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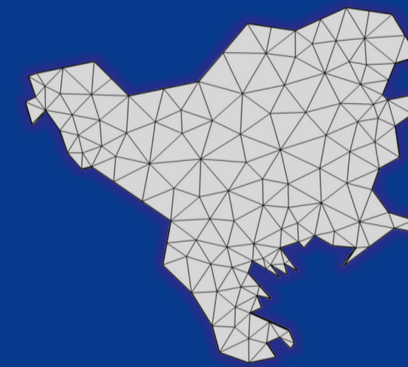

The Potential of Non-Terrestrial Networks for 6G: Technologies and Challenges

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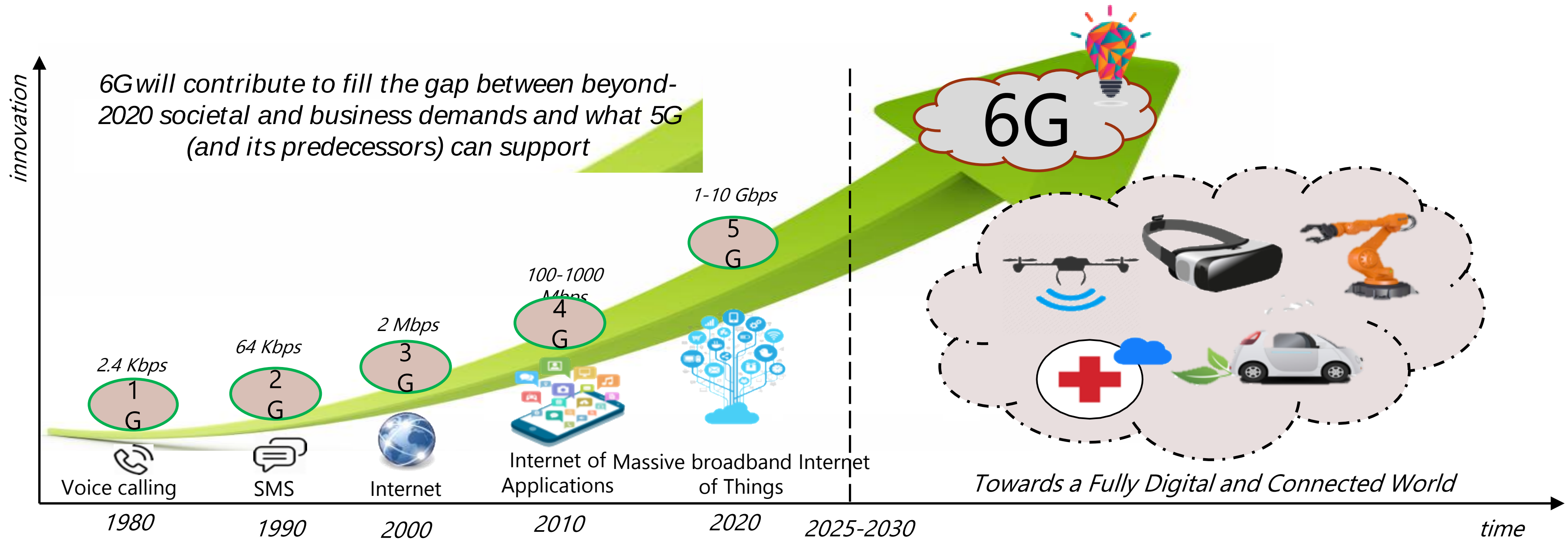
(Joint work with Marco Giordani, Alessandro Traspadini, Matteo Pagin and many others)

Università degli Studi di Padova

SIGNET

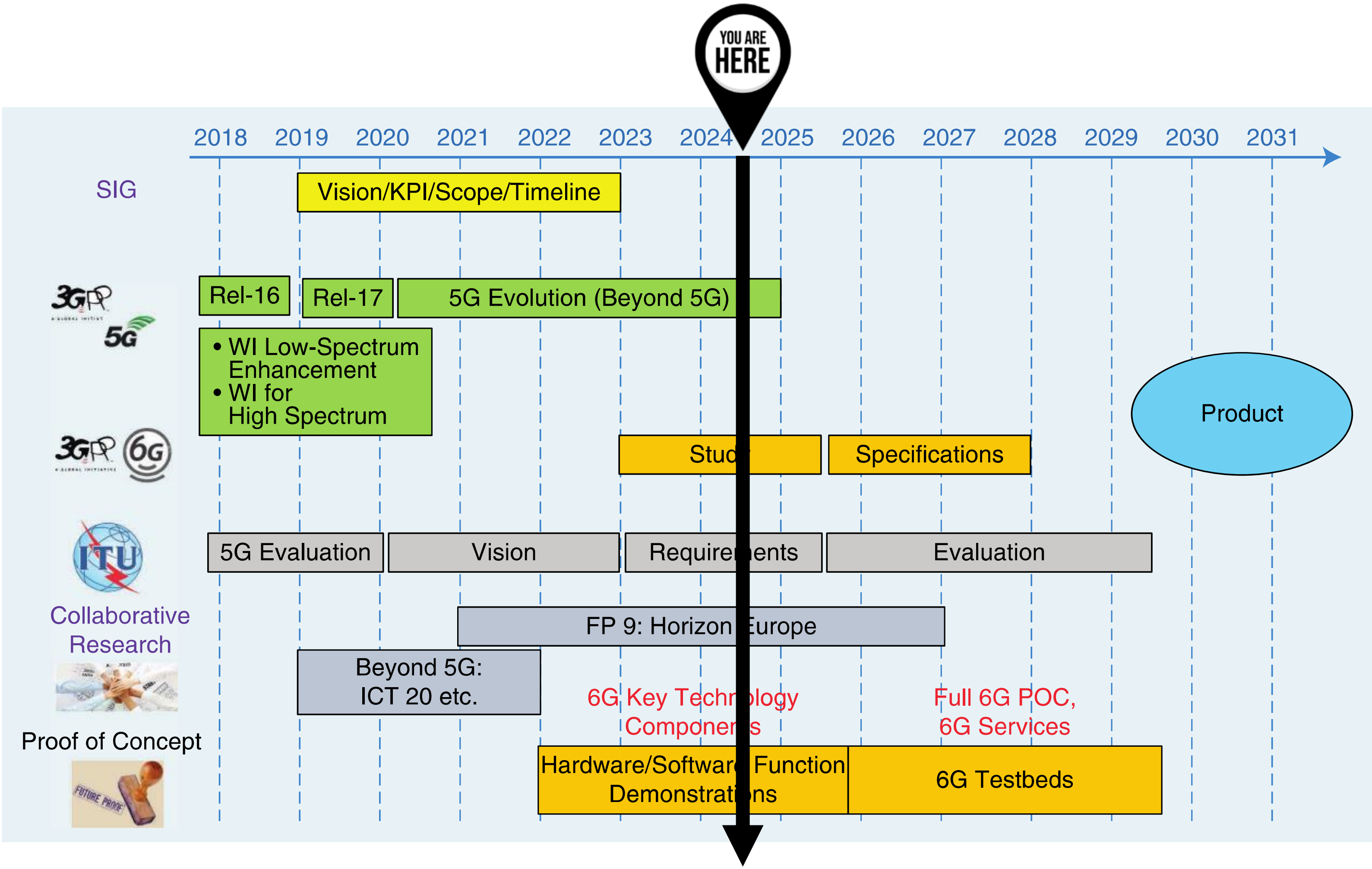
Introduction

- From 1G to 5G, each generation of mobile technology has tried to meet the needs of network operators and final consumers
- The rapid development of data-centric automated processes may exceed the capabilities of 5G systems, calling for a new wireless generation



M. Giordani, M. Polese, M. Mezzavilla, S. Rangan and M. Zorzi, "Toward 6G Networks: Use Cases and Technologies," in IEEE Communications Magazine, vol. 58, no. 3, pp. 55-61, March 2020.

6G standardization activities



E. Calvanese Strinati et al., "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication," in IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 42-50, Sept. 2019.

6G use cases


Pervasive
Communication


Virtual Reality


E-Health

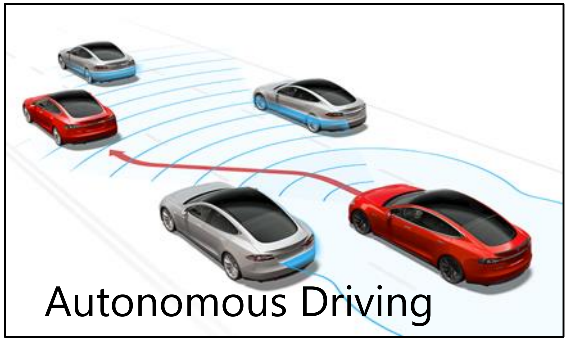

High-Speed Mobility


Worlwide Connectivity


Industry 4.0

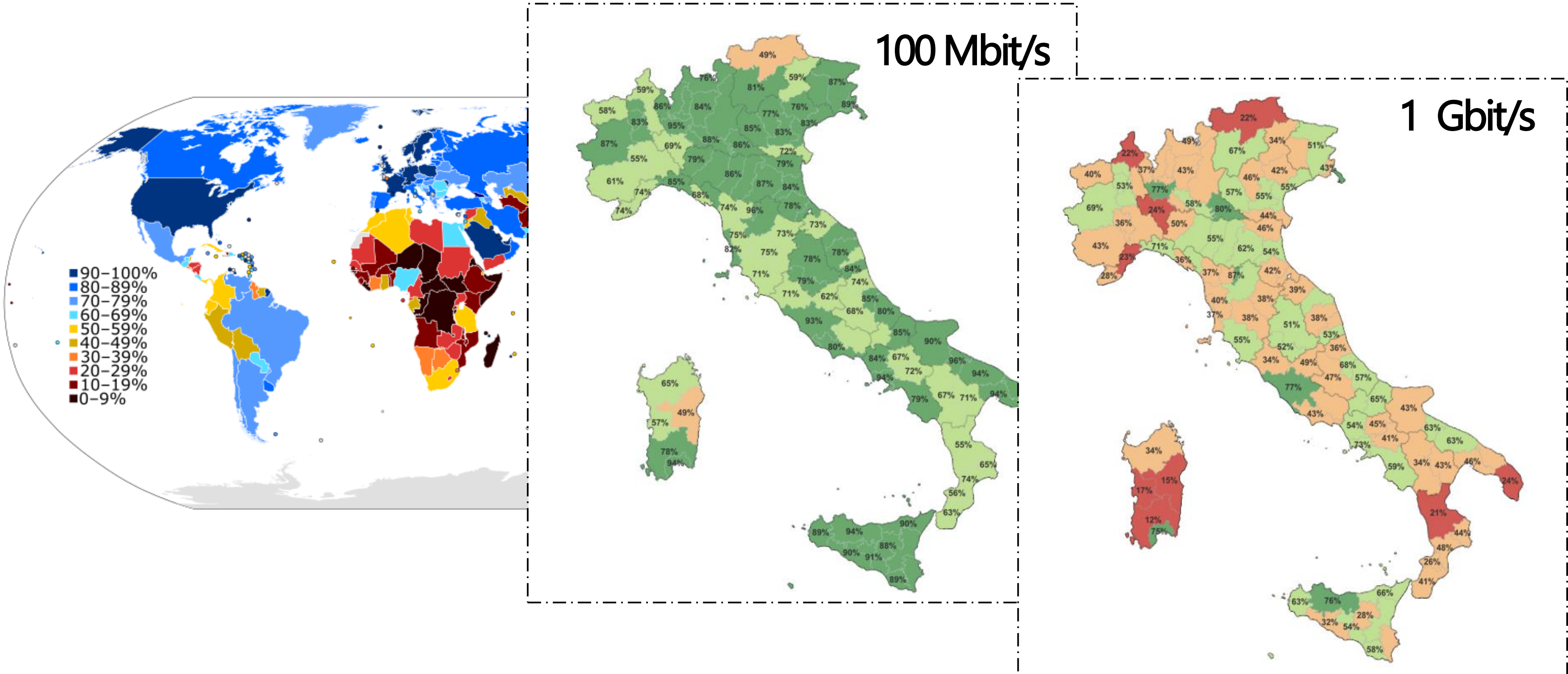

Smart Cities


Holographic Telepresence


Autonomous Driving

Worldwide connectivity

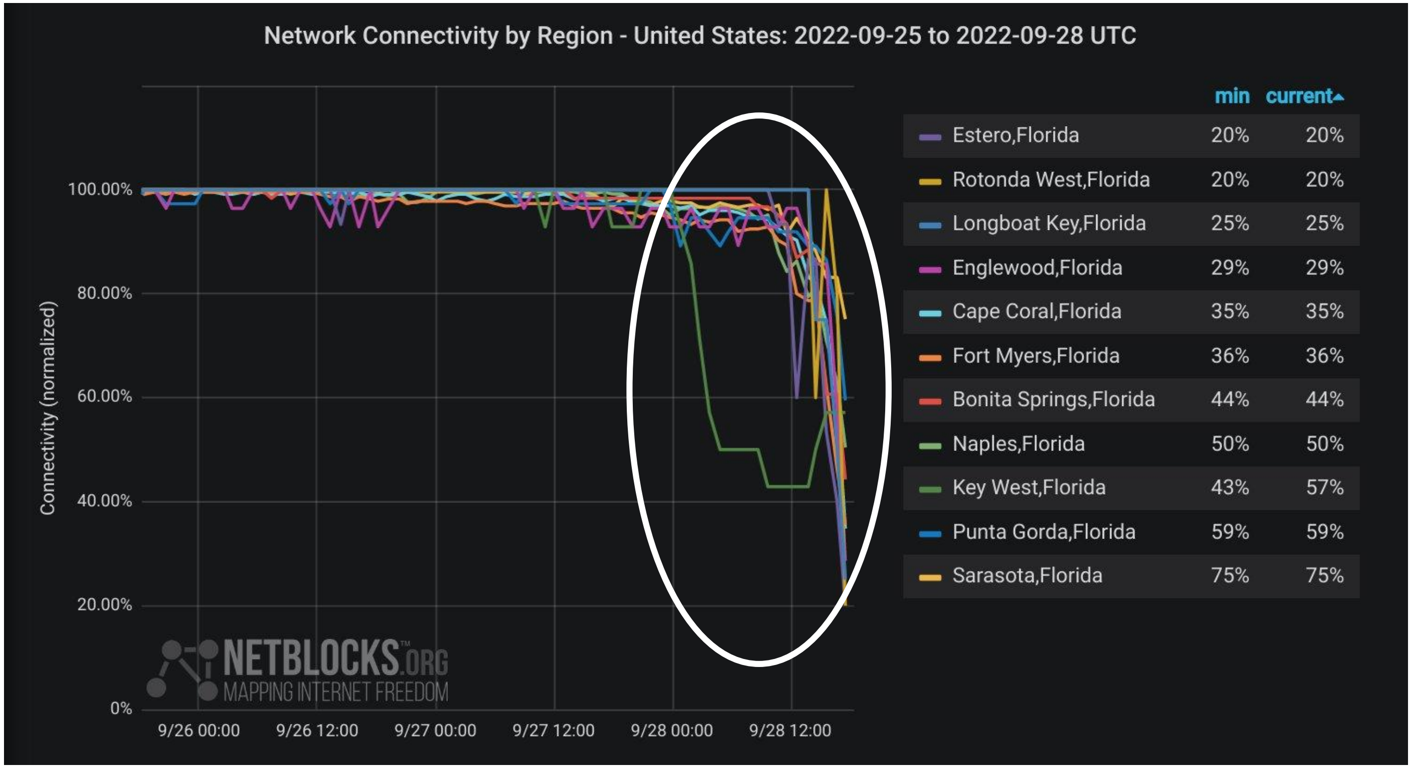
- In 2021, 55% of the global population lived in urban areas
  - 67% had a mobile subscription, but only 4.9 billion people were using Internet



Source: http://agcom.it

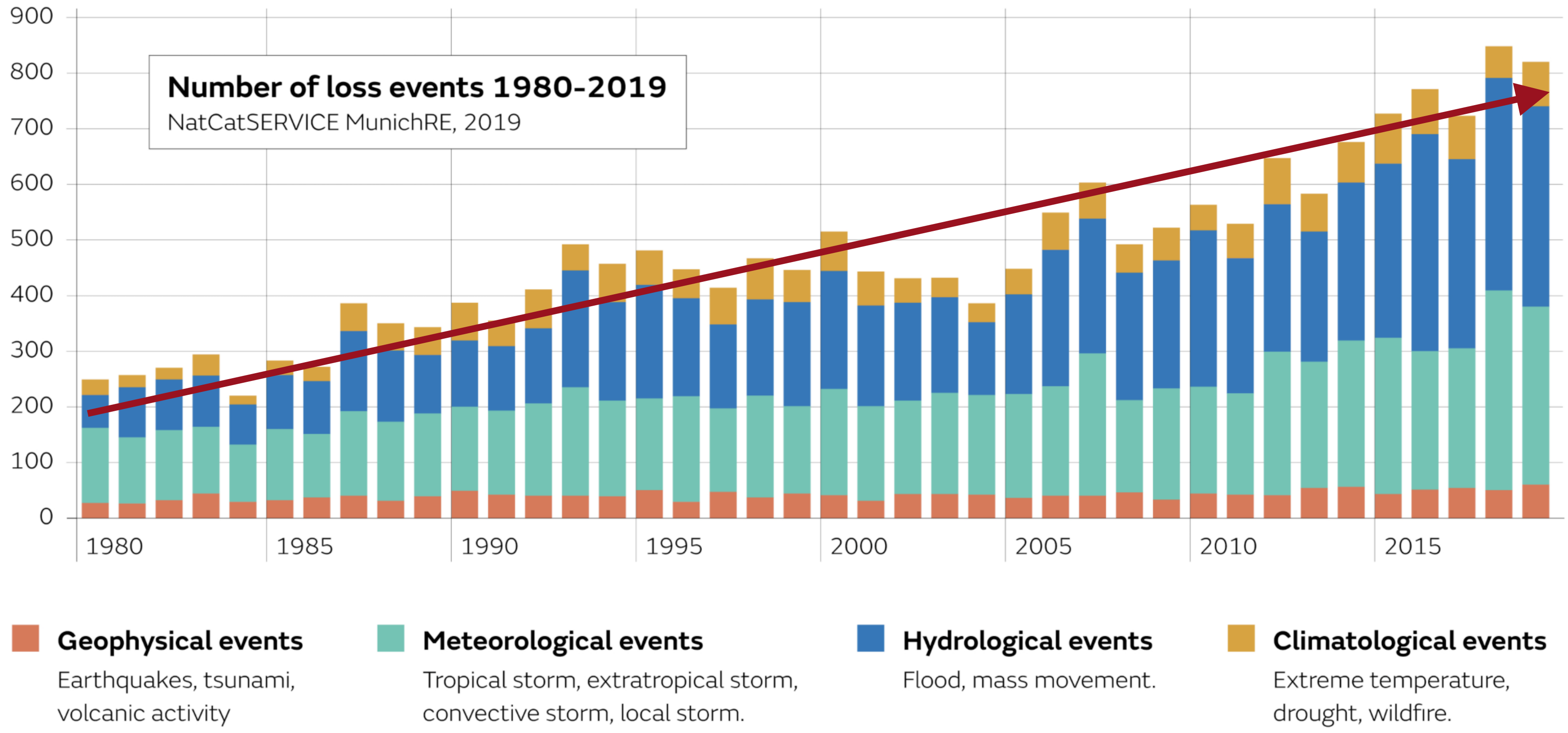
Worldwide connectivity

- 5G lacks the level of reliability requested by future wireless applications, and shows vulnerability to **natural disasters** or other **attacks** (significant *damage to business*, and *loss of livelihood*).



Worldwide connectivity

- Number of natural disasters: an **increasing trend.**

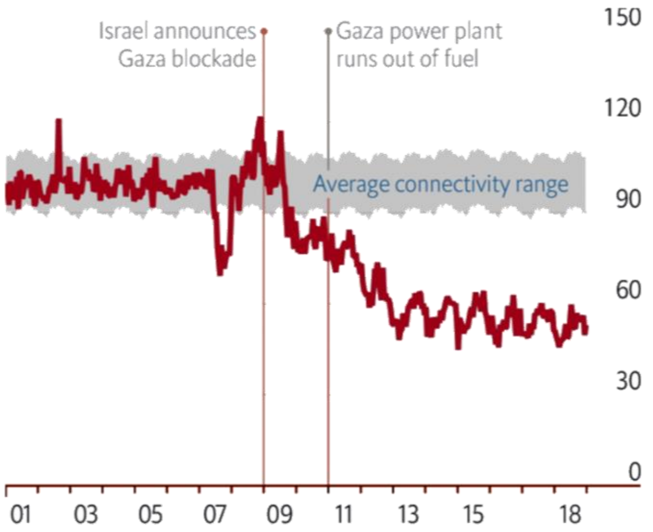


Worldwide connectivity

- It is not only natural disasters, but also **human disasters**.
  - This demonstrates how vulnerable telecom networks are.

Ukraine, Feb. 23rd, 2022

Gaza, Oct. 2023



Worldwide connectivity

Worldwide connectivity issues

Network **densification** will lead to energy crunch, with environmental issues
(ICT systems are responsible for ~5% of the world's CO2 emissions)

Remote areas may not have ample connectivity to the **power sources**

Remote maintenance of network infrastructures is impaired due to harsh weather and terrain, or lack of transport connectivity

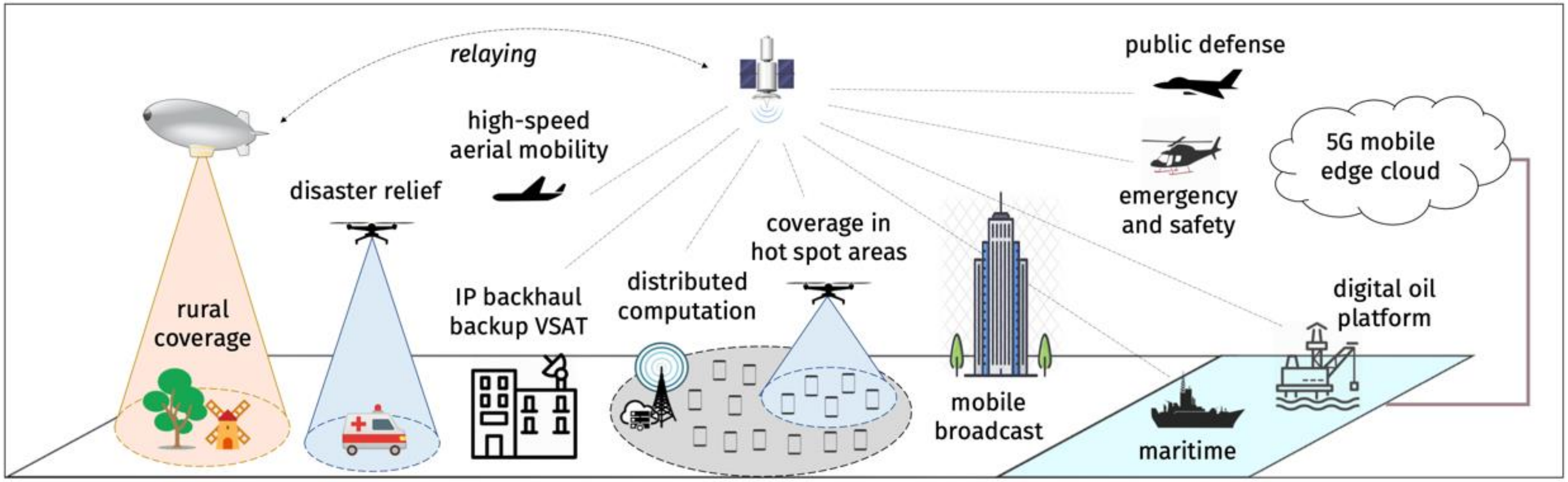
Limited economic resources for **spectrum auctions**, while sub-6 GHz unlicensed bands are already crowded

Worldwide connectivity

RESEARCH TOWARDS Internet of Everyone (IoE)

Non-terrestrial networks (NTN)

- 5G networks have been designed to provide connectivity for an almost **two-dimensional** space, i.e., network base stations are deployed to offer connectivity to devices on the ground
- 6G research focuses on **non-terrestrial networks (NTNs)** to provide 3D coverage by complementing terrestrial infrastructures with aerial nodes (drones, satellites, high altitude platforms, etc.)



- M. Giordani, M. Zorzi, “Satellite Communication at Millimeter Waves: a Key Enabler of the 6G Era”, IEEE ICNC, 2020.
- M. Giordani and M. Zorzi, "Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities," in IEEE Network, vol. 35, no. 2, pp. 244-251, Mar. 2021.
- D. Wang, M. Giordani, M. -S. Alouini and M. Zorzi, "The Potential of Multilayered Hierarchical Nonterrestrial Networks for 6G: A Comparative Analysis Among Networking Architectures," in IEEE Vehicular Technology Magazine, vol. 16, no. 3, pp. 99-107, Sept. 2021.

NTN platforms

Unmanned Aerial Vehicle (UAV)

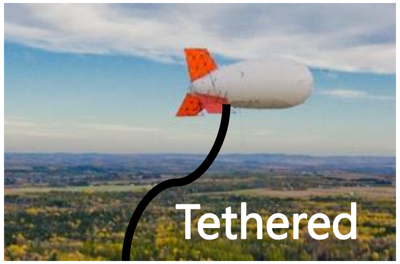
PROs	CONs
Fly at low altitude	High propulsion energy
High flexibility	Small coverage umbrella
Deployed on-demand	




NTN platforms

High Altitude Platform (HAP)

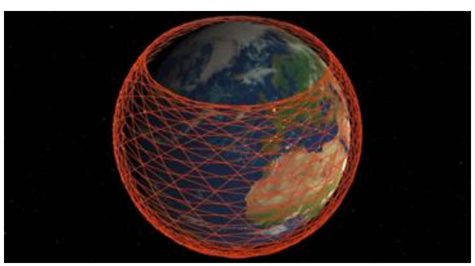
PROs	CONs
Quick deployment	Need for refueling
Large geographical coverage	Difficult stabilization
Low deployment costs	
Low energy consumption (solar-powered)	



NTN platforms

GEO/MEO/LEO Satellites

Satellite	PROs	CONs
GEO	Huge coverage	Huge delays and attenuation
		Capacity saturation
MEO/LEO	Large coverage	Non-stationary (need for constellations)

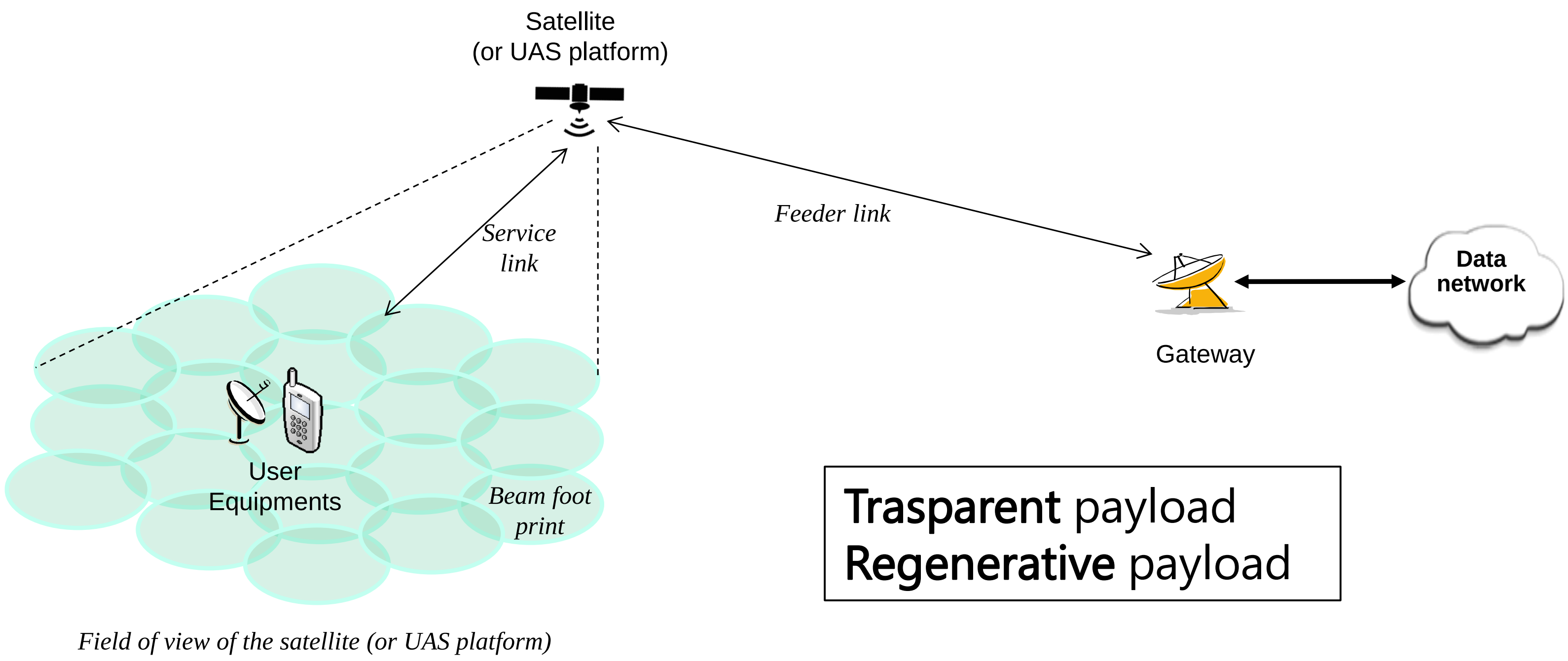




NTN scenario

Non-terrestrial systems feature:

- a terrestrial **terminal**, an aerial/space **station**, a **service** link, a gateway that connects to the core network through a **feeder** link.

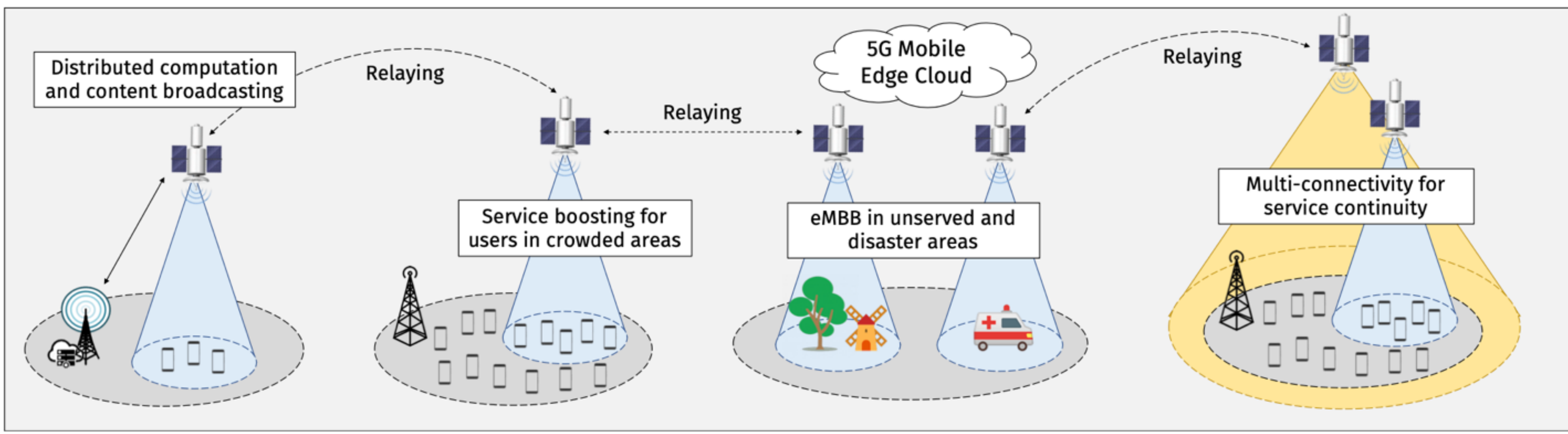


Trasparent payload
Regenerative payload

*Non-terrestrial network typical scenario based on transparent payload – **3GPP TR 38.821 [Figure 4.1-1]***

Use cases

- **Communication resilience** (in rural areas or when terrestrial infrastructures are not available)
- **Resource optimization** on parallel backhaul links (find alternate route to preserve connection)
- **QoS enhancement** through MEC (provide terrestrial users with an execution environment)
- Reduced **energy consumption** (avoid management costs of always-on terrestrial infrastructures)
- Global **satellite overlay** (connect two base stations over spacecraft relays, rather than optical fiber)
- Ubiquitous **Internet of Things (IoT)** broadcasting (convey multimedia contents to many sensors)
- Energy-efficient **hybrid multiplay** (provide efficient, clean, and renewable energy via solar panels)



M. Giordani and M. Zorzi, "Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities," in IEEE Network, vol. 35, no. 2, pp. 244-251, Mar. 2021.

NTN issues

- The effects on (and the challenges for) the 5G NR stack

NTN feature	Effect	Impact on NR stack
Motion of the space/aerial vehicles (especially for NGSO-based access networks)	Moving cell pattern	Handover/paging
		Initial access
	Delay variation	Synchronization / TA adjustment
	Doppler	
Altitude	Long propagation delay	HARQ
		MAC/RLC control loops
		Access scheme (TDD/FDD)
		Scheduling (especially in uplink)
		Transport layer (especially TCP)
Cell size	Differential delay	Random access response messages
	Massive number of UEs	Handover/paging
		Capacity saturation
Propagation channel	Channel impairments	DM-RS frequency density
		Channel modeling
Spectrum	Regulatory constraints	Spectrum co-existence

NTN issues

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6G research effort:

NTN calls for a **massive re-design** of many baseline NR protocols

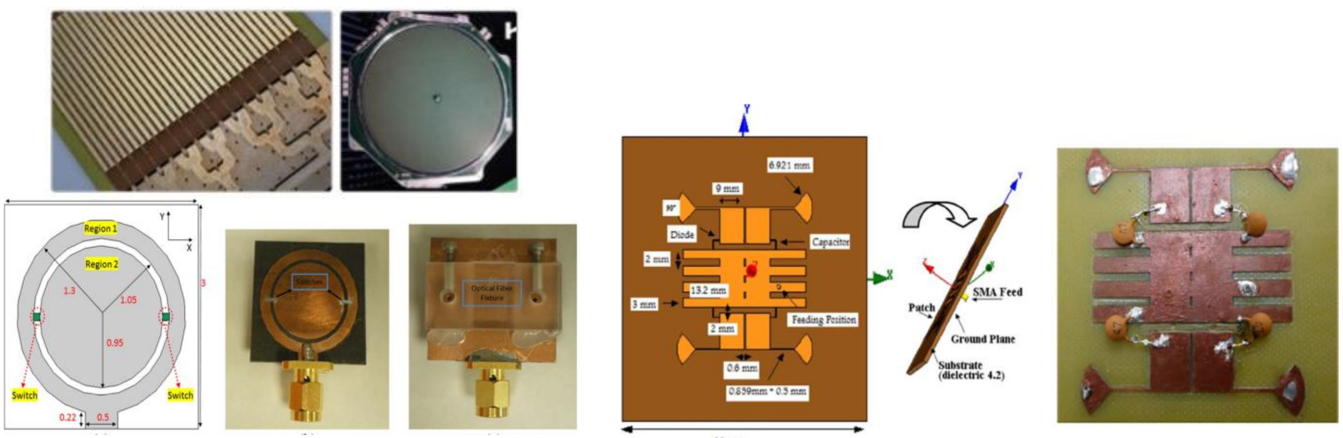
Research questions

Network planning?	Which / where / how / how many?
Network management?	Constellation / swarm management
Protocol design?	NTN-specific protocol stack
Energy efficiency?	Battery-powered drones
Communication / computing	Data offloading optimization
Network sustainability	Cost for deployment and management
Performance	Does it work?

Enabling technologies (1/3)

Antenna design advancements

- New **reconfigurable phased antennas** offer *electronic* beam-steering with lower energy consumption compared to mechanical products, and reduced size, weight and power challenges compared to existing antenna technologies.
- **Multibeam architectures** allow to maximize spectrum efficiency by simultaneously sending data to different spot beams on the ground.
- **Flexible payloads** allow services to autonomously adapt to evolving requirements, after launch and throughout the satellite lifetime, and support cross-band inter-beam configurations.



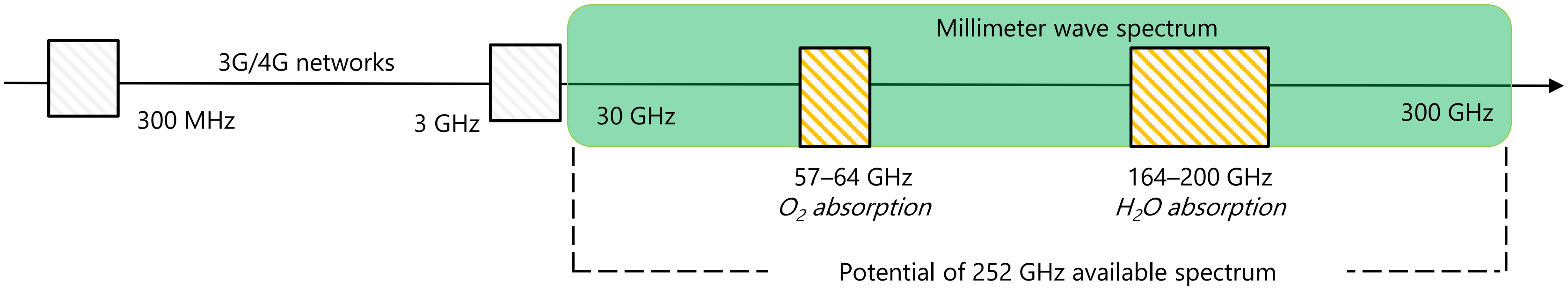
C. G. Christodoulou, et al., "Reconfigurable Antennas for Wireless and Space Applications," in Proceedings of the IEEE, vol. 100, no. 7, pp. 2250-2261, July 2012.

High Throughput Satellite

Enabling technologies (2/3)

Spectrum advancements

- The availability of compact high-gain antennas and radio transceivers satisfying power/size constraints will make it feasible for satellites to operate in the **millimetre wave** bands as a means to increase system capacity.
- New **waveforms** and **modulation and coding** schemes improve satellite communications in the presence of signal distortions introduced at mmWaves.

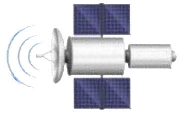


<u>**QUESTION:**</u> Can we really use millimeter waves to reach satellites despite the very long **transmission distances** and the severe **attenuation** experienced at those frequencies?

mmWave satellite channel

The potential of mmWaves to support satellite communications has been recognized by the **3GPP** which defines satellite network deployment scenarios and related system parameters, including **channel modeling** at NR frequencies

$$PL = PL_{\mathcal{B}} + PL_{\mathcal{E}} + PL_{\mathcal{G}} + PL_{\mathcal{S}}$$



3GPP, "Study on New Radio (NR) to support non terrestrial networks," TR 38.811 (Release 15), 2018.

Basic Path Loss
Accounts for the signal's free space propagation, the shadow fading, and the clutter loss (attenuation of the power due to surrounding buildings and objects on the ground)

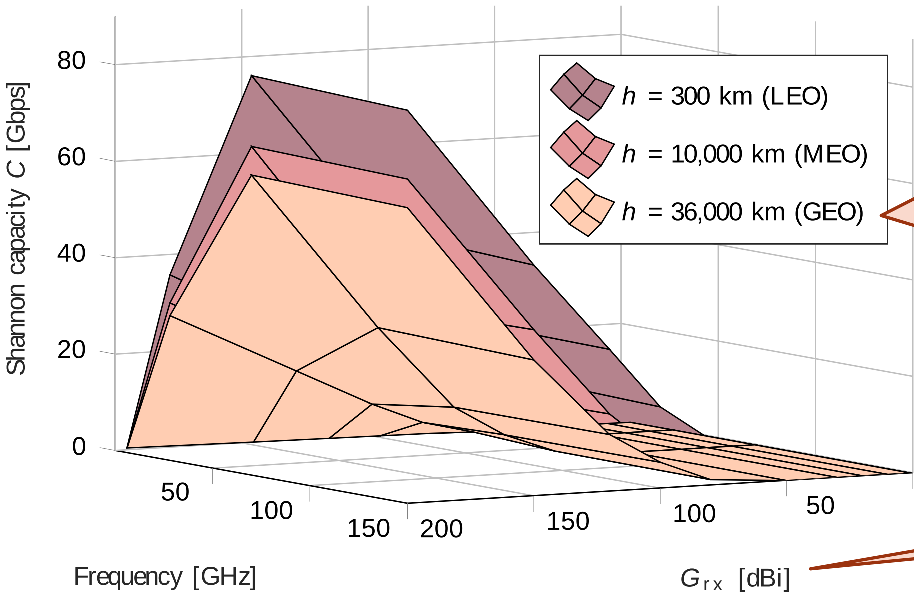
Tropospheric Scintillation
Attenuation by sudden changes in the refractive index due to the variation of temperature, water vapor content, and barometric pressure

Building Entry Loss
Attenuation in case of NLOS communication with an indoor terrestrial terminal

Atmospheric Absorption
Attenuation due to dry air (oxygen, and pressure-induced nitrogen) and water vapor

Simulation results

Terrestrial (2 GHz)	Satellite (6 GHz)	Satellite (28 GHz)	Satellite (70 GHz)	Satellite (150 GHz)
BW = 20 MHz	BW = 20 MHz	BW = 800 MHz	BW = 2 GHz	BW = 3 GHz



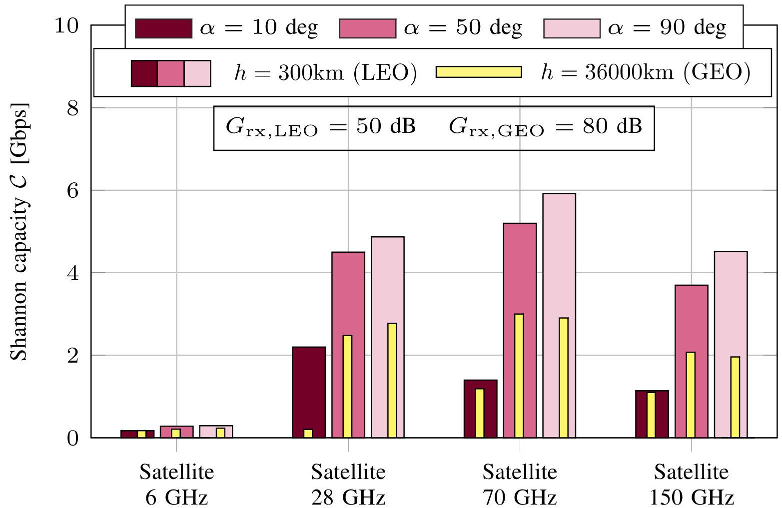
Transition from LEO to GEO with **increased gain** → practically feasible since GEO operates for fixed communication services and are continuously visible from terrestrial terminals.

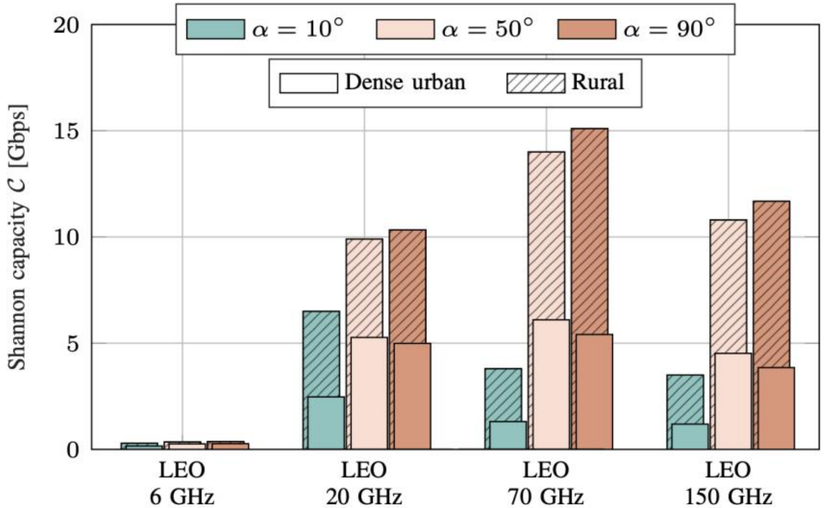
Higher capacity at mmWaves with appropriate antenna gain, despite the increased frequency.

The gain progressively reduces with the frequency → more severe impact of the **path loss** (*atmospheric absorption* and *tropospheric scintillation*) at mmWave frequencies

M. Giordani and M. Zorzi, "Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities," in IEEE Network, vol. 35, no. 2, pp. 244-251, Mar. 2021.

Simulation results



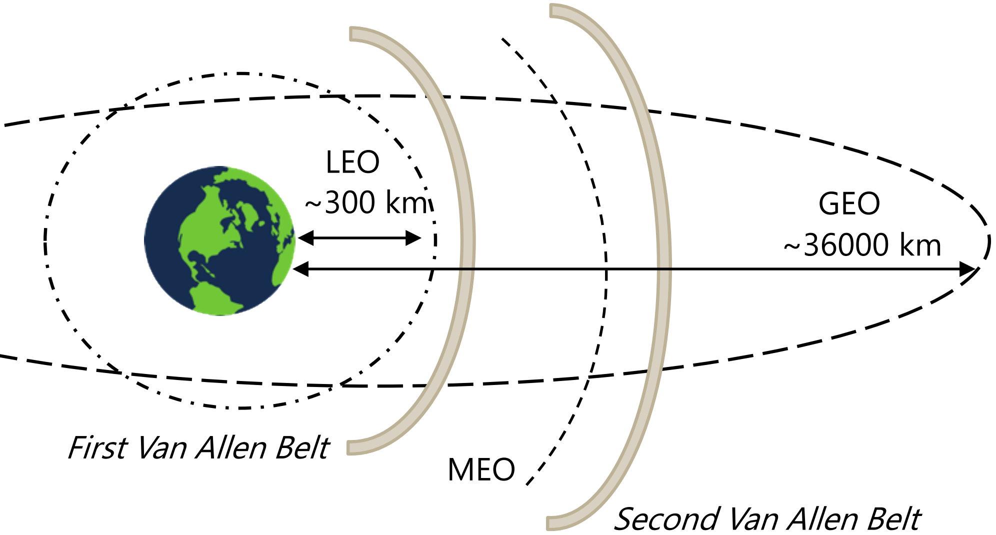


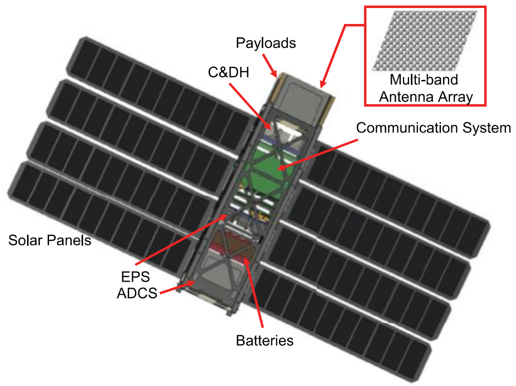
- The Shannon rate considerably **decreases** for decreasing values of **elevation angle** α:
  - Amplitude of the tropospheric scintillation becomes more severe due to multipath effects
  - The Earth–to-satellite signal transits longer through the atmosphere, resulting in more attenuation
- **Correlation** between elevation angle and LOS probability (in LOS, troposcatter, free space and diffraction effects are minimized, resulting in better propagation)
- **Urban scenario** → blockage reduces the capacity by more than 60% at high elevation

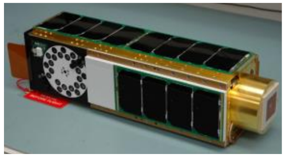
- M. Giordani, M. Zorzi, "Satellite Communication at Millimeter Waves: a Key Enabler of the 6G Era", *IEEE ICNC*, 2020.
- M. Giordani and M. Zorzi, "Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities," in IEEE Network, vol. 35, no. 2, pp. 244-251, Mar. 2021.

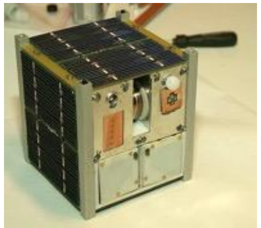
Architecture advancements

- Minimization of capital and operational costs for satellite deployment (e.g., LEO **nanosatellites** like *CubeSats* have rapidly gained attention for the availability of cheap components and launches at reduced cost).
- Transition to **NFV** and **SDN**, with 5G **network slicing**, guarantees improved flexibility, automation, and agility in satellite service delivery.
- Availability of **heterogeneous satellite networks** (e.g., LEO, MEO, and GEO constellations) makes it possible to obtain better spatial and temporal coverage performance by leveraging stations in different types of orbits.





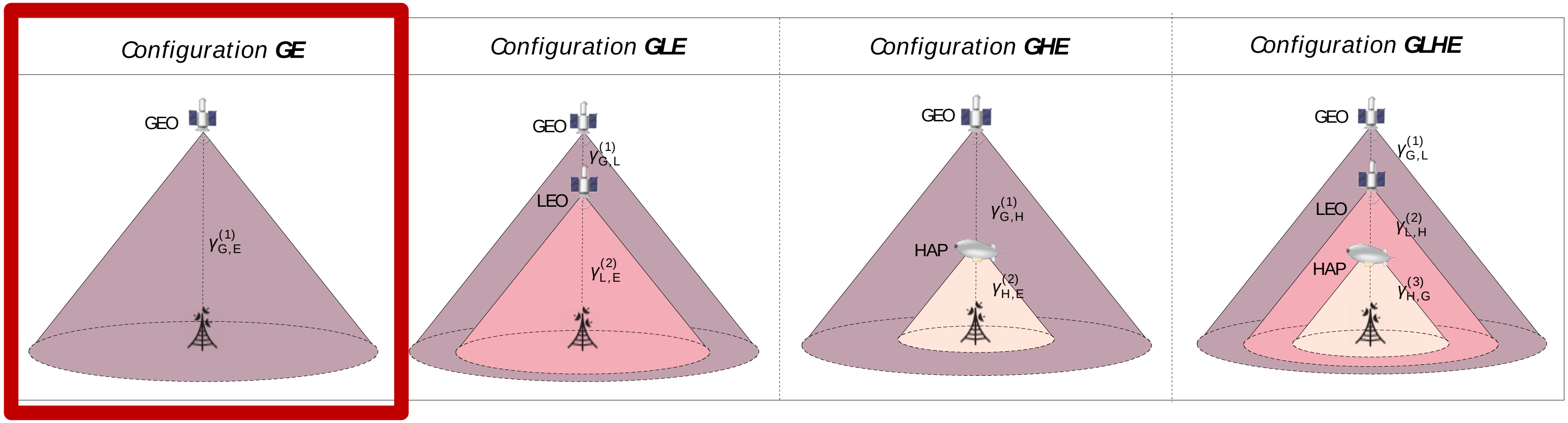




I. Akyildiz, at al., "A new cubesat design with reconfigurable multi-band radios for dynamic spectrum satellite communication networks," Ad Hoc Networks, 2019.

Multi-Layered NTNs

Multi-layered hierarchical networks, i.e., the orchestration among different aerial/space platforms co-operating at different altitudes, currently represents one the most attractive options to solve coverage and latency constraints associated with non-terrestrial networks



Unlike traditional standalone architectures, multi-layered NTNs require *end-to-end* (rather than *point-to-point*) optimization

D. Wang, M. Giordani, M.-S. Alouini, M. Zorzi, “The Potential of Multi-Layered Hierarchical Non-Terrestrial Networks for 6G”, submitted to the IEEE VTM, 2020.

Parameters

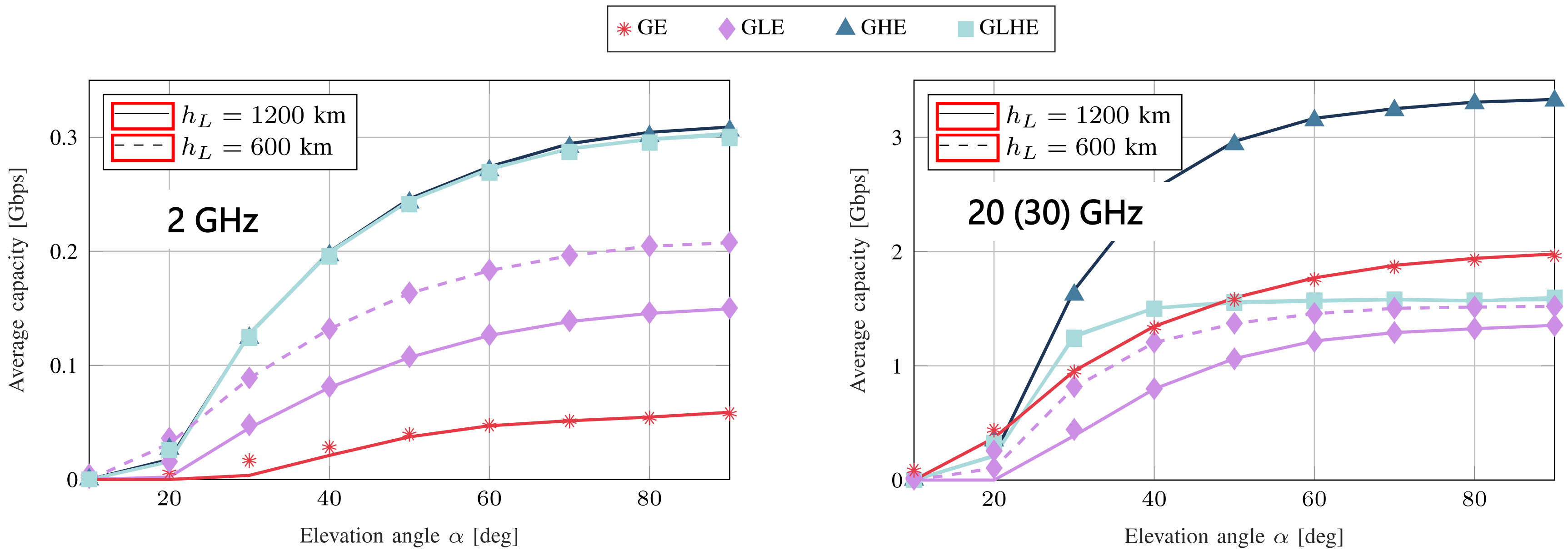
Parameter	Space								Aerial	Terrestrial	
	Downlink				Uplink						
	GEO		LEO		GEO		LEO		HAP	Base station	
Altitude (h) [km]	35,786		{1200, 600}		35,786		{1200, 600}		20	0.03	
Frequency (f_c) [GHz]	2	20	2	20	2	30	2	30	38	2	20
Max. EIRP* [dBW]	73.8	66	54	36	73.8	46.2	48.6	46.2	27.9	N/A‡	N/A‡
System bandwidth (B) [MHz]	30	400	30	400	30	400	30	400	400	N/A‡	N/A‡
Rx. antenna-gain-to-noise-temperature† (G/T) [dB/K]	−31.6	15.9	−31.6	15.9	19	28	1.1	13	27.7	N/A‡	N/A‡
Rx. antenna gain (G_R) [dBi]	N/A‡ (already included in G/T)									0	39.7
Noise figure (NF) [dB]	N/A‡ (already included in G/T)									7	1.2
Antenna temperature T_a (K)	N/A‡ (already included in G/T)									290	150
Ambient temperature T_0 (K)	N/A‡ (already included in G/T)									290	
Fading	Shadowed-Rician $\{b_0, m, \omega\} = \{0.158, 19.4, 1.29\}$ [13]								Rician $C = 10$ [14]	N/A‡	

Antenna transmit power, cable loss, and transmit antenna gain

Receive antenna gain, ambient/antenna temperature, noise figure

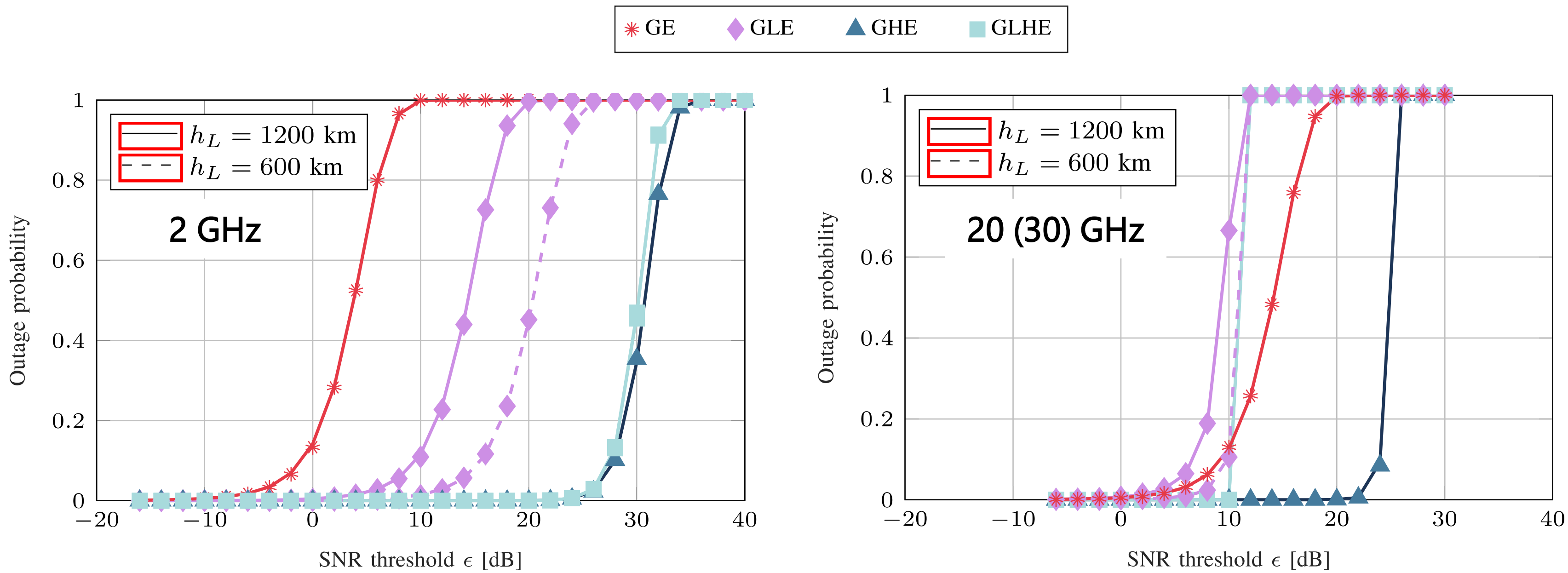
- 3GPP, "Solutions for NR to support non-terrestrial networks", TR 38.821 (Release 16), 2020.
- ITU-R, "Deployment and technical characteristics of broadband high altitude platform stations in the fixed service in the frequency bands 6 440-6 520 MHz, 21.4-22.0 GHz, 24.25-27.5 GHz, 27.9-28.2 GHz, 31.0- 31.3 GHz, 38.0-39.5 GHz, 47.2-47.5 GHz and 47.9-48.2 GHz used in sharing and compatibility studies," F.2439-0, 2018.

Results – Average capacity



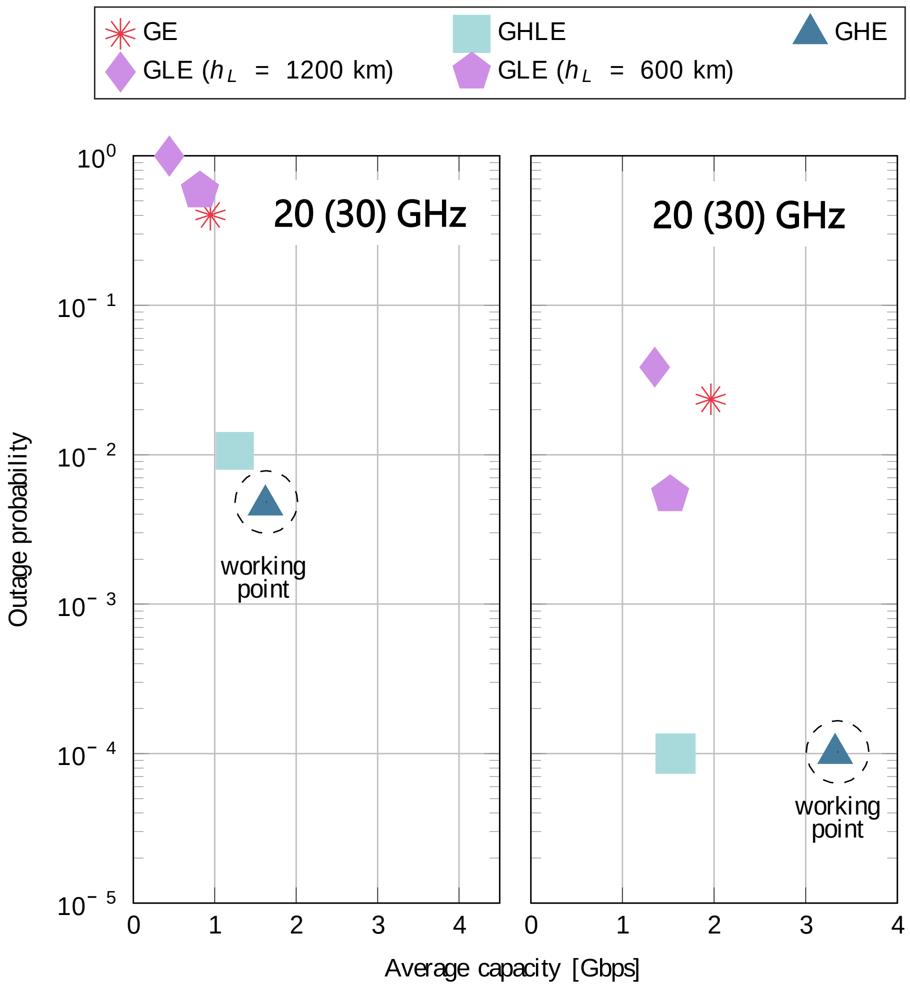
- Higher **capacity** in the Ka-bands (mmWaves) → larger bandwidth
- GHE better than GLE → it allows to decrease the **length** of the (bottleneck) Earth link traversing the atmosphere to only 20 km
- GLE works better when LEO is at **600 km** → shorter space-Earth link
- At 20 GHz, GLHE underperforms GHE, and more **complex** architecture
- At 20 GHz, GLE underperforms GE → simpler hardware/antenna implementation

Results – Outage probability



- Communication quality decreases when ε increases
- Multi-layer architecture offers **better coverage** → intermediate nodes permit to establish shorter-range communications in the Earth link
- LEO relays work worse than HAP relays
- 2 GHz is more reliable than 20 GHz → increased variability at mmWaves
  - GLE: –20 dB; GHE: –5 dB

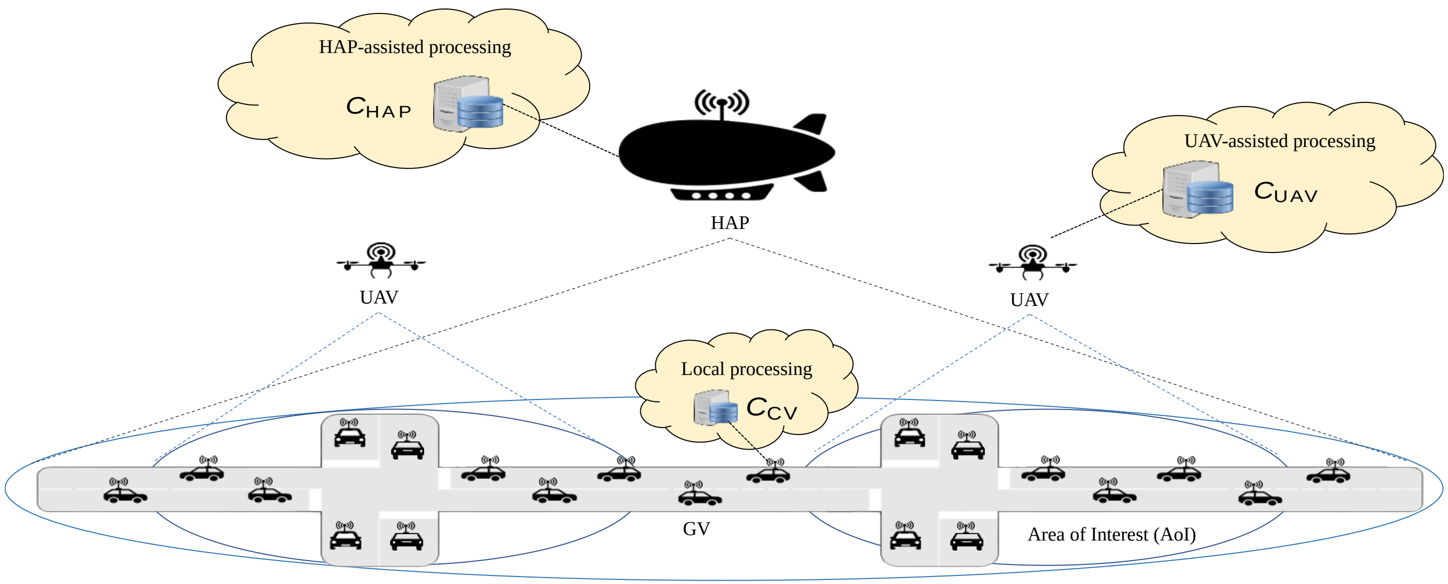
Results – Comparison



- **GHE is the optimal configuration**
  - 1.75x better capacity than GE
  - 2x better capacity than GLE
  - More robust communications
- LEO relays are <u>NOT</u> desirable
- Fully-integrated GLHE is <u>NOT</u> desirable
  - –42% capacity than GHE

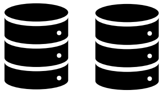
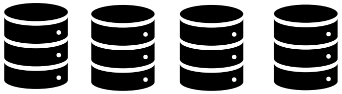
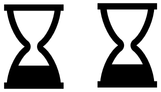
NTN for computation

- NTNs can act as edge servers to **process** computational tasks offloaded by energy-constrained terrestrial devices:
  - Delay-sensitive, distributed, flexible (migration) computation

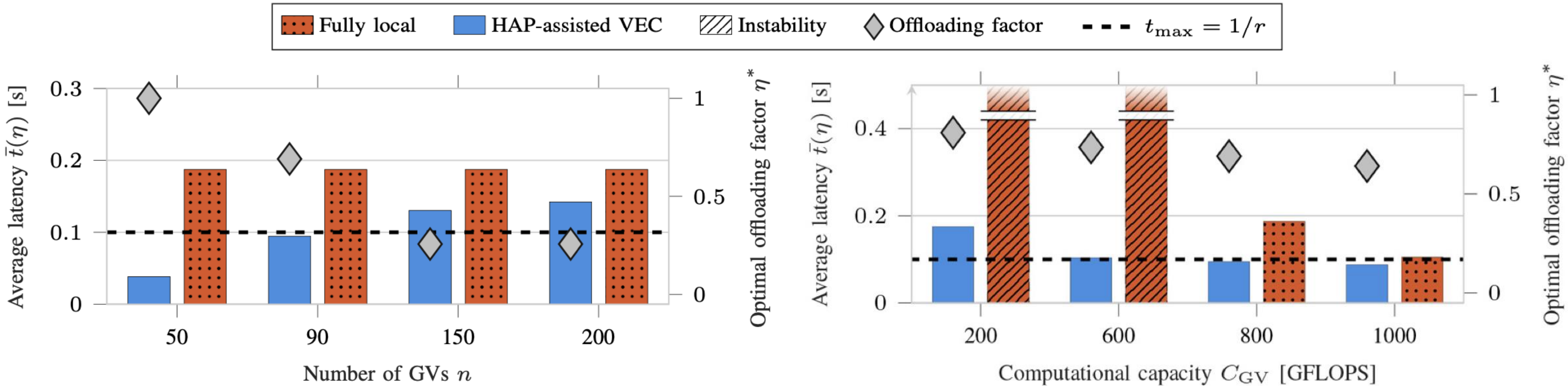


- A. Traspadini, M. Giordani, M. Zorzi, "UAV/HAP-Assisted Vehicular Edge Computing in 6G: Where and What to Offload?," EuCNC/6G Summit, 2022.
- A. Traspadini, M. Giordani, G. Giambene, M. Zorzi, "Real-Time HAP-Assisted VECfor Rural Areas," IEEE WCL, 2023.

NTN for computation

Terminal	Computational capacity	Transmissions delays
		
		
		

Performance results

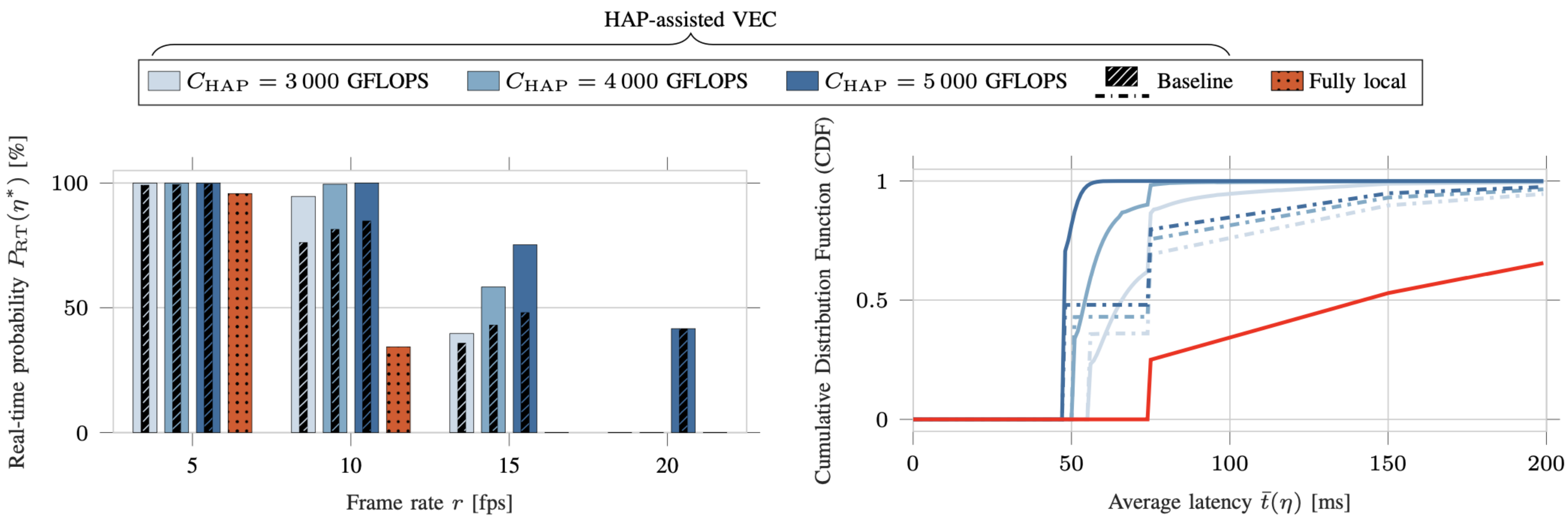


(a) $C_{\rm GV} = 800$ GFLOPS.

(b) $n = 90$ GVs.

- The average latency for processing data via the HAP grows with *n.*
- HAP-assisted VEC: reduce latency by up to 5 times (despite tx delays).
- η^* decreases with the number of GVs.
  - More populated queues may overload the available channel bandwidth.
- η^* decreases as C_{GV} increases (vehicles are more powerful)

Performance results

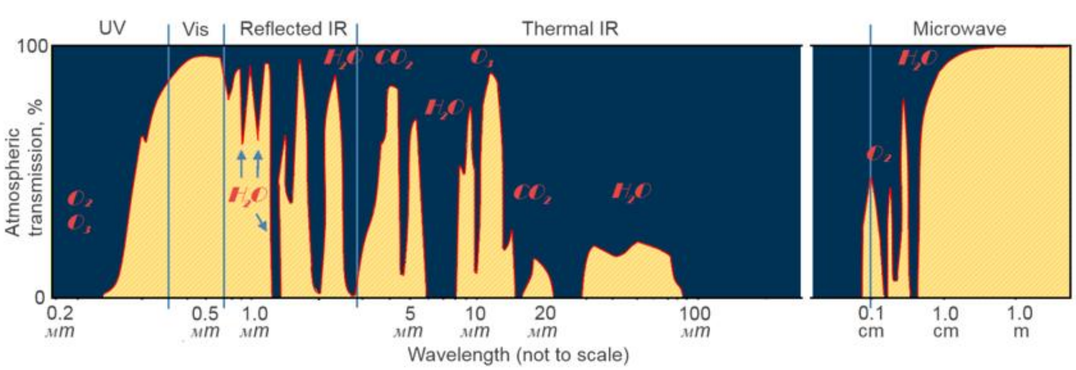


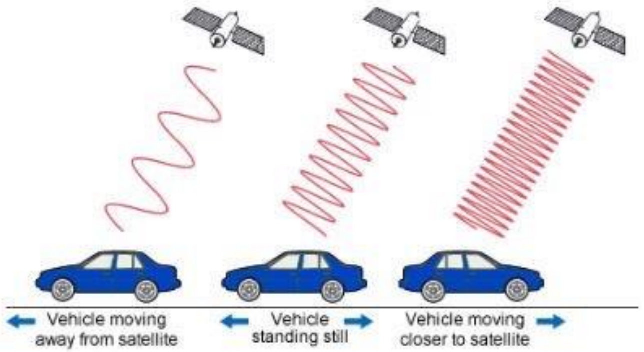
- Increase *r*: sensors capture data at better resolution.
- Real-time probability is a decreasing function of *r*.
  - HAP requires at least a capacity of 5000 GFLOPS.
- HAP-assisted VEC can better support real-time processing.
  - Importance of optimization (*baseline*: works only for r < 10 fps).

Open challenges

Channel modeling

- Missing adequate characterization of mmWave **second order statistics** (correlation in space and time)
- Missing adequate characterization of impact of Doppler, fading, and multipath
- Missing general model of a **fully-layered** space-air-ground channel

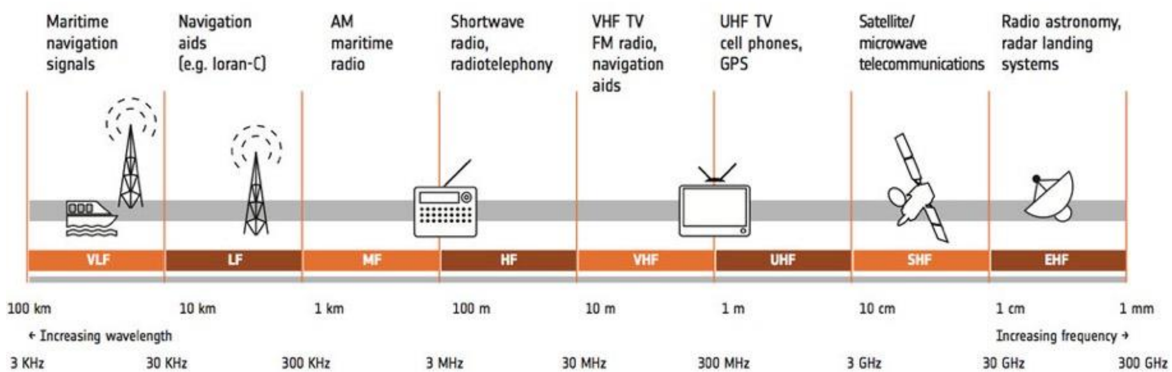


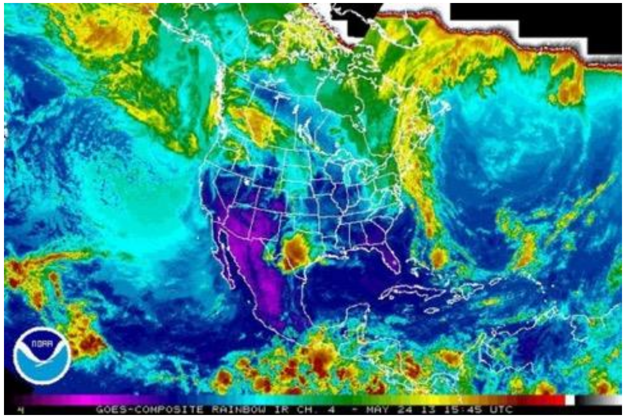


Open challenges

Spectrum co-existence

- Millimeter wave satellite communications have to **co-exist** with other systems operating in the Ka-bands (e.g., satellites offering weather forecasting services)
- Development of spectrum sharing techniques that maintain adequate **isolation** among different communications while ensuring **reasonable licensing costs**

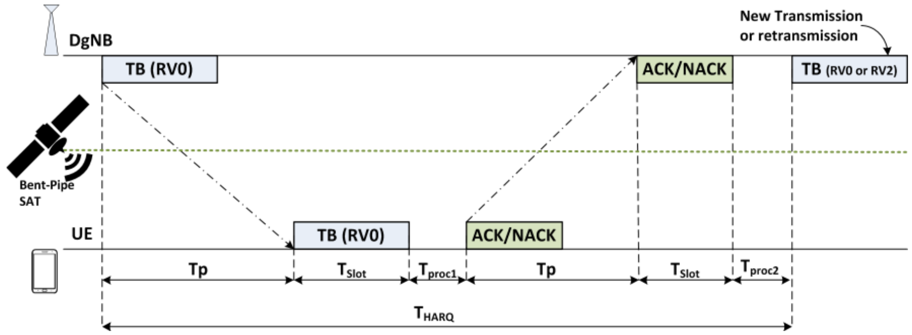




Open challenges

PHY procedures

- Design of flexible **numerology** to compensate for large Doppler shift
- Non-linear payload **distortions** may complicate signal reception
- Large RTTs make it infeasible to operate in **TDD**
- Large RTTs may exceed the maximum possible number of **HARQ processes** → simply increasing the number of processes may not be feasible due to memory restrictions at the mobile terminal's side



Timing diagram of a single HARQ process for a NTN with a single bent-pipe satellite in the link 3GPP TR 38.811 [Figure 7.3.3.1.1-1]

Open challenges

Synchronization

- Non-terrestrial systems are fast-moving, and typically feature larger cells compared to terrestrial networks.
  - Large non-terrestrial station's footprint creates a **differential propagation delay** among users in the cell (especially at low elevation)

	Typical cell size	Maximum delay difference*2
GEO	1000 km	6.44ms
	500km	3.26ms
LEO	200 km	LEO600:1.306ms LEO1200: 1.308ms
	100 km	LEO600: 0.654ms LEO1200:0.654ms

*Maximum delay difference*2 for typical GEO and LEO cell*
3GPP TR 38.821 [Table 7.2.1.1.1.2-1]

Open challenges

Initial access and mobility management

- Channel dynamics may result in **obsolete** channel estimates
- In multi-layered architecture, intermediate nodes associate to a gateway based on its own **unilateral benefit**, neglecting the potential disadvantages on the whole network performance.
- **Directionality** complicates user tracking, handover, and RLF recovery

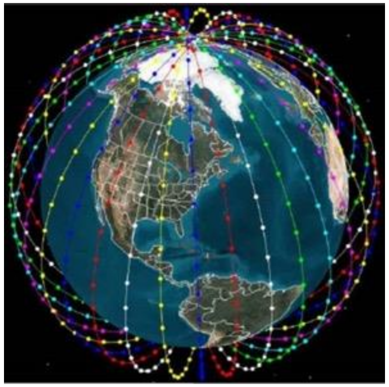
Cell Diameter (km)	Approximate Cell Area (km^2)	Average UE density (UE/km^2)	Satellite speed (km/s)	Time to HO all UEs in cell (s)	Average "hand-out" rate (UE/s)	Average HO Rate (in+out) (UEs/s)
50	1964	33.36	7.56	6.61	9912	19824
100	7854	8.34		13.23	4952	9904
250	49087	1.33		33.07	1981	3962
500	196000	0.33		66.14	991	1982
1000	785000	0.08		132.28	495	990

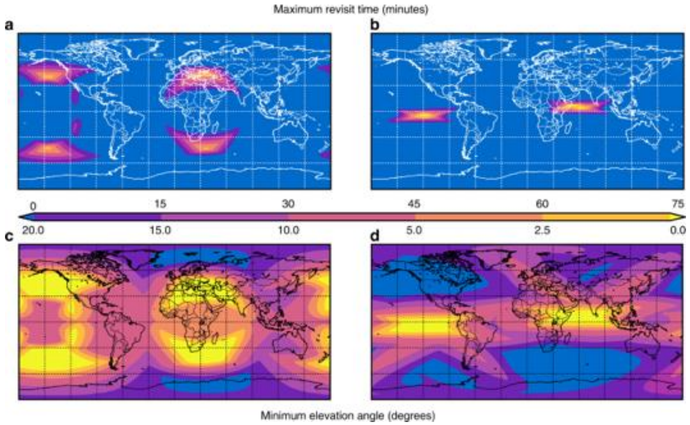
*Average HO rate for a given cell diameter, assuming 65519 connected – **3GPP TR 38.821 [Table 7.3.2.1.6-1]***

Open challenges

Constellation management

- Non-terrestrial stations may need to serve a **large number of users**
- **Constellations** are necessary to maintain ubiquitous service continuity
  - High cost of satellite launches complicates constellation deployment
  - Coordination of multi-layered nodes complicates constellation management

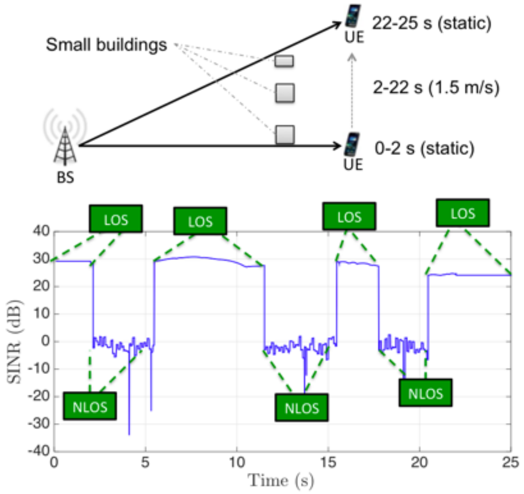


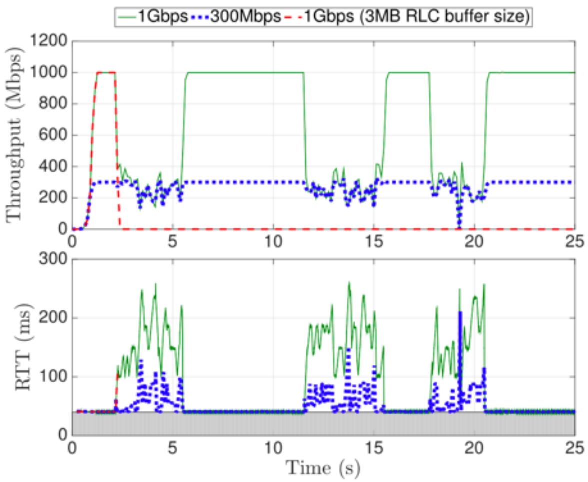


Open challenges

Higher-layer design

- Channel dynamics result in **obsolete topology** information
- Large RTTs result in longer duration of the **slow start phase** of TCP
- Channel dynamics result in **sudden drops** in the link quality





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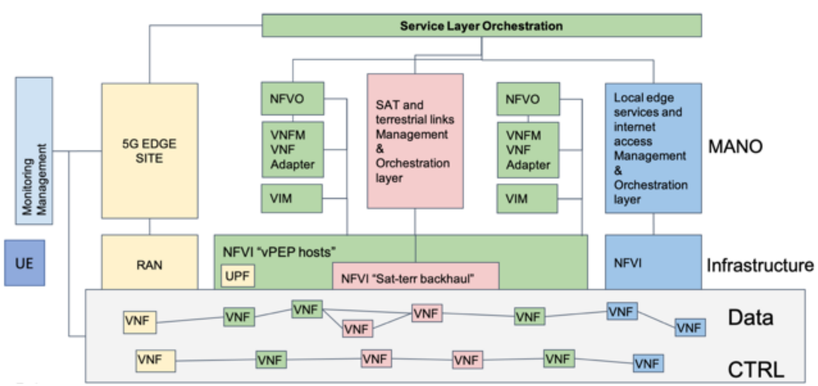
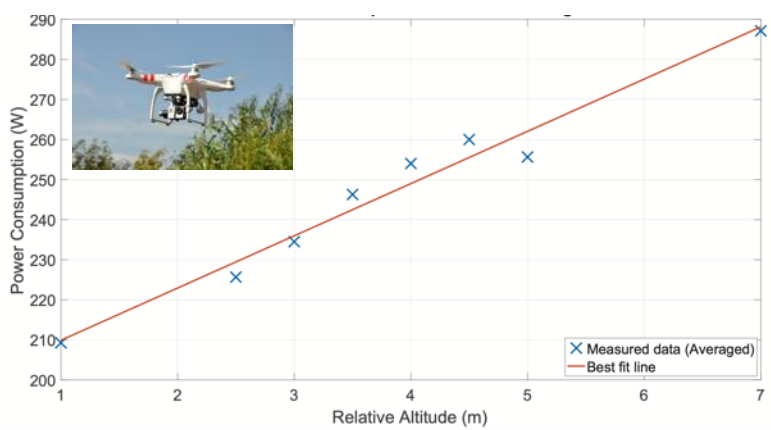
Open challenges

Architecture technologies

- Unclear where to distribute **SDN planes** (depending on the available processing capabilities or the transmission rate)
- Long distances prevent long duration of **batteries** (P_{TX} close to saturation)
- Design of central authority for **secure** communication





A. Abdelsalam, et al., "Implementation of Virtualised Network Functions (VNFs) for Broadband Satellite Networks," in EuCNC, 2019.

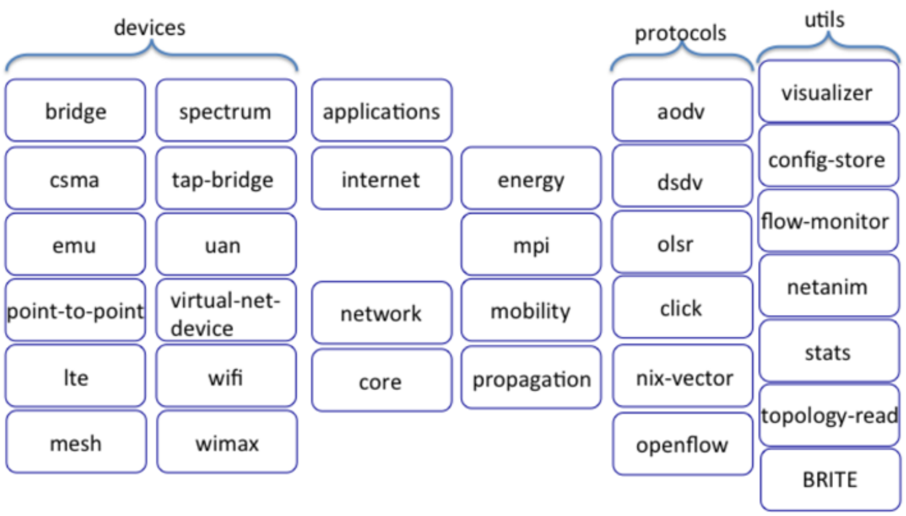
Simulation

How to validate new research?

Analysis

Experiements

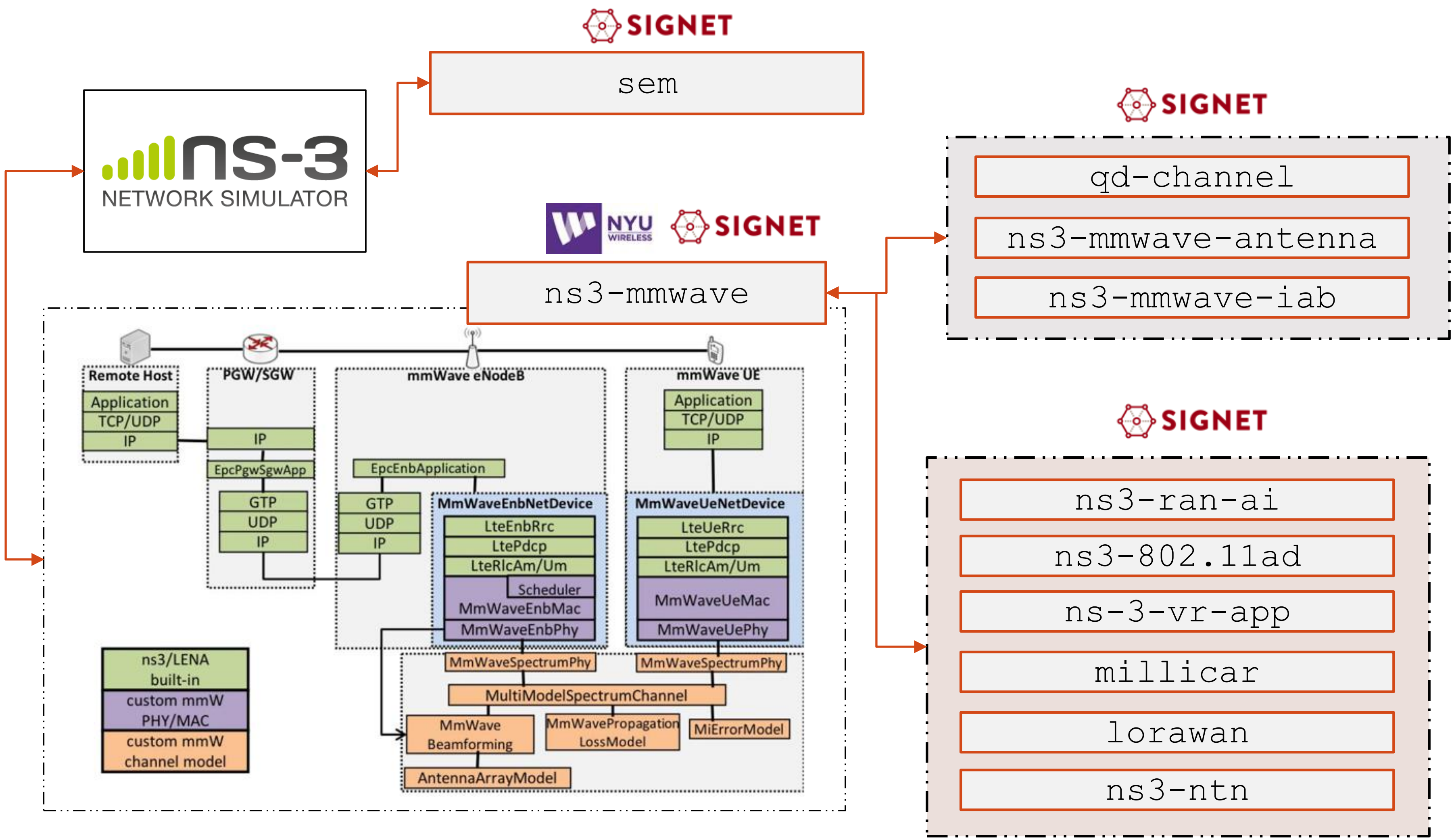
Simulations



ns-3 NETWORK SIMULATOR

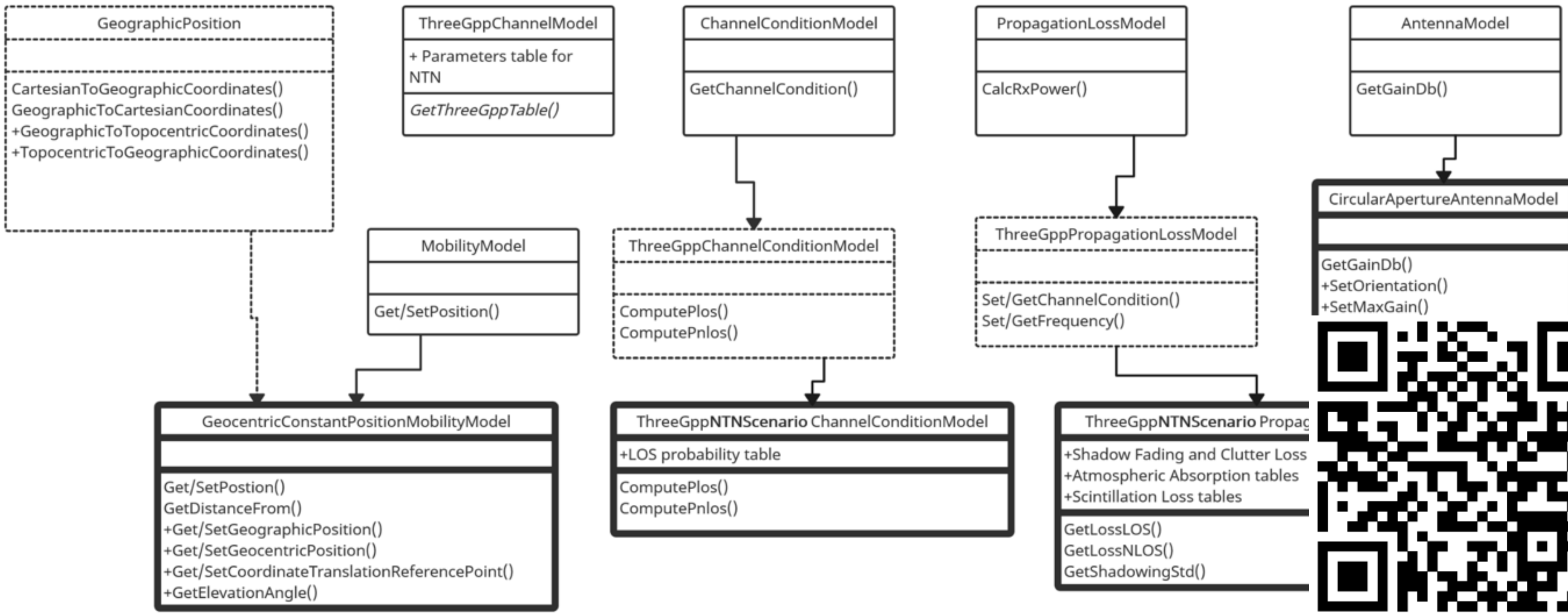
https://www.nsnam.org

ns3-mmwave module



https://github.com/signetlabdei

ns3-ntn module

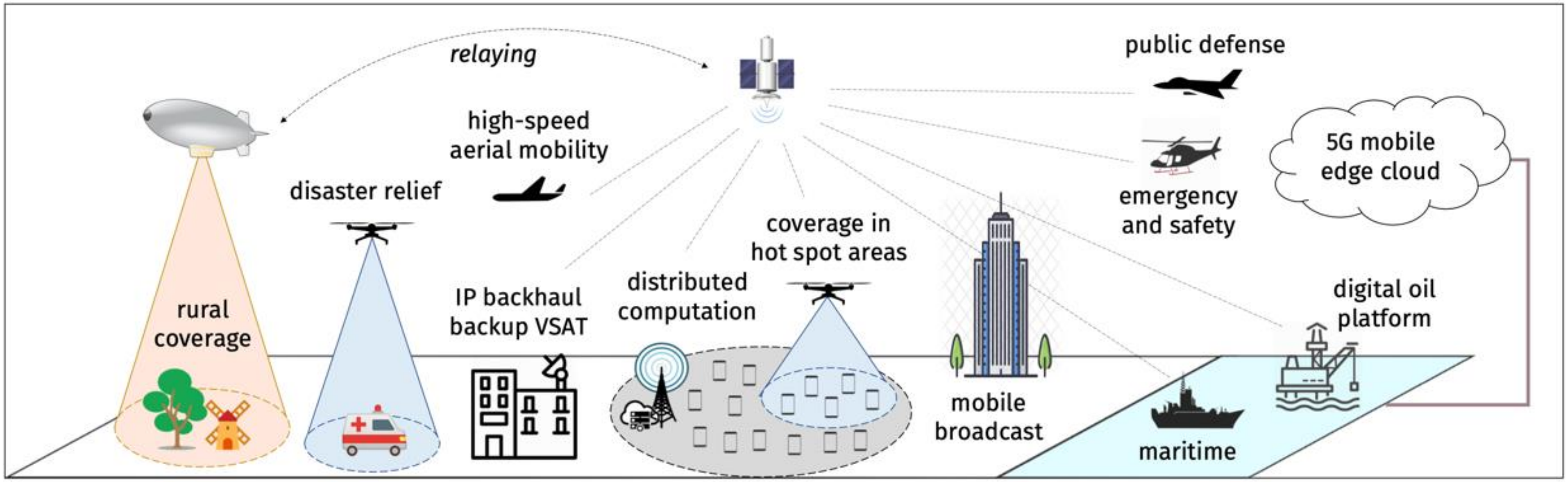


DOWNLOAD for FREE
https://gitlab.com/mattiasandri/ns-3-ntn

M. Sandri, M. Pagin, M. Giordani, M. Zorzi, "Implementation of a Channel Model for Non-Terrestrial Networks in ns-3," WNS3, 2023.

Conclusions

- It is by now widely recognized that **NTNs** will be a key component of the future 6G telecommunication landscape.
  - Support of trunking, backhaul, mobility, hybrid multiplay, robustness, etc.
- Joint efforts by researchers, policymakers and industry players will lead to a dramatically improved connectivity experience for tomorrow's generation that will deliver **ubiquitous and continuous services**.
- However, there are **many questions** to answer for proper network design.



Conclusions

NTN feature	Effect	Impact on NR stack
Motion of the space/aerial vehicles (especially for NGSO-based access networks)	Moving cell pattern	Handover/paging
		Initial access
	Delay variation	Synchronization / TA adjustment
	Doppler	
Altitude	Long propagation delay	HARQ
		MAC/RLC control loops
		Access scheme (TDD/FDD)
		Scheduling (especially in uplink)
		Transport layer (especially TCP)
Cell size	Differential delay	Random access response messages
	Massive number of UEs	Handover/paging
		Capacity saturation
Propagation channel	Channel impairments	DM-RS frequency density
		Channel modeling
Spectrum	Regulatory constraints	Spectrum co-existence

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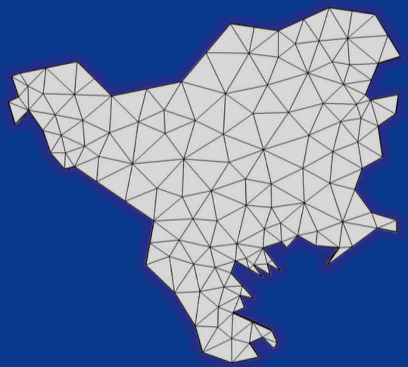

The Potential of Non-Terrestrial Networks for 6G: Technologies and Challenges

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