the beam selection problem, deep learning is mainly used because it is a classification learning problem. However, since compensation for selecting the wrong beam is another problem, it is expected that a technique for post-processing the selected beam through reinforcement learning is expected.

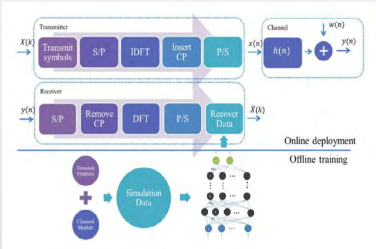
[1] A. Klautau, N. Gonzalez-Prelcic, and R. W. Heath Jr,"LIDAR data for deep learning-based mmWave beam-selection," IEEE Wireless Commun. Lett., vol. 8, no. 3, pp. 909–912, Jun. 2019.
[2] M. S. Sim, Y. Lim, S. H. Park, L. Dai and C. -B. Chae, "Deep Learning-Based mmWave Beam Selection for 5G NR/6G With Sub-6 GHz Channel Information: Algorithms and Prototype Validation," IEEE Access, vol. 8, pp. 51634-51646, 2020.

AI-based PHY technology

MIMO Optimization: In a MIMO environment where there are relatively many optimization factors, research is also being conducted on sending and receiving a large amount of information with low transmission/reception power.

Trend of MIMO Optimization Research: The encoder and decoder responsible for compressing and decoding information are viewed as one DNN and learned simultaneously. There are many combinations with Compressive Sensing.

[2]



- In [1], combined with compressive sensing, compressing CSI is implemented through deep learning. However, a metric such as mean-squared error used to evaluate image compression performance is used, so examine communication metric is required.
- [2] introduces the results of using deep learning for channel estimation and symbol detection in the MIMO-OFDM system. However, there is a limitation in that the channel data used for learning is artificially generated.

[1] C. Wen, W. Shih, and S. Jin, "Deep Learning for Massive MIMO CSI Feedback," IEEE Wireless Commun. Lett., vol. 7, no. 5, Oct. 2018, pp. 748–51.
[2] H. Ye, G. Y. Li and B. Juang, "Power of Deep Learning for Channel Estimation and Signal Detection in OFDM Systems," IEEE Wireless Commun. Lett., vol. 7, no. 1, pp. 114-117, Feb. 2018

AI-based PHY technology

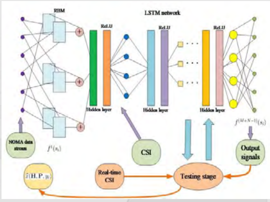
Multiple Access: Deep learning is sometimes applied to NOMA, which has relatively good spectral efficiency. Since **high computational complexity is required to implement NOMA**, transmission power distribution in the NOMA environment is solved through deep learning.

When deep learning is applied to NOMA, the learning method of DNN is the main issue. According to NOMA's characteristics, a DNN that is universally applicable to various channel models is required. There are NOMA studies that apply deep learning in various channel models.

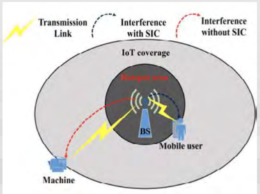
- In [1], a deep learning-based NOMA using long short term memory (LSTM) was proposed, and its performance was verified through a block-error-rate. However, since LSTM focuses only on time series data, there is a limitation that it requires data measured for a long time in advance.
- In [2], NOMA assuming incomplete successive interference cancelation (SIC) was optimized through deep learning. Here, too, consideration in the initial situation is needed to utilize a recurrent neural network that uses time-series data.

Since the entire NOMA transmission process is learned with one black box, it is necessary to obtain a decoding block or a transmission power distribution block as an individual model for actual implementation.

[1]



[2]



[1] G. Gui, H. Huang, Y. Song and H. Sari, "Deep Learning for an Effective Nonorthogonal Multiple Access Scheme," IEEE Trans. Vehicular Tech, vol. 67, no. 9, pp. 8440-8450, Sept. 2018
[2] M. Liu, T. Song and G. Gui, "Deep Cognitive Perspective: Resource Allocation for NOMA-Based Heterogeneous IoT With Imperfect SIC," in IEEE Internet of Things Journal, vol. 6, no. 2, pp. 2885-2894, April 2019

Acronym

3D	3-Dimensional
6DOF	6 degrees of Freedom
ADC	Analog-to-Digital Converter
AF	Amplifying-and-Forward
AI	Artificial Intelligence
AmBC	Ambient Backscatter Communication
BBU	Baseband Unit
BSs	Base Stations
BWP	Bandwidth Part
CAN	Controller Area Network
CAVs	Connected/Autonomous Vehicles
CPS	Cyber Physical Systems
C-RAN	Cloud Radio Access Network
CS	Compressed Sensing
CSI	Channel State Information
D2D	Device-to-Device
DetNet	Deterministic Networking
DF	Decode-and-Forward
DL	Deep Learning
DNN	Deep Neural Network
DPI	Deep Packet Inspection
E2E	End-to-End
EE	Energy-Efficient
EM	Electromagnetic
eMBB	enhanced Mobile Broadband
FPGA	Field Programmable Gate Array
FSO	Free Space Optics
FSS	Fixed Satellite Service
Gbps	Giga-bits per second
GEO	Geostationary Orbit
GHz	Gigahertz
gNB	Next Generation Node-b

HAP	High Altitude Platform
HTS	High Throughput Satellites
IAB	Integrated Access and Backhaul
IAX	Integrated Access and Everything
IDS	Intrusion Detection System
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IRS	Intelligent Reflecting Surface
ISL	Inter Satellite Links
IVN	In Vehicle Network
L2	Layer 2
LAN	Local Area Network
LDPC	Low Density Parity Check
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
LoS-MIMO	Light of Sight-Multiple-input Multiple-output
LSTM	Long Short Term Memory
M2M	Machine to Machine
Mbps	Mega-bits per second
MIMO	Multiple-Input Multiple-Output
MIMO-OFDM	Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing
ML	Machine Learning
mMTC	massive Machine-Type Communications
MPLS	Multi-Protocol Label Switching
MU-MIMO	Multi User-Multiple Input Multiple Output
NFV	Network Function Virtualization
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NTN	Non-Terrestrial Network
OAM	Orbital Angular Momentum
OBP	On Board Processing
OoE	Overall operations Effectiveness
PDP	Power Delay Profile
PGN	Performance Guaranteed Networking
PHY	Physical Layer
PSK	Phase Shift Keying
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network

RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RL	Reinforcement Learning
RRC	Radio Resource Control
RTT	Round-Trip Time
SAGIN	Space-Air-Ground Integrated Network
SAS	Spectrum Access System
SDN	Software Defined Networking
SIC	Successive Interference Cancelation
NIC	Network Interface Card
SMM	Spatial Mode Multiplexing
SR	Symbiotic Radio
SSTIS	Self-organization Satellite Terrestrial Integrated System
SWaP	Size, Weight, and Power
Tbps	Tera-bits per second
TCP	Transmission Control Protocol
TSN	Time-Sensitive Networking
UAV	Unmanned Aerial Vehicle
UD-IAX	Ultra-Dense Integrated Access and Everything
UDN	Ultra-Dense Network
UDP	User Datagram Protocol
UEs	User Equipments
UM-MIMO	Ultra-Massive Multiple-Input Multiple-Output
URLLC	Ultra-Reliable Low-Latency Communication
V2X	Vehicle to Everything
VHTS	Very High Throughput Satellites
VM	Virtual Machine
XR	Extended Reality

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