

Wireless Systems and Applications: Evolution, Technologies, and Road Ahead

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**National
and Kapodistrian
University of Athens**

Established in 1827

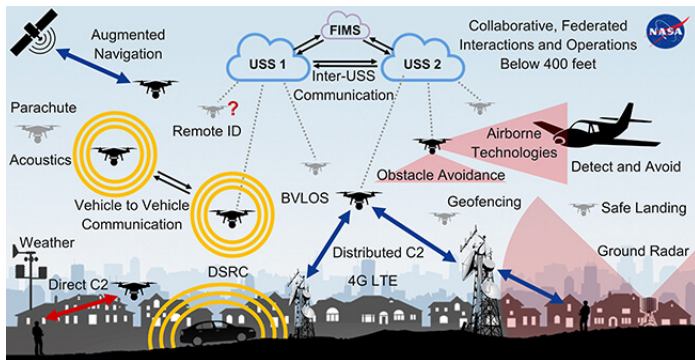


**Department of
Informatics and Telecommunications**

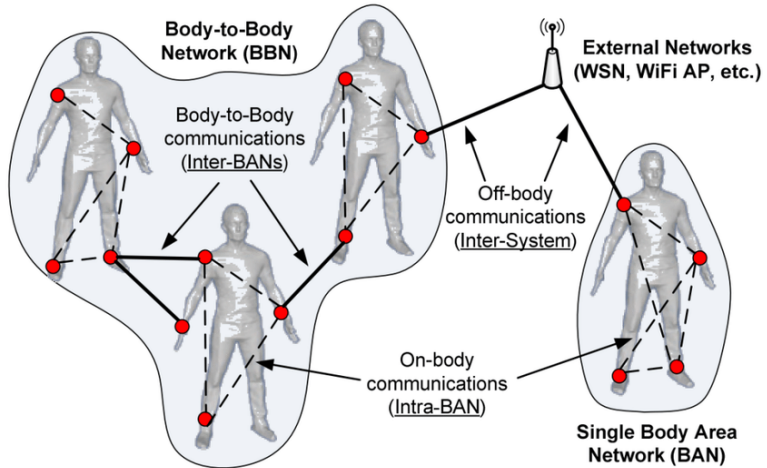
Some of Today's Wireless Applications

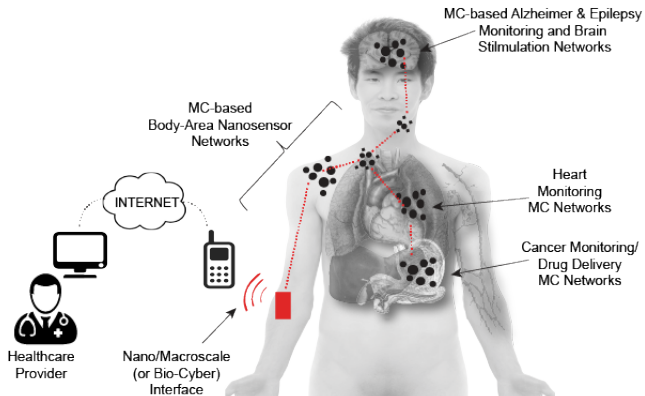


Air/Ground/Space Wireless Communications



Body-Area Wireless Networks





Smart Devices and IoT



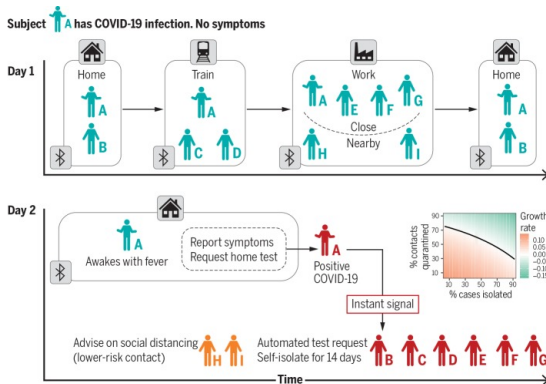


- e.g., ferrofluid, aerogel, metal foam, nanotube, amorphous alloy.

Wireless Communications Responded to COVID-19



A Location-Based COVID-19 Contact Tracing App



- Advises isolation of individual A after SARS-CoV-2 positive test and quarantine of its contacts; runs using Bluetooth.

Ferretti *et al.*, "Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing," *Science*, May 2020.

Autonomous Vehicles



Aurora SDK for non-AV's

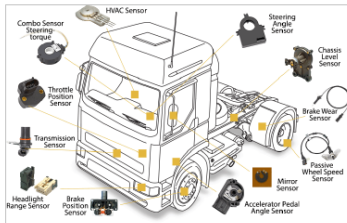


AV Shuttle

On-Board Units

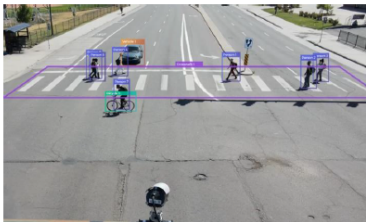


Wireless OBU Equipment

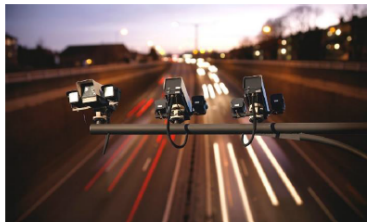


Multiple onboard sensors

AI Surveillance



AI being overlayed on a "dumb" camera image



AI can work with existing CCTV providing sufficient clarity

Drone Delivery



Amazon's render was a PR action, but is now being considered



Potential for Vaccines and vital organ delivery

What's next?

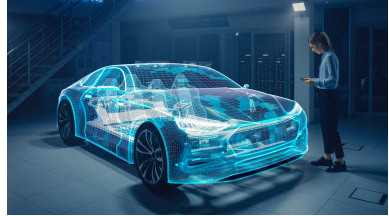
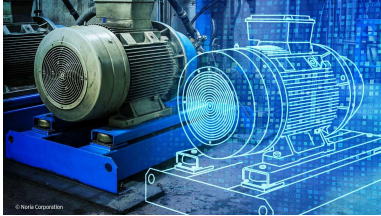
Metaverse over Wireless Networks

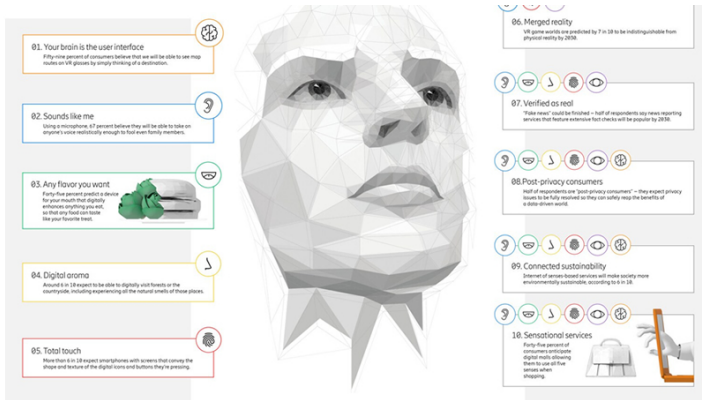


Holographic Teleportation



Digital Twins





How did everything happen?

Maxwell, Hertz, and Lodge

- In **1865**'s publication "A Dynamical Theory of the Electromagnetic Field," **James Clerk Maxwell** demonstrated that electric and magnetic fields travel through space as waves moving at the speed of light; derives an electromagnetic wave equation with a velocity for light in close agreement with measurements made by experiment, and deduces that light is an electromagnetic wave.
- In **1888**, **Heinrich Hertz** demonstrated that one could produce and detect electromagnetic radiation, based on the work of James Clerk Maxwell.
- In **1894**, **Oliver Joseph Lodge** identified electromagnetic radiation independent of Hertz's proof and demonstrated an early radio wave detector. A relevant patent was awarded in **1898** by the US Patent Office.

UNITED STATES PATENT OFFICE.

OLIVER JOSEPH LODGE, OF LIVERPOOL, ENGLAND.

ELECTRIC TELEGRAPHY.

SPECIFICATION forming part of Letters Patent No. 609,154, dated August 16, 1898.

Application filed February 1, 1898. Serial No. 668,752. (No model.)

To all whom it may concern:

Be it known that I, OLIVER JOSEPH LODGE, a subject of the Queen of Great Britain, residing at Liverpool, in the county of Lancaster, England, have invented certain new and useful improvements in Electric Telegraphy, of which the following is a specification.

The object of my invention is to enable an operator, by means of what is now known as
10 "Hertzian-wave telegraphy," to transmit messages across space to any one or more of a number of different individuals in various localities, each of whom is provided with a suitably-arranged receiver, and to effect the
15 ancillary improvements the nature of which are hereinafter more particularly described and claimed.

The method of intercommunication consists, according to my invention, in utilizing
20 certain processes and apparatus for the purpose of producing and detecting a sufficiently-prolonged series of rapid electric oscillations

is utilized for receiving purposes. Fig. 5 depicts the more prominent features of a long-distance arrangement, both sending and receiving. Figs. 12 and 13 illustrate alternative forms of connection of apparatus in a syntonie receiving-circuit with appendages, and Fig. 11 is a detail view hereinafter more particularly referred to.

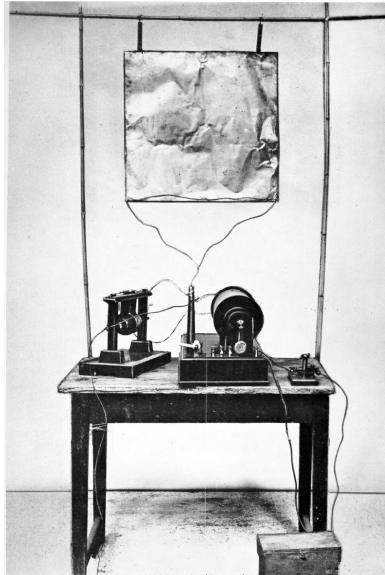
Like letters and figures of reference indicate
60 similar parts throughout the drawings.

A complete installation of Hertzian-wave telegraphy consists, in its simplest form, of the arrangement depicted in Fig. 1, wherein A represents the emitting apparatus, and B the
65 receiving apparatus.

In the emitter illustrated in Fig. 1 electricity from a suitable source, such as a Ruhmkorff coil *a*, is supplied to a pair of conductors which discharge into each other from
70 knobs *b* and *c* and thus excite oscillations, which emit one or two waves before they are damped out.

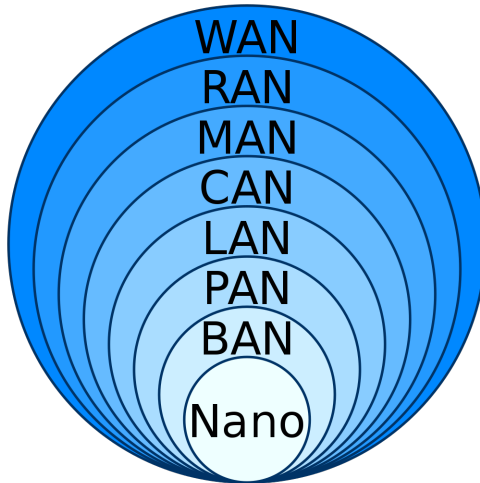
- In **1894**, **Guglielmo Giovanni Maria Marconi** demonstrated a radio transmitter and receiver to his mother, a set-up that made a bell ring on the other side of the room by pushing a telegraphic button on a bench.
- In **1895**, his system became capable of transmitting signals up to 3.2 km and over hills. He concluded that a device could become capable of spanning greater distances, with additional funding and research, and would prove valuable both commercially and militarily.
- Marconi is being credited as the inventor of radio and shared the **1909** Nobel Prize in Physics with Karl Ferdinand Braun *in recognition of their contributions to the development of wireless telegraphy.*

Marconi's 1894 First Radio Transmitter



How did things evolve?

Computer Network Types by Scale



Some Wireless Standards

- **Wireless wide area network (WWAN):** EDGE, Flash-OFDM, GPRS, Lorawan, LTE, RTT, UMTS over W-CDMA, UMTS-TDD, Narrowband IoT, NR.
- **Wireless local area network (WLAN):** IEEE 802.11a, 802.11b, 802.11g, 802.11n, 802.11ac, 802.11ax standards (Wi-Fi).
- **Wireless personal area network (WPAN) and most wireless sensor actor networks (WSAN):** 6LoWPAN, ANT, UWB, Bluetooth, ZigBee, and Wireless USB.
- The technologies for **cellular networks** (WWANs) are often split into generations, 1G till 5G (now).

Some of the IEEE 802.11 Standards

Name of the Standard	Went Live	Bands	Max Network Bandwidth	Remarks
802.11be (WiFi 7) Extremely High Throughput (EHT)	Currently in works	2.4 GHz, 5 GHz, and new 6 GHz band	30 Gbps (Theoretically)	- Based on draft 802.11be standard drafted in 2021. - The WiFi 7 standard is backward compatible with 2.4 GHz and 5 GHz devices. - The 6 GHz band yields drastically less interference as compared to the 2.4 and 5 GHz bands.
802.11ax (WiFi 6) High-Efficiency Wireless (HEW)	2019		10 Gbps	- Will replace 802.11ac as a de-facto wireless standard. - Uses less power more reliable in congested environments. - Supports better security.
802.11ac (WiFi 5)	2014	5 GHz band	1300 Mbps (5 GHz Band) 450 Mbps (2.4 GHz Band)	- Uses dual-band wireless technology, supporting simultaneous connections on both 2.4 GHz and 5 GHz WiFi devices. - Most wireless routers are compliant with this standard. - Most expensive to implement.
802.11n (WiFi 4)	2009	2.4 GHz, and 5 GHz bands	600 Mbps	- Uses MIMO technology. - Supports a better range over WiFi standards due to its increased signal intensity. - Significant bandwidth improvement over earlier standards. - More expensive to implement over 802.11g (WiFi 3)
802.11g (WiFi 3)	2002-2003	2.4 GHz bands	Up to 54 Mbps	- Uses the 2.4 GHz range. - Combines best of 802.11a and 802.11b. 802.11g access points work with 802.11b wireless network adaptors and vice versa. - Least expensive. - Supported by all wireless devices.
802.11a (WiFi 2)	1999	5 GHz band	upto 54 Mbps (5 GHz Band)	802.11a and 802.11b use different frequencies and hence are incompatible.
802.11b (WiFi 1)	July 1999	2.4 GHz band	2 Mbps (TCP) 3 Mbps (UDP)	- Unregulated. - An issue with interference from microwave ovens and other appliances using the 2.4 GHz range.

Predicted Features for Wi-Fi 7

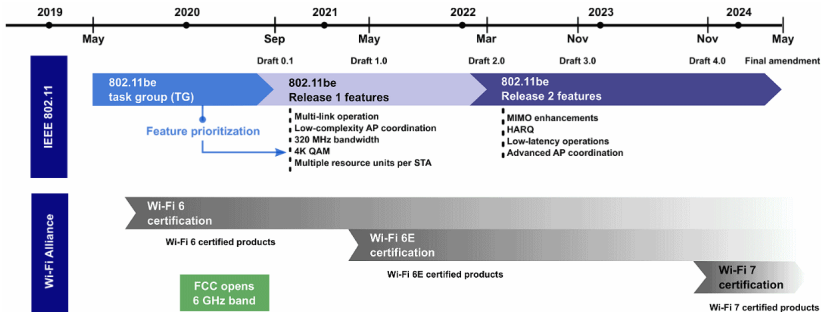


Fig. 1: Illustration of the current Wi-Fi 7 standardisation, certification, and commercialisation timelines.

WLAN Sensing - IEEE 802.11bf



R. Du, H. Hua, H. Xie, X. Song, Z. Lyu, M. Hu, *et al.*, "An overview on IEEE 802.11bf: WLAN sensing," *IEEE CST*, early access, 2024.

The Evolution of Gs (1/2)

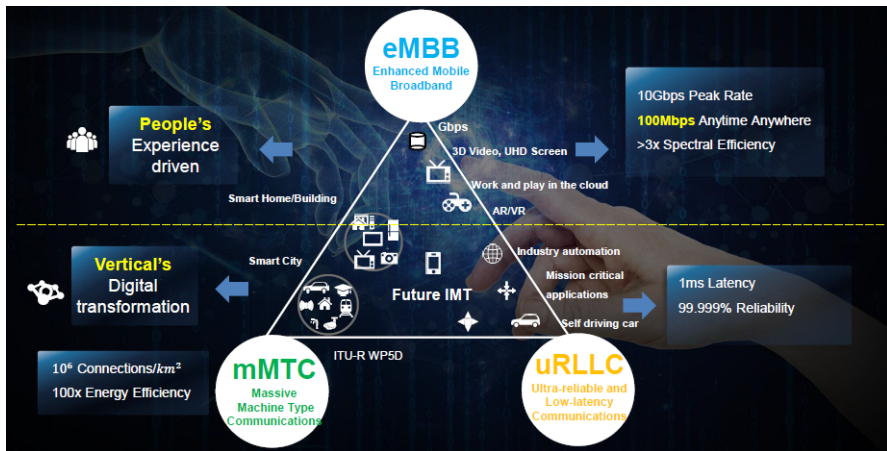


The Evolution of Gs (2/2)

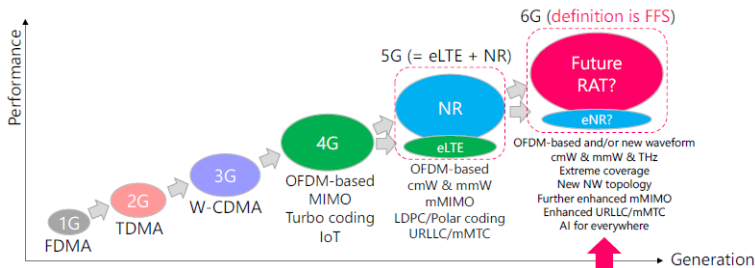
Generations	1G	2G	2.5G	2.75G	3G	3.5G	4G	5G
Technology	Analog Voice	GSM	GPRS	EDGE	CDMA 2000	HSPA	Wi-Fi	IPv6 LAN/WAN/PAN
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	TDMA, CDMA	CDMA	CDMA	CDMA, OFDM	CDMA, BDMA
Switching	Circuit	Circuit, Packet	Packet	Packet	Packet	Packet	Packet	Packet
Band type	Narrow	Narrow	Narrow	Narrow	Broadband	Wideband	Ultra wide	Ultra wide
Handoff	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal, vertical	Horizontal, vertical
Main network	PSTN	PSTN	GSM, TDMA	WCDMA	Packet	GSM, TDMA	Internet	Internet
Carrier frequency	30 kHz	200 kHz	200 kHz	200 kHz	5 MHz	5 MHz	15 MHz	15 MHz
Bandwidth	150 kHz	5–20 MHz	5–20 MHz	5–20 MHz	25 MHz	25 MHz	100 MHz	1–2 GHz
Data rate	2.4–14.4 kb/s	14.4–64 kb/s	64–200 kb/s	470 kb/s	3.1–14.7 Mb/s	14.4–63 Mb/s	100 Mb/s–1 Gb/s	1 Gb/s and above
Features	Voice only	Data, voice	Data, voice	Data, voice	Data, voice	HD data, voice	Ultra HD, VOIP	Ultra HD, VOIP

- 1G (1970/1984)
- 2G (1980/1999)
- 3G (1990/2002)
- 4G (2000/2010)
- 5G (2010/2015)

The 5G Use Cases



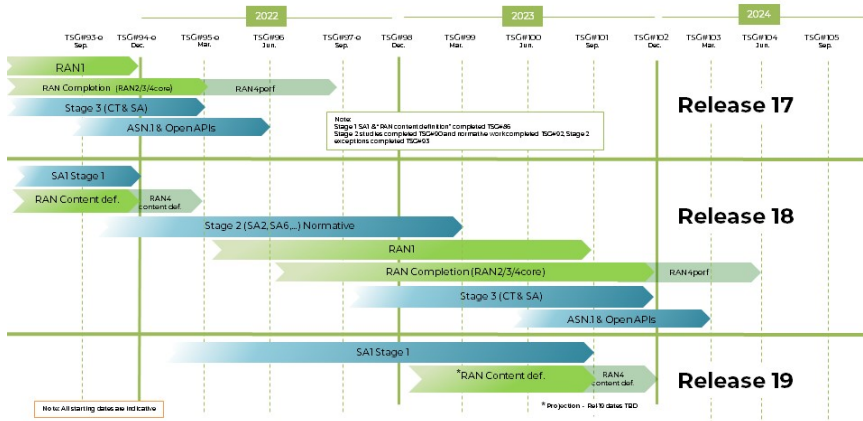
Each G's Key Technologies



- More massive MIMO, densification, and higher frequencies.
- Learn, predict, and adapt via intelligent algorithms.
- Need for cost- and power-efficient transceiver hardware.

3GPP Release Timelines

Ongoing Release timelines (March 2022)



- R18 (5G-Advanced) frozen in June 2024; R19 is now the focus.

3GPP Release 17 Features



Multi-cast and Broadcast services

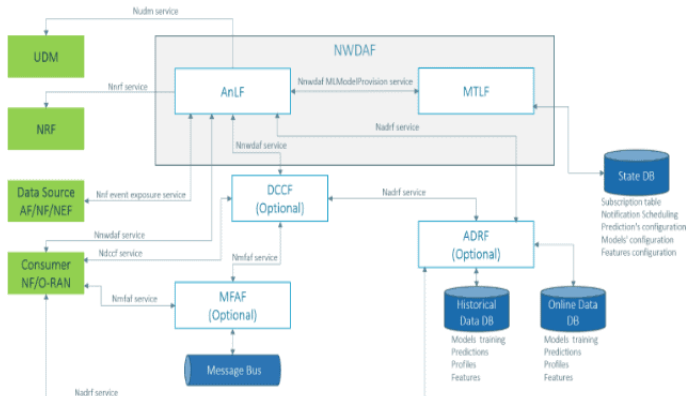


Non-terrestrial networks



Non-public networks

Network Data Analytics Function Enhancements



- Collects data from user equipment, network functions, OAM systems, etc. from the 5G core, cloud, and edge networks.

Content of 3GPP Release 18



Release 18



TSG SA priorities*

SA2 led - System Architecture and Services

- XR (Extended Reality) & media services
- Edge Computing Phase 2
- System Support for AI/ML-based Services
- Enablers for Network Automation for 5G Phase 3
- Enh. support of Non-Public Networks Phase 2
- Network Slicing Phase 3
- 5G Co-Location Services Phase 3
- 5G multicast-broadcast services Phase 2
- Satellite access Phase 2
- 5G System with Satellite Backhaul
- 5G Timing Resiliency and TSC & URLLC enh.
- Evolution of IMS multimedia telephony service
- Personal IoT Networks
- Vehicle Mounted Relays

SA3 led - Security and Privacy

- Privacy of identifiers over radio access
- SECAM and SCAS for 3GPP virtualized network products and Management Function (MnF)
- Mission critical security enhancements Phase 3
- Security and privacy aspects of RAN & SA features

SA4 led - Multimedia Codecs, Systems and Services

Systems & Media Architecture:

- 5G Media, Service Enablers
- Split-Rendering
- 5G AR Experiences Architecture

Media:

- Video codec for 5G
- Media Capabilities for Augmented Reality Glasses
- AI/ML Study

Real-Time Communications:

- XR conversational services
- WebRTC-based services and collaboration models

Immersive Voice & Audio:

- EVS Codec Extension
- For Immersive Voice and Audio Services (IVAS_Codec)
- Terminal Audio quality performance and Test methods for Immersive Audio Services (ATIAS)

Streaming & Broadcast services:

- 5GMS Enh. (Network Slicing, Low latency, Background traffic, 5GMS Uplink)
- Further MBS Enh. (Free to air, Hybrid unicast/broadcast)

*these are preliminary lists (As of SA#94-e)

- Access Traffic Steering, Switching & Splitting support in the 5G system architecture Phase 3
- Proximity-based Services in 5GS Phase 2
- UPF enh. for Exposure & SBA
- Ranging based services & sidelink positioning
- Generic group management, exposure & communication enh.
- 5G UE Policy Phase 2
- UAS, UAV & UAM Phase 2
- 5G AM Policy Phase 2
- RedCap Phase 2
- Support for 5WWC Phase 2
- System Enabler for Service Function Chaining
- Extensions to TSC Framework to support DetNet
- Seamless UE context recovery
- MPS when access to EPC/5GC is WLAN

SA5 led - Management, Orchestration and Charging

Operations, Administration, Maintenance and Provisioning (OAM&P):

- Intelligence and Automation: Self-Configuration of RAN NEs, Enh. autonomous network levels, Evaluation of autonomous network levels, Enh. intent driven management services for mobile networks, AI/ML management, Enh. of the management aspects related to NWDAF

- Management Architecture and Mechanisms: Network slicing provisioning rules, Enh. service based management architecture
- Support of New Services: Enh. Energy Efficiency for 5G Phase 2, New aspects of Energy Efficiency for 5G networks Phase 2, Enh. management of Non-Public Networks, Network and Service Operations for Energy Utilities, Key Quality Indicators (KQIs) for 5G service experience, Deterministic Communication Service Assurance

Charging:

- Charging Aspects for Enh. Support of Non-Public Networks

SA6 led - Application Enablement & Critical Communication Applications

Critical Communications:

- MCX Enhancements – MC over 5GS (5MBS, ProSe) Ad-hoc group comm., MCPTT Enh.
- Railways - Gateway UE, Interworking Service Frameworks
- Edge App Architecture Enh., SEAL Enh., Subscriber-Aware API (CAPI Enh.)
- Fused location, Application Data Analytics, App Layer NW Slicing
- Enablers for Vertical applications
- Enhancements to V2X, UAS application-enablement
- Future Factories, Personal IoT networks, Capability exposure for IoT platforms

See the 3GPP Work Plan for full details, as Release 18 develops:
www.3gpp.org/specifications/work-plan

TSG RAN priorities*

RAN1 led - Radio Layer 1 (Physical layer)

- NR-MIMO Evolution
- AI/ML - Air Interface
- Evolution of duplex operation
- NR Sidelink Evolution
- Positioning Evolution
- RedCap Evolution
- Network energy savings
- Further UL coverage enhancement
- Smart Repeater
- DSS
- Low power WUS
- CA enhancements

RAN2 led - Radio layer 2 & layer 3 Radio Resource Control

- Mobility Enhancements
- Enhancements for XR
- Sidelink Relay Enhancements
- NTN (Non-Terrestrial Networks) evolution - NR
- NTN (Non-Terrestrial Networks) evolution - IoT
- UAV (Uncrewed Aerial Vehicle)
- Multiple SIM (MUSIM) Enhancements
- In-Device Co-existence (IDC) Enhancements
- Small data
- MBS

RAN3 led - UTRAN/E-UTRAN/NG-RAN architecture & related network interfaces

- Additional topological improvements – IAB/VMR
- AI/ML for NG-RAN WI
- AI/ML for NG-RAN SI
- SON/MDT Enhancements
- QoE Enhancements
- Resiliency of gNB-CU-CP

RAN4 led - Radio Performance and Protocol Aspects

- RAN4-led spectrum items
- <5MHz in dedicated spectrum

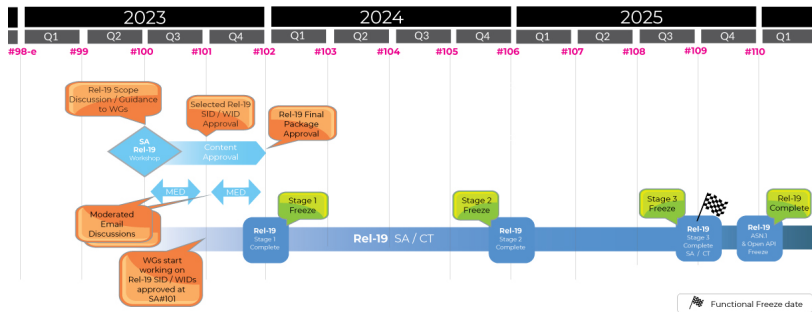
Rel-18 Workplan for TSG CT

CT will work on Stage 3 completion and ASN.1 code and OpenAPI freeze of Rel-17 until June 2022 [TSG#94].
Work Item discussion on Rel-18 Stage 2 / Stage 3 (under CT) from June 2022.

*Source: RP-213697 (RAN#94-e)

© 3GPP, Dec. 2021

Timeplan of 3GPP Release 19



3GPP Release 19 Technical Priorities

TSG SA major Rel-19 topics



Core topics:

- 1 Satellite Architecture Enh.
- 2 NRM Enh. and Metaverse
- 3 AI/ML Enh.
- 4 Multi-access (Dual 3GPP + ATSSS Enh.)
- 5 Integrated Sensing and Communication
- 6 Ambient IoT
- 7 Energy Efficiency/Energy Saving as a Service
- 8 IMS and NG-RAN Enh.
- 9 Edge Computing Enh.
- 10 Proximity Services Enh.
- 11 TSC/ABLLC/TTS Enh.
- 12 Network Sharing
- 13 User Identities + Id of device behind RG/WiP
- 14 5G Femto
- 15 UAS Enh.
- 16 VMI Enh.
- 17 UPEAS Enh.

Misc. topics:

- 1 SBA framework Enh. / 5GS Enh. for Cloud Native Deployment
- 2 Network Slicing
- 3 5G SA Roaming services and Intermediaries (GSMA SMRR request)
- 4 Traffic Management (Monitoring + + QUIC)
- 5 Enh. in handling of Radio Capabilities
- 6 5GC Enh. for IP routing
- 7 Enh. Emergency Services when Zero CS network coverage
- 8 NPN Enh.
- 9 Ranging Phase 2
- 10 LCS Enh.
- 11 Mobile VPN
- 12 Architecture Enh. for Energy Utilities
- 13 eUEPO (UE Policy) Enh.
- 14 Interworking of Non-3GPP Digital Terrestrial Broadcast Networks with 5GS Multicast Broadcast Services
- 15 RYAS (Roaming Value-Added Services)

Core denotes topics for which 5GPs were agreed at SA/NR meeting

Misc denotes topics that will be discussed for inclusion during Q423

The remaining topics will not be part of Rel-19 work

TSG RAN major Rel-19 topics



- AI/ML Air Interface
- MIMO Ev.
- Duplex Ev.
- Ambient IoT
- Network Energy Saving Enh.
- Mobility Enh.
- NTN Ev.
- XR Ev.
- AI/ML for NG-RAN
- SON / MDT
- Channel modelling & possibly additional aspects (SAC, etc) for further Ev.

Additional RAN1 led candidate topics

- LP-WUS/WUR
- Multi-carrier Enh.
- Coverage Enh.
- Positioning Enh.
- SL Ev.

Additional RAN2 led candidate topics

- NCR
- SL Relay Enh.
- UAM / UAM
- MU-SIM
- Broadcast / multicast
- UE aggregation, collaboration and backup

Additional RAN3 led candidate topics

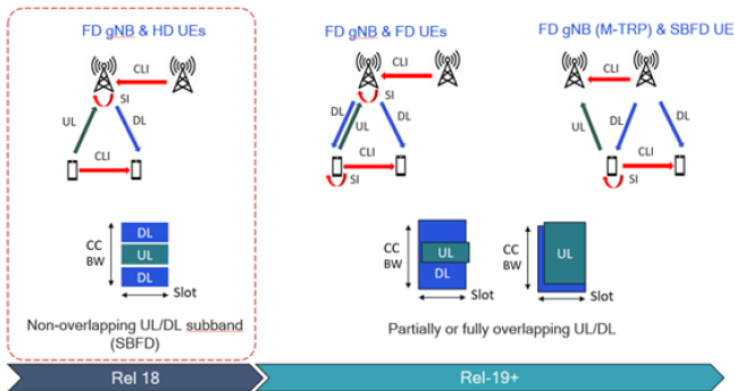
- Topological Enh.
- IAB/WiFi/Femto
- Public safety, emergency services, etc
- QoE

Additional / Other candidate topics

- Lean protocol stack / High speed packetization / Layer 2 UP Enh.
- RAN architectural Enh. / AS Security Enh.
- Network / Outer coding
- RedCap Enh. / High reliability and low complexity IoT
 - Combination w/ SL or NTN to be discussed in the SL / NTN topics respectively
- TaaS (Timing as a service) / High Accuracy Timing Service
- SDT Enh.
- LTE Enh.
- Dynamic UE capability update
- Others (idle/inactive Enh., RAN slicing Enh., etc.)

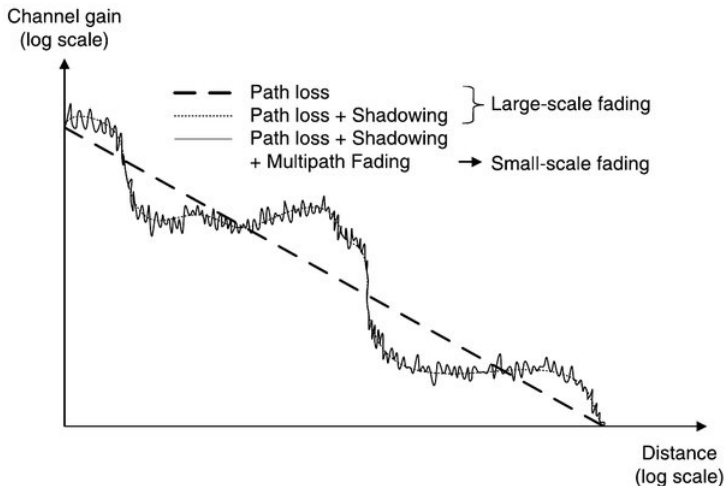


The Evolution of Full Duplex Technologies

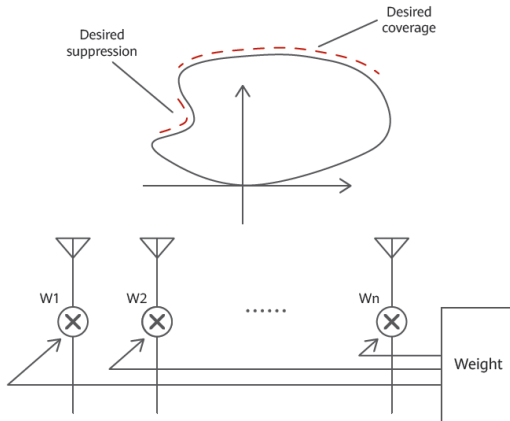


How do wireless systems work?

Fading in Wireless Communications

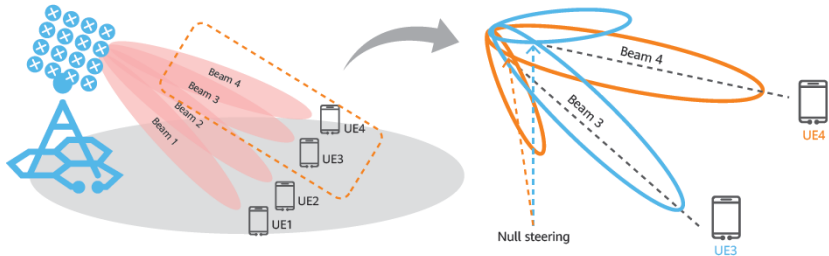


Multi-Antenna Transceivers and Beamforming



- MIMO systems comprise of multi-antenna TXs and RXs.
- What about H/W cost and power consumption?

Multi-User Beamforming and Massive MIMO



- Spatial multiplexing of multiple users in the same time and frequency.

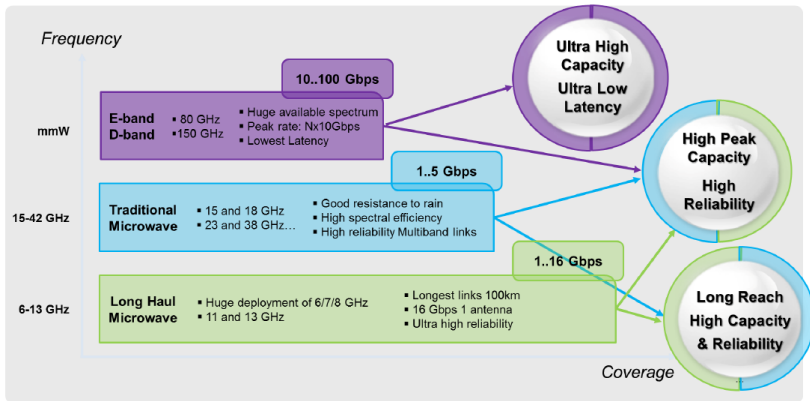
The Rate Formula

- The rate per user in bps is given by:

$$\mathcal{R} = \frac{\text{BW} \times \text{SM gain}}{K} \times \text{SE}$$

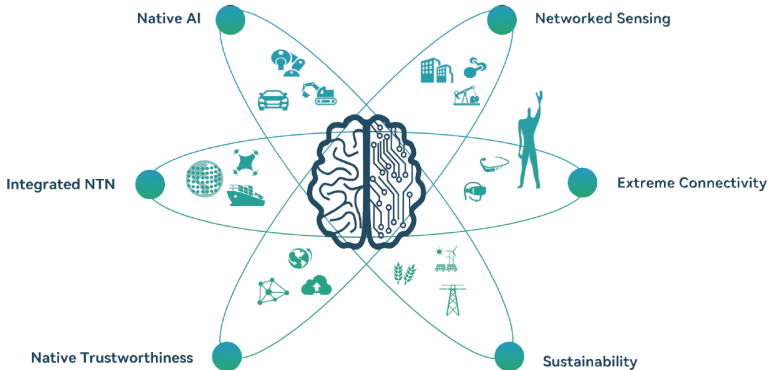
- BW is the bandwidth (*more can provide higher rates*)
- SM gain with MIMO, depends on the number of antennas
- K is the number of users in the system
- SE depends on: S&N&I powers and SP techniques; upper bound given by Shannon's formula

Higher Frequencies for Higher Throughput

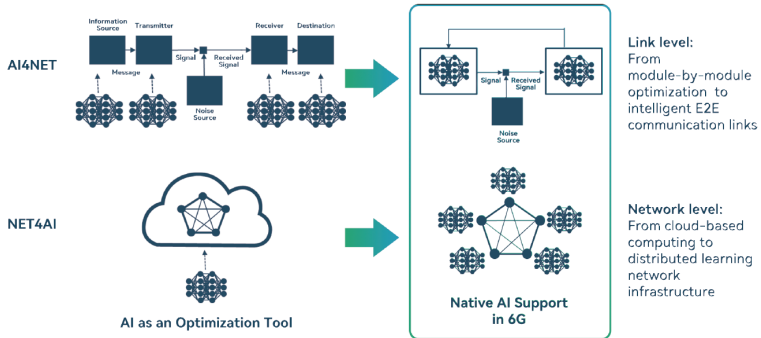


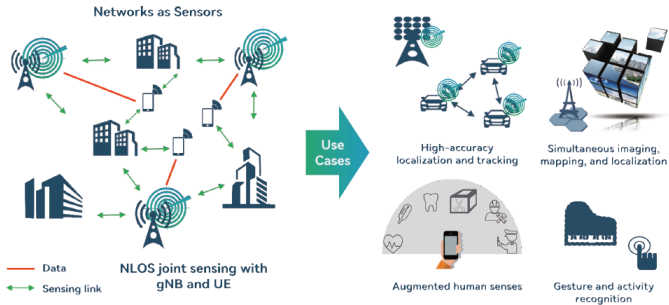
What are the targets for 6G?

6G Key Capabilities

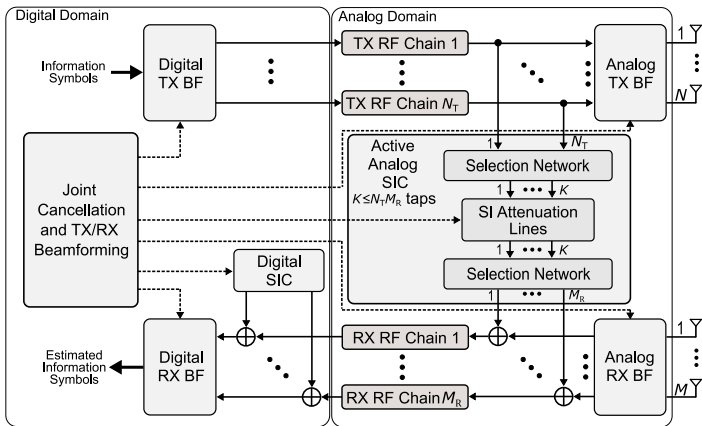


AI/ML for Wireless Networks





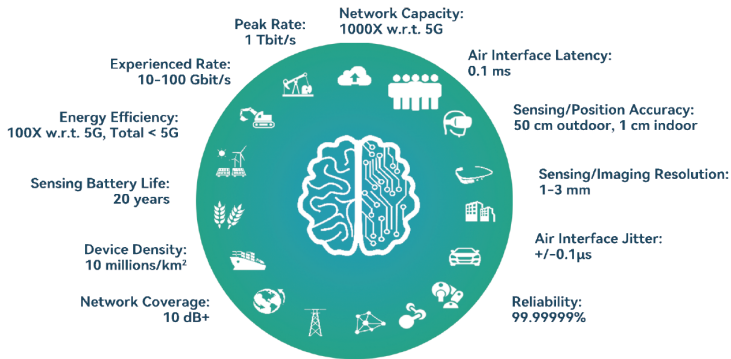
Full-Duplex-Enabled ISAC

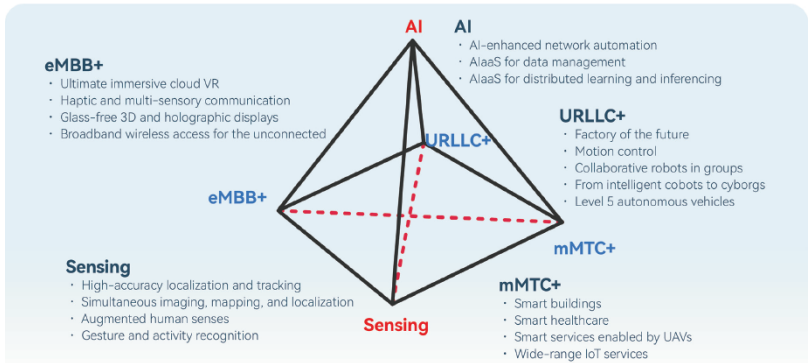


B. Smida, A. Sabharwal, G. Fodor, G. C. Alexandropoulos, H. A. Suraweera, and C.-B. Chae, "Full-duplex wireless for 6G: Progress brings new opportunities and challenges," *IEEE JSAC*, 2023.

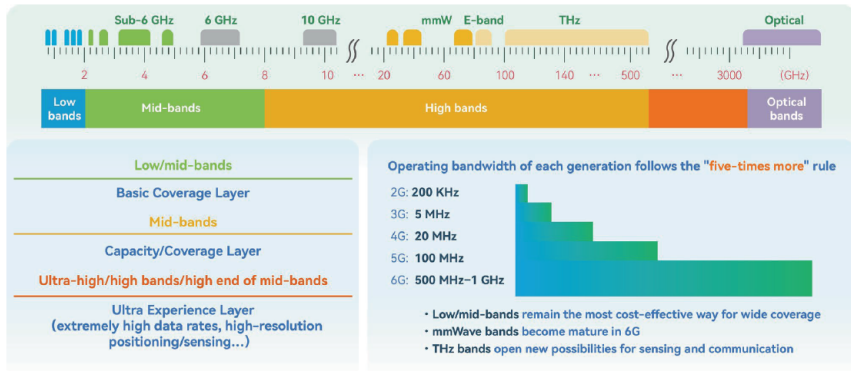
M. A. Islam, G. C. Alexandropoulos, and B. Smida, "Direction-assisted beam management in full duplex millimeter wave massive MIMO systems," *IEEE ICC*, 2021. **(Best Paper Award)**

6G RAN Key Performance Indicators





Spectrum for 6G

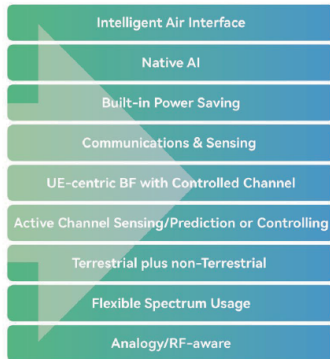


Paradigm Shift

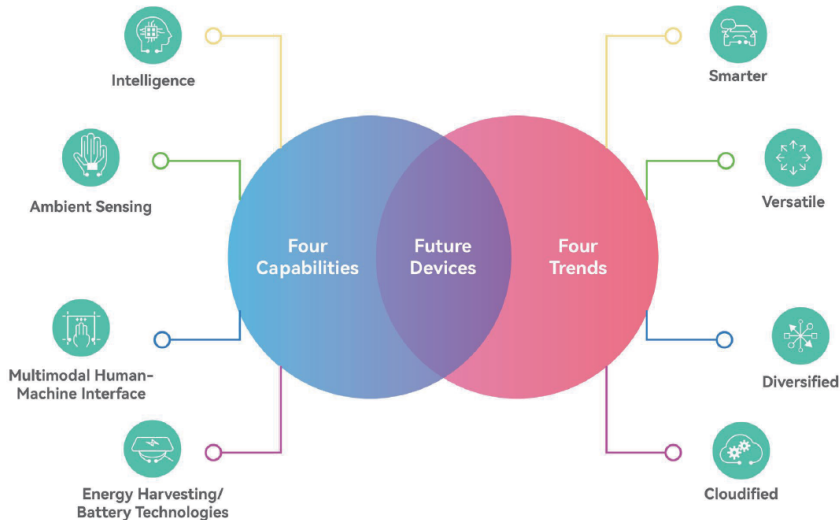
5G



6G

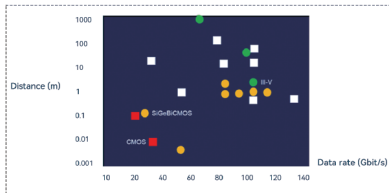


Capabilities and Trends for Future Devices



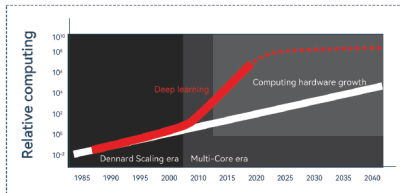
Challenges in H/W Components and Computing

(a) Low Efficiency for mmWave RF Amplifier



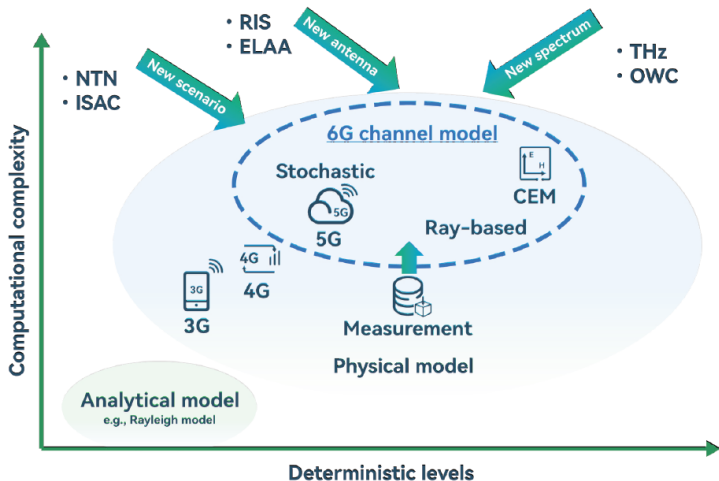
Single digit efficiency of power amplifier to overcome additional 20dB propagation path loss

(b) Deep Learning Computing Requirement

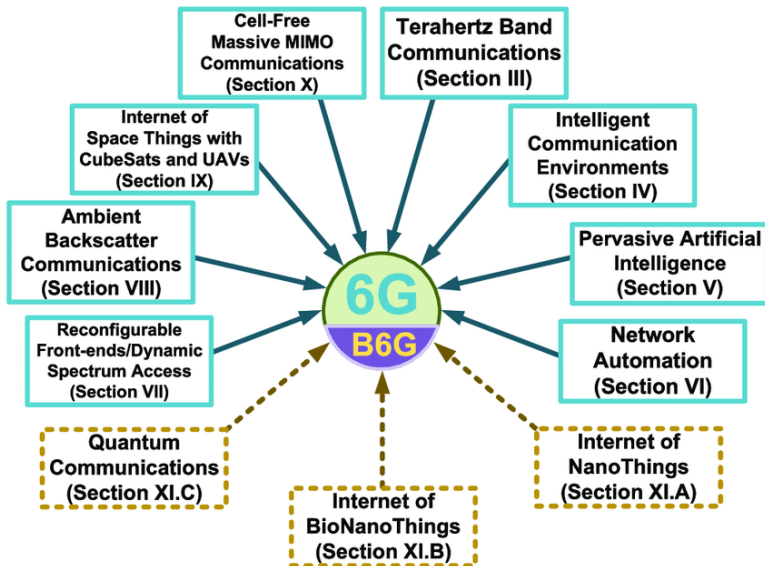


Computing demand double every 2-3 months
Open source software have difficulty to sustain

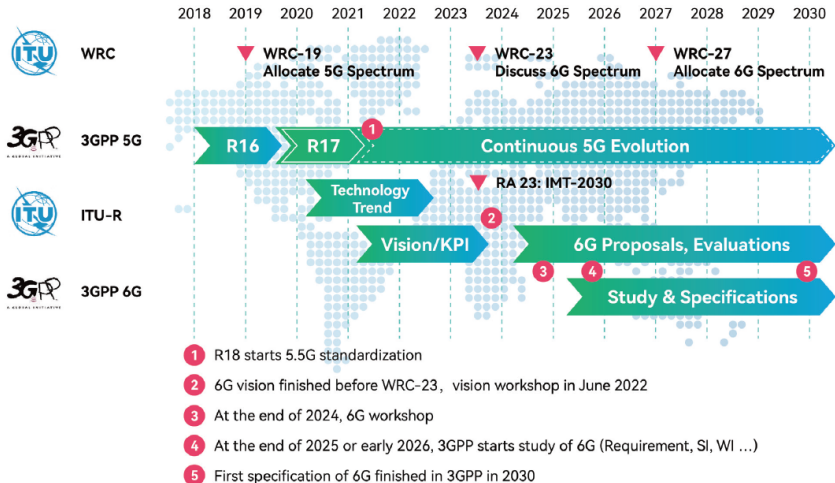
Challenges in Channel Modeling



6G and Beyond Key Technologies

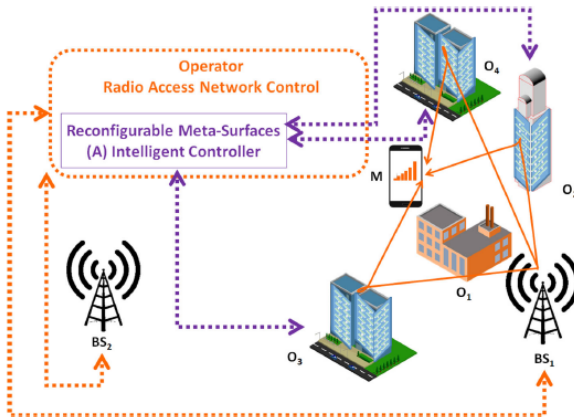


6G Timeline



A Promising 6G Technology: Reconfigurable Intelligent Surfaces

Programmable Over-The-Air Signal Propagation



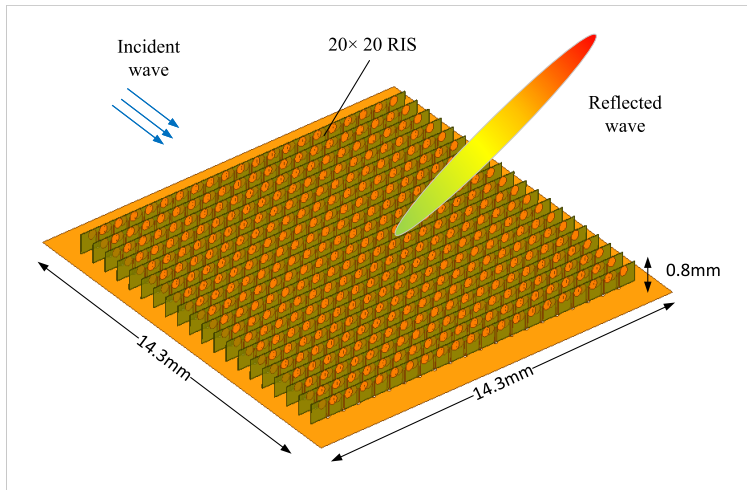
M. Di Renzo, M. Debbah, D.-T. Phan-Huy, A. Zappone, M.-S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos *et al.*, "Smart radio environments empowered by AI reconfigurable meta-surfaces: An idea whose time has come," *EURASIP JWCN*, May 2019. (**EURASIP Best Paper Award 2021**)

C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, "Reconfigurable intelligent surfaces for energy efficiency in wireless communication," *IEEE TWC*, 2019. (**IEEE Marconi Award 2021**)

Available Fabricated RISs

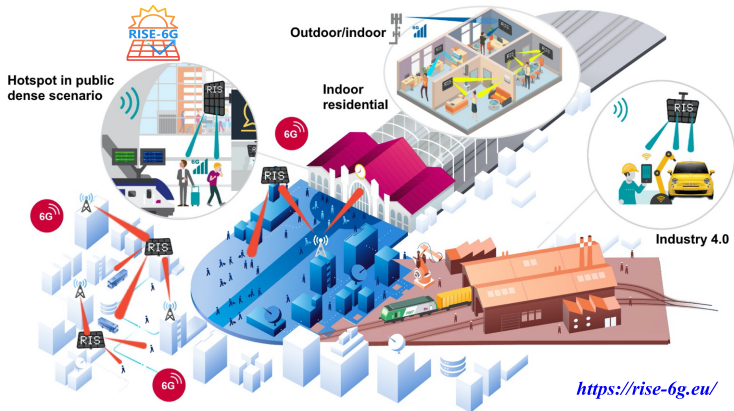


A Simulated 20×20 RIS @50 – 150GHz



Q. Luo, G. C. Alexandropoulos, Y. Zhou, and X. Ma, "Ultra-wideband metasurface at SubTHz: Hardware design and reflection optimization," *EuCAP*, 2022.

Wireless Environment as a Service

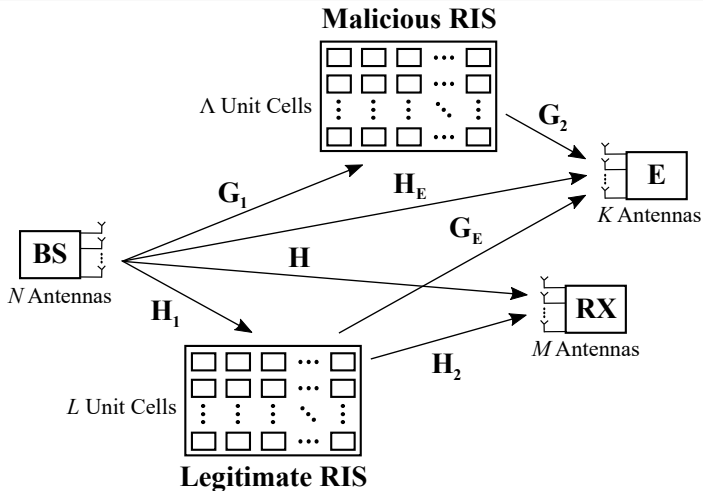


E. Calvanese Strinati, G. C. Alexandropoulos *et al.*, "Wireless environment as a service enabled by reconfigurable intelligent surfaces: The RISE-6G perspective," *Joint EuCNC & 6G Summit*, 2021.

E. Calvanese Strinati, G. C. Alexandropoulos *et al.*, "Reconfigurable, intelligent, and sustainable wireless environments for 6G smart connectivity," *IEEE COMMAG*, 2021.

G. C. Alexandropoulos *et al.*, "Smart wireless environments enabled by RISs: Deployment scenarios and two key challenges," *Joint EuCNC & 6G Summit*, 2022.

RISs for Secrecy and Eavesdropping



G. C. Alexandropoulos, K. Katsanos, M. Wen, and D. B. da Costa, "Safeguarding MIMO communications with reconfigurable metasurfaces and artificial noise," *IEEE ICC*, 2021.

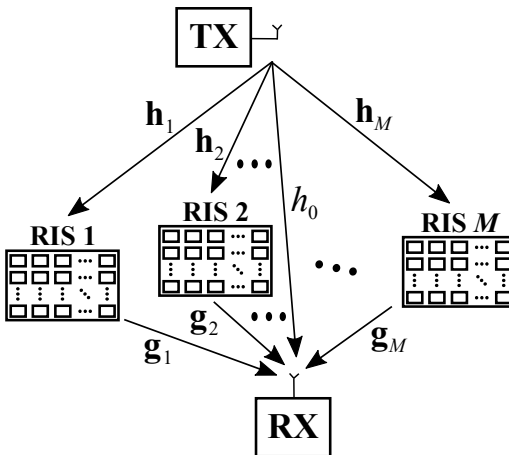
G. C. Alexandropoulos, K. Katsanos, M. Wen, and D. B. da Costa, "Counteracting eavesdropper attacks through reconfigurable intelligent surfaces: A new threat model and secrecy rate optimization," *IEEE OJCOM*, 20223.

The legitimate BS formulates and solves the following problem:

$$\begin{aligned} \mathcal{OP}_L : \quad & \max_{N_d, \mathbf{U}, \mathbf{V}, \mathbf{Z} \succeq \mathbf{0}, \phi} \quad \hat{\mathcal{R}}_s \triangleq \mathcal{R}_{RX} - \hat{\mathcal{R}}_E \\ \text{s.t.} \quad & \text{Tr}(\mathbf{V}^H \mathbf{V}) + \text{Tr}(\mathbf{Z}) \leq P, \\ & \|\mathbf{U}\|_F^2 \leq 1, \quad 1 \leq N_d \leq \min\{M, N\}, \\ & |\phi_\ell| = 1 \quad \forall \ell = 1, 2, \dots, L \end{aligned}$$

$$\begin{aligned} \mathcal{R}_{RX} &\triangleq \log_2 \left| \mathbf{I}_{N_d} + \mathbf{U}^H \tilde{\mathbf{H}} \mathbf{V} \mathbf{V}^H \tilde{\mathbf{H}}^H \mathbf{U} \left(\mathbf{U}^H \left(\sigma^2 \mathbf{I}_M + \tilde{\mathbf{H}} \mathbf{Z} \tilde{\mathbf{H}}^H \right) \mathbf{U} \right)^{-1} \right| \\ \hat{\mathcal{R}}_E &\triangleq \log_2 \left| \mathbf{I}_K + \mathbf{H}_E \mathbf{V} \mathbf{V}^H \mathbf{H}_E^H \left(\sigma^2 \mathbf{I}_K + \mathbf{H}_E \mathbf{Z} \mathbf{H}_E^H \right)^{-1} \right| \end{aligned}$$

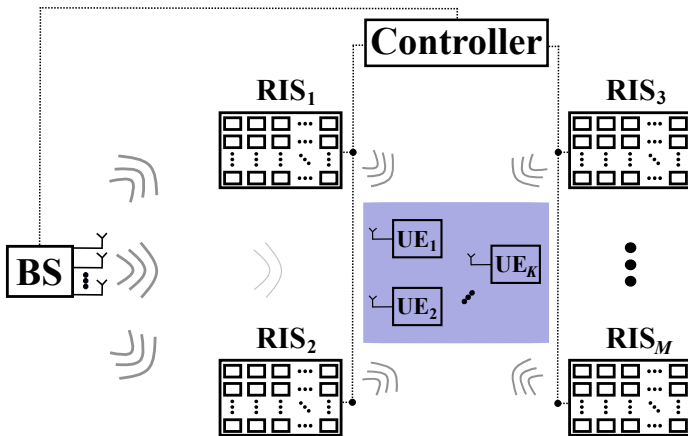
RIS Configuration via Supervised Learning



C. Huang, G. C. Alexandropoulos, C. Yuen, and M. Debbah, "Indoor signal focusing with deep learning designed reconfigurable intelligent surfaces," *IEEE SPAWC*, 2019.

G. C. Alexandropoulos, S. Samarakoon, M. Bennis, and M. Debbah, "Phase configuration learning in wireless networks with multiple reconfigurable intelligent surfaces," *IEEE GLOBECOM*, 2020.

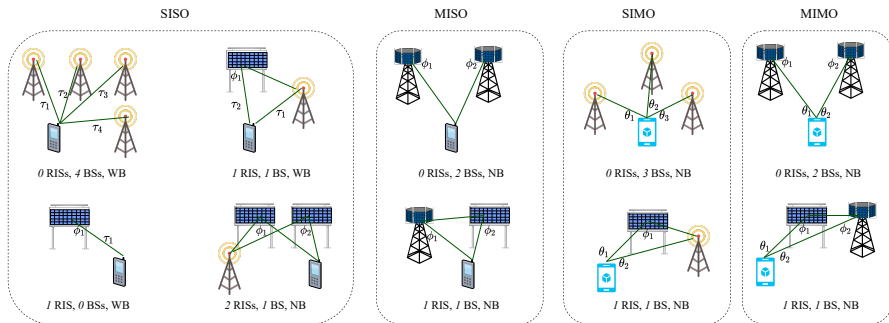
DRL-Based Orchestration



G. C. Alexandropoulos, K. Stylianopoulos, C. Huang, C. Yuen, M. Bennis, and M. Debbah, "Pervasive machine learning for smart radio environments enabled by reconfigurable intelligent surfaces," *Proc. IEEE*, 2022.

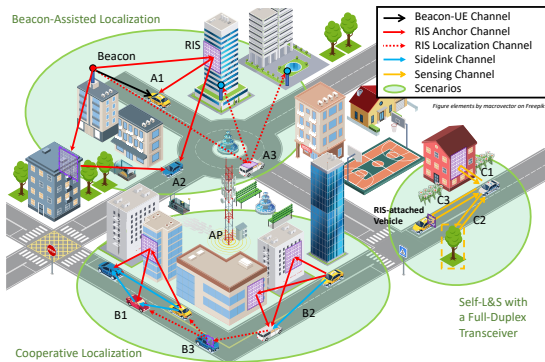
C. Huang, Z. Yang, G. C. Alexandropoulos, K. Xiong, L. Wei, C. Yuen, Z. Zhang, and M. Debbah, "Multi-hop RIS-empowered terahertz communications: A DRL-based hybrid beamforming design," *IEEE JSAC*, 2021. (IEEE Communications Society Leonard G. Abraham Prize 2024)

Enabling 3D Localization with Passive RISs



K. Keykhosravi, B. Denis, G. C. Alexandropoulos, Z. S. He, A. Albanese, V. Sciancalepore, and H. Wymeersch, "Leveraging RIS-enabled smart signal propagation for solving infeasible localization problems," *IEEE VTM*, 2023.

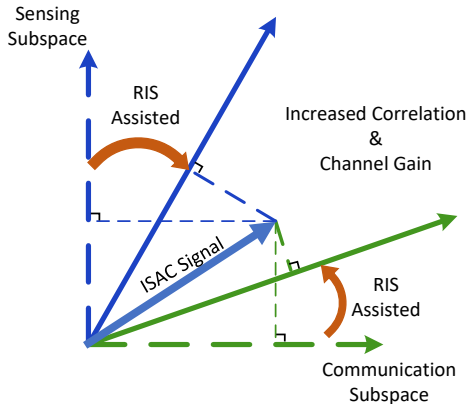
RISs for Seamless Localization and Sensing



H. Chen, H. Kim, M. Ammous, G. Seco-Granados, G. C. Alexandropoulos, S. Valaee, and H. Wymeersch, "RISs and sidelink communications in smart cities: The key to seamless localization and sensing," *IEEE COMMAG*, 2023.

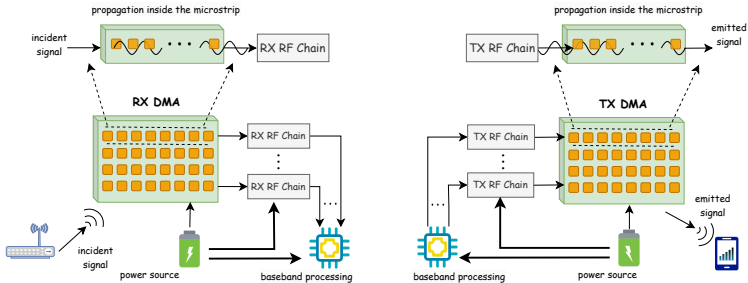
C. Huang, S. Hu, G. C. Alexandropoulos, A. Zappone, C. Yuen, R. Zhang, M. Di Renzo, and M. Debbah, "Holographic MIMO surfaces for 6G wireless networks: Opportunities, challenges, and trends," *IEEE WCOM*, 2022. (IEEE Communications Society Fred W. Ellersick Prize 2023)

The RIS Potential for ISAC



S. Prabhakar Chepuri, N. Shlezinger, F. Liu, G. C. Alexandropoulos, S. Buzzi, and Y. C. Eldar, "Integrated sensing and communications with reconfigurable intelligent surfaces," *IEEE SPMAG*, 2023.

Multi-Functional RISs



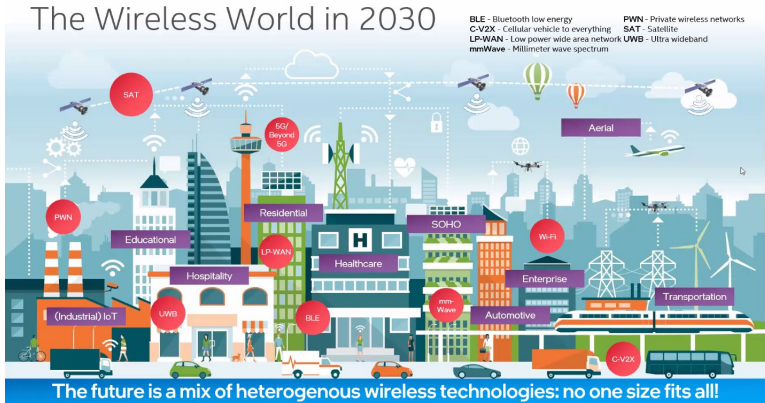
G. C. Alexandropoulos, N. Shlezinger, I. Alamzadeh, M. F. Imani, H. Zhang, and Y. C. Eldar, "Hybrid reconfigurable intelligent metasurfaces: Enabling simultaneous tunable reflections and sensing for 6G wireless communications," *IEEE VTM*, 2023.

E. Basar, G. C. Alexandropoulos, Y. Liu, Q. Wu, S. Jin, C. Yuen, O. Dobre, and R. Schober, "Reconfigurable intelligent surfaces for 6G: Emerging applications and open challenges," *IEEE VTM*, 2024.

N. Shlezinger, G. C. Alexandropoulos, M. F. Imani, Y. C. Eldar, and D. R. Smith, "Dynamic metasurface antennas for 6G extreme massive MIMO communications," *IEEE WCOM*, 2021. (**IEEE Communications Society Fred W. Ellersick Prize 2024**)

Should I invest in wireless communications expertise?

The Wireless World in 2030



- **Some key vendors:** Ericsson, Nokia, Huawei, Samsung, Qualcomm, Intel, Cisco, NEC, Capgemini, Ciena, D-link, ZTE, Fujitsu, NXP, Mavenir
- **Top 10 mobile operators:** AT&T, Orange, Vodafone, MTN, América Móvil, China Mobile, Telefonica, Deutsche Telekom, Airtel, Verizon
- **Various new players:** Apple, Google, Continental, etc.

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