

An overview of 6G Multi-Functional Satellite Systems for Communication, Sensing and Positioning

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Who we are?

SIGCOM Research Group

Head:



Prof. Symeon Chatzinotas

Fellow IEEE

Full Professor/Chief Scientist I

Interdisciplinary Centre for Security, Reliability and Trust

SIGCOM in Numbers



Total **budget** 2025 ~ ca 12MEuros



Personnel: 97

- 1 Prof. (IEEE Fellow)
- 5 Research Scientists (permanent)
- 5 Research Scientists (contract)
- 33 PostDocs
- 29 PhDs
- 13 Research Fellows
- 7 R&D specialists
- 4 Support Personnel



Main Areas:

- Wireless Comms & Networking
- Non-Terrestrial Networks
- Quantum Communications



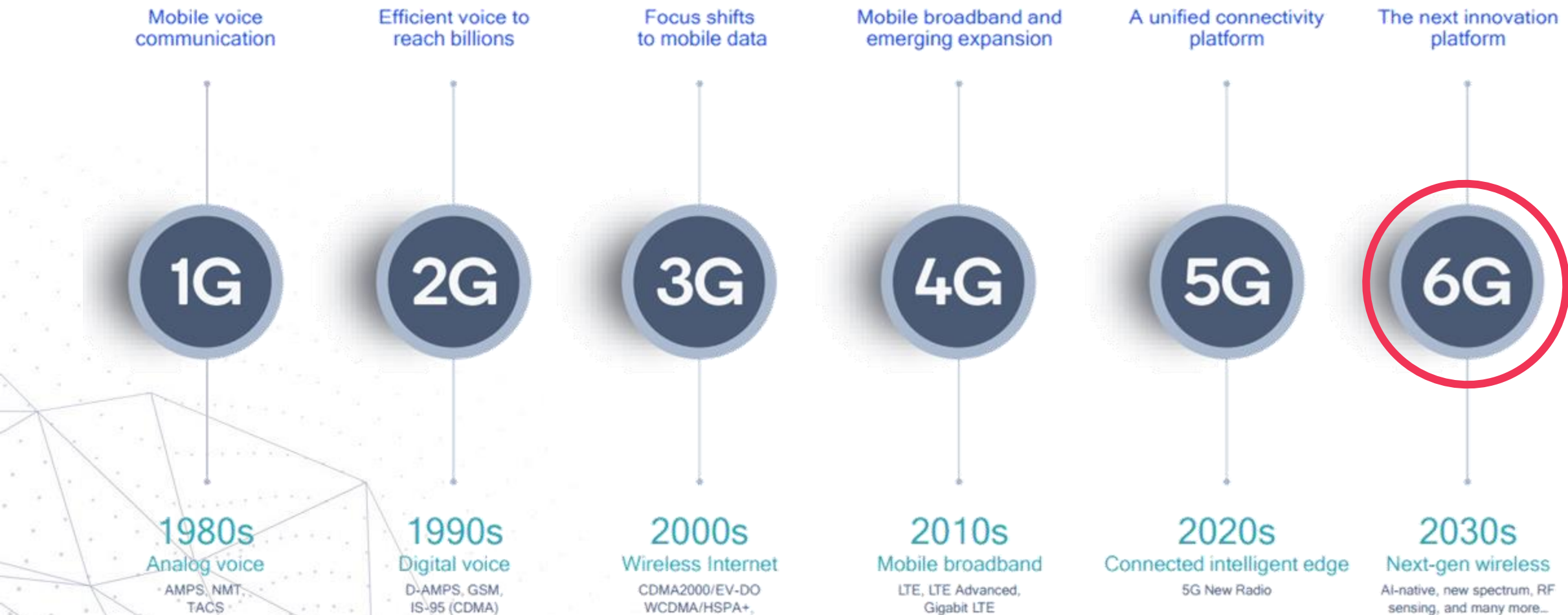
Outline

- **Who we are? [5 min]**
- **Part I: Multi-Functional Satellite Systems (MFSS) in 6G-NTN [20 min + 5 min Q&A]**
- **Part II: Joint Communications and Sensing (JCAS) [35 min + 10 min Q&A]**
 - Introduction
 - Applications
 - Sensing-centric Design
 - Communication-centric Design
 - Future Directions
- **Part III: Joint Communications and PNT (JCAP) [35 min + 10 min Q&A]**
 - Introduction
 - JCAP Architectures
 - JCAP Receivers
 - Performance PNT limits
 - Challenges and future trends



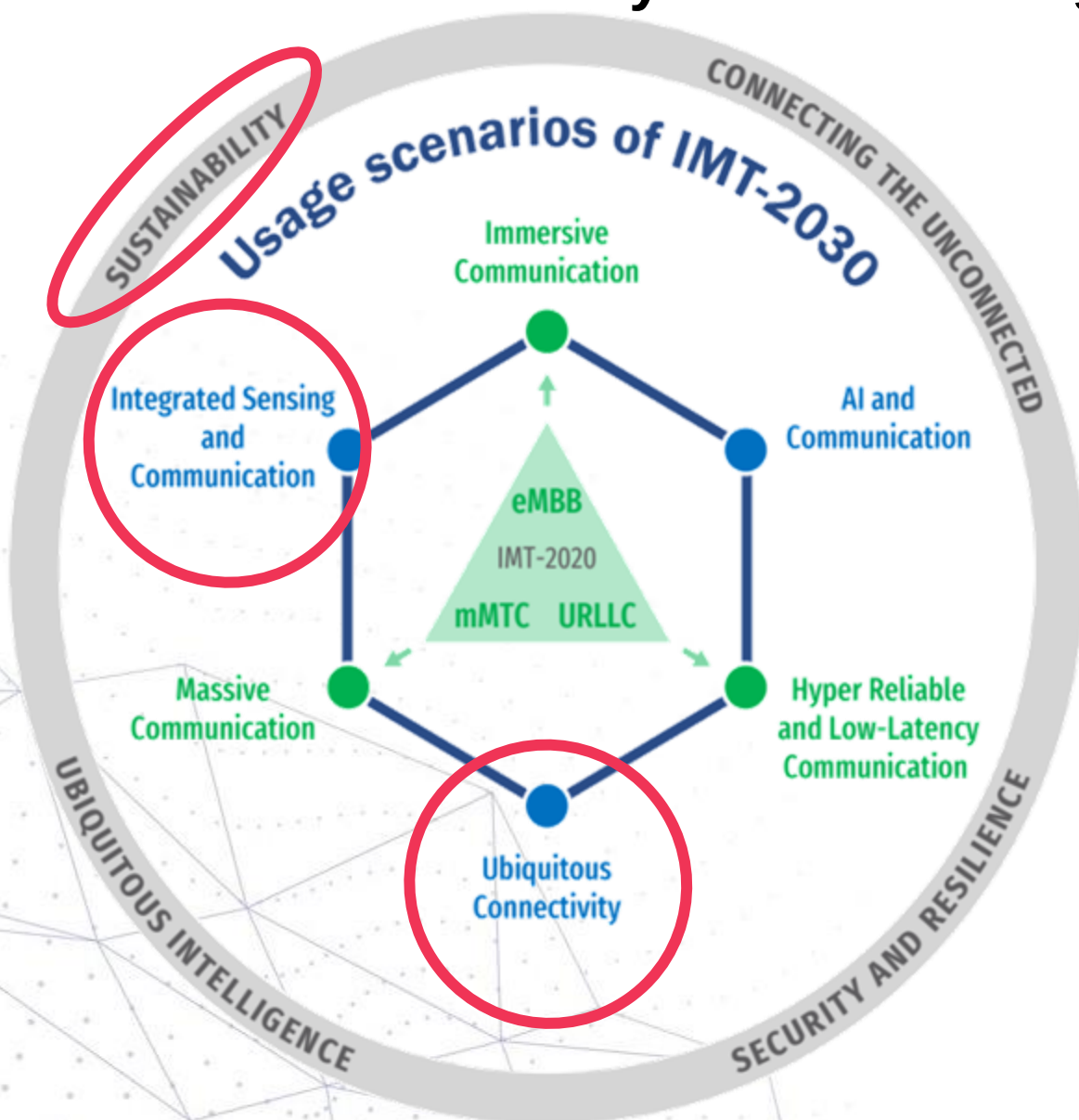
Multi-Functional Satellite Systems (MFSS) in 6G-NTN

Communications System – Evolution of Mobile Networks

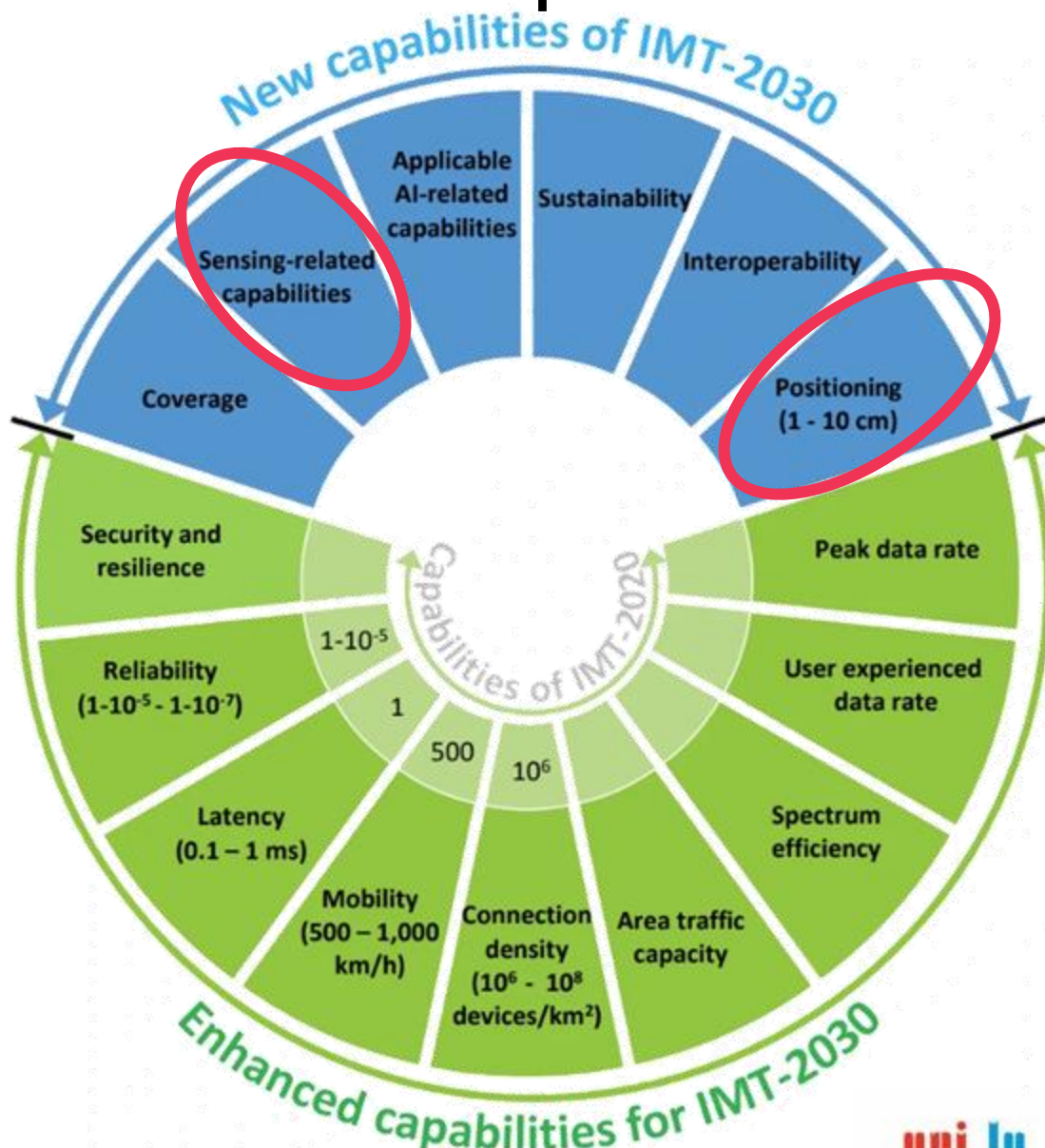


Evolution of mobile communication networks

Communications System – 6G Usage Scenarios and Requirements

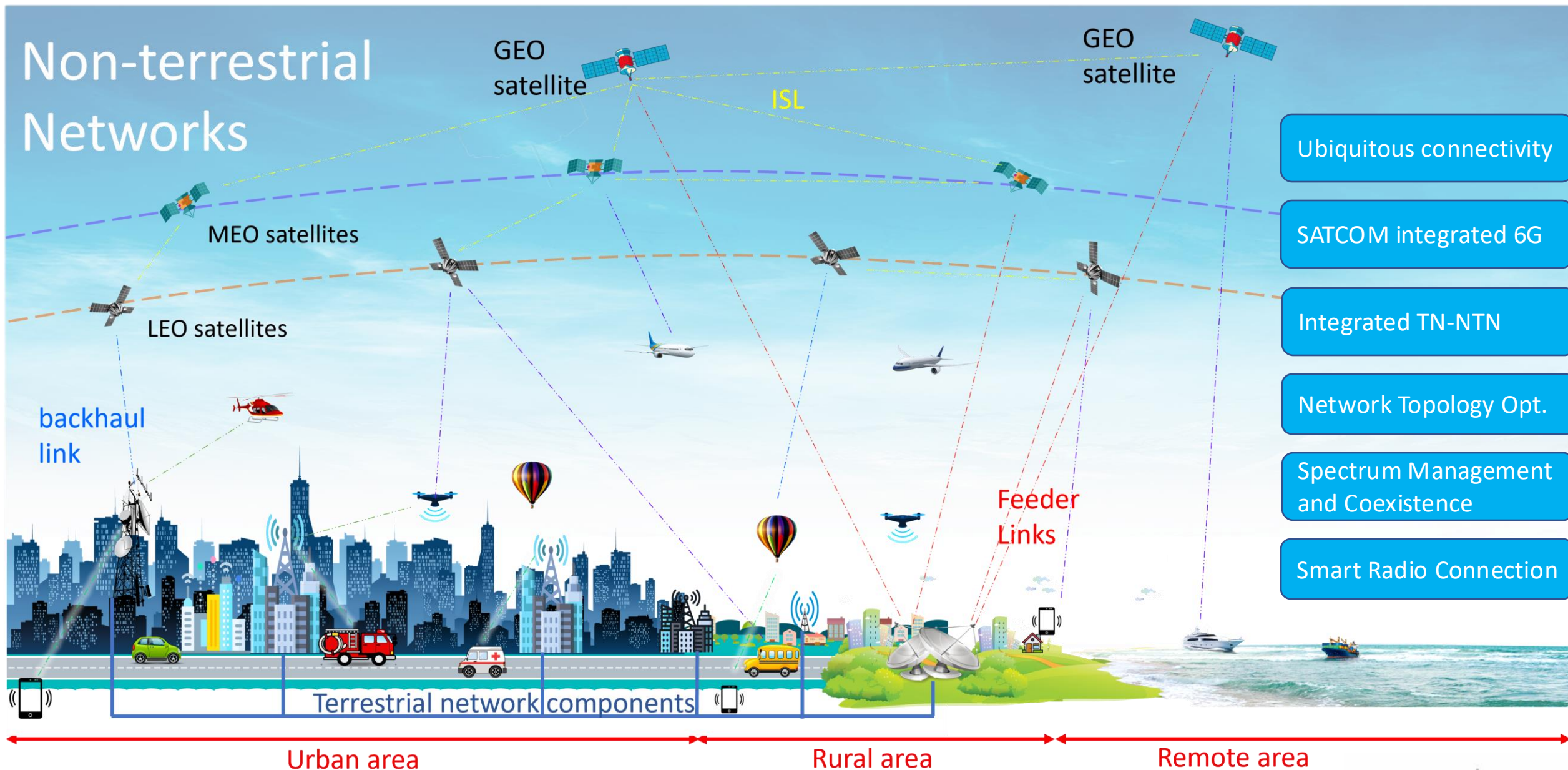


6G usage scenarios

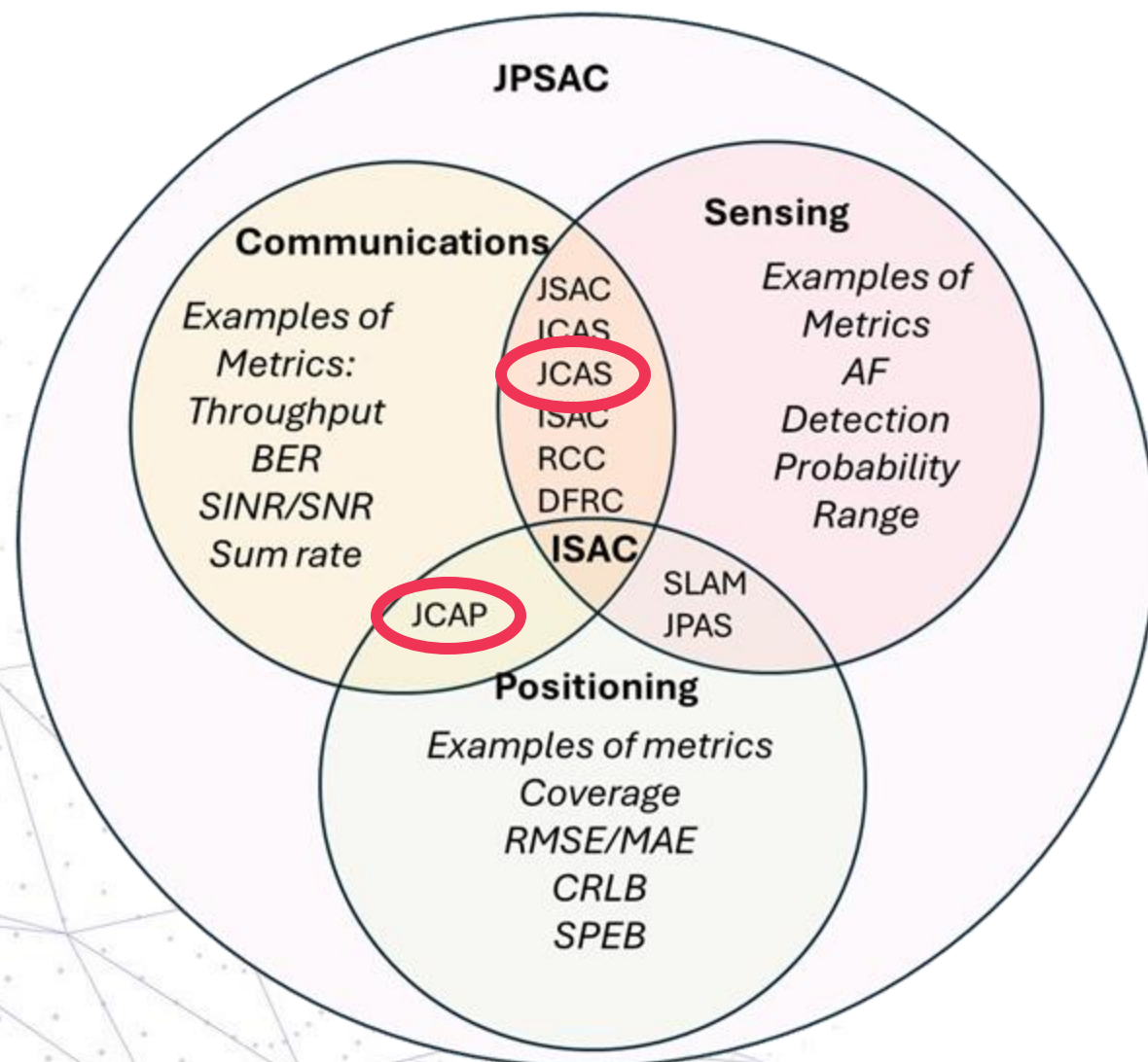


6G requirements

Non-terrestrial Networks



Joint Functionality Nomenclature in Scientific Papers



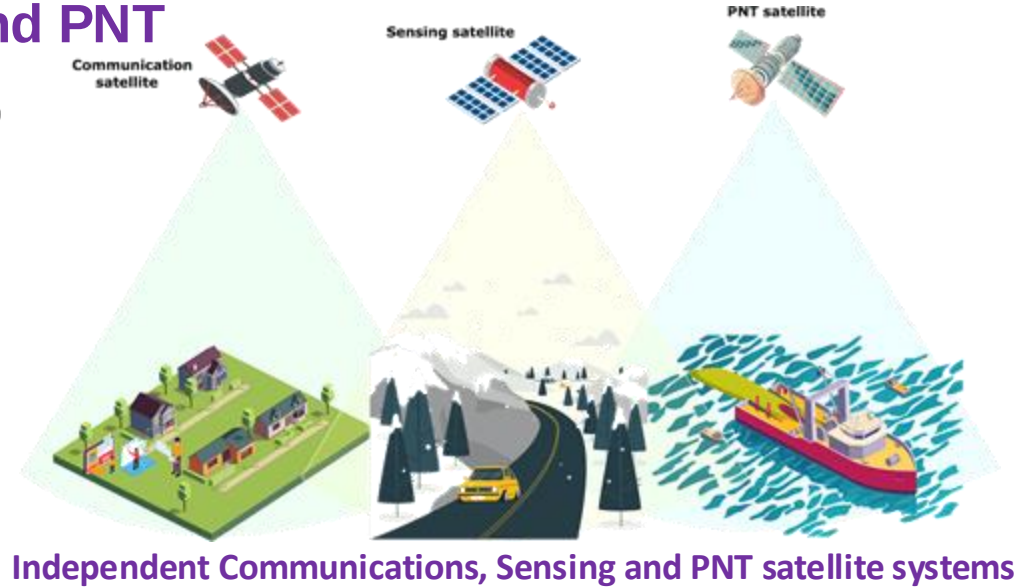
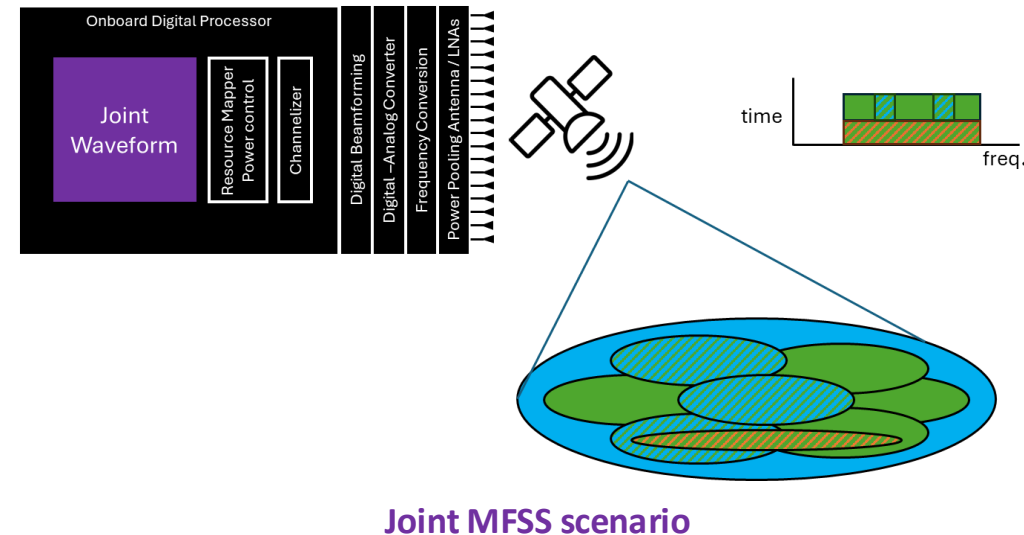
Enabler from SATCOM 6G-NTN perspective:

Multi-Functional Satellite Systems (MFSS)

Multi-Functional Satellite Systems (MFSS)

New MFSS paradigm: concurrent comms, sensing and PNT

- ❑ Different levels of inter-system interaction (see next slides)
- ❑ MFSS main advantages:
 - ❑ Extremely High Spectral Efficiency: Integration of systems
 - ❑ Reduced Launching Mass/Costs: Combined operations
 - ❑ Enhanced Energy Efficiency: Eliminating redundant hardware
 - ❑ Lower Hardware Costs: Merging multiple functionalities
 - ❑ Mutual Benefits: Better coordination
- ❑ Grand Challenges:
 - ❑ Multi-service interference modelling and management
 - ❑ Spatio-temporal-spectral multiplexing and DL/UL duplexing
 - ❑ Joint MFSS satellite payload, terminal and waveform design



MFSS Inter-system Interaction Levels

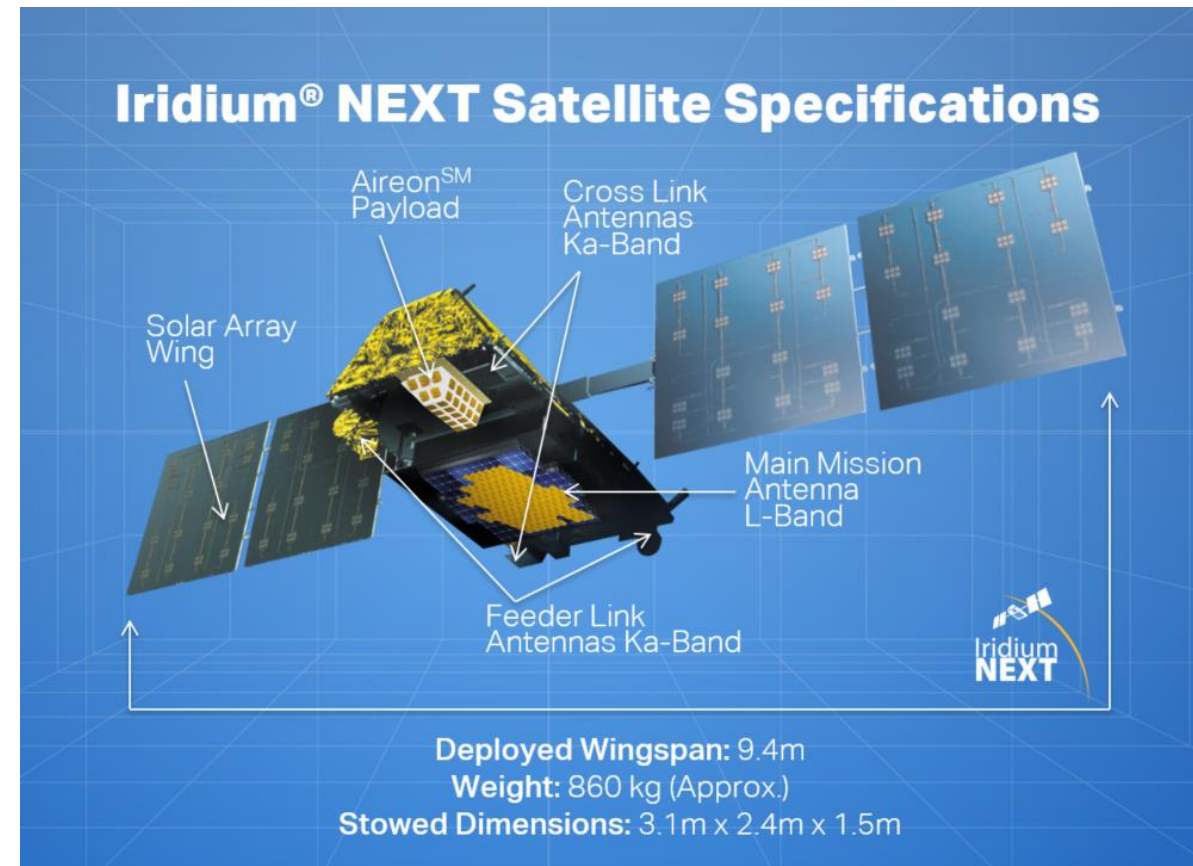
MFSS Precursor: Hosted Payloads

- ❑ Same Satellite Platform (shared satellite subsystems)
- ❑ Independent payloads and antennas/carrier freq.
- ❑ Hosted payloads are a commercial reality

“A portion of a satellite, such as a sensor, instrument or a set of communications transponders that are owned by an organization or agency other than the primary satellite operator [Owner]. The hosted portion of the satellite operates independently of the main spacecraft, but shares the satellite’s power supply, transponders, and in some cases, ground systems.”

❑ Example: Aireon ADS-B service on Iridium NEXT

- ❑ Automatic Dependent Surveillance–Broadcast (1090 MHz)
- ❑ Iridium User Links (1616 MHz – 1626.5 MHz)



MFSS Inter-system Interaction Levels

Level 1: Co-located Systems

- ❑ Shared payload hardware (SDR)
- ❑ Independent antennas/carrier freq.

Software-Defined Radio (SDR) payloads are state-of-the art

- ❑ **Satellite Communications:** Eutelsat Quantum, Iridium NEXT, SES-17
- ❑ **Spaceborne Sensing:** NASA CYGNSS, NASA RainCube, ICEYE SAR

Examples of operational SDR-based satellite payloads (with single functionality)



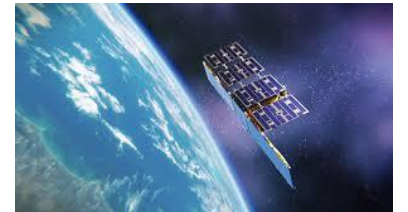
EUTELSAT



iridium



SES
beyond frontiers



ICEYE

❑ Main Challenges:

- ❑ **Payload Integration Complexity:** requires advanced coordination to ensure compatibility
- ❑ **Security and Data Privacy:** ensuring secure communication and data privacy in multi-operator
- ❑ **Constellation Design:** targeted use cases for satcom, spaceborne sensing and PNT must meet similar requirements

MFSS Inter-system Interaction Levels

Level 1: Co-located Systems

- ❑ There are already operational cases of JCAS and JCAP in Co-located MFSS

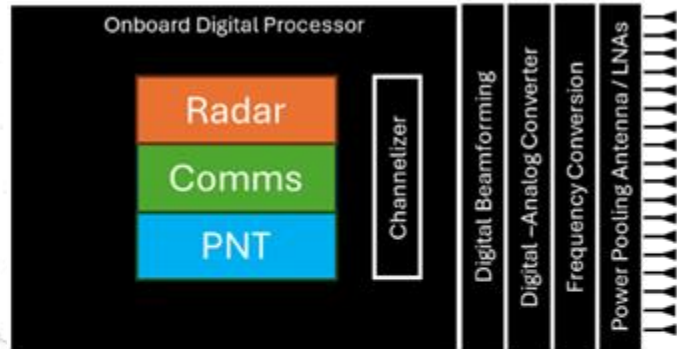
Satellite	Comms.	Sensing	Positioning	Key Applications
ISARA (Integrated Solar Array and Reflectarray Antenna)	✓	✓		Earth observation + high-speed data links
CYGNSS (Cyclone Global Navigation Satellite System)	✓	✓		Hurricane tracking + GNSS reflectometry + Ka-band downlink
FSSCat (Federated Satellite Systems 3Cat Mission)	✓	✓		Climate monitoring + data relay
TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats)	✓	✓		Weather observation + real-time comms
Galileo Second Generation (G2G) Satellites (<i>Planned</i>)	✓		✓	Navigation + flexible inter-satellite links
TDRS (Tracking and Data Relay Satellite) Series	✓		✓	Spacecraft comms + precise orbit tracking

MFSS Inter-system Interaction Levels

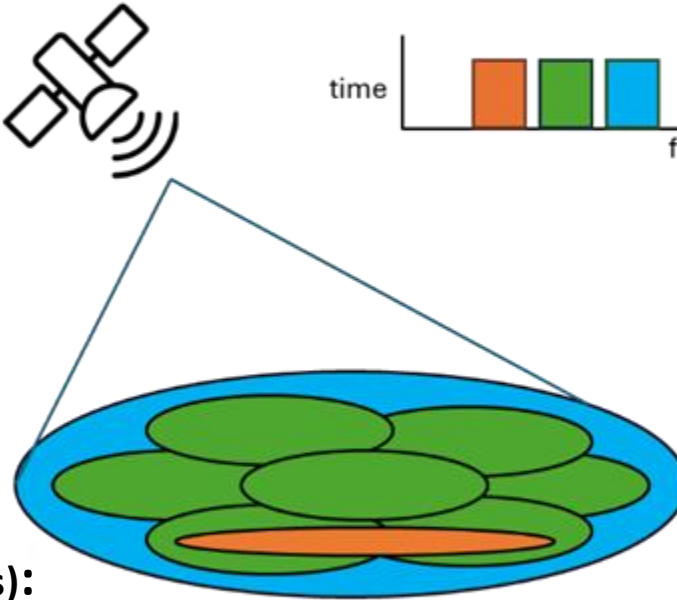
Level 2: Cooperative Systems

- ❑ Shared antennas/carrier freq.
- ❑ Operate in independent sub-bands

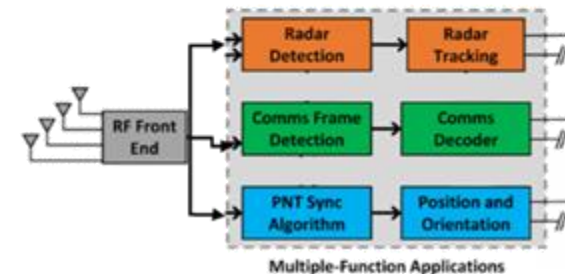
Cooperative payload



Reuse antenna system and channelizer (same OBDP), operate in FDM in same band, need for interference mitigation



- ❑ Main Challenges (added to previous ones):
 - ❑ Need for adjacent channel interference mitigation
 - ❑ Synchronization and coordination between Functions (DL/UL)



MFSS Inter-system Interaction Levels

Level 2: Cooperative Systems

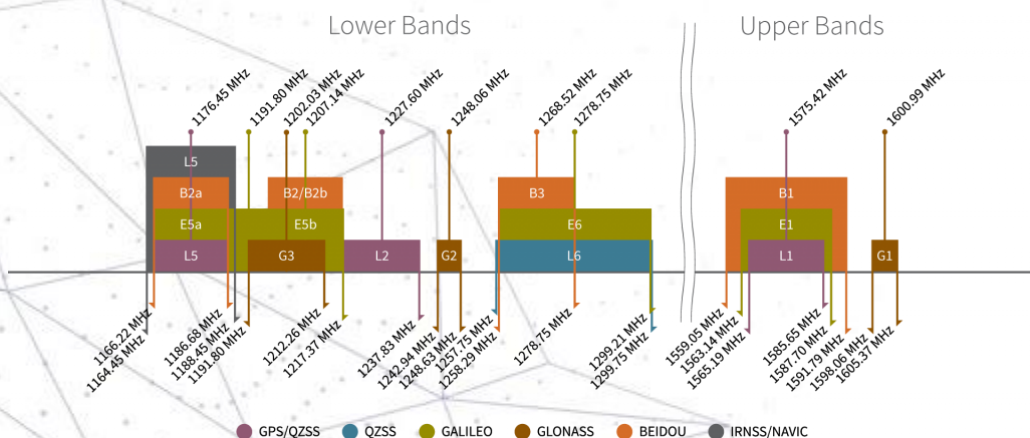
❑ Current allocations show potential adjacent bands to be used with same antenna and SDR payload

Frequency band	Frequency range (GHz)	Satellite service type	Applications
L-band	1.518-1.675	MSS (mobile satellite services)	Civil mobile communication services, global positioning system, weather radar systems
S-band	1.97-2.69	MSS	Satellite TV, mobile broad band services, radio broadcasting, in-flight connectivity
C-band	3.4-7.025	FSS (fixed satellite services)	Data services, satellite TV networks, unprocessed satellite feeds
X-band	7.25-8.44	FSS	Military operations, pulse radar systems, weather monitoring, air traffic control
Ku-band	10.7-14.5	FSS, broadband satellite service (BSS)	Fixed satellite television data services
Ka-band	17.3-30	FSS, BSS	Two-way broadband services, fixed satellite data services
Q/V band	37.5-51.4	MSS, BSS	High-speed broadband services, in-flight connectivity

Satellite Communications frequency bands

Satellite Frequency Bands	Allocated Frequency for Active Sensing	Assigned Bandwidth for Sensors				
		Scatterometer	Altimeter	SAR	Precipitation radar	Cloud profile radar
P (0.3-1 GHz)	432-438 MHz			6 MHz		
L (1-2 GHz)	1215-1300 MHz	5-500 kHz		20-85 MHz		
S (2-4 GHz)	3100-3300 MHz		200 MHz	20-200 MHz		
C (4-8 GHz)	5250-5570 MHz	5-500 kHz	320 MHz	20-320 MHz		
X (8-12 GHz)	8550-8650 MHz	5-500 kHz	100 MHz	20-100 MHz		
	9300-9900 MHz	5-500 kHz	300 MHz	20-600 MHz		
Ku (12-18 GHz)	13.25-13.75 GHz	5-500 kHz	500 MHz		0.6-14 MHz	
	17.2-17.3 GHz	5-500 kHz			0.6-14 MHz	
K (18-27 GHz)	24.05-24.25 GHz				0.6-14 MHz	
Ka (27-40 GHz)	35.5-36 GHz	5-500 kHz	500 MHz		0.6-14 MHz	
W (75-110 GHz)	78-79 GHz					0.3-10 MHz
	94-94.1 GHz					0.3-10 MHz
G (110-300 GHz)	133.5-134 GHz					0.3-10 MHz
	237.9-238 GHz					0.3-10 MHz

Frequency bands allocated for spaceborne radars



GNSS frequency bands

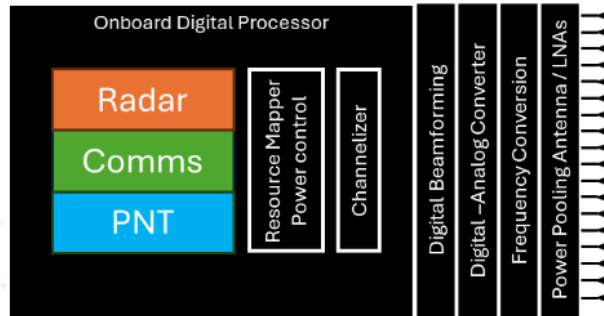
Source: <https://www.tallysman.com/gnss-constellations-radio-frequencies-and-signals/>

MFSS Inter-system Interaction Levels

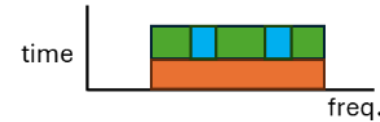
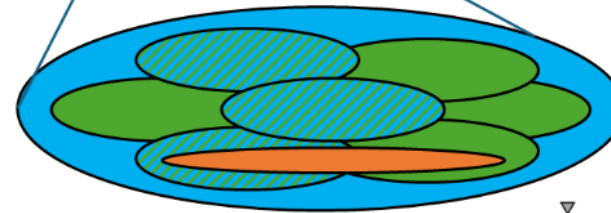
Level 3: Integrated Systems

- ❑ Shared Digital Signal Processing (DSP) Blocks
- ❑ Shared (sub-)band → Need for time/freq./space multiplexing

Integrated payload

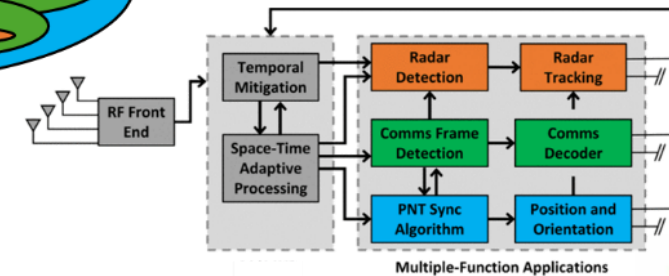


Reuse digital processing blocks, operate in TDM+FD in same band, need for joint optimization, potential use of full-duplex



❑ Main Challenges (added to previous ones):

- ❑ Advanced resource allocation and interference mitigation
- ❑ Requirement of DL/UL full-duplex (in some cases)
- ❑ Latency and processing overhead

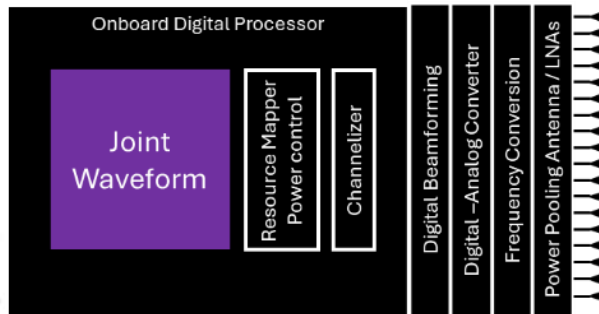


MFSS Inter-system Interaction Levels

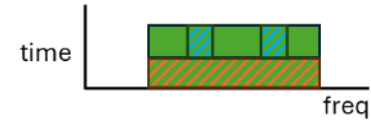
Level 4: Jointly Designed Systems

- ❑ Unified and common waveform
- ❑ Flexible and reconfigurable in real-time

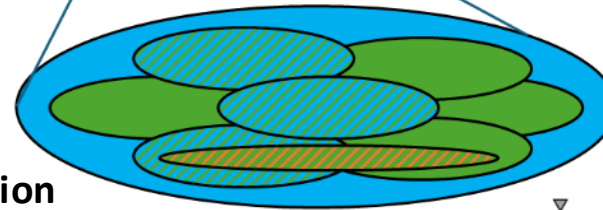
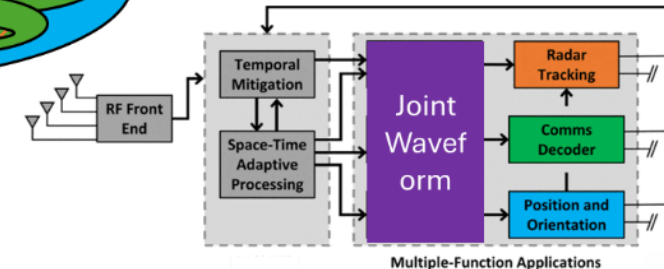
Joint payload



Joint waveform design, may operate dynamically in full-duplex, need for optimized operation



- ❑ Main Challenges (added to previous ones):
 - ❑ Joint Waveform and Beamforming Optimization
 - ❑ Self-Shielding Techniques Against Radar Interference
 - ❑ Optimal Receiver Design for Superimposed Signals







Joint Communications and Sensing (JCAS)

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- Communications System
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- Joint Communications and Sensing Systems

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- Enhanced Navigation and Tracking
- Security
- Emergency and Disaster Management
- Digital Twin

2.3. Sensing-centric Design

- Design Principles
- Transceiver Design
- Waveform Design and Signal Processing
- Parameter Estimation

2.4. Communication-centric Design

- Design Principles
- Transceiver Design
- Waveform Design and Signal Processing
- Parameter Estimation

2.5. Future Directions

- JSAC Design Challenges
- Joint Design Principles
- Joint Design Challenges

Introduction

Communications System – Service Aspects

1G – 4G

„Infrastructure-as-a-Service“

Connectivity

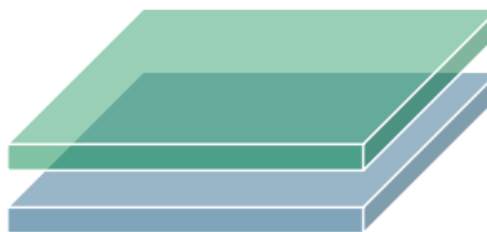


Phones

5G

„Infrastructure-as-a-Service“

Computing
Connectivity



Things

6G

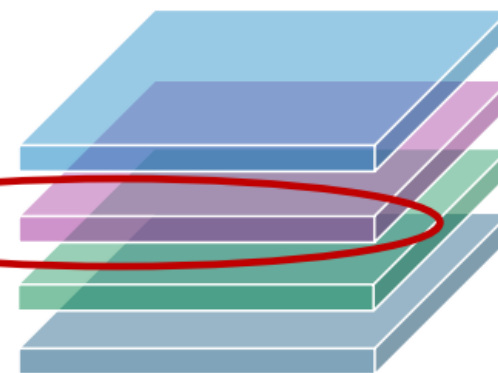
„Everything-as-a-Service“

Intelligence

Sensing

Computing

Connectivity



Intelligent Things

Fig. 1: Service aspects of different generations of mobile communication networks

Communications System – Limitations

- ❖ Limitations of existing mobile communication networks:
 - ❖ They **support only active localization** techniques or device-based sensing.
 - ❖ I.e., **device must be connected to the network** and able to communicate to enable location services.
 - ❖ **Communication and sensing systems are built independently.**

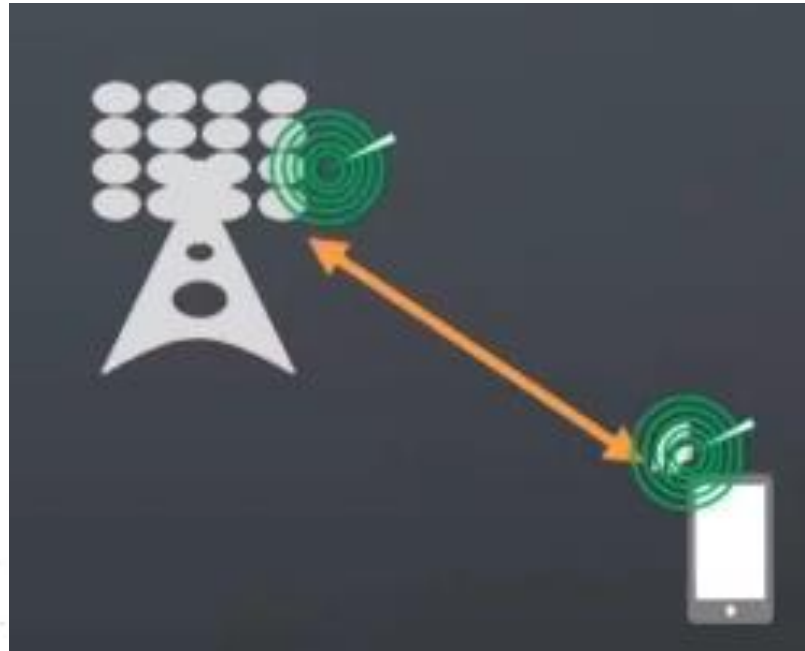


Fig. 2: Device-based sensing

Communications System – 6G Features

- ❖ Limitations of existing mobile communication networks:
 - ❖ They **support only active localization** techniques or device-based sensing.
 - ❖ I.e., **device must be connected to the network** and able to communicate to enable location services.
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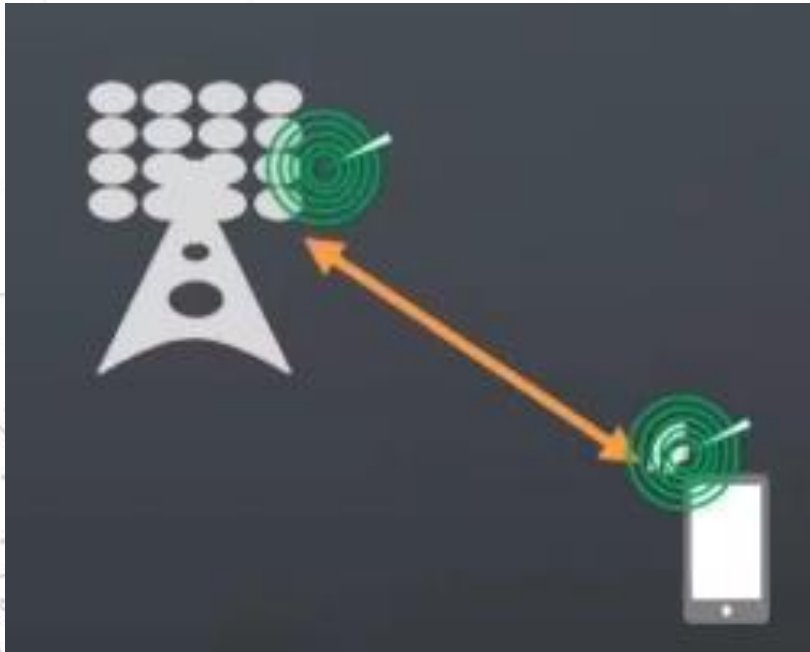


Fig. 2: Device-based sensing

- ❖ 6G features:
 - ❖ 6G will **support both active and passive sensing.**
 - ❖ I.e., can support both device-based and **device-free sensing.**
 - ❖ Aims to design **a single system that can mutually support both communications and sensing.**

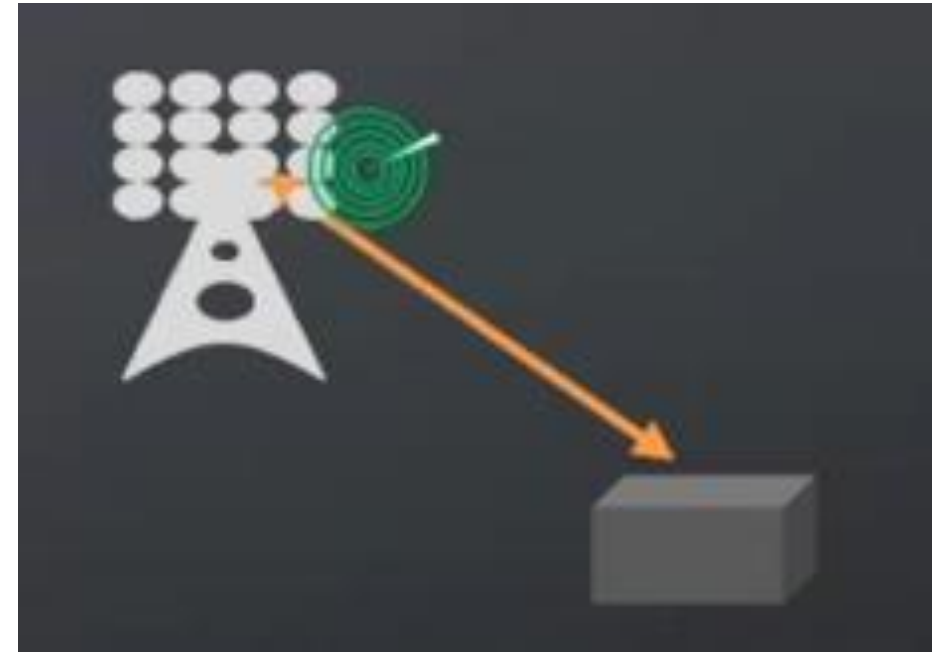


Fig. 3: Device-free sensing

Sensing System – Introduction

- ❖ In modern sensing system, **radio signals are used to sense, detect, and track objects.**
- ❖ The objects to be sensed or detected can be illuminated by any radio signals of sufficient power, such as **TV signals, Wi-Fi signals, and mobile/cellular communication signals.**
- ❖ Both terrestrial network and **non-terrestrial network nodes with multiple-input and multiple-output (MIMO)** antenna elements are used for sensing and tracking purposes.
- ❖ Object, activity, and event recognition through radio sensing **can support diverse range of applications** in different domains.
- ❖ **Location, range, velocity, angle of arrival, and angle of departure** are some parameters to be estimated in sensing systems.
- ❖ Sensing parameter estimation types:
 - ❖ **Absolute** – The case in which **transmitter and receiver are synchronized and acting cooperatively.**
 - ❖ **Relative** – The case in which **transmitter and receiver are not synchronized and acting independently.**

Sensing System – Types

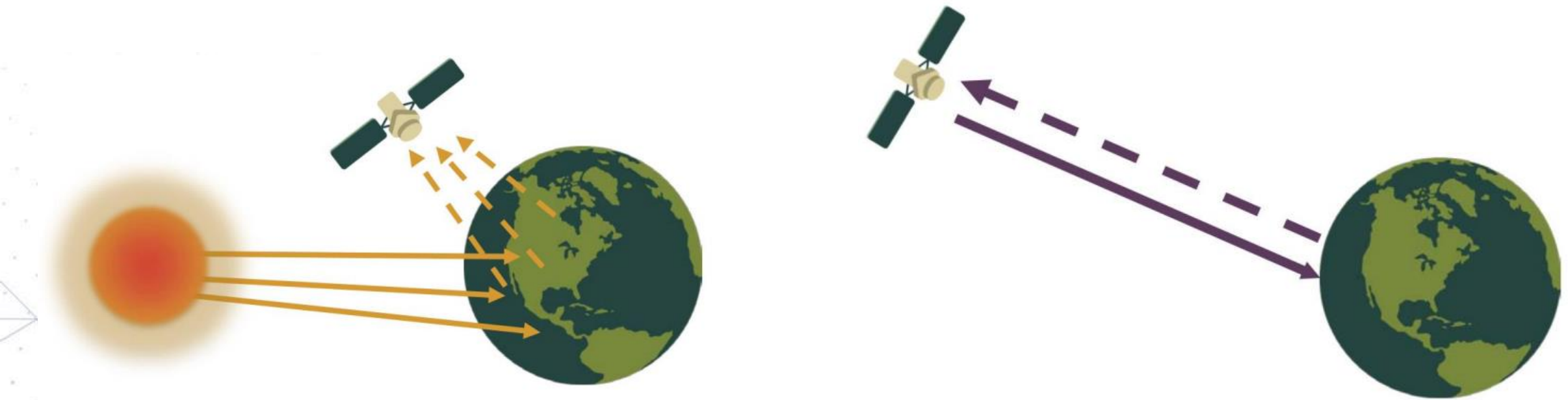


Fig. 4: Passive and active sensing systems

Sensing System – Classification

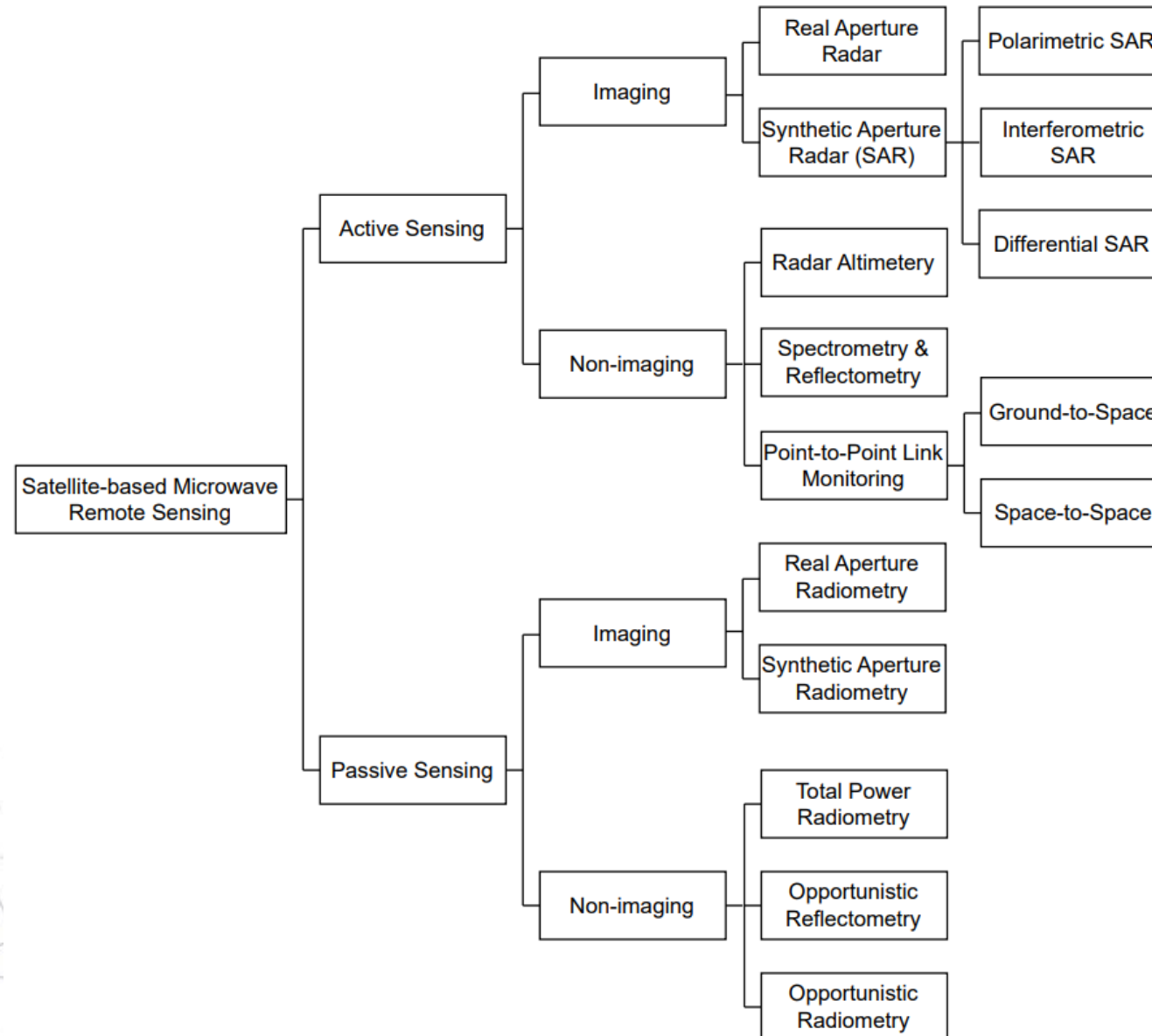


Fig. 5: Classification of microwave sensing techniques

Sensing System – Architectures

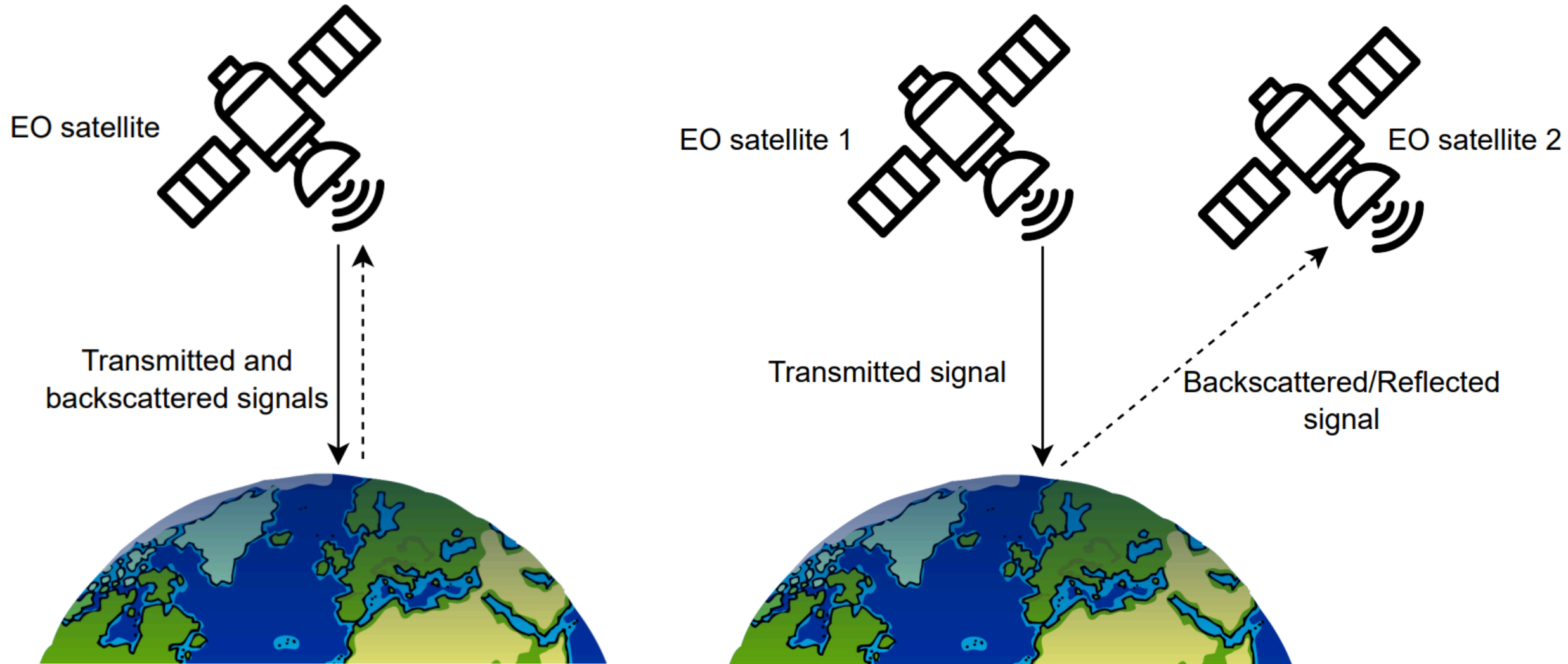


Fig. 6: Monostatic, bistatic, and multistatic sensing systems

Sensing System - Limitations

- ❖ Large bandwidth is assigned for better sensing and detection.
- ❖ Typically use high transmission power for better accuracy.
- ❖ Relative estimation of sensing parameters at the receiver end may cause ambiguity due to lack of knowledge of the transmitted signals and inaccuracy.

Communications System vs. Sensing System

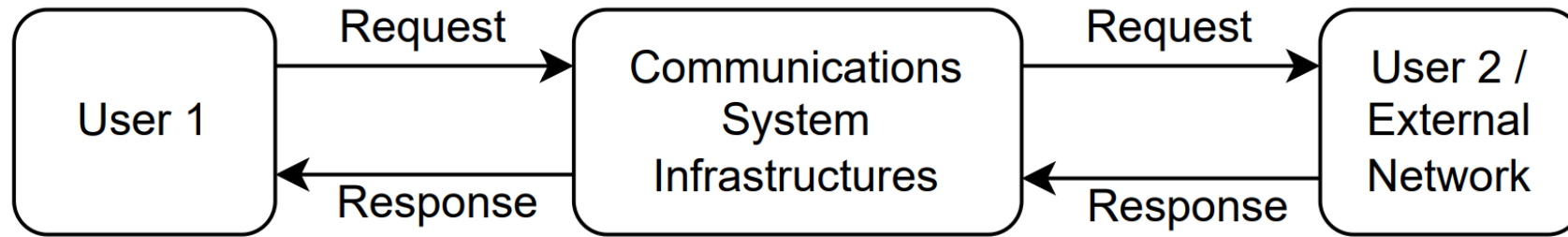


Fig. 7: A high-level view of communications system

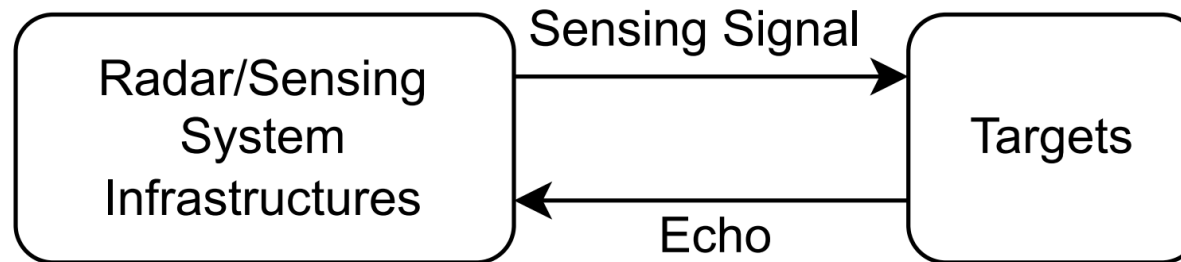


Fig. 8: A high-level view of radar/sensing system

Co-existence of Communications and Sensing Systems

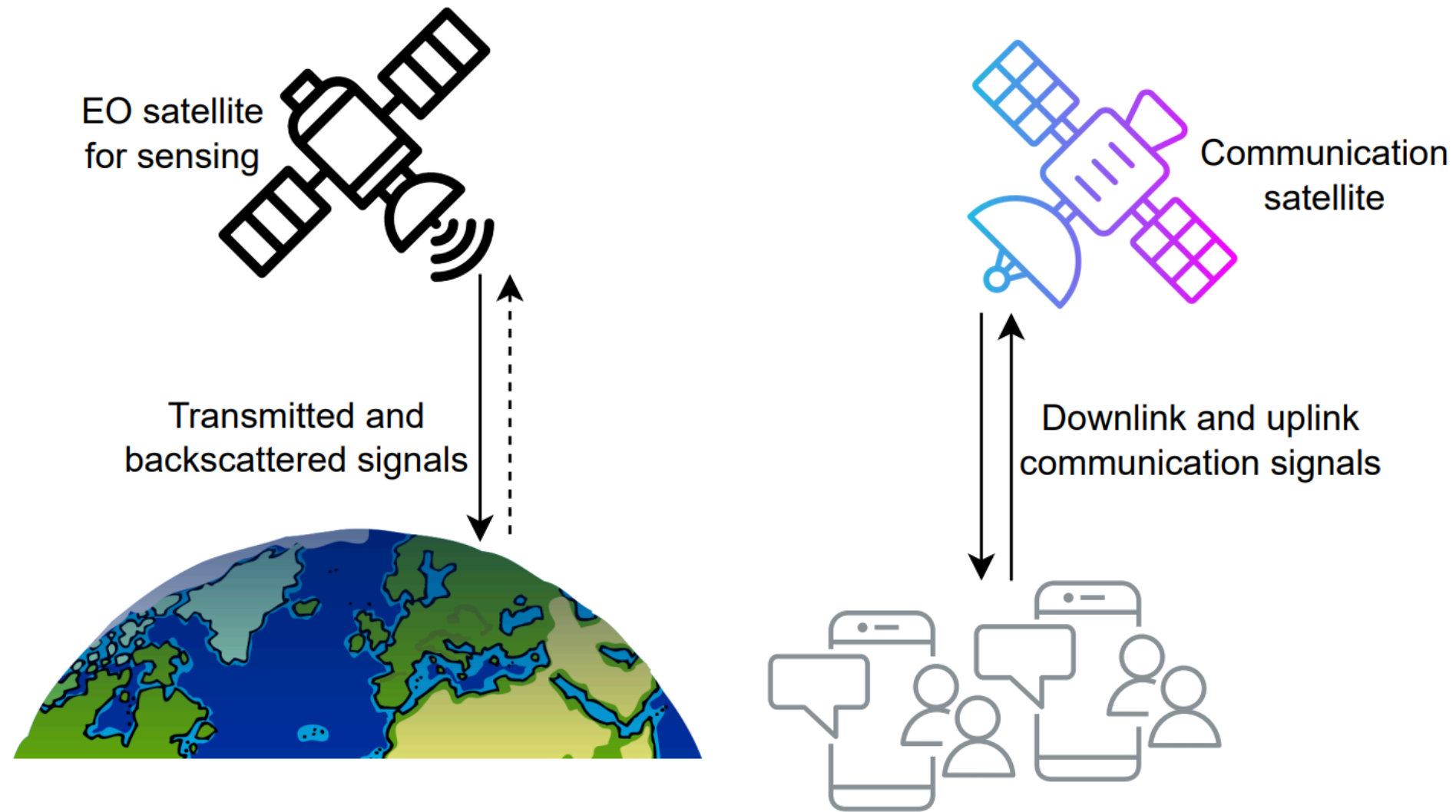


Fig. 9: Independent communication and sensing systems

Co-existence of Communications and Sensing Systems – Frequency Bands

Frequency Band	Radar Systems	Communication Systems
L-band (1-2GHz)	Long-range surveillance radar, ATC radar	LTE, 5G NR
S-band (2-4GHz)	Moderate-range surveillance radar, ATC radar, airborne early warning radar	IEEE 802.11b/g/n/ax/y WLAN, LTE, 5G NR
C-band (4-8GHz)	Weather radar, ground surveillance radar, vessel traffic service radar	IEEE 802.11a/h/j/n/p/ac/ax WLAN
MmWave band (30-300GHz)	Automotive radar, high-resolution imaging radar	IEEE 802.11ad/ay WLAN, 5G NR

Table 1: Shared frequency bands for communication and sensing systems

Co-existence of Communications and Sensing Systems – Interference Issue (1/2)

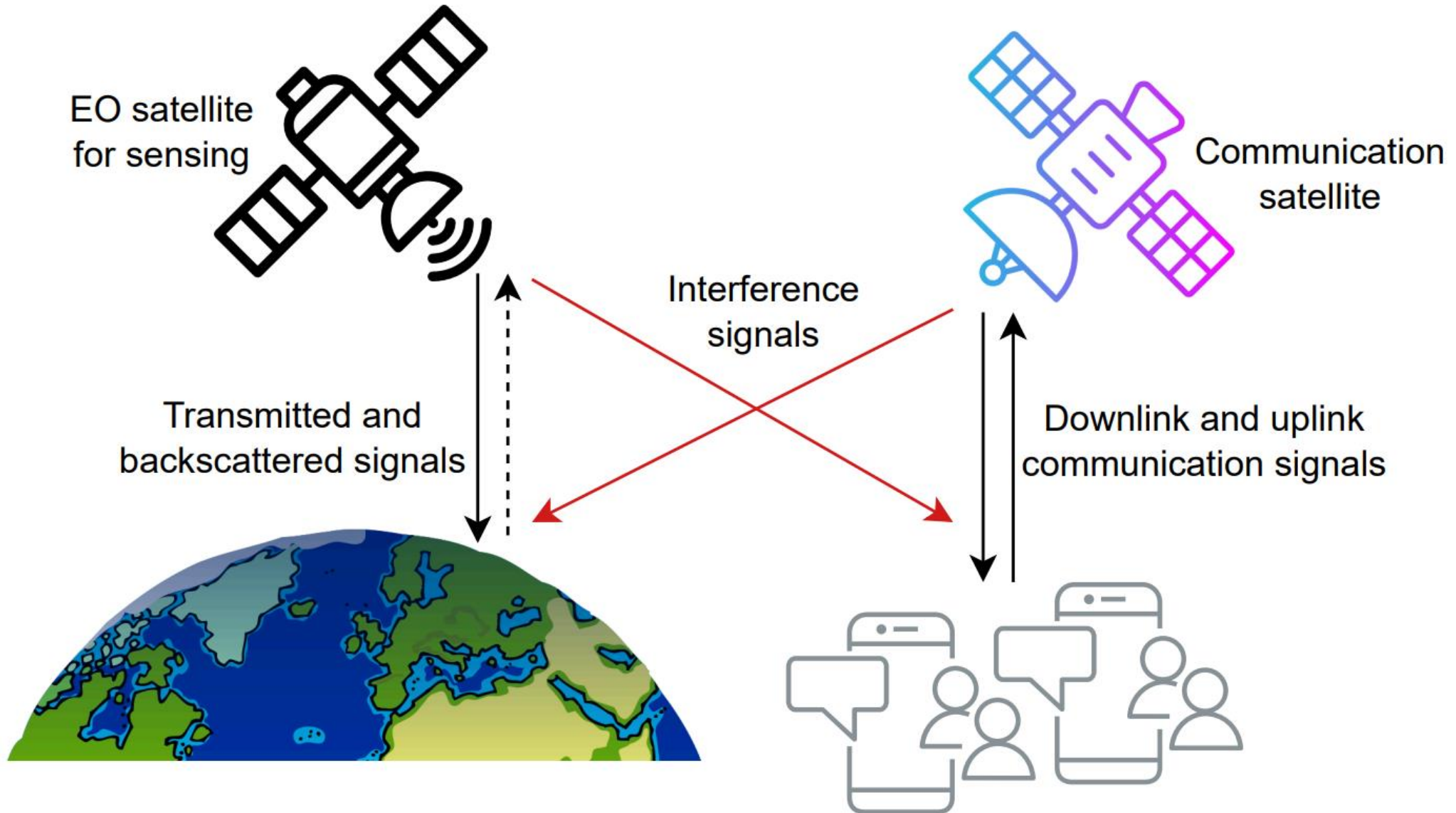


Fig. 10: Interference issue in coexistence of communication and sensing systems

Co-existence of Communications and Sensing Systems – Interference Issue (2/2)

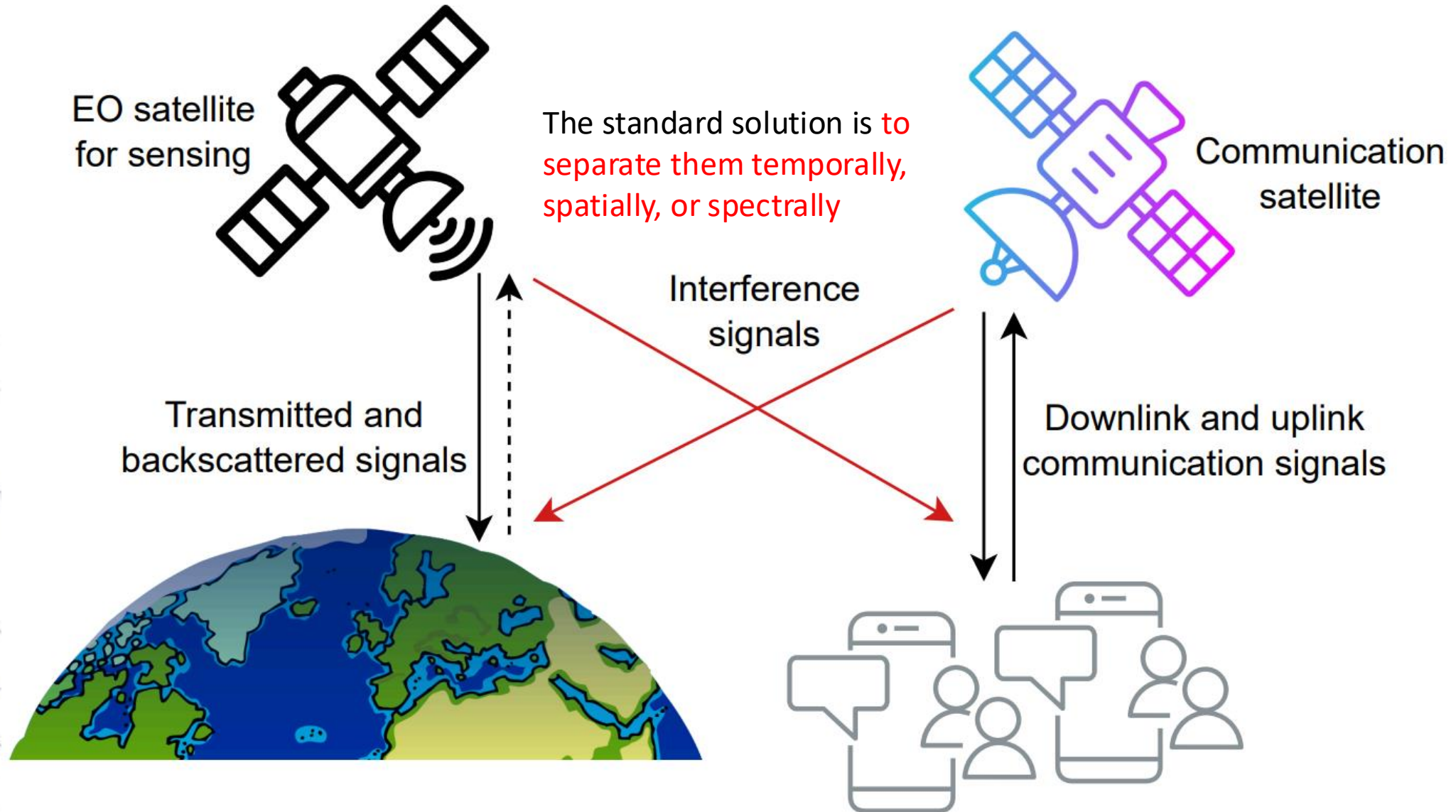


Fig. 10: Interference issue in coexistence of communication and sensing systems

Coexistence of Communications and Sensing Systems - Limitations

- ❖ Sensing systems typically **use large bandwidth and high transmission power** for better accuracy. However, it may cause severe interference to communications systems in coexistence scenarios.
- ❖ In coexistence of communications and sensing systems, great efforts have been devoted to **mutual interference cancellation** by using resource sharing methods such as cooperative spectrum sharing and opportunistic spectrum sharing (also known as cognitive radio).
- ❖ However, effective interference cancellation depends on the **mobility of nodes** and the information exchanged between them. Hence, spectral efficiency in those methods are limited.
- ❖ Moreover, **cooperative resource sharing methods require a good cooperation of nodes and complicated signal processing**, whereas **cognitive radio methods cannot guarantee the performance of secondary systems** and even may affect the performance of primary systems.

Joint Communications and Sensing (JCAS)

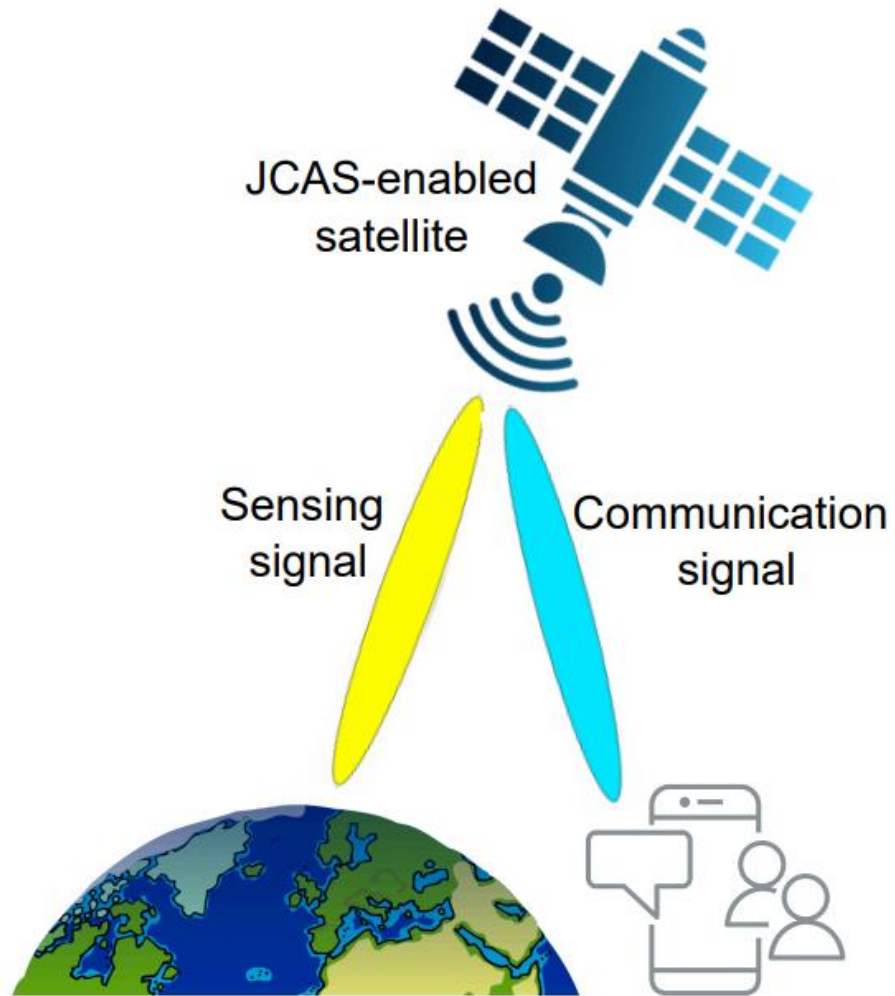


Fig. 11: Joint communication and sensing satellite

❖ JCAS is also known as:

- ❖ Integrated Sensing and Communications (ISAC)
- ❖ Joint Sensing and Communications (JSAC)
- ❖ Dual-Functional Radar and Communications (DFRC)
- ❖ Joint Radar and Communications (JRC)
- ❖ Joint Communications and Radar (JCR)
- ❖ Radar and Communications (RadCom)

JCAS – Motivation and Need (1/2)

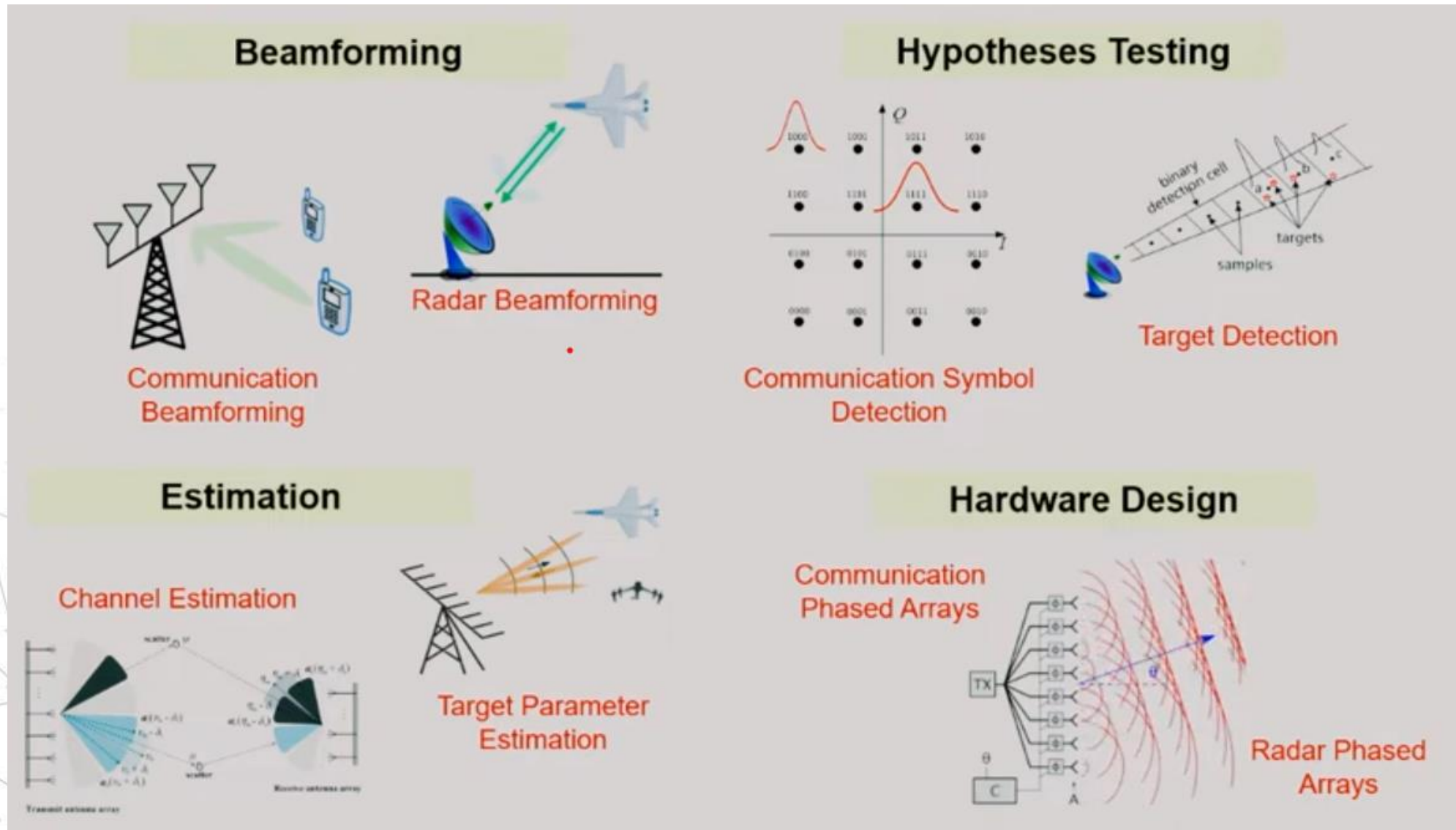


Fig. 12: Common functionalities of communications and sensing systems

JCAS – Motivation and Need (2/2)

❖ Better resource utilization:

- ❖ JCAS system cooperates instead of competing for resources.
- ❖ JCAS can share the same frequency band and hardware to improve the spectrum efficiency, reduce the hardware cost, and save energy.

❖ Mutual benefits:

- ❖ Communication links can provide better coordination among multiple nodes for sensing.
- ❖ Sensing provides environment-awareness to communications.
- ❖ Communication system infrastructures can be leveraged to realize wide-area and pervasive sensing.

❖ Support future requirements:

- ❖ JCAS can support future 6G applications such as smart transportation, agriculture, and immersive entertainment services that require both high-performance sensing and communication simultaneously.
- ❖ 6G will use high-frequency bands (e.g., millimeter wave and terahertz bands) with massive MIMO antennas, which can support high-resolution in both time and angular domain for enabling JCAS.

JCAS – Gains

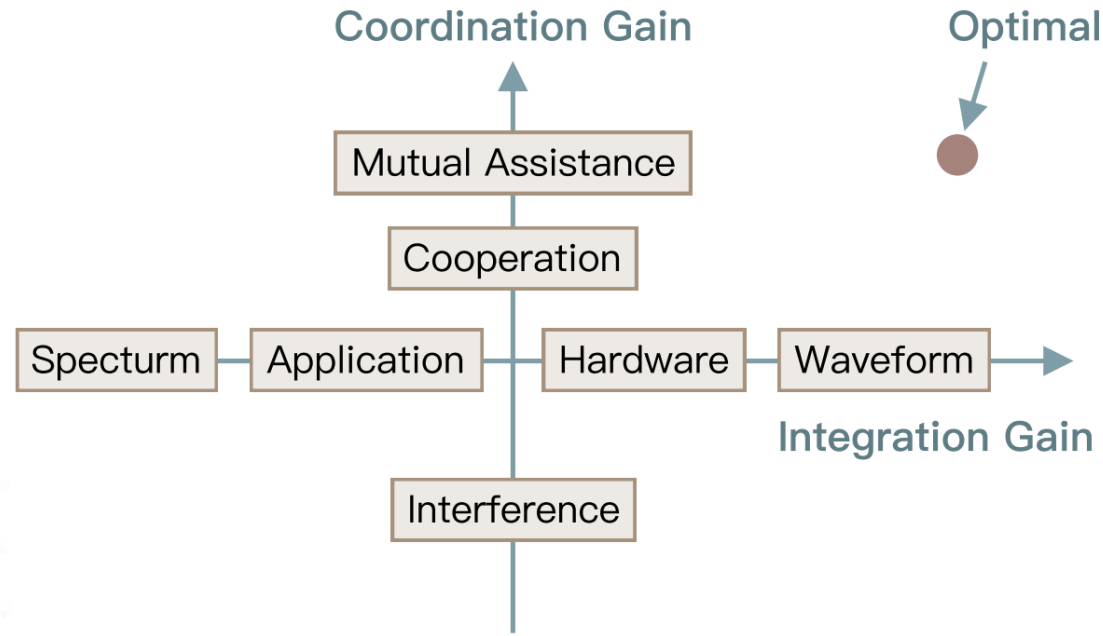


Fig. 13: The integration and coordination gains in JCAS

- ❖ Integration gain: It deals with **effective utilization of the existing communication and radar infrastructure resources**.
- ❖ Coordination gain: It deals with sharing system resources for co-design to **balance the performance of dual-functional systems with mutual assistance between communication and sensing systems**.

JCAS – Different Levels of Integration

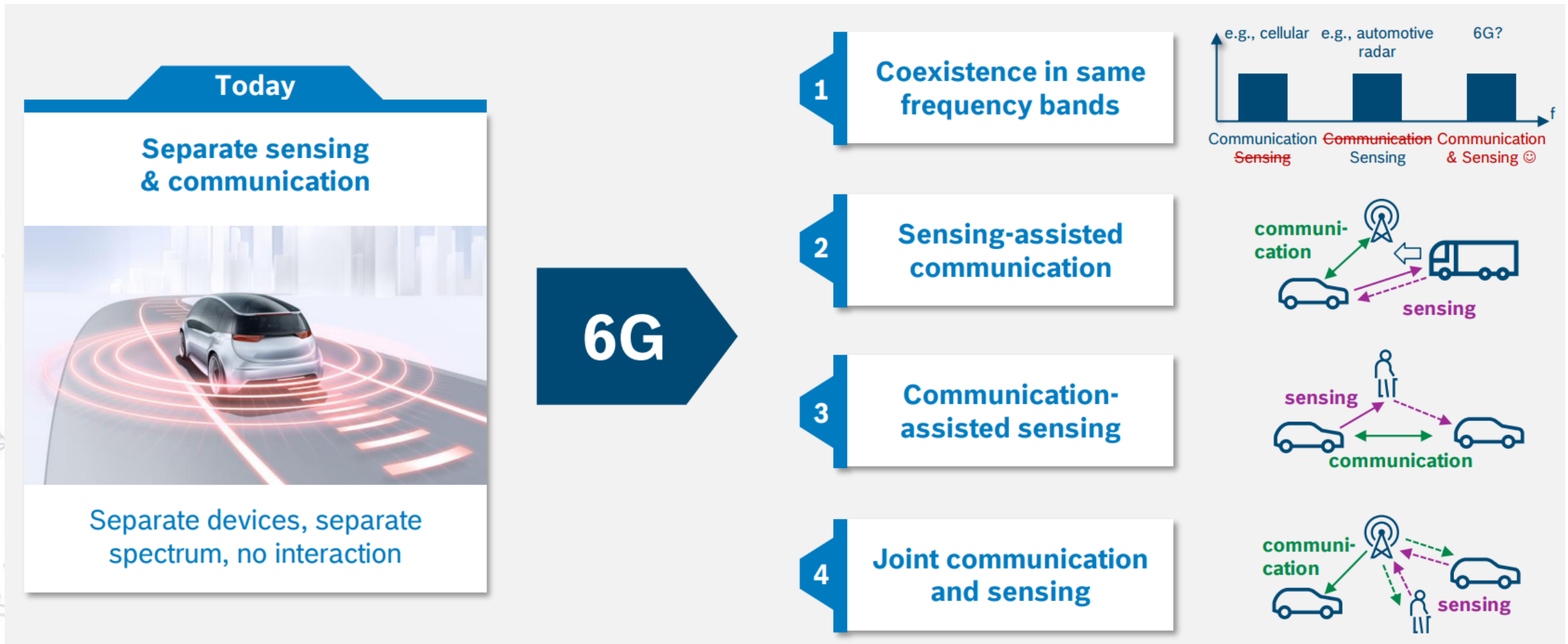


Fig. 14: Different levels of integration of communication and sensing

Applications

Remote Sensing and Earth Observation

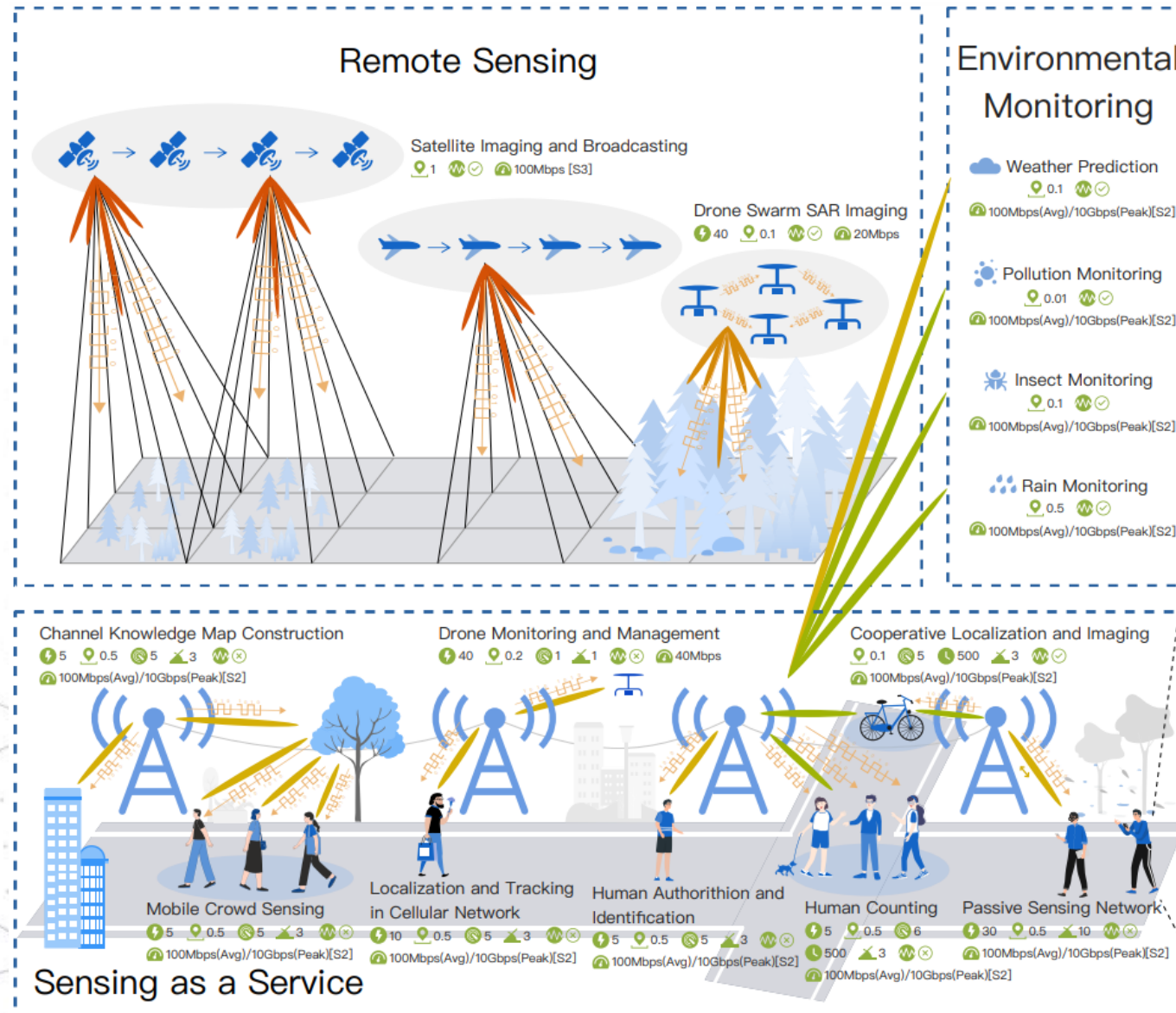


Fig. 15: An illustration of remote sensing and earth observation scenarios of JSAC

Enhanced Navigation and Tracking

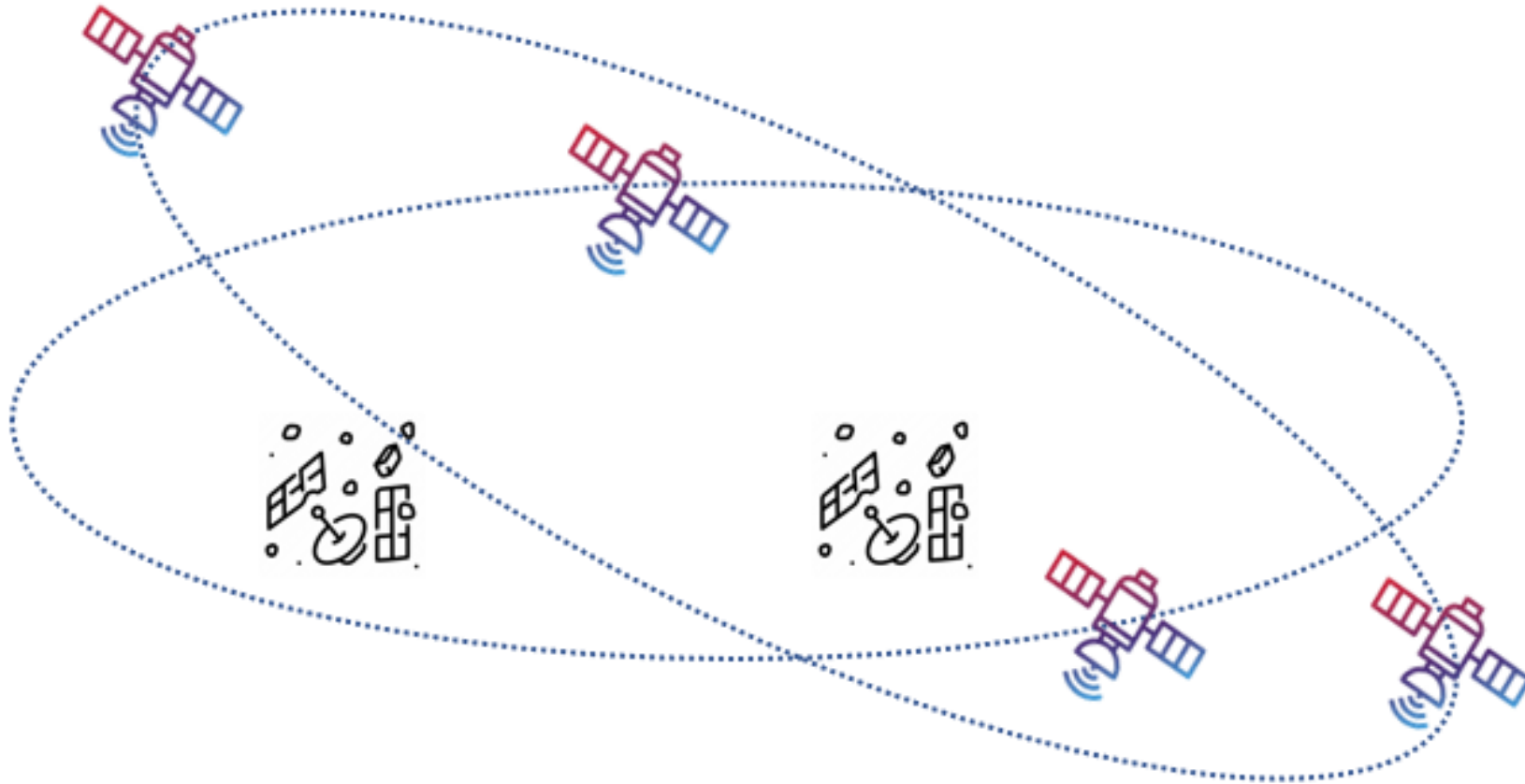


Fig. 16: An illustration of space navigation and collision avoidance

Enhancing Security

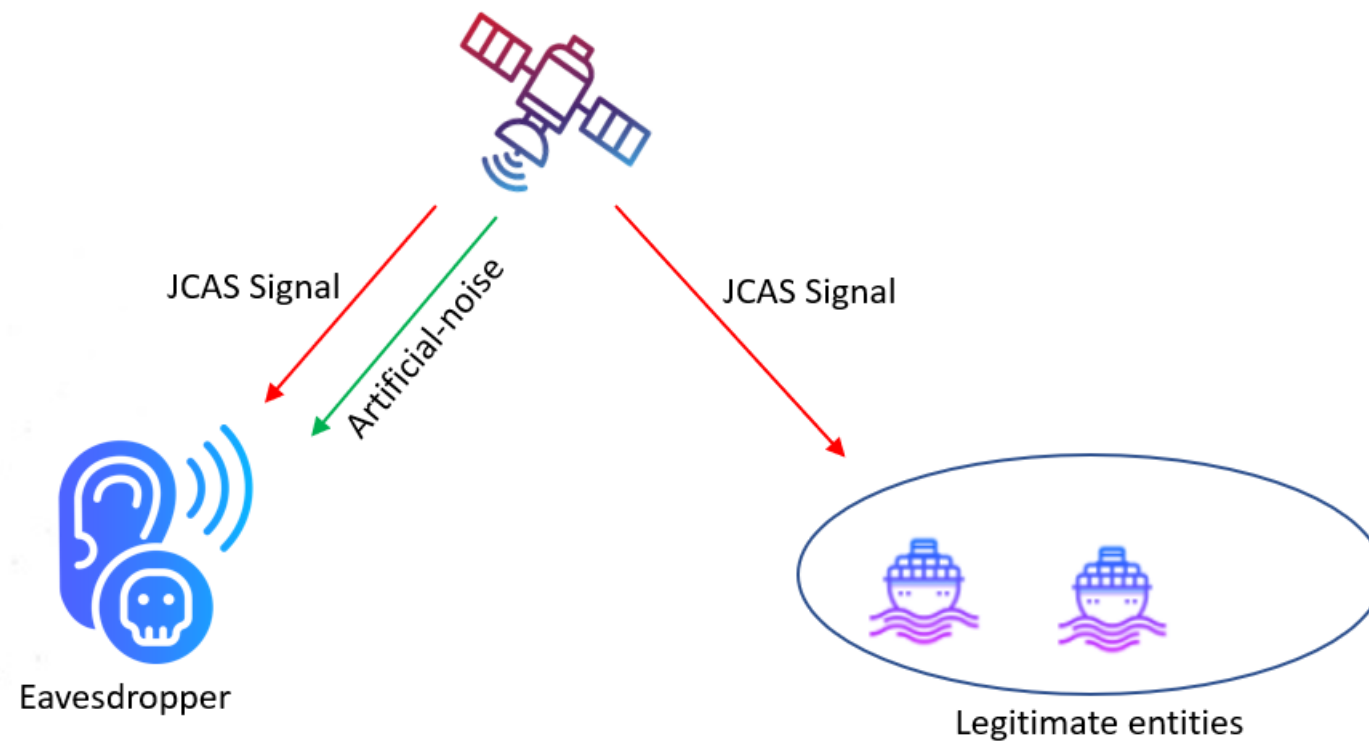


Fig. 17: An illustration of securing the communication with legitimate entities

Emergency and Disaster Management – Monitoring and Managing from Space

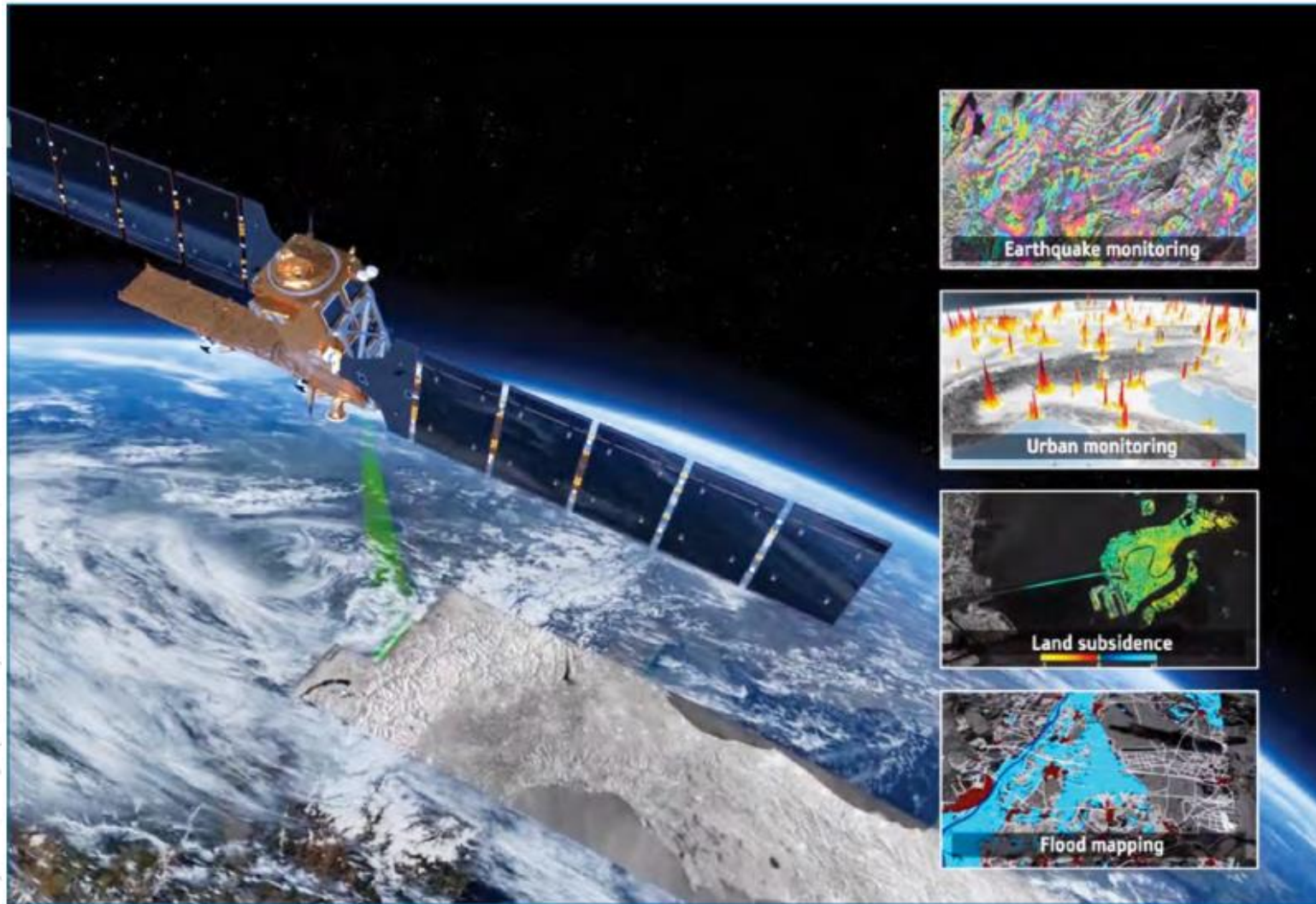


Fig. 18: Disaster monitoring and management from space

Digital Twin

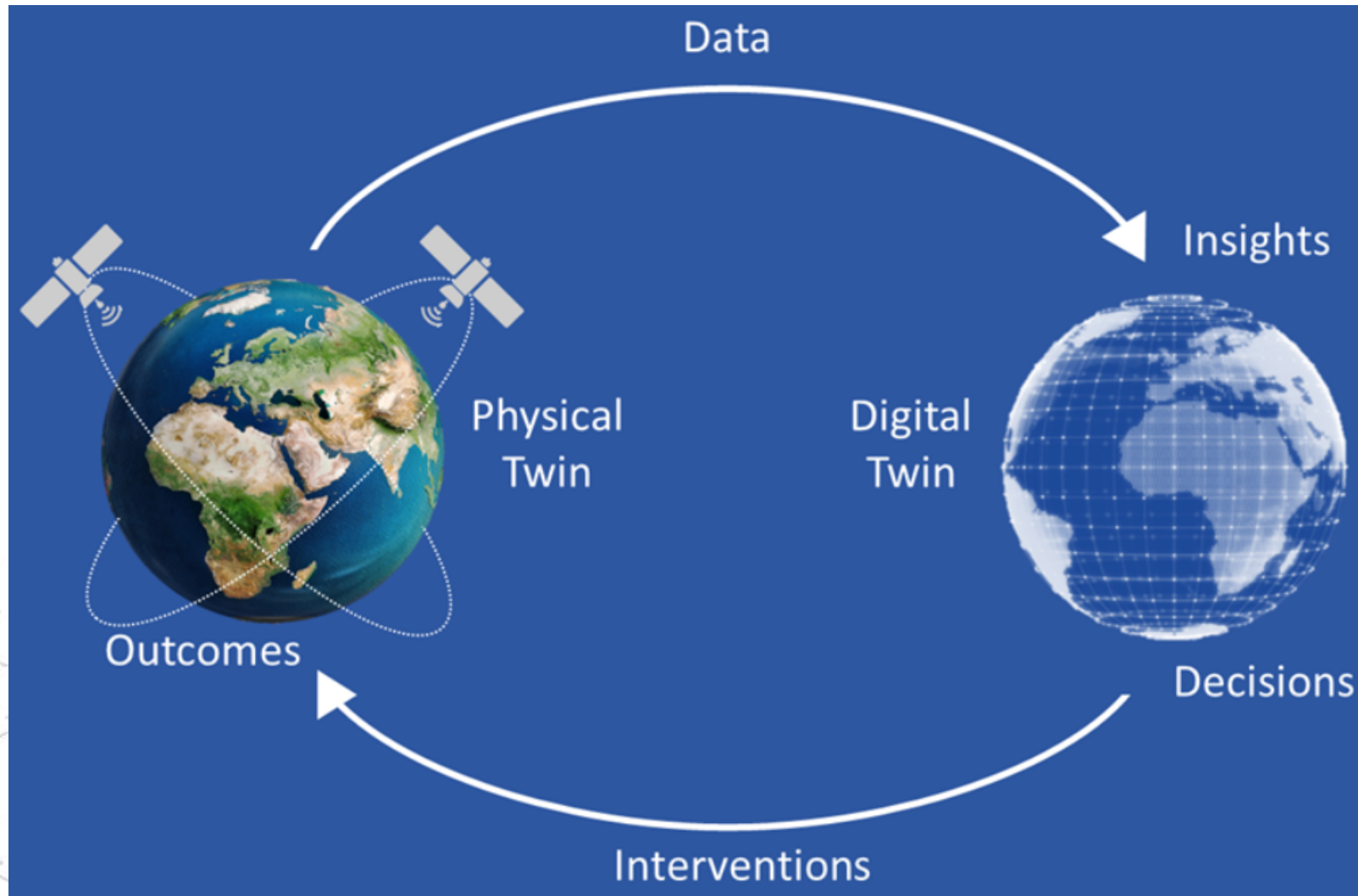


Fig. 19: An illustration of digital twin of the Earth environment

Sensing-centric Design

Design Principles

- ❖ Sensing-centric or radar-centric design **gives more priority to sensing tasks while providing information to assist communication** for achieving high integration gain.
- ❖ This approach aims to **introduce/embed information signalling in known radar waveform**.
- ❖ As the transmission power of radar systems is high, **very long range communications** can be achieved.

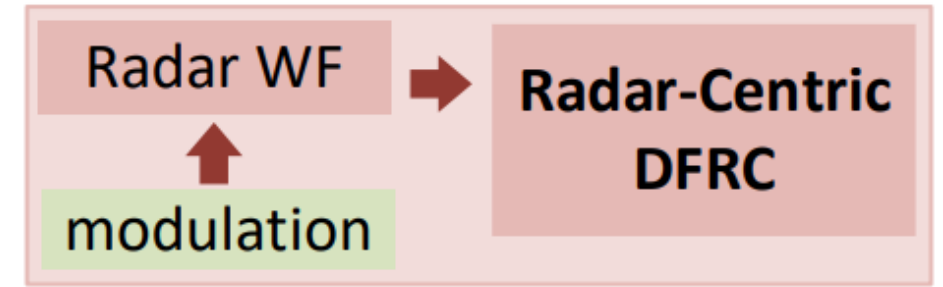


Fig. 20: A high-level representation of radar-centric design

Transceiver Design

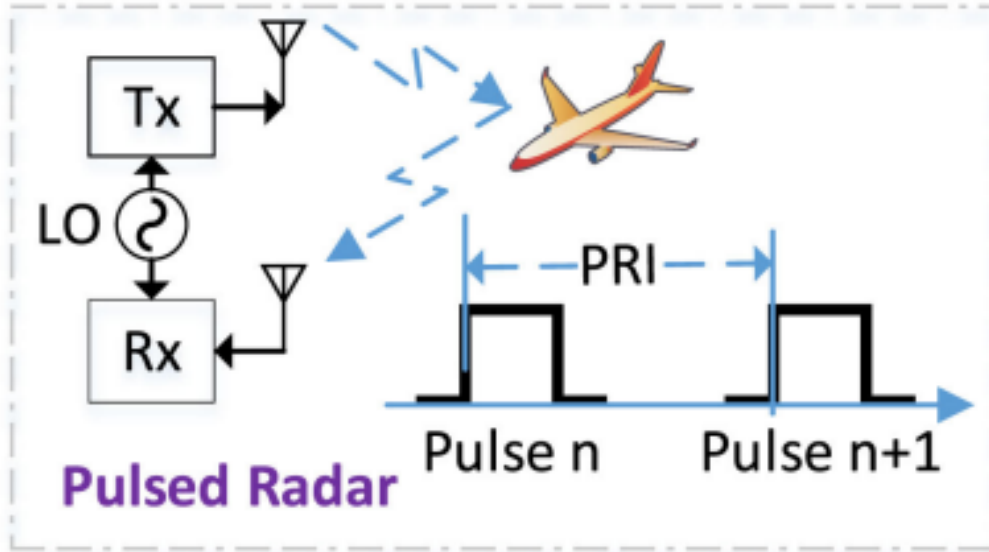


Fig. 21: Pulsed radar system

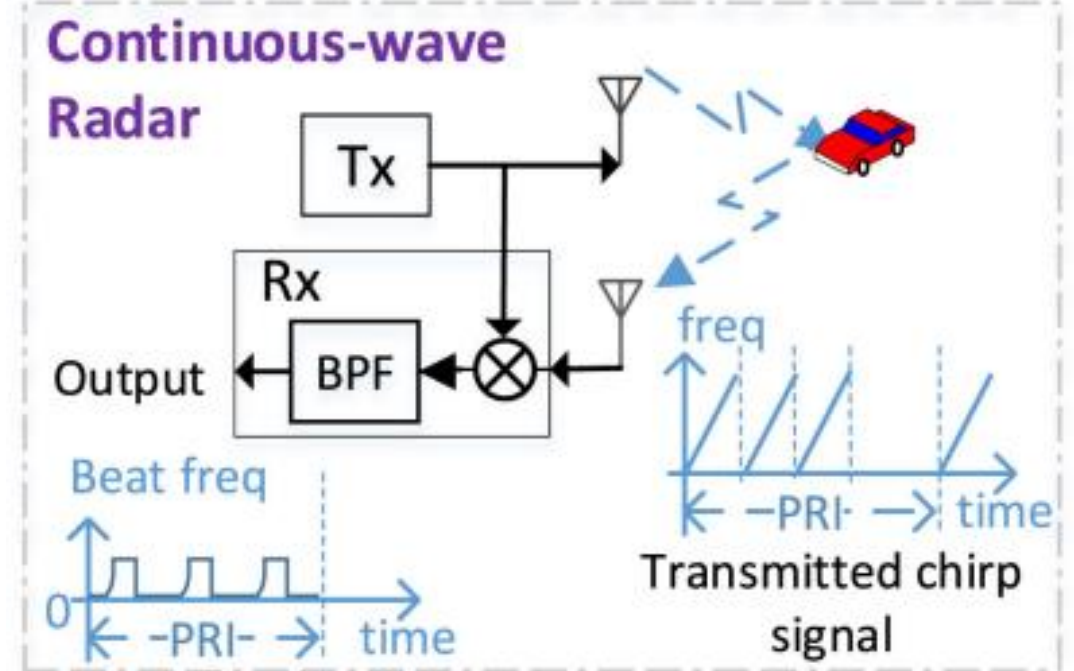


Fig. 22: Continuous-wave radar system

- ❖ In pulsed radar system, **short pulses of large bandwidth are transmitted**.
- ❖ Continuous-wave radar system **transmits chirp signals**, typically **scanning over a large range of frequencies**.
- ❖ In both radar systems, **the waveforms are typically non-modulated and they also can be used in MIMO radar**.

Waveform Design and Signal Processing (1/3)

- ❖ Radar systems typically **use specially designed waveforms** such as short pulses and chirps, which enable high-power radiation and simple signal processing at receiver.
- ❖ Radar signals are typically **designed to achieve high localization and tracking accuracy** and to enable simple sensing parameter estimation.
- ❖ Sensing-centric design mainly **exploits side information** of radar waveform for enabling communication.

Waveform Design and Signal Processing (2/3)

- ❖ Time-frequency embedding:
 - ❖ Amplitude, phase and/or frequency shift keying techniques are used to embed information in traditional radar waveforms.

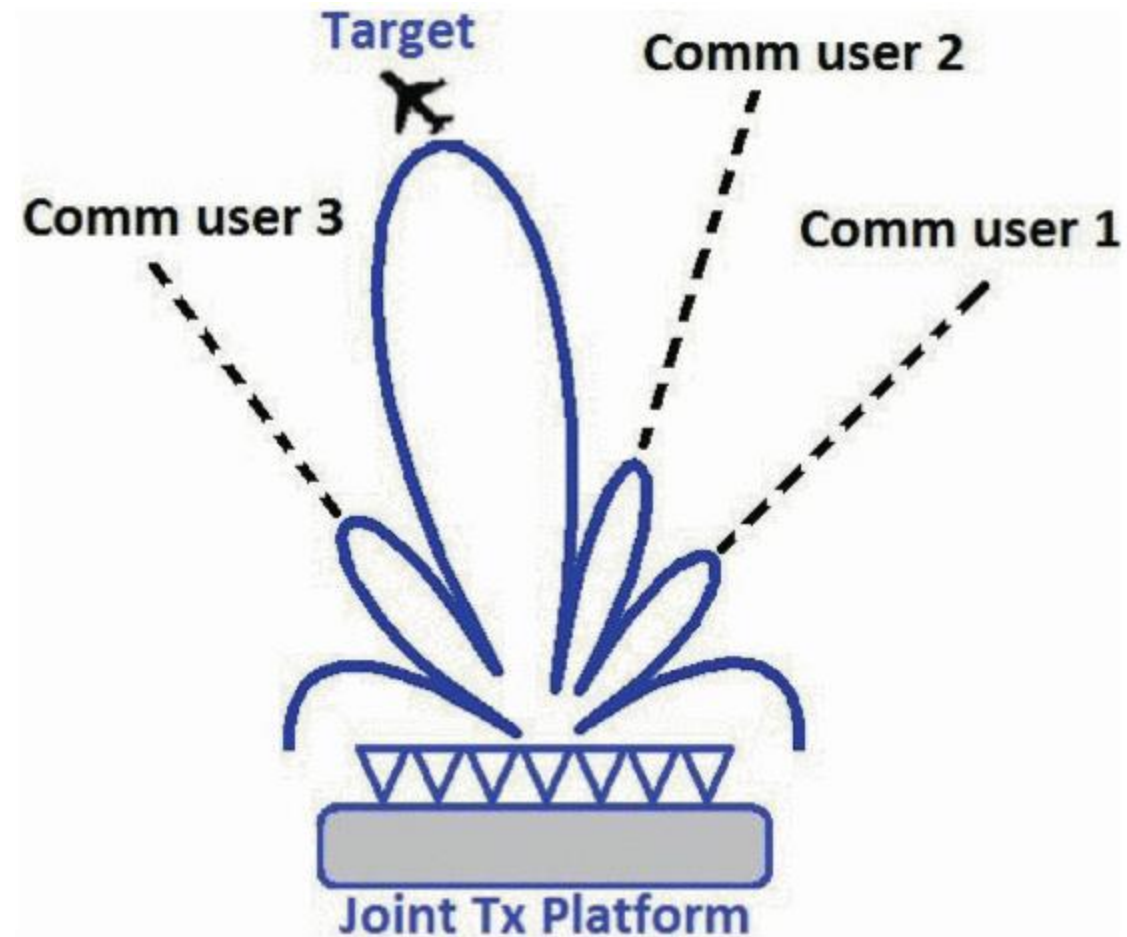


Fig. 23: Waveform design

Waveform Design and Signal Processing (3/3)

❖ Index modulation:

- ❖ Information is represented by the indexes of antennas, frequencies, and/or codes of the signals.
- ❖ For example, MIMO-OFDM radars use the indexes of subcarriers and transmitting antenna elements to embed the information.

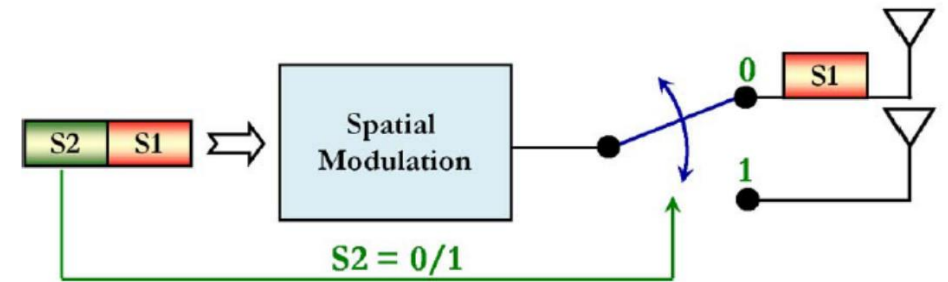


Fig. 24: An example of index modulation block diagram

Parameter Estimation

❖ Sensing:

- ❖ Time delay, **range, velocity, Doppler frequency**, and magnitude of multipath signals.
- ❖ Angle of arrival/departure estimation.

❖ Communication:

- ❖ **Achievable data rate** using radar signals.
- ❖ Short **latency time** at high spectral efficiency.

Communication-centric Design

Design Principles

- ❖ Communication-centric design **gives more priority to communications while introducing radio sensing as an add-on** to a communication system for achieving high integration gain.
- ❖ This approach aims to **use communication waveform to extract sensing information through target echoes**.
- ❖ Communication-centric design **exploits communication signals and network cooperation** for enabling sensing.
- ❖ It is also called **perceptive mobile networks** when the communication infrastructures are enhanced to include sensing capabilities as well.

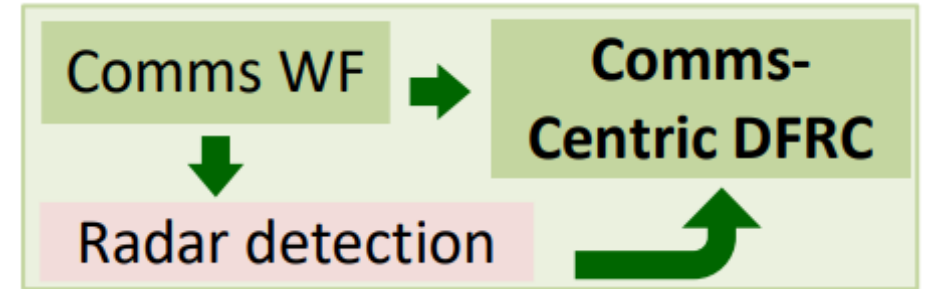


Fig. 25: A high-level representation of comms-centric design

Transceiver Design

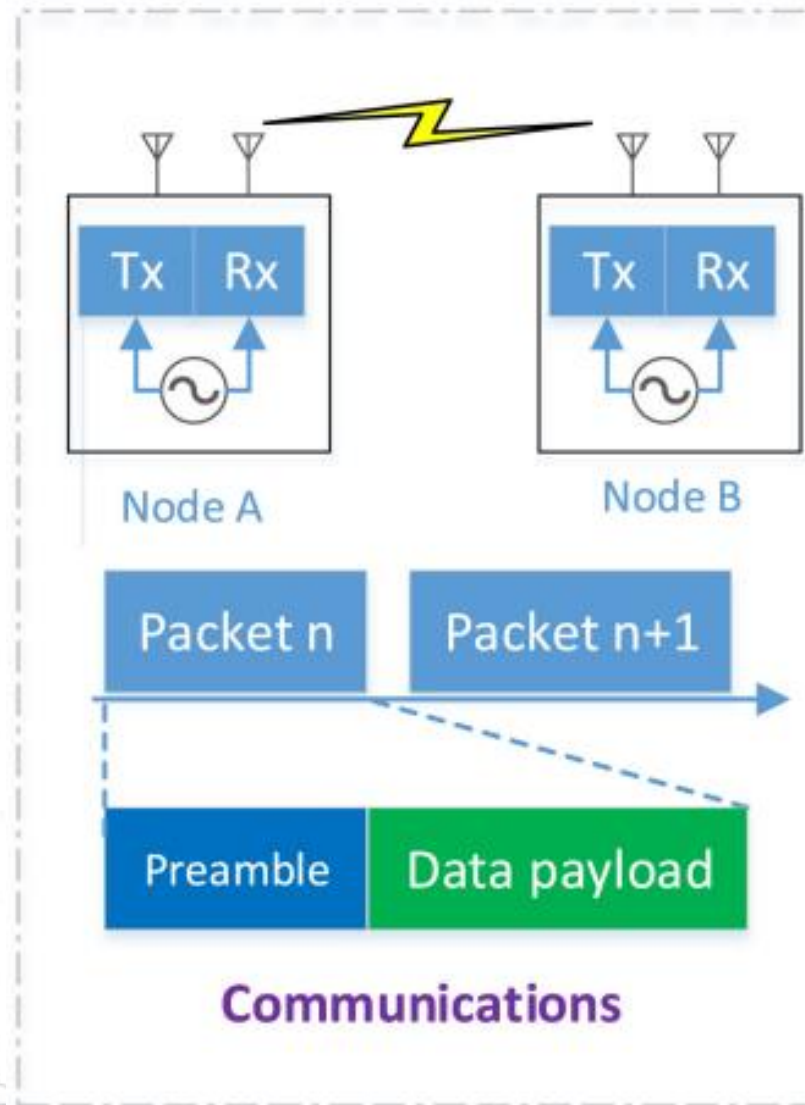


Fig. 26: Communications system

Possible Sensing Types

❖ Uplink sensing:

- ❖ Transmitters (e.g., UE) and receivers (e.g., satellite) are **non-synchronized**.
- ❖ Exact **transmitted signal format is not known** at the receivers.
- ❖ Satellites can **estimate only the relative sensing parameters**, not absolute due to non-synchronization, such as time delay and Doppler frequency.

❖ Downlink sensing:

❖ Downlink passive sensing:

- ❖ Transmitters (e.g., satellite) and receivers (e.g., ground radar receivers) are **non-synchronized**.
- ❖ Exact **transmitted signal format is not known** at the receivers.
- ❖ Ground radar receivers can **estimate only the relative sensing parameters**, not absolute due to non-synchronization, such as time delay and Doppler frequency.

❖ Downlink active sensing:

- ❖ Transmitters (e.g., satellite) and receivers (e.g., satellites and ground base stations) are **synchronized**.
- ❖ Exact **transmitted signal format is known** at the receivers.
- ❖ Satellites and ground base stations can **estimate absolute sensing parameters** such as time delay and Doppler frequency.

- ❖ **Communication reference signals** (e.g., pilot signals, demodulation reference signals (DMRS), channel state information reference signals (CSI-RS), sounding reference signals (SRS), positioning reference signals (PRS)), and synchronization signal blocks can be used for sensing.

Waveform Design and Signal Processing (1/2)

- ❖ Communication signals are designed for effective utilization of resources such as information carrying capabilities and spectral efficiency.
- ❖ Communication signals are designed to serve diverse services and meet various quality of service requirements.
- ❖ Communication signals are modulated, discontinuous, and fragmented to improve the service quality.

Waveform Design and Signal Processing (2/2)

- ❖ Orthogonal frequency division multiplexing (OFDM):
 - ❖ **Comb-type pilot signals** which are circularly shifted across OFDM symbols can be used for sensing.

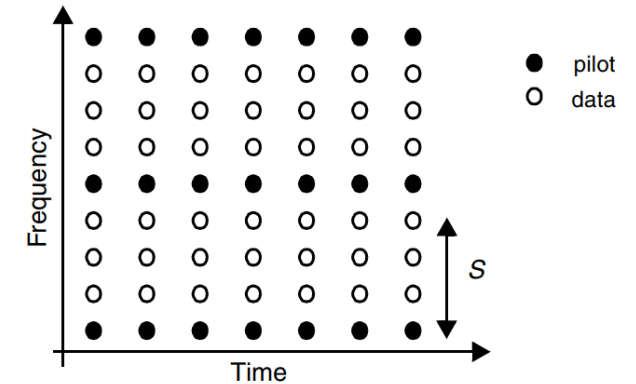


Fig. 27: OFDM comb-type pilot arrangement

- ❖ Modifications required to existing communications system:
 - ❖ In the case of monostatic sensing, full-duplex operation is expected for better sensing performance.
 - ❖ In the case of bistatic sensing, clock synchronization is required between different communication nodes.
 - ❖ With limited communication signal transmitted power, long range sensing is difficult.

Parameter Estimation

❖ Communication:

- ❖ Data rate
- ❖ Symbol/bit error rate

❖ Sensing:

- ❖ Accuracy
- ❖ Resolution

Parameter Estimation

❖ Communication:

- ❖ Data rate
- ❖ Symbol/bit error rate

❖ Sensing:

- ❖ Accuracy
- ❖ Resolution

Future Directions

Comparison of JCAS Designs

Design Methodologies	Representative Techniques	Advantages	Disadvantages
Sensing-centric	Pulse signal Chirp signal MIMO radar	Guaranteed sensing performance	Low data rate
Communication-centric	OFDM	Guaranteed comm. performance	Unreliable sensing performance

Table 2: Pros and cons of different levels of integration of communication and sensing

JCAS Design Challenges

❖ Sensing-centric design:

- ❖ Due to their simple and special signal form and hardware, the existing radar systems generally **cannot support very high-rate** communications.

❖ Communication-centric design:

- ❖ Conventional channel estimation techniques can be used to obtain channel coefficients, but **sensing parameter estimation requires extraction of the channel composition** rather than channel coefficients only.
- ❖ The complicated existing communication signals are very different to conventional radar and **demand new sensing algorithms** and the knowledge on signal structure is required for coherent detection.
- ❖ There are also **practical limitations in communication systems**, such as full-duplex operation and asynchronization between transmitting node and receiving node, which requires new sensing solution to be developed.

Joint Design Principles

- ❖ Joint design **offers a tunable trade-off** between communications and sensing for achieving high coordination gain.
- ❖ This approach aims to **jointly design communications and sensing waveform to meet the needs** of users and network operators.
- ❖ **Mutually benefit the real-time performance** of both communications and sensing systems.

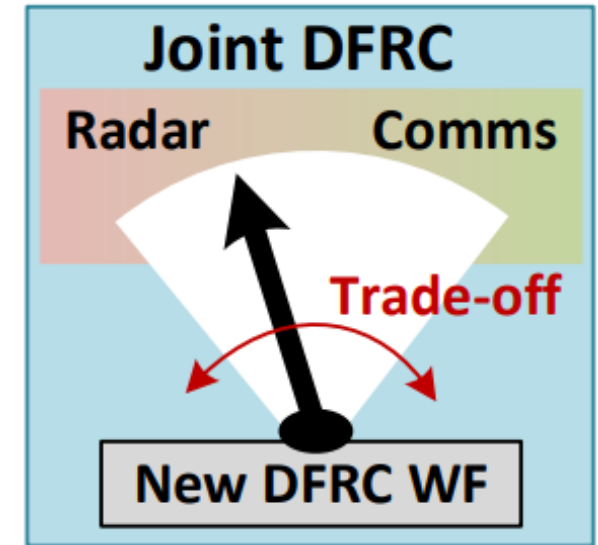


Fig. 28: A high-level representation of joint design

Joint Design Challenges

- ❖ New signal waveform design (e.g., OTFS) would be required to mutually and flexibly accommodate the requirements of sensing- and communications-based services.
- ❖ New hardware with enhanced and additional capabilities would be required to process communications and sensing signals in parallel.
- ❖ New techniques and algorithms may be required to estimate sensing and communications related parameters accurately with high resolution.
- ❖ In the case of distributed sensing, the estimation of parameters may be ambiguous and inaccurate when do joint signal processing from multiple sources, particularly when they are not well coordinated.





Joint Communications and PNT (JCAP)

Outline

1. Introduction to PNT and JCAP

- What is PNT
- Actual and future PNT use cases. Requirements
- Legacy GNSS
- 5G NR NTN
- Solving GNSS and 5G NTN drawbacks
- JCAP from LEO
- Current LEO-PNT missions

2. JCAP Architecture

- System architecture
- Waveforms

3. JCAP Receivers

- Observable extraction
- PNT modes
- PVT Engines

4. Performance PNT limits

- Theoretical limits. Cramer-Rao Lower Bound
- Sources of errors

5. Challenges and future trends

- Signal acquisition in high mobility scenarios
- Interference Management
- Inter-satellite synchronization

Introduction

Introduction to PNT and JCAP

- What are PNT services?
- Actual and future PNT use cases. Requirements
- Legacy GNSS
- 5G NR NTN
- Solution to GNSS and NTN drawbacks. JCAP
- JCAP from LEO. Taxonomy
- Current LEO-PNT and planned missions

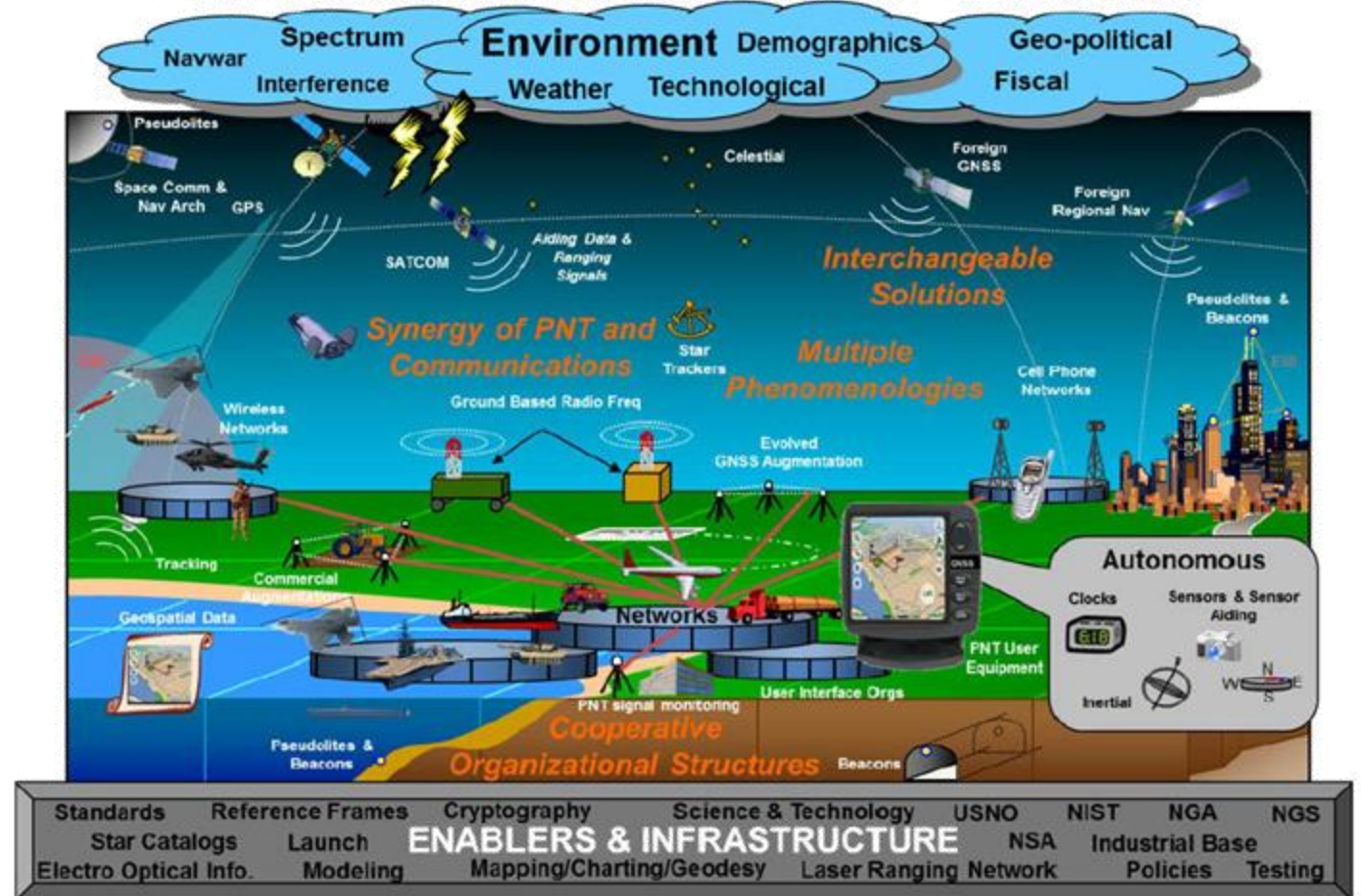
What are PNT services?

PNT services are public or private services that offer a Reference Framework to locate assets on a certain area.

- Public services are well known, for example Global Navigation Satellite Systems (GNSS) such as GPS, Galileo, Glonass, Beidu offer global coverage.

- Private global services such as PULSAR from Xona Space Systems, offer their clients enhanced accuracy and resilience to complement GNSS services globally. Other private regional services are offered by mobile operators, using their cellular network, they can locate their subscribers.

National PNT Architecture



Actual and Future use cases for PNT

- Aviation & Aerospace
- Critical infrastructure. Time synchronization
- Military
- Policy & Governance.
- Geodesy and mapping
- Science
- Transportation (non-aerial)
- Enhanced Communication
- Immersive gaming
- Emergency services
- Autonomous drones
- Urban Air mobility
- Space Exploration. Moon and Mars surface navigation
- Smart cities
- Secure communication
- Precision Agriculture

Use cases requirements for PNT

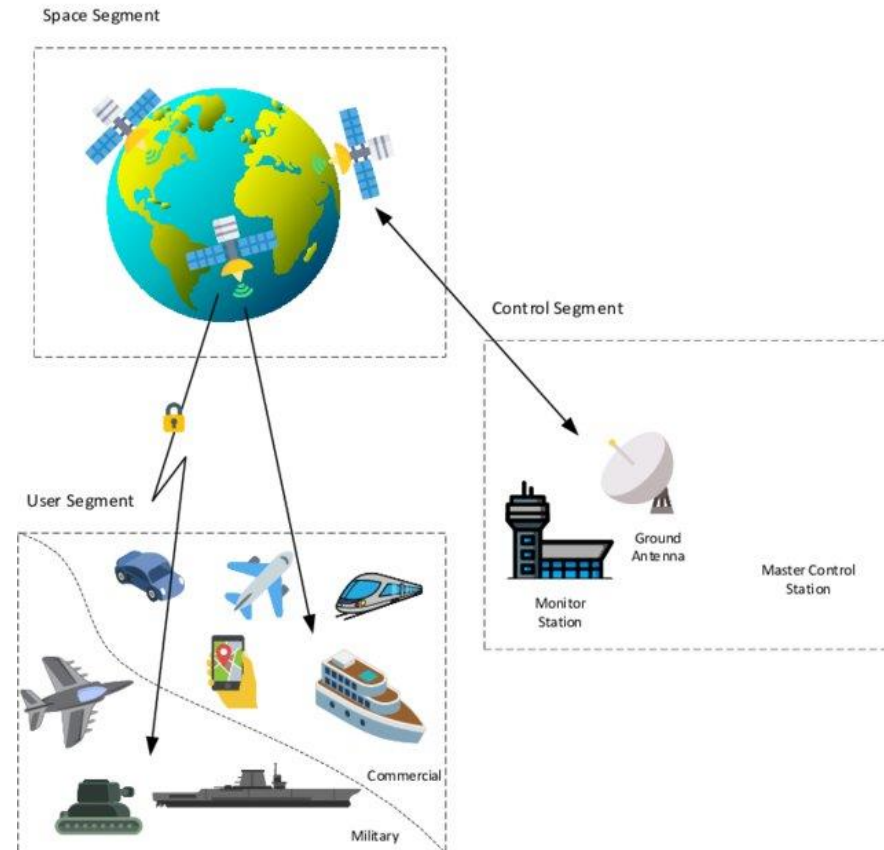
Use Case	Position Accuracy	Timing Accuracy	Sigma level	Time to First Fix
GNSS (General use)	1-10 m (civilian)	10-100 ns	1	30-60 s (cold start)
Autonomous vehicles	0.1-1 m	1us	2	1-5 s
Aviation	3-5 m	1 us	2	10-30 s
5G Networks	1 m	1-10 ns	1	5-15 s
SAR	5-10m	10-100 ns	1	5-30 s
Precision Agriculture	2-5 cm	1 us	2	5-10 s
Urban air mobility	0.1-1 m	1 ns	3	1-5 s

- The ITU-R document “M.2160 : Framework and overall objectives of the future development of IMT for 2030 and beyond” recently published offer a summary of some of the requirements for PNT services offered by 6G networks. With a research target of accuracy of 1-10 cm and including sensing capabilities.

Global Navigation Satellite System (GNSS) as a PNT reference system

GNSS offer Global coverage for PNT services.
It is composed by:

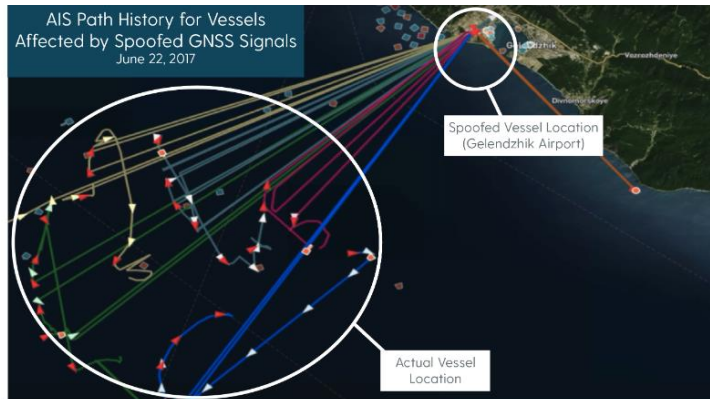
- Space Segment. Satellites or Space Vehicles (SV)
- Ground segment. Monitor and control stations
- User segment



Source: R. Morales-Ferre, P. Richter, E. Falletti, A. de la Fuente and E. S. Lohan, "A Survey on Coping With Intentional Interference in Satellite Navigation for Manned and Unmanned Aircraft," in *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 249-291, Firstquarter 2020, doi: 10.1109/COMST.2019.2949178

GNSS drawbacks

- Any disruption of these PNT services could be **catastrophic for the users**.
- At this moment, most of PNT services rely on Global Navigation Space Services (GNSS).
- This could be **easily attacked/disrupted** intentionally (jamming and spoofing techniques) or unintentionally (solar storms)



Spoofed GNSS Signal in the Black Sea. Source: C4ADS.
“Above Us Only Stars. Exposing GPS Spoofing in Russia and Syria”. Accesible via:

<https://www.c4reports.org/aboveusonlystars>



Safety Information Bulletin Operations – ATM/ANS

SIB No.: 2022-02

Issued: 17 March 2022

Subject: Global Navigation Satellite System Outage Leading to Navigation / Surveillance Degradation

Ref. Publications:
None.

Applicability:
National Aviation Authorities (NAAs), Air Navigation Service Providers (ANSPs) and air operators.

Description:
In the current context of the Russian invasion of Ukraine, the issue of Global Navigation Satellite Systems (GNSS) jamming and/or possible spoofing has intensified in geographical areas surrounding the conflict zone and other areas.

Eurocontrol, Network of Analysts and open-source data reports analysed by EASA indicate that since 24 February 2022, there are four key geographical areas where GNSS spoofing and/or jamming has intensified, namely:

- Kaliningrad region, surrounding Baltic sea and neighbouring States;
- Eastern Finland;
- The Black Sea; and
- The Eastern Mediterranean area near Cyprus, Turkey, Lebanon, Syria and Israel, as well as Northern Iraq.

The effects of GNSS jamming and/or possible spoofing were observed by aircraft in various phases of their flights, in certain cases leading to re-routing or even to change the destination due to the inability to perform a safe landing procedure. Under the present conditions, it is not possible to predict GNSS outages and their effects. The magnitude of the issues generated by such outage would depend upon the extent of the area concerned, on the duration and on the phase of flight of the affected aircraft.

The latest report about GNSS outage for flights. Source: EASA Operations ATM/ANS. “Global Navigation Satellite System Outage Leading to Navigation/Surveillance Degradation”. Safety Information bulletin No: 2022-02. 17 March 2022.

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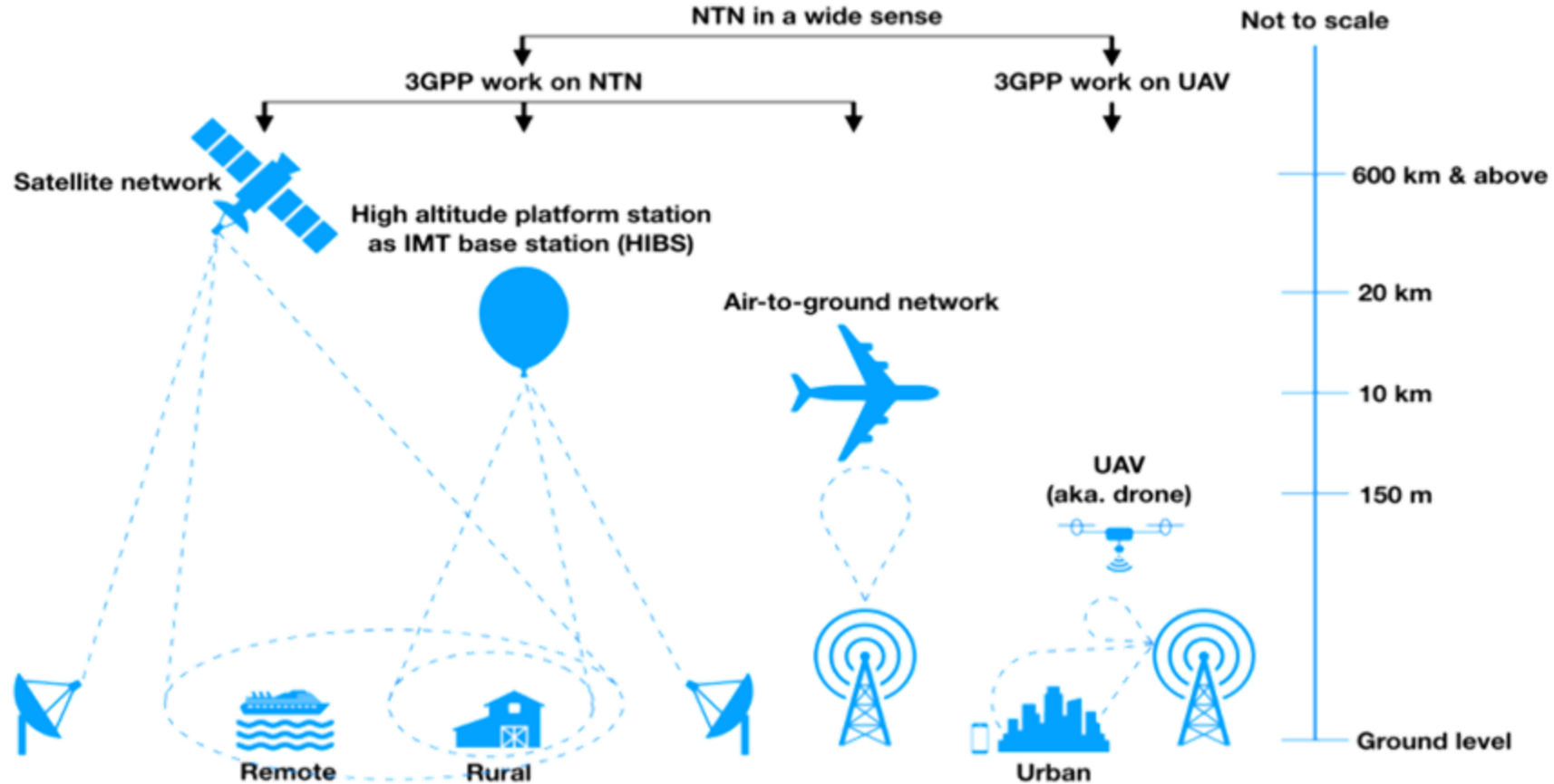
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Commercial GNSS jammer accessible by anyone

5G NTN



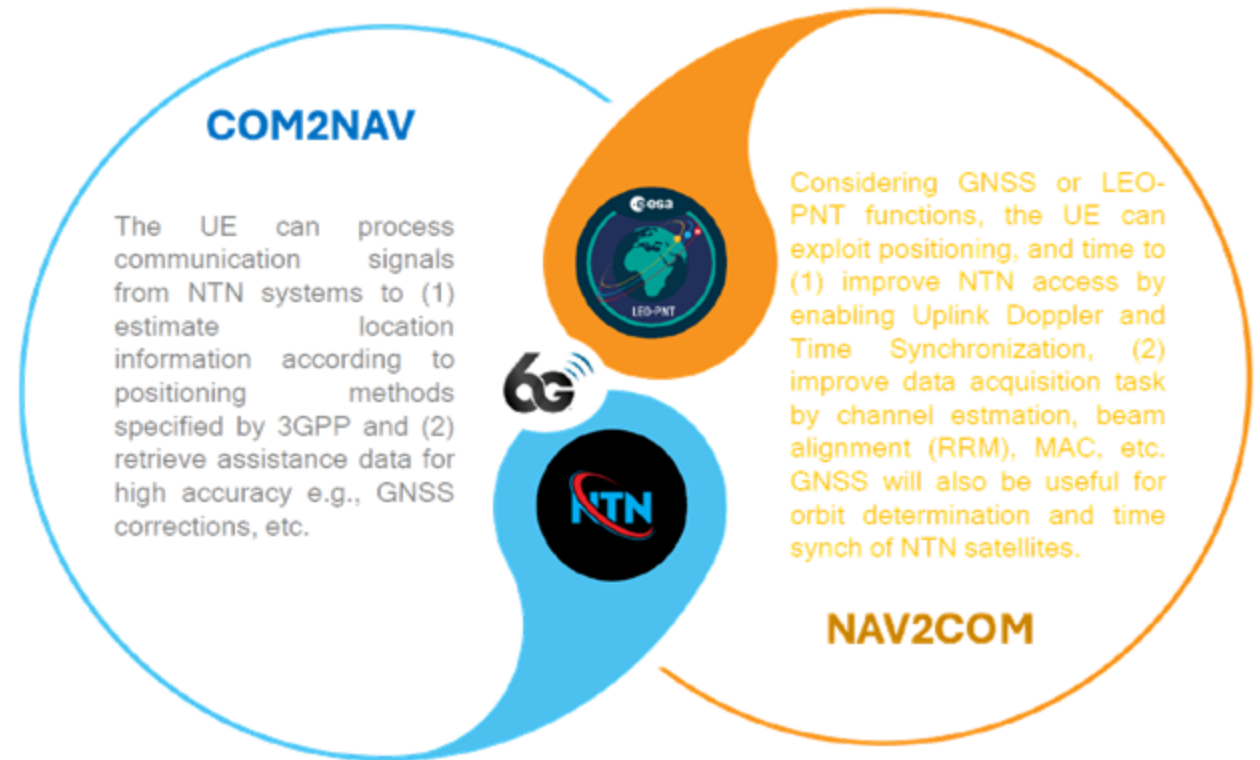
Source: X. Lin, S. Rommer, S. Euler, E. A. Yavuz and R. S. Karlsson, "5G from Space: An Overview of 3GPP Non-Terrestrial Networks," in IEEE Communications Standards Magazine, vol. 5, no. 4, pp. 147-153, December 2021, doi: 10.1109/MCOMSTD.011.2100038

NTN drawbacks

- Up to release 18, the user equipment requires to have a GNSS receiver to be synchronized with the NTN element.
 - The network operator service rely on a third party system outside its control
 - Some applications and use cases that needs to be very power efficient (IoT for example) are burden by adding a GNSS receiver at the user.
 - Some business models that plan the deployment of thousands of devices are jeopardized by including a GNSS receiver

Solution Joint Communication and Positioning (JCAP)

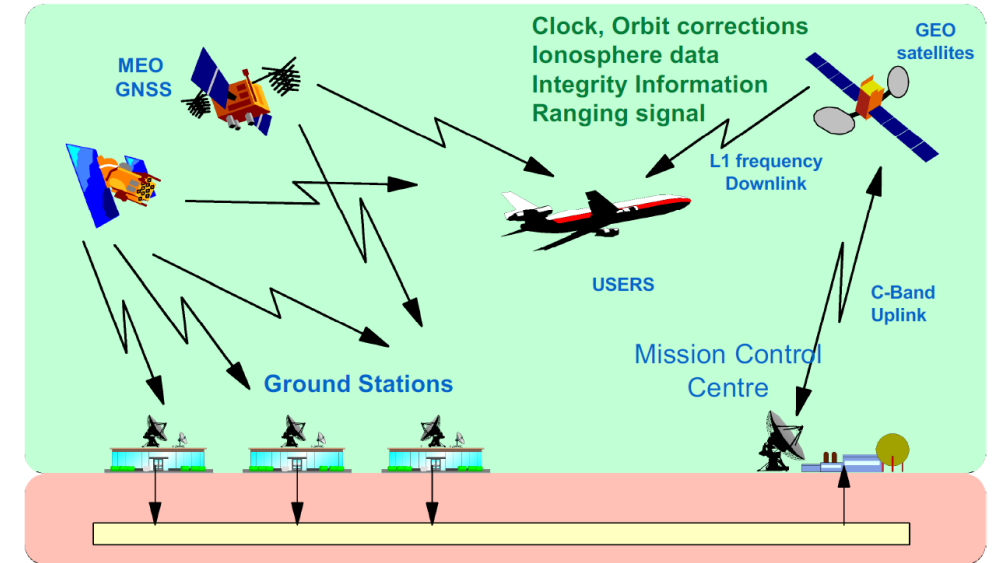
- Efficient spectrum usage
- Infrastructure sharing
- Single receiver for both services
- Sovereignty of the network. No dependency on third party system.
- Redundancy and robustness
- Enhance Search and Rescue
- Signal authentication
- ...



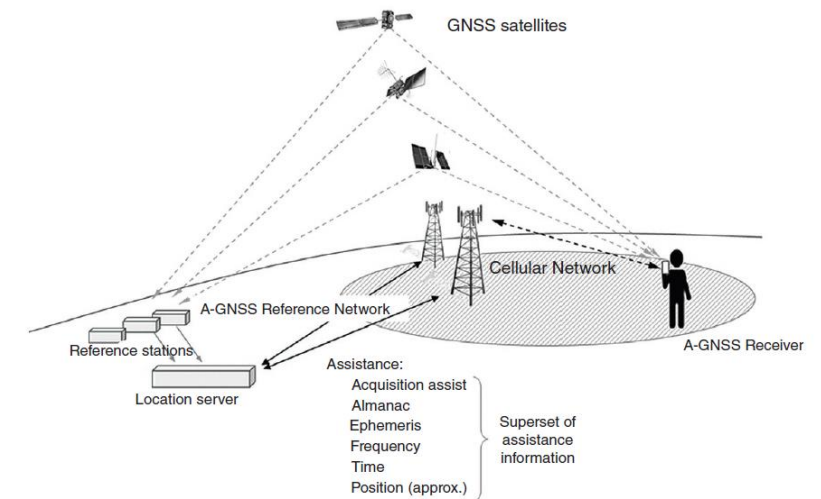
Source: ESA

Actual examples of JCAP

- They are co-located systems, using a higher data throughput of the communication link to assist the GNSS receivers via the navigation message and/or corrections:
- The Satellite Based Augmentation is a communication system used to complement the actual GNSS by sending the navigation messages from GEO satellites
- 5G GNSS assisted message. The 5G Network provides the UE assisted information to the GNSS receivers in the UE to accelerate the Time To First Fix and its accuracy



SBAS: Satellite Based Augmentation Credit ESA EGNOS



JCAP taxonomy for LEO satellites payload

Purpose-built LEO-PNT

PNT measurements derived from PNT signals – dedicated SV or PNT hosted payload (e.g. on satcom)

- Signal / frequencies designed for PNT
- Geometry designed for PNT (dedicated) or for hosting systems

Fused PNT with Satcom

PNT measurements derived from satcom signals

- Signals / frequencies designed for satcom, with tailoring for PNT
- Constellation geometry and antenna coverage : constrained by hosting system

Signals of Opportunity (SOOP)

PNT measurements derived from 3rd party signals

- Signal / Frequencies designed for 3rd party missions
- Constellation geometry and antenna coverage: constrained by hosting system
- Ad-hoc monitoring necessary to support commitment of PNT service provider

LEO PNT differentiators - a combination of LEO specificities, Frequency diversity, NAV / COM synergies

Lower free space losses

- Facilitator for compact payloads, frequency diversity and 2way PNT links

GNSS-enabled ODTs

- Complemented by ISL

Measurement Diversity

- Decorrelation, whitening of multipath, shorter outages, etc.

2-way PNT links

Frequency Diversity



5G Satcom - NTN
(Non-Terrestrial
Networks)

Current LEO-PNT systems and planned missions



ESA FutureNAV LEO-PNT Demonstrator.

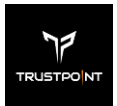
https://www.esa.int/Applications/Satellite_navigation/ESA_kicks_off_two_new_navigation_missions



Pulsar from Xona Space Systems. <https://www.xonaspace.com/>



Satelles STL-PNT. <https://satelles.com/technology/reliable-and-secure-pnt-stl/>



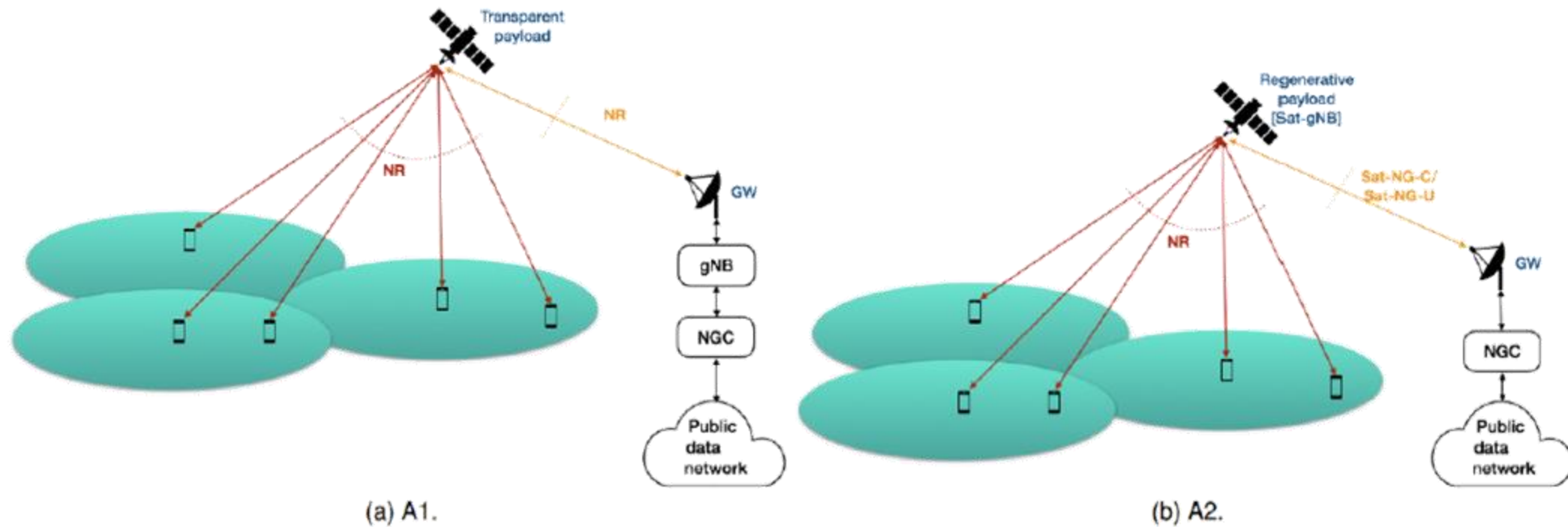
TrustPoint. <https://www.trustpointgps.com/>

JCAP system components

JCAP system components

- System architecture
 - Space segment
 - Ground Segment
 - User segment
- Waveform and multiplexing
 - Narrowband
 - DSSS
 - OFDM
 - OTFS

System architecture for JCAP in 5G NTN



Architectures for RAN in NTN Comms

Source: 3GPP

System architecture for JCAP in 5G NTN

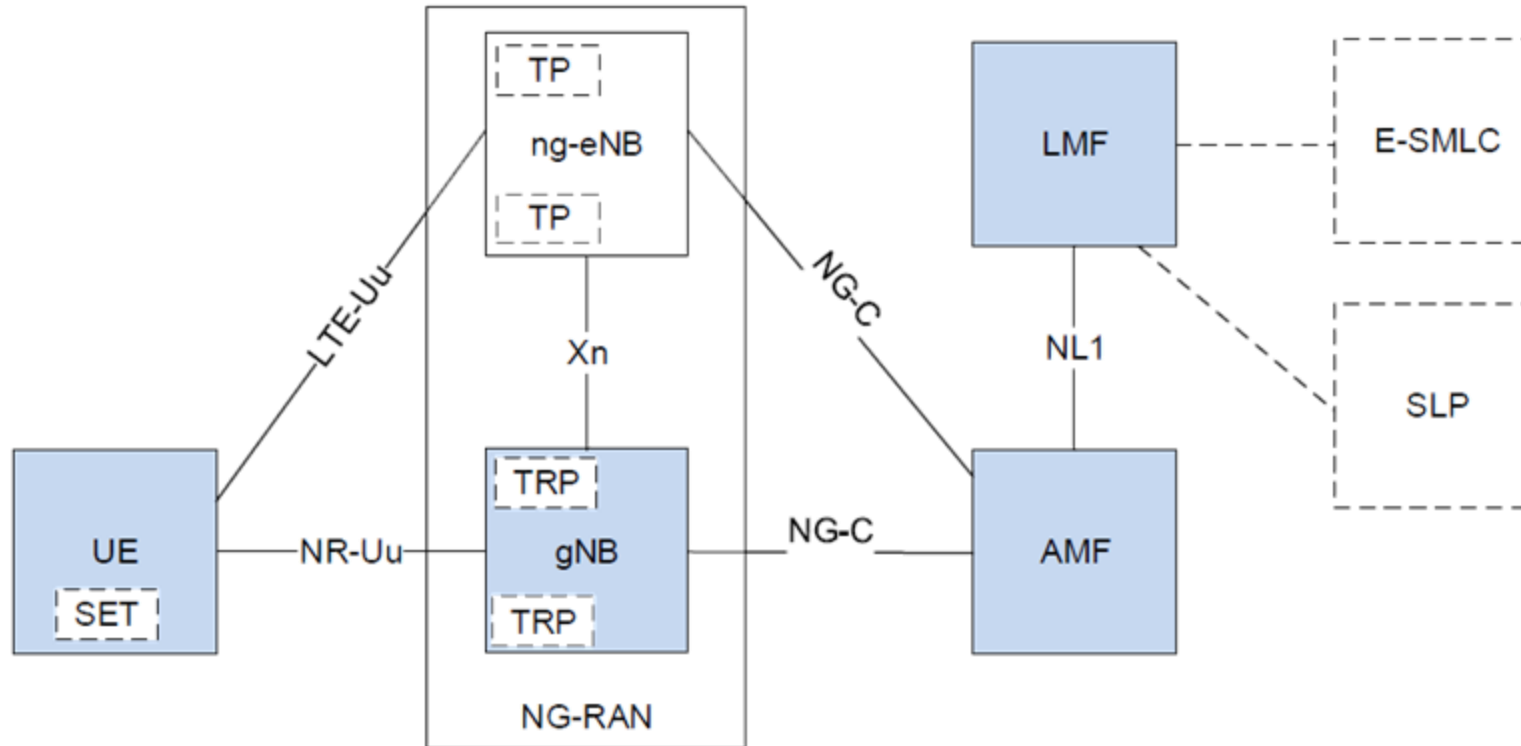


Figure 3-35: Overall architecture of 5G UE positioning [RD6].

Space segment in JCAP

- Generate the reference signal and transmit to the users
- Receive the corrections and include into the navigation message before its transmission
- RAN functions in the case of regenerative payload

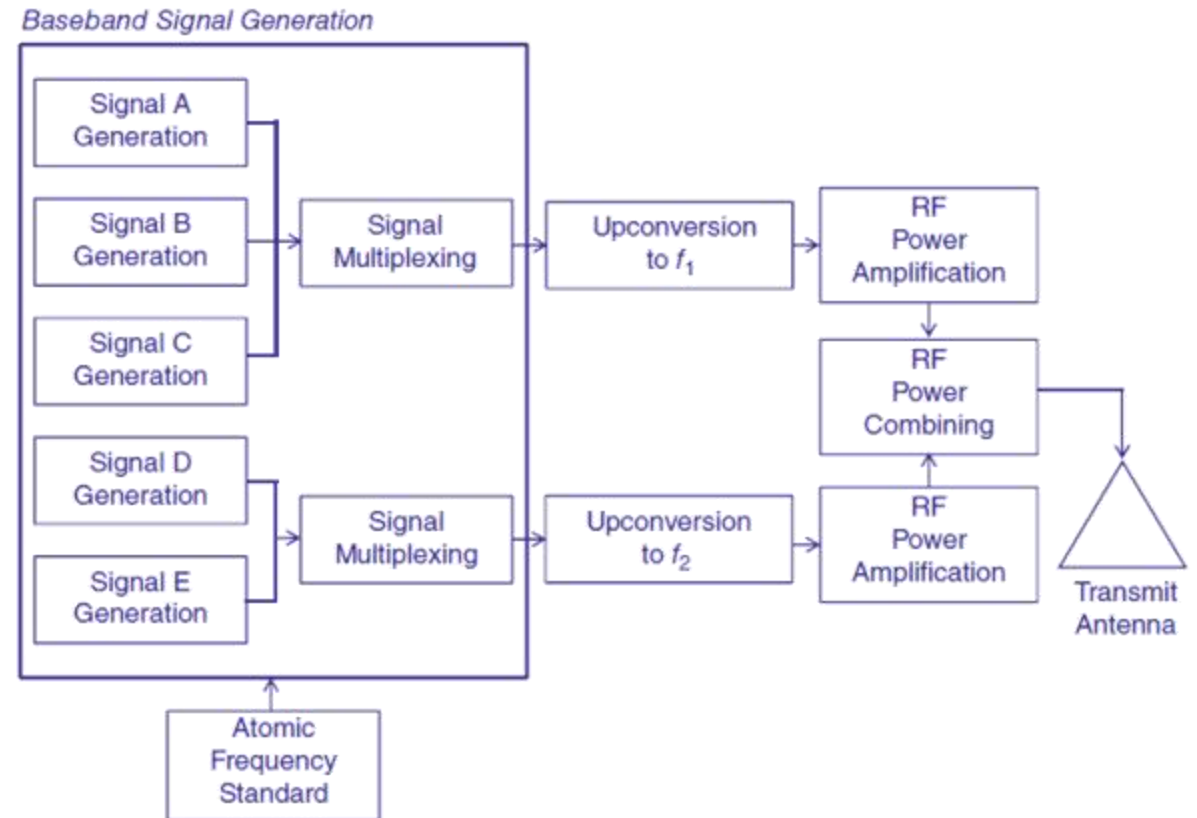
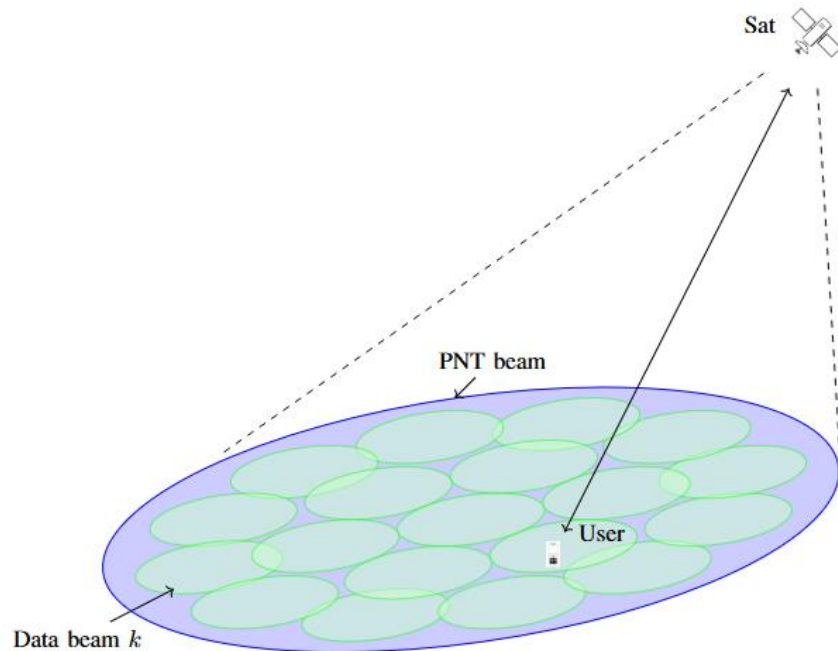
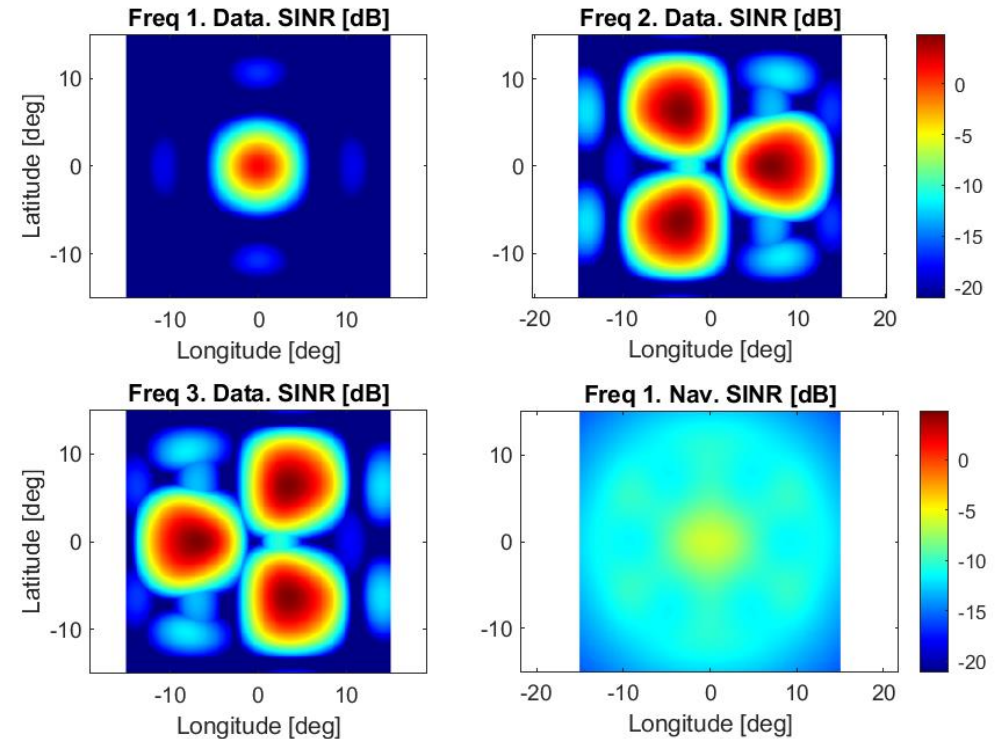


Figure 2.3 Satnav satellite payload [3]. Source: Reproduced with permission of IEEE.

Space segment in JCAP



Source: Alejandro Gonzalez Garrido, Jorge Querol, Henk Wymeers, Symeon Chatzinotas. "Joint Communication and Navigation from LEO Multi-Beam satellite." Submitted to OJ-COMMS, preprint available at <https://www.techrxiv.org/users/889763/articles/1267093-joint-communication-and-navigation-from-leo-multi-beam-satellite>

Ground segment in JCAP

The main task of the ground segment are to update the satellites with:

- Ephemeris
- Clock monitoring and corrections
- Satellite and payload status monitoring
- 5G Core Network

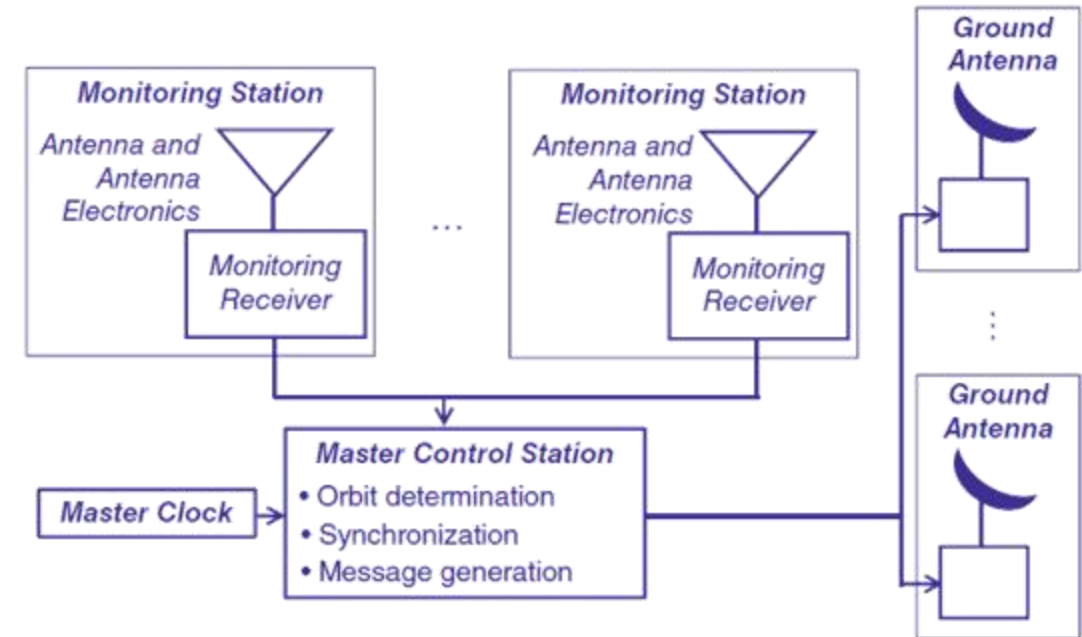


Figure 2.6 Ground segment architecture.

Source: Position, navigation, and timing technologies in the 21st Century: integrated satellite navigation, sensor systems, and civil applications. Volume 2. Hoboken, NJ: Wiley : IEEE Press, 2021.

User segment in JCAP

Depending the receiver use (for PNT or COMS) it will look for a different parameter. However the signal will provide both, and it can be exploited by a JCAP receiver

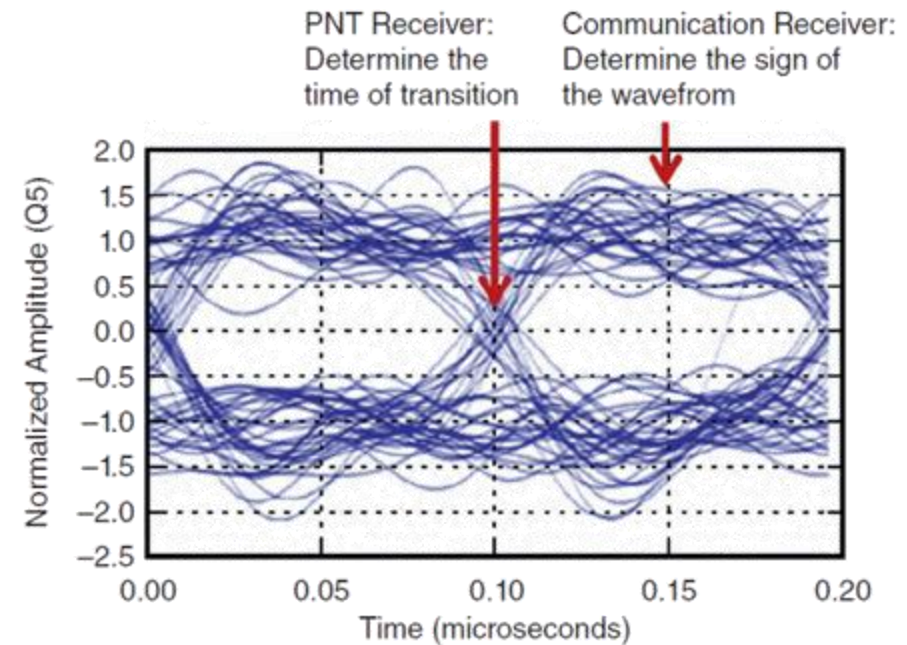
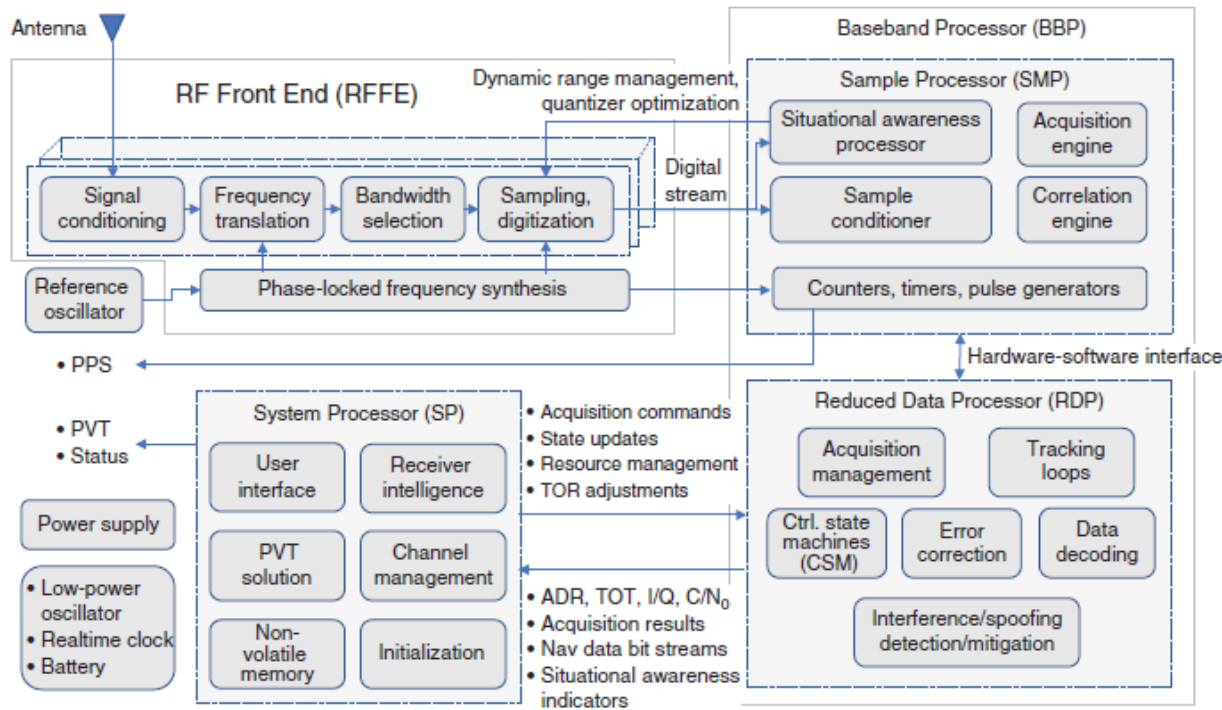


Figure 14.1 Phase transition eye diagram for a BPSK-modulated signal containing noise, phase jitter, and distortion (live sky GPS L5Q chip transitions) [2].

Source: Morton et al – 2020. Position, navigation and timing technologies

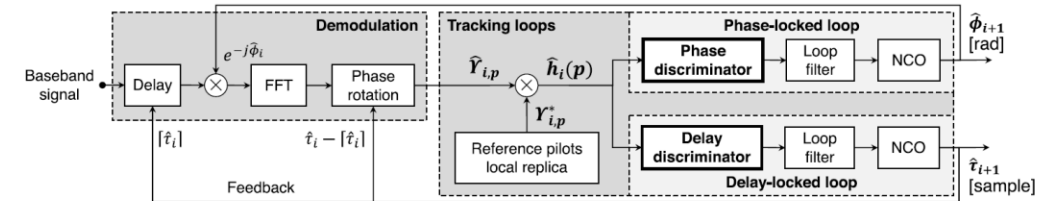
User Segment in JCAP

GNSS Receiver



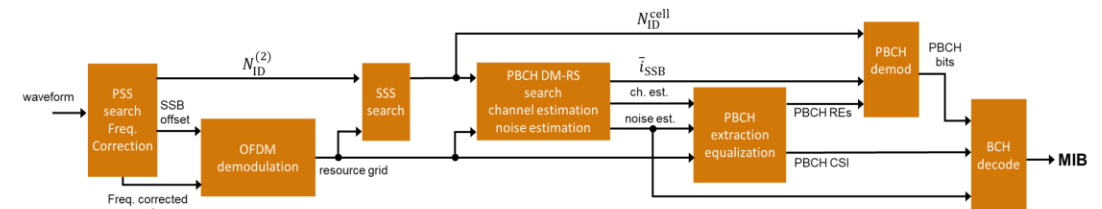
Source: Position, navigation, and timing technologies in the 21st Century: integrated satellite navigation, sensor systems, and civil applications. Volume 2. Hoboken, NJ: Wiley : IEEE Press, 2021.

5G NR Receiver for NAV



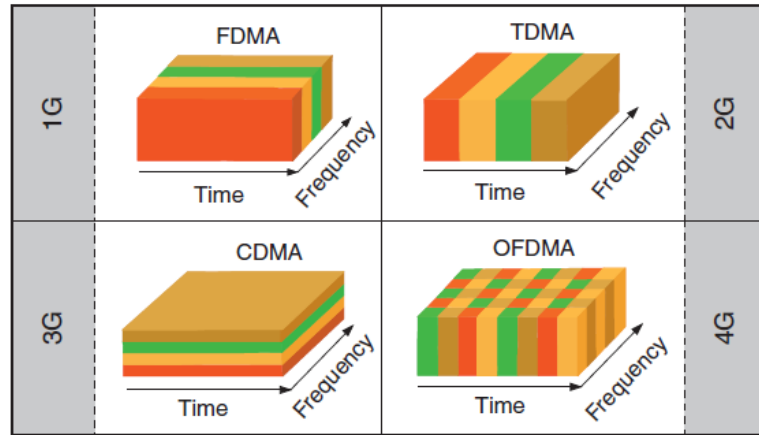
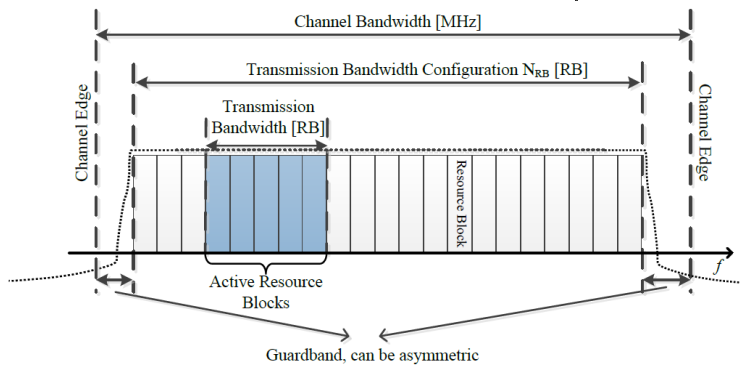
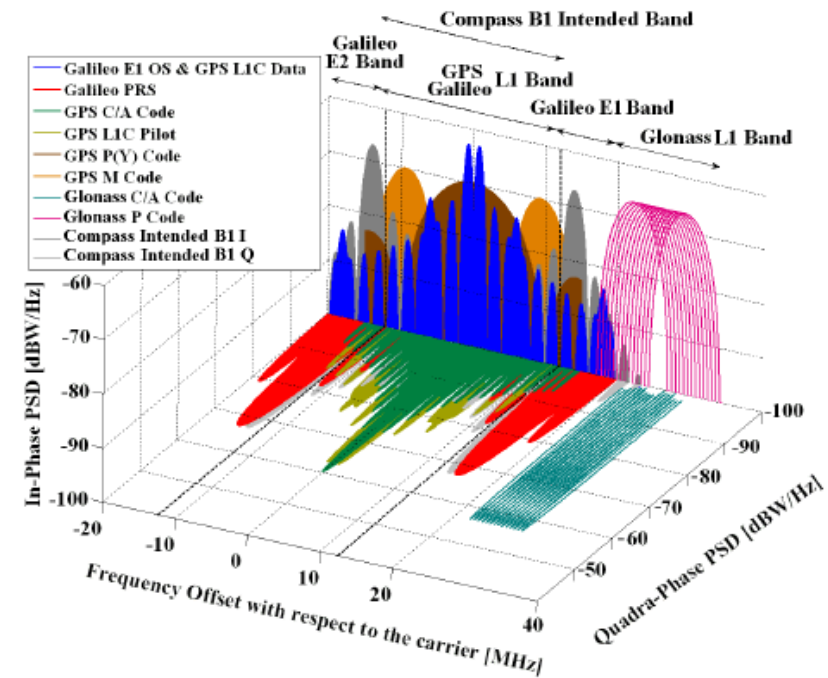
I. Lapin, G. S. Granados, J. Samson, O. Renaudin, F. Zanier, and L. Ries, "STARE: Real-Time Software Receiver for LTE and 5G NR Positioning and Signal Monitoring," in *2022 10th Workshop on Satellite Navigation Technology (NAVITEC)*, Noordwijk, Netherlands: IEEE, Apr. 2022, pp. 1–11. doi: [10.1109/NAVITEC53682.2022.9847544](https://doi.org/10.1109/NAVITEC53682.2022.9847544).

5G NR Receiver for COMMS



Source: Matlab

Waveforms and multiplexing



Waveforms and multiplexing

Signal combination at baseband

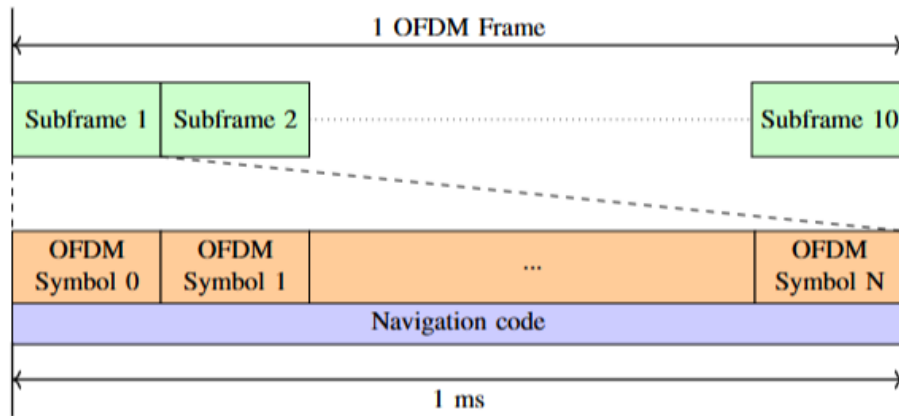
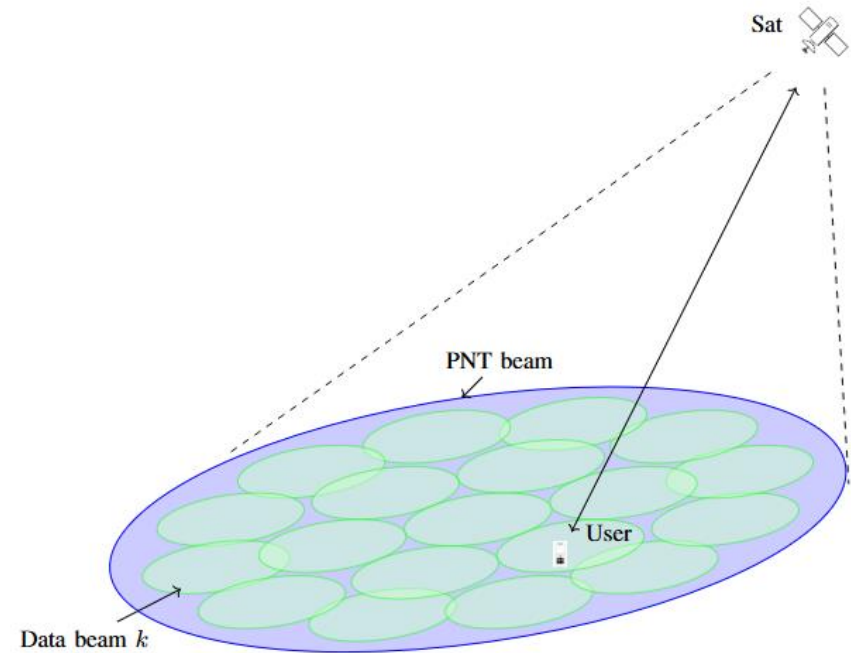


Fig. 1: Time-Code OFDM combining data transfer and a navigation signal using the 5G Frame structure.

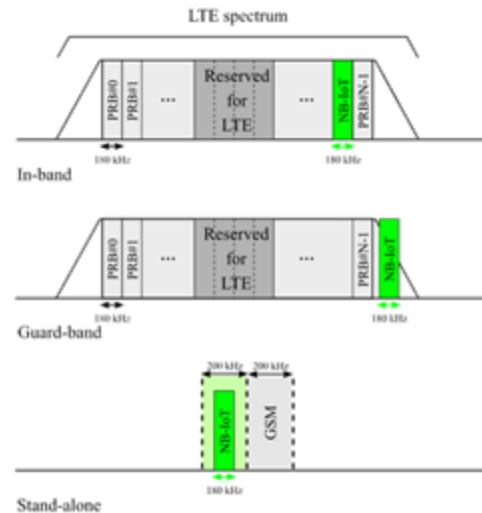
Signal combination Over the Air (OTA)



Waveforms. Narrowband signals

- NB-IoT signal

Source: M. Kanj, V. Savaux and M. Le Guen, "A Tutorial on NB-IoT Physical Layer Design," in *IEEE Communications Surveys & Tutorials*, vol. 22, no. 4, pp. 2408-2446, Fourthquarter 2020, doi: 10.1109/COMST.2020.3022751



- Better for Doppler measurements.
- Can be embedded between broadband transmission.
- Can be pure tones or specific pilots known at the receiver

- Starlink beacons

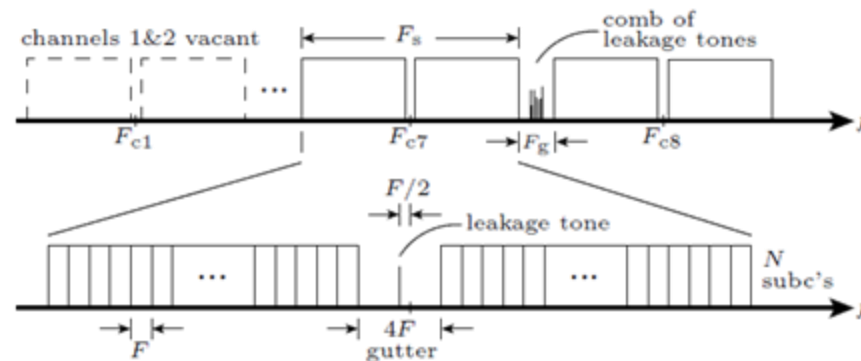
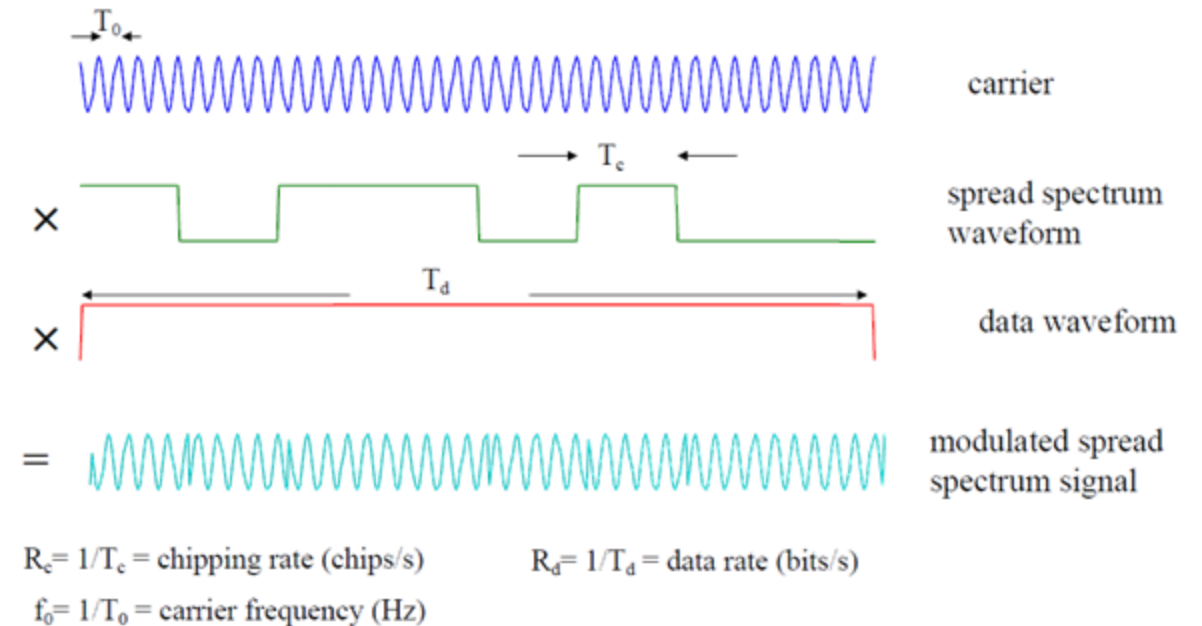


Fig. 5: Channel layout for the Ku-band Starlink downlink.

Waveforms. Direct Sequence Spread Spectrum (DSSS)

This waveform uses a code to distinguish between transmitters. Widely used in GNSS. The maximum number of simultaneous transmitters is limited by the length of the code.

Produces a constant envelope signal, that is very efficient in High Power Amplifiers (HPA)



Waveforms. Orthogonal Frequency Division Multiplexing (OFDM)

CP-OFDM Signal model

$$x^{(i)}(t) = \sqrt{P_{tx}} \sum_{m=0}^{M-1} \sum_{k=0}^{N_{SCS}-1} s^{(i)}[m, k] e^{j2\pi f_k t} \text{rect}\left(\frac{t - mT_s}{T_s}\right)$$

- M Number of Symbols
- N_{SCS} Number of subcarriers
- $s^{(i)}$ Resource Grid of the signal
- $f_k = k\Delta f$ Subcarrier frequency
- $T_s = T + T_{cp}$ Complete symbol time = Symbol time + cyclic prefix duration

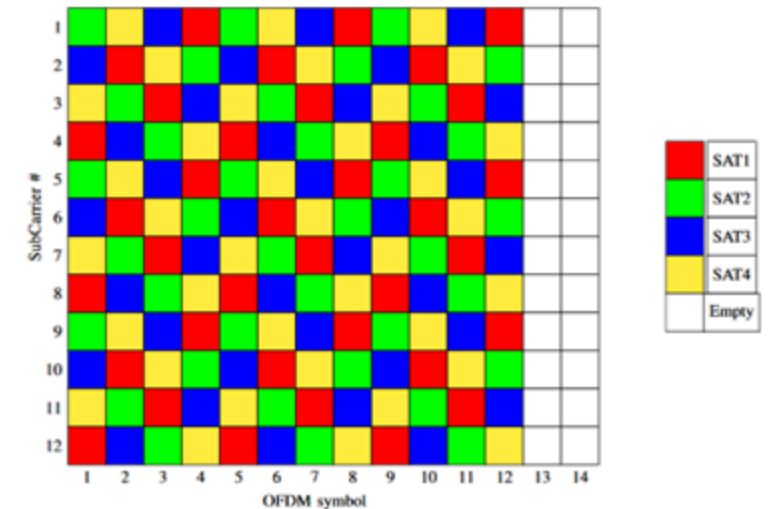


Fig. 2: 5G PRS Transmitted Resource Grid example to multiplex 4 different satellites (each color is the PRS transmission from a different satellite). Size 1 Resource Block $\times$ 1 Slot and a Comb Size (frequency periodicity of the PRS per transmitter) of 4.

Waveform. Time-Coded OFDM

- The NAV block of the receiver, thanks to the correlation gain, can extract the navigation signal. It treats the communication signal as "extra" interference.
- The communication block at the receiver, once the navigation signal is detected, it removes it (It can follow a Sequential Interference Cancellation (SIC) approach). And then demodulate the signal, with the aid of the parameters estimated from the nav signal (delay, Doppler, SINR)
- The nav signal can be in the order of -10dB or less power than the data.
- This design can be backwards compatible with 5G NTN as the modifications are minimum at the UE side

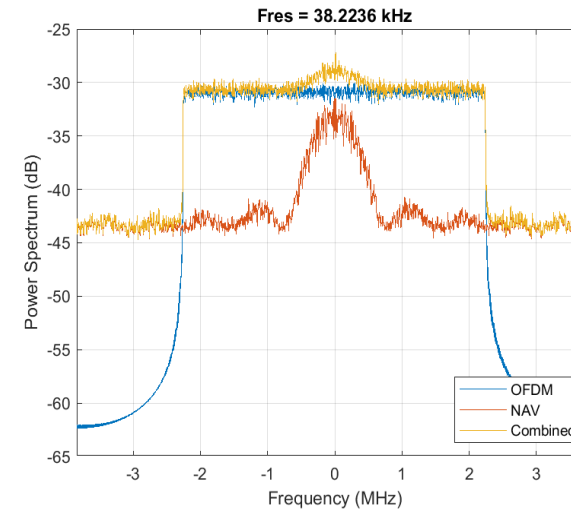
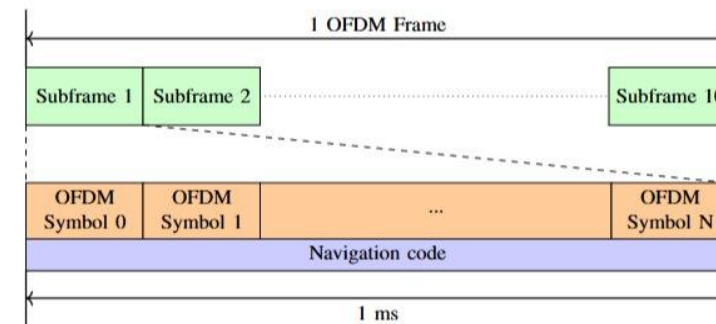
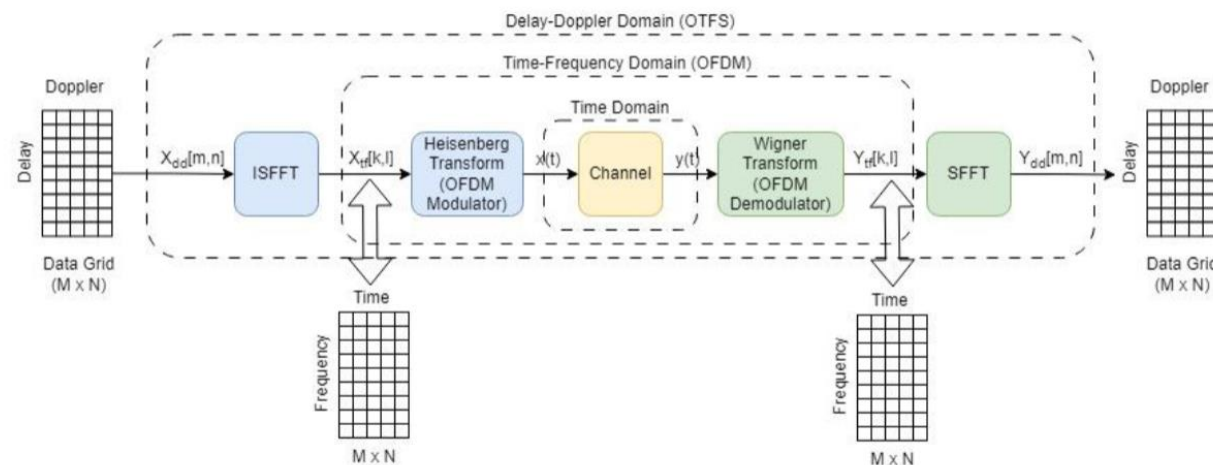


Fig. 1: Time-Code OFDM combining data transfer and a navigation signal using the 5G Frame structure.

Waveform. Orthogonal Time-Frequency Space (OTFS)



$$x_i(t) = \sqrt{P_{TX}} \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} A_i[m, n] e^{j2\pi\left(\frac{nk}{N} - \frac{ml}{M}\right)} g_{tx}(t - kT) e^{j2\pi l \Delta f (t - kT)}$$

In the delay-Doppler domain the channel is sparse. Easier for a communication receiver to equalize. Furthermore, it can be exploited for navigation purposes as in the channel estimation the receiver have the delay and Doppler observables

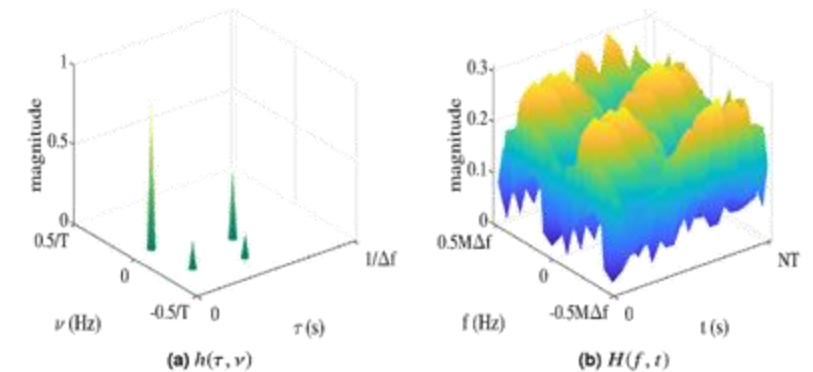


FIGURE 2.5 The continuous delay-Doppler vs time-frequency channel representation of a high-mobility multipath channel (linear time-varying).

PNT Techniques

PNT Techniques

- Observable extraction
 - Acquisition
 - Fine estimation
 - Tracking loop
- PNT Measurement models. Single point and multi-epoch
 - ToA
 - TDoA
 - FDoA
 - Multi-RTT
- PVT Engines
 - WLS
 - KF

Observable Extraction. 1. Acquisition

- This step is the first estimation of the delay and Doppler of a received signal.
- It also serve to evaluate the presence of a signal or not.
- It is based in the cross-correlation between the received signal and a local replica. When the signal is present, a peak appears in the output.
- The detection of the signal is based on a threshold in the cross-correlation output. It can be fixed or dynamic

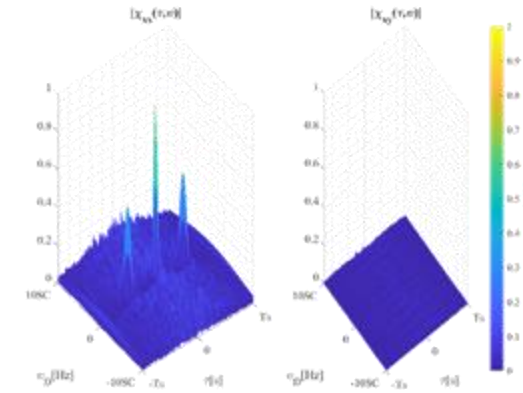


Figure: Cross Ambiguity Function for the 5G PRS

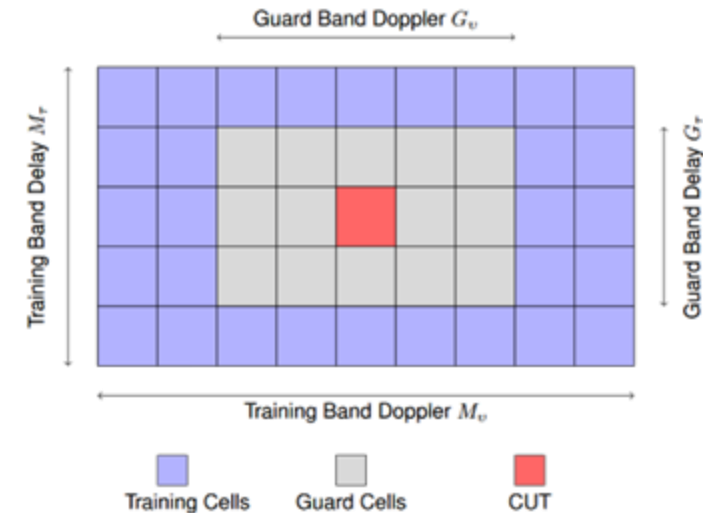


Figure 31: 2D CA-CFAR algorithm in the Delay/Doppler Map

Observable Extraction. 2. Fine Delay and Doppler

- Channel estimation by using the pilots and the local replica

$$\hat{h}_i(p) = \hat{\Upsilon}_{i,p} \Upsilon_{i,p}^* \quad \text{for } p = 0, 1, \dots, P_i - 1,$$

- Doppler Offset Estimation: Using two consecutive estimations of the channel:

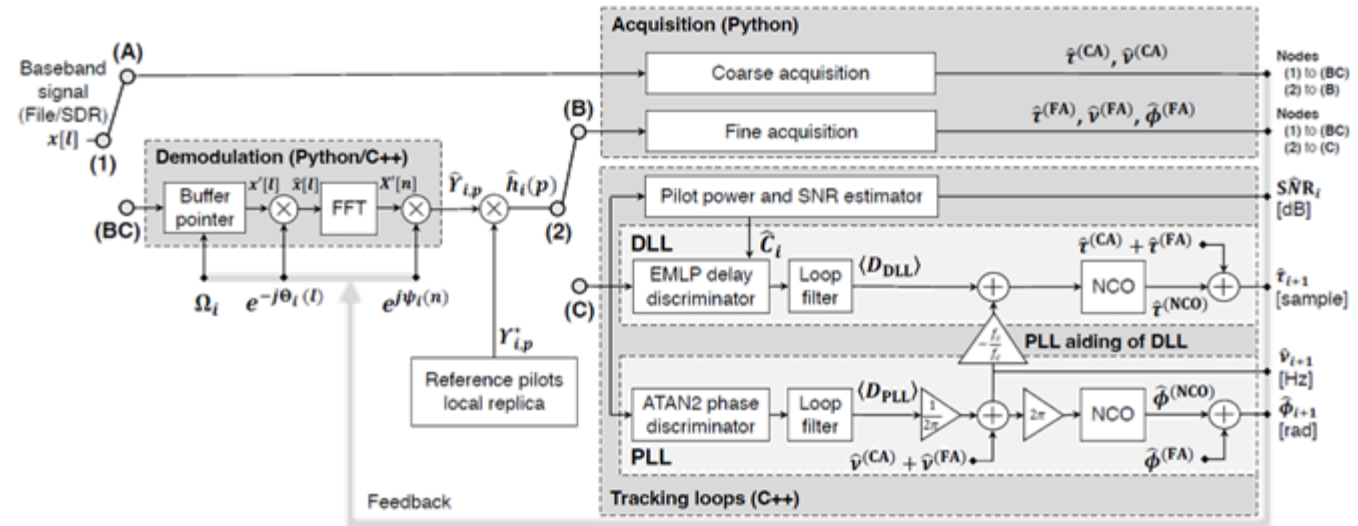
$$\hat{v}_i^{(\text{FA})} = \frac{1}{2\pi T_\eta} \angle \left(\sum_{p=0}^{P-1} \hat{h}_i(p) \hat{h}_{i+\ell}^*(p) \right) \text{ [Hz]},$$

- Delay Offset Estimation using the ESPRIT algorithm

$$\begin{aligned} \hat{\tau} &= \text{sort} \left(-\frac{\psi}{2\pi \Delta P \Delta f} \right) \\ &= [\hat{\tau}_0, \hat{\tau}_1, \dots, \hat{\tau}_{L-1}]^T \in \mathbb{C}^{L \times 1} \text{ [s]}, \end{aligned}$$

Observable Extraction. 3. Tracking loops

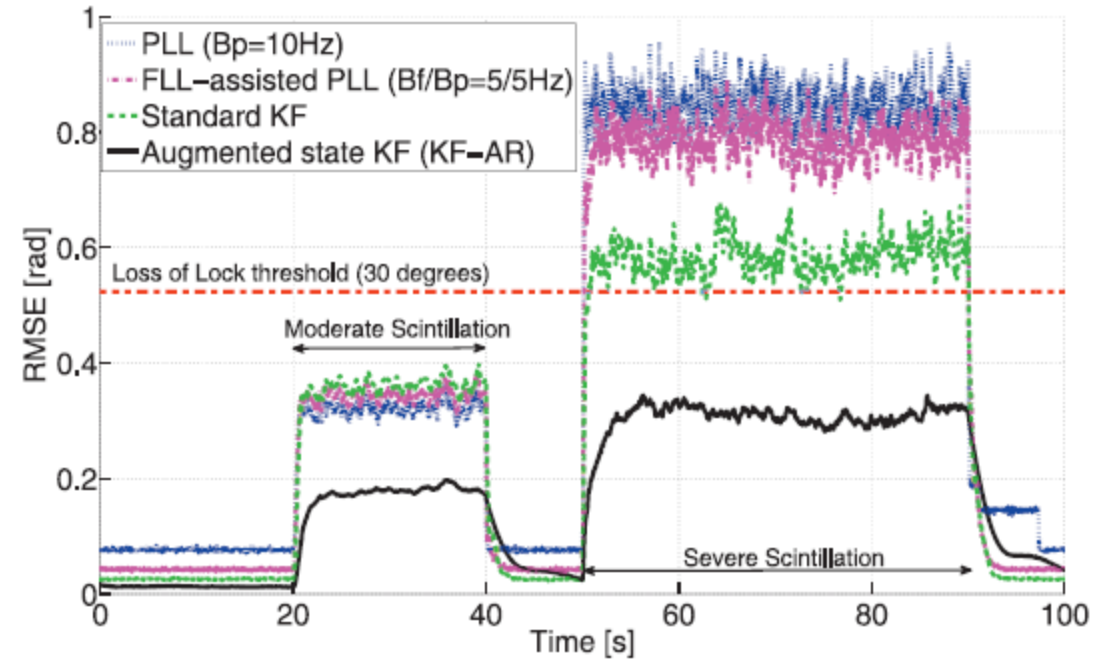
The classical approach is to use one close loop to track the changes in the delay, a DLL. Another closed loop to track changes in the phase, a PLL. And depending on the implementation, an initial frequency locked loop (FLL) and aiding the PLL with the DLL. Or a cascade architecture.



Source: I. Lapin, G. S. Granados, J. Samson, O. Renaudin, F. Zanier, and L. Ries, "STARE: Real-Time Software Receiver for LTE and 5G NR Positioning and Signal Monitoring," in *2022 10th Workshop on Satellite Navigation Technology (NAVITEC)*, Noordwijk, Netherlands: IEEE, Apr. 2022, pp. 1–11. doi: [10.1109/NAVITEC53682.2022.9847544](https://doi.org/10.1109/NAVITEC53682.2022.9847544).

Observable Extraction. 3. Tracking loops

The classical tracking loops as PLL/FLL/DLL can be substituted by Bayesian approaches as Kalman filters

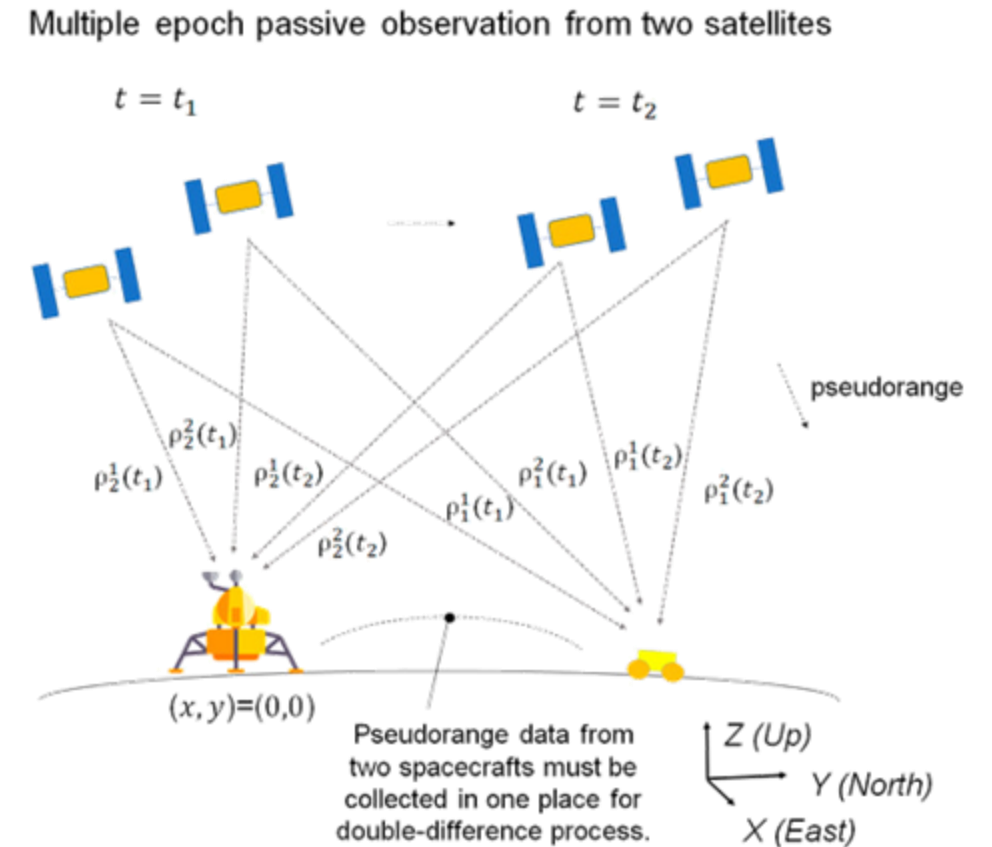


(a) Carrier phase RMSE

J. Vila-Valls, P. Closas, M. Navarro, and C. Fernandez-Prades, "Are PLLs dead? A tutorial on kalman filter-based techniques for digital carrier synchronization," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 32, no. 7, pp. 28–45, Jul. 2017, doi: [10.1109/MAES.2017.150260](https://doi.org/10.1109/MAES.2017.150260).

PNT single-point and multi-epoch algorithms

Snapshot Algorithm	UE State parameters	Observables	Min Number of satellites in LOS
One way range	UE position and clock bias	ToA	4
One way Doppler	UE position, velocity and clock drift	FoA	7
One way range and Doppler	UE position, velocity, clock bias and drift	ToA and FoA	4
Two way Range	UE position	Round trip time	3
Two way Doppler	UE position and velocity	Round trip Doppler	6
Two way range and Doppler	UE position and velocity	Round trip time and Doppler	3
Difference of ToA	UE position and clock bias	TDoA	4



Source: Tanaka, T.; Ebinuma, T.; Nakasuka, S.; Malki, H. A Comparative Analysis of Multi-Epoch Double-Differenced Pseudorange Observation and Other Dual-Satellite Lunar Global Navigation Systems. *Aerospace* **2021**, *8*, 191.

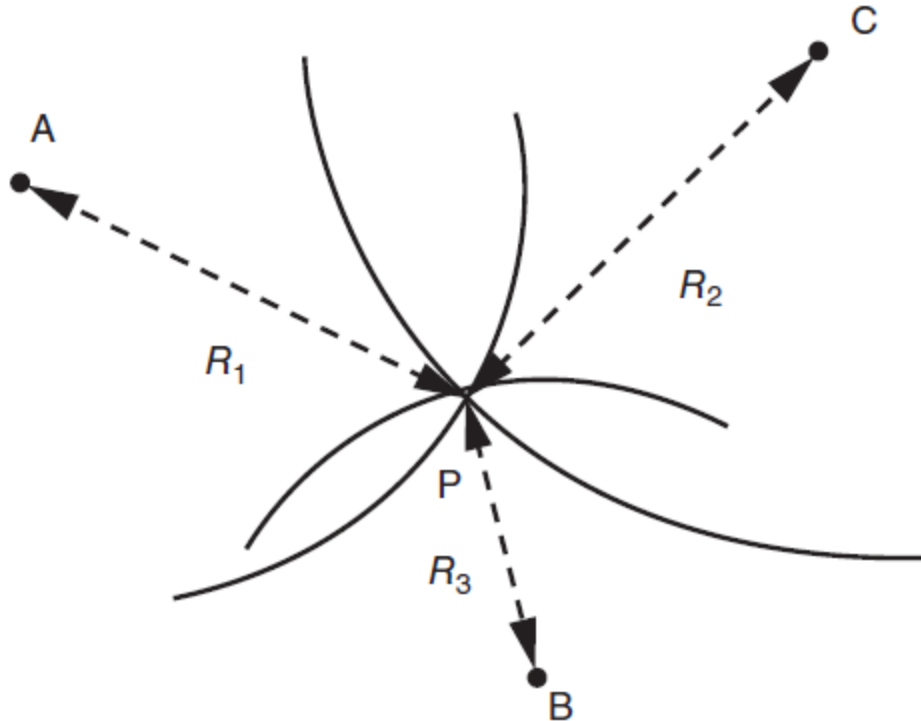
<https://doi.org/10.3390/aerospace8070191>

PNT modes. ToA

$$ToA = t_{rx} - t_{tx}$$

$$D = (t_{rx} - t_{tx}) \cdot v_p$$

$$(x - a)^2 + (y - b)^2 + (x - c)^2 = ((t_{rx} - t_{tx}) \cdot v_p)^2 + e_{toa}^2$$



$$\underline{\Delta \rho} = \begin{bmatrix} \Delta \rho_{UE}^{Sat_1} \\ \Delta \rho_{UE}^{Sat_2} \\ \vdots \\ \Delta \rho_{UE}^{Sat_N} \end{bmatrix} = \underline{H} \begin{bmatrix} \Delta x_{UE} \\ \Delta y_{UE} \\ \Delta z_{UE} \\ c_0 b_{UE} \end{bmatrix} + \begin{bmatrix} \varepsilon_{\rho, Sat_1} \\ \varepsilon_{\rho, Sat_2} \\ \vdots \\ \varepsilon_{\rho, Sat_N} \end{bmatrix} = \underline{H} \cdot \underline{\Delta X_{UE}^{DL-ToA}} + \underline{\varepsilon_{DL-ToA}}$$

$$\underline{H} = \begin{bmatrix} \frac{(\underline{X_{Sat_1}} - \underline{X_{UE}})^T}{\|\underline{X_{Sat_1}} - \underline{X_{UE}}\|} & -1 \\ \frac{(\underline{X_{Sat_2}} - \underline{X_{UE}})^T}{\|\underline{X_{Sat_2}} - \underline{X_{UE}}\|} & -1 \\ \vdots & \vdots \\ \frac{(\underline{X_{Sat_N}} - \underline{X_{UE}})^T}{\|\underline{X_{Sat_N}} - \underline{X_{UE}}\|} & -1 \end{bmatrix}_{N \times 4} = \begin{bmatrix} [\underline{H_1}]_{N \times 3} & -I_{n \times 1} \end{bmatrix}_{N \times 4}$$

where

- $\underline{\Delta \rho}$ ($= \Delta \rho_{UE}^{Sat_i}$) is the vector of observations, constituted by the range differentials between UE and i -th satellite,
- $\underline{\Delta X_{UE}^{DL-ToA}}$ is the vector of unknowns, including UE position differentials (i.e. Δx , Δy , Δz) and the UE clock error (i.e., b_{UE}), being c_0 is the speed of light,
- $\underline{H}$ defines the design, geometry or Jacobian matrix
- $\underline{\varepsilon_{DL-ToA}}$ is the vector of the measurements noise including contribution from
 - o Thermal noise ($\varepsilon_{\rho, UE}^{Sati}$), the RFI ($RFI_{\rho, UE}^{Sati}$), the MAI ($MAI_{\rho, UE}^{Sati}$) and the MP ($MP_{\rho, UE}^{Sati}$)
 - o The residual for the LEO 5G satellite clock and orbits
 - o The residual for the atmospheric models (when applicable) for the ionosphere ($I_{\rho, UE}^{Sati}$) or troposphere ($T_{\rho, UE}^{Sati}$).
 - o Note: In case some system scenarios comprises dual-frequency corrections for ionosphere, the noise amplification factor would apply within the terms ($\varepsilon_{\rho, UE}^{Sati}$), ($RFI_{\rho, UE}^{Sati}$), ($MAI_{\rho, UE}^{Sati}$) and ($MP_{\rho, UE}^{Sati}$) calculated in both frequencies.
- N is the number of satellites in view.

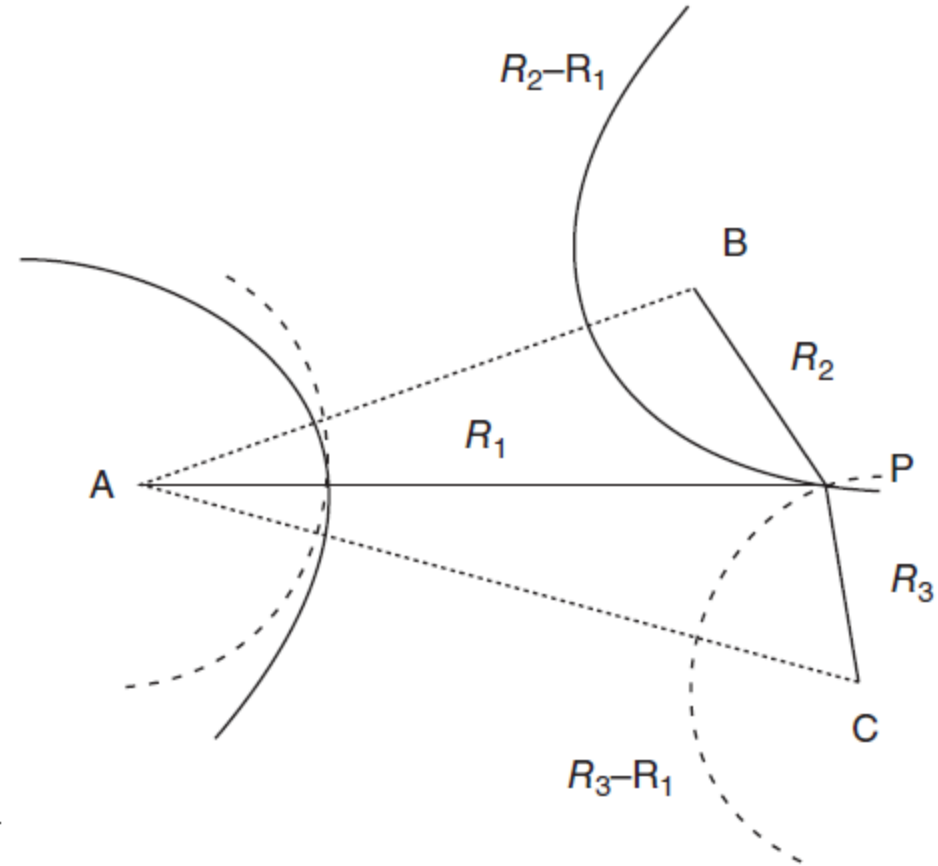
PNT modes. TDoA

$$(d_2 - d_1) = (t_{rx2} - t_{rx1}) \cdot v_p$$

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$

$$\overline{RxTx_2} - \overline{RxTx_1} = (t_{rx2} - t_{rx1}) \cdot v_p + e_{tdoa}$$

$$\overline{RxTx_i} = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}$$



PNT modes. FDoA

Doppler Observable model

$$f_D(t) = \frac{f_0}{c} \frac{d}{dt} \rho(t) \quad (4)$$

Where:

- $\rho_n(t) = |\vec{r}_{SATn} - \vec{r}_{UE}|$
- $\frac{d}{dt} \rho_n(t) = \frac{\vec{r}_{SATn} - \vec{r}_{UE}}{|\vec{r}_{SATn} - \vec{r}_{UE}|} (\vec{v}_{SATn} - \vec{v}_{UE}) = \hat{u}_{SATn} \vec{v}_{SATn,UE}$

Cost Function:

$$\mathcal{L} = \hat{f}_D - \frac{f_0}{c} \hat{u}_{SATn,UE} \vec{v}_{SATn,UE} \quad (5)$$

Position estimation:

$$\hat{x} = \operatorname{argmin}_x \mathcal{L} \quad (6)$$

$$\Delta \underline{\dot{\rho}} = \begin{bmatrix} \Delta \dot{\rho}_{Sat_1} \\ \Delta \dot{\rho}_{Sat_2} \\ \vdots \\ \Delta \dot{\rho}_{Sat_n} \end{bmatrix} = \underline{\underline{G}} \begin{bmatrix} \Delta x_{UD} \\ \Delta y_{UD} \\ \Delta z_{UD} \\ c_0 \dot{b}_{UD} \end{bmatrix} + \begin{bmatrix} \varepsilon_{\dot{\rho},Sat_1} \\ \varepsilon_{\dot{\rho},Sat_2} \\ \vdots \\ \varepsilon_{\dot{\rho},Sat_n} \end{bmatrix} = \underline{\underline{G}} \cdot \Delta \underline{X}_{UD}^{OWD} + \underline{\varepsilon}_{OWD}$$

$$\underline{\underline{G}} = \begin{bmatrix} \left\{ \frac{\vec{X}_{Sat_1} - \vec{X}_{UD}}{\|\vec{X}_{Sat_1} - \vec{X}_{UD}\|} \times \left(\frac{\vec{X}_{Sat_1} - \vec{X}_{UD}}{\|\vec{X}_{Sat_1} - \vec{X}_{UD}\|} \times \frac{\|\vec{V}_{Sat_1} - \vec{V}_{UD}\|}{\|\vec{X}_{Sat_1} - \vec{X}_{UD}\|} \right)^T \right\} & -1 \\ \left\{ \frac{\vec{X}_{Sat_2} - \vec{X}_{UD}}{\|\vec{X}_{Sat_2} - \vec{X}_{UD}\|} \times \left(\frac{\vec{X}_{Sat_2} - \vec{X}_{UD}}{\|\vec{X}_{Sat_2} - \vec{X}_{UD}\|} \times \frac{\|\vec{V}_{Sat_2} - \vec{V}_{UD}\|}{\|\vec{X}_{Sat_2} - \vec{X}_{UD}\|} \right)^T \right\} & -1 \\ \vdots & \vdots \\ \left\{ \frac{\vec{X}_{Sat_n} - \vec{X}_{UD}}{\|\vec{X}_{Sat_n} - \vec{X}_{UD}\|} \times \left(\frac{\vec{X}_{Sat_n} - \vec{X}_{UD}}{\|\vec{X}_{Sat_n} - \vec{X}_{UD}\|} \times \frac{\|\vec{V}_{Sat_n} - \vec{V}_{UD}\|}{\|\vec{X}_{Sat_n} - \vec{X}_{UD}\|} \right)^T \right\} & -1 \end{bmatrix}_{n \times 4} = \begin{bmatrix} \left[\underline{\underline{G}} \right]_{n \times 3} & -I_{n \times 1} \end{bmatrix}_{n \times 4}$$

PNT modes. Multi-RTT

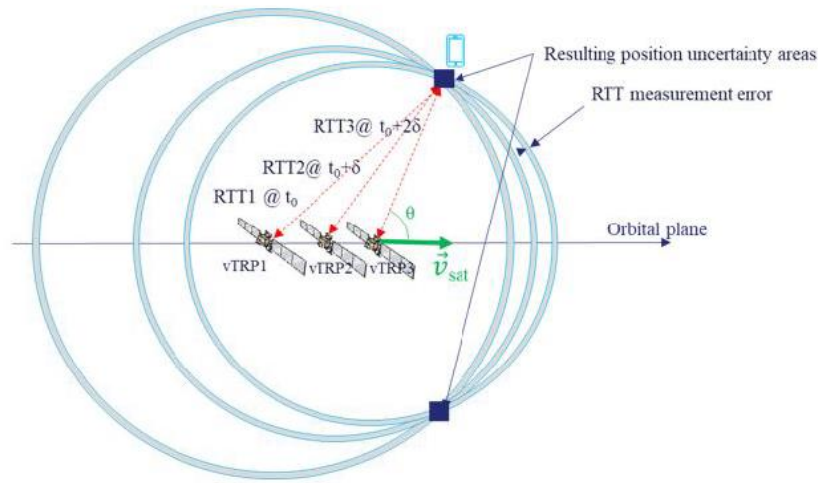


Figure 3-1: Single-satellite multi-RTT positioning method for NTN positioning [RD5].

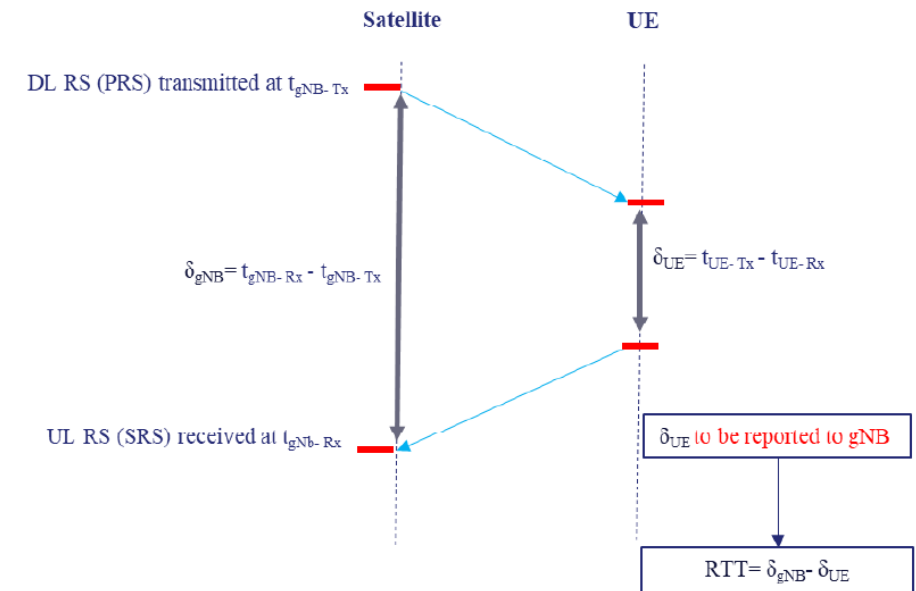


Figure 3-2: Single-satellite multi-RTT measurement [RD4].

$$RTT = (t_{rx,ack} + \tau tx) - (t_{tx,s} + \tau tx) = t_{rx} - t_{tx}$$

The measurement model is the same as ToA as it describes circles

PVT Engine. Weighted least squares

- After linearizing the measurement model $h()$ for H , x can be estimated by:

$$\hat{\mathbf{x}}_{i+1} = \hat{\mathbf{x}}_i + (\mathbf{H}^T \mathbf{W} \mathbf{H})^{-1} \mathbf{H}^T \mathbf{W} (\mathbf{y} - \mathbf{h}(\hat{\mathbf{x}}_i))$$

Where W are the weight (or relative quality) of each of the measurements. W can be obtained based on the variance of the measurements

$$\mathbf{W} = \text{diag} (\sigma_1^{-2}, \sigma_2^{-2}, \sigma_3^{-2}, \dots, \sigma_m^{-2}) ,$$

PVT Engine. Kalman Filtering

1. Prediction step. It estimates what is going to be the state $\mathbf{x}_{k+1}$ at time $k+1$ from on the previous state $\mathbf{x}_k$ at time k based on the state transition matrix $\mathbf{F}$

$$\hat{\mathbf{x}}_{k+1} = \mathbf{F}\mathbf{x}_k \quad (45)$$

2. After the state prediction, it is necessary to update the covariance matrix of the error in the prediction $\mathbf{P}$ using the matrix $\mathbf{Q}$ as the process noise covariance, or how good is our model $\mathbf{F}$ to the reality:

$$\mathbf{P}_{k+1} = \mathbf{F}\mathbf{P}_k\mathbf{F}^T + \mathbf{Q} \quad (46)$$

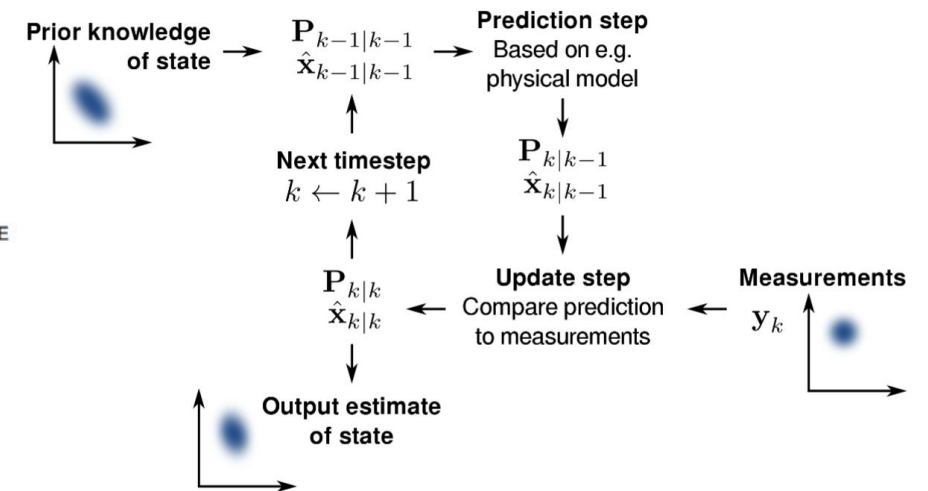
3. The state update with the measurements. The measurement model we have seen before in (44), $h = -\frac{f_0}{c} \mathbf{u}_{\text{SAT,UE}}^T \mathbf{v}_{\text{SAT,UE}}$ is used to update the prediction done in the previous step $\hat{\mathbf{x}}_{k+1}$

$$\mathbf{y}_{k+1} = \mathbf{z}_{k+1} - h(\hat{\mathbf{x}}_{k+1}) \quad (47)$$

4. Then it is required to update the measurement covariance matrix $\mathbf{S}_{k+1}$ using the Jacobian of the measurement model $\mathbf{H}$ and the measurement noise covariance matrix $\mathbf{R}$

$$\mathbf{S}_{k+1} = \mathbf{H}_{k+1}\mathbf{P}_{k+1}\mathbf{H}_{k+1}^T + \mathbf{R} \quad (48)$$

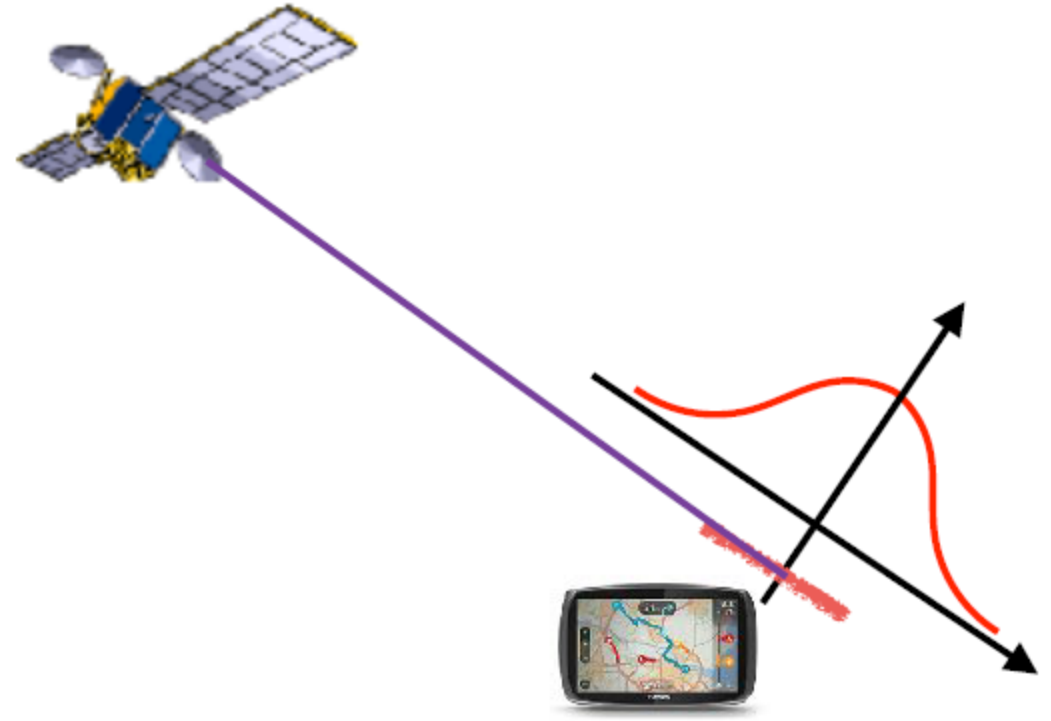
5. Then the Kalman gain is obtained as: $\mathbf{K}_{k+1} = \mathbf{P}_{k+1}\mathbf{H}_{k+1}^T\mathbf{S}_{k+1}^{-1}$
6. With the Kalman gain, the final state estimation can be obtained: $\mathbf{x}_{k+1} = \hat{\mathbf{x}}_{k+1} + \mathbf{K}_{k+1}\mathbf{y}_{k+1}$
7. And finally update the covariance matrix of the error in the prediction $\mathbf{P}_{k+1} = (\mathbf{I} - \mathbf{K}_{k+1}\mathbf{H}_{k+1})\mathbf{P}_k$



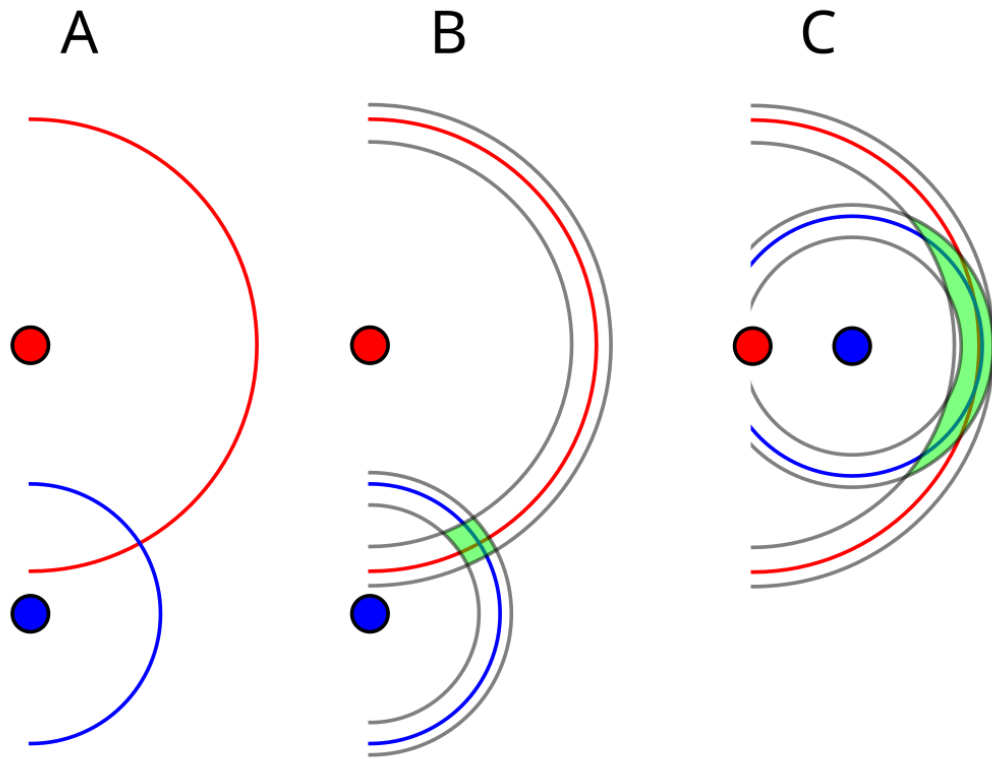
Performance limits

Performance limits

- Theoretical limits. Cramer-Rao Lower Bound
- Sources of errors
 - Geometrical Dilution of Precision
 - Clocks and Synchronization
 - Radio propagation
 - Interference and multipath



Sources of error. Geometrical Dilution of Precision (GDOP)



$$Q = (H^T H)^{-1} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} & \sigma_{14} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} & \sigma_{24} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} & \sigma_{34} \\ \sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_{44} \end{bmatrix}$$

The theoretical analysis of the GDOP is done in the reference [17]. Starting with the definition of the measurement matrix H which contains $K \geq 4$ range residuals:

$$H \triangleq \begin{bmatrix} h_{1x} & h_{1y} & h_{1z} & 1 \\ \dots & \dots & \dots & \dots \\ h_{ix} & h_{iy} & h_{iz} & 1 \\ \dots & \dots & \dots & \dots \\ h_{Kx} & h_{Ky} & h_{Kz} & 1 \end{bmatrix}$$

Where each residual is the component of a unit vector from the UE coordinates (x, y, z) to the i_{th} BS coordinates (x_i, y_i, z_i) .

$$h_{ix} = \frac{x_i - x_{UE}}{R_i}$$

And R is the euclidean estimated distance between the UE position and the BS position:

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}$$

$$GDOP_{xyz} = \sqrt{\text{sum}(\text{diag}(Q))} = \sqrt{\sigma_{11} + \sigma_{22} + \sigma_{33} + \sigma_{44}}$$

GDOP Value	Rating
≤ 1	Ideal
1 – 2	Excellent
2 – 5	Good
5 – 10	Moderate
10 – 20	Fair
> 20	Poor

Sources of Error. Clocks

Clock technologies for LEO platforms:

- CSAC: Chip Scale Atomic Clock
- VCXO: Voltage-Controlled Crystal Oscillator
- TXCO: Temperature-compensated Crystal Oscillator
- OCXO: Oven-Controlled Crystal Oscillator
- MCXO: Microcomputer-compensated Crystal Oscillator
- USO: Ultra-Stable Oscillator
- RAFS: Rubidium Atomic Frequency Standard
- CAFS: Cesium Atomic Frequency Standard

Oscillator type	Stability (log10)	Aging/10 year (log10)	Power consumption (W)
CSAC	-11, -9	-8	0.1
TCXO	-9, -8	-7	1e-4
OCXO	-12, -10	-8	3
MCXO	-12, -9	-6	2e-4
USO	-13, -12	-8	8
Rubidium	-11	-10, -9	12
Cesium	-12, -11	-12, -11	40

Sources of Error. Ionospheric and Tropospheric propagation

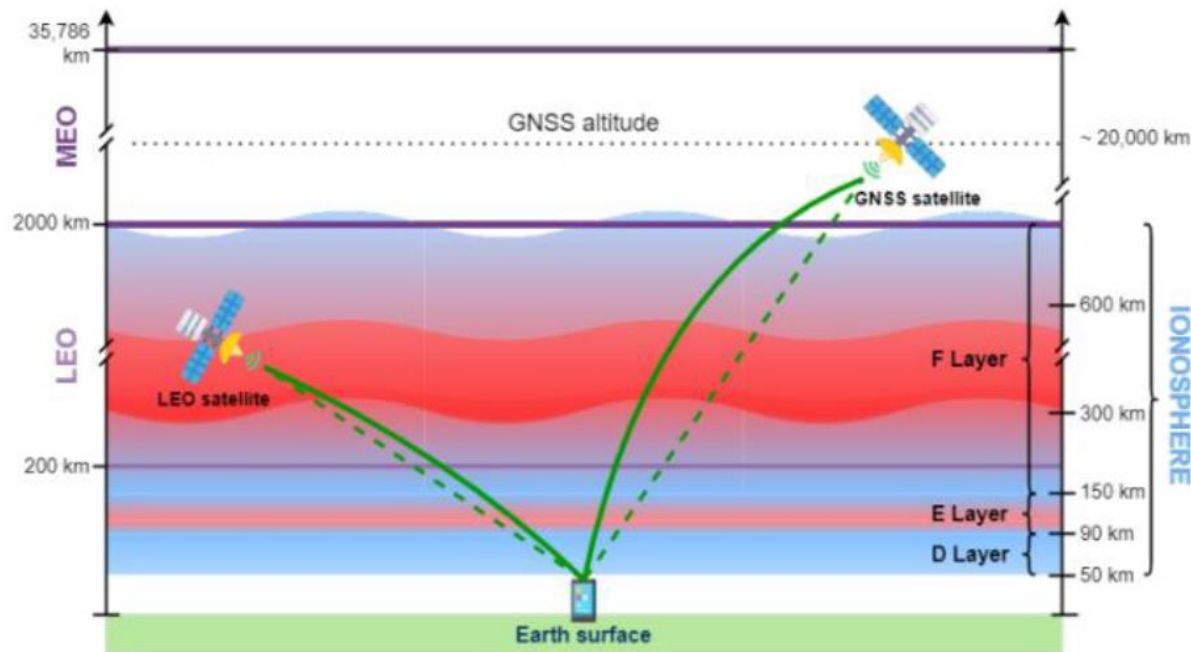


Figure 6-6: Ionosphere Layer Representation w.r.t. to satellite altitudes [RD56].

Source: M. Imad, A. Grenier, X. Zhang, J. Nurmi, E.S. Lohan, "Ionospheric Error Models for Satellite-Based Navigation—Paving the Road towards LEO-PNT Solutions", Computers, vol. 13, no. 1:4, 2024. <https://doi.org/10.3390/computers13010004>

There are two models for the ionosphere:

- Klobuchar: Used in GPS
- NeQuick: Used in Galileo and Beidou

Both of them estimate the Total Electron Content (TEC) between the satellite and the user.

New models are required for LEO missions that operate below C-Band as the TEC will be smaller as in MEO missions at L-Band

Sources of error. Interference

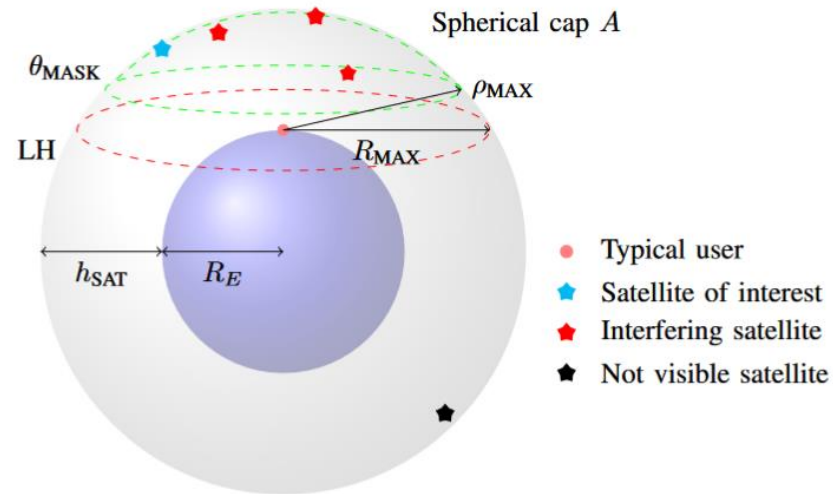


Fig. 3: Typical satellite user view. Where the maximum slant range is defined by R_{MAX} at an elevation angle of 0° . It shows also the usable area as a spherical cap A in green, defined by minimum elevation angle θ_{MASK} . At the elevation angle θ_{MASK} the satellite is at the maximum usable distance ρ_{MAX} . It also shows different satellites, one of interest, 3 that could interfere with the interest and one out of sight from the user

$$I_i = \sum_{s \neq i}^{S-1} \rho_s^{-2} P_{TX} |\chi_{x_s x}(\Delta\tau_s, \Delta v_s)|^2.$$

Sources of Error. Multipath

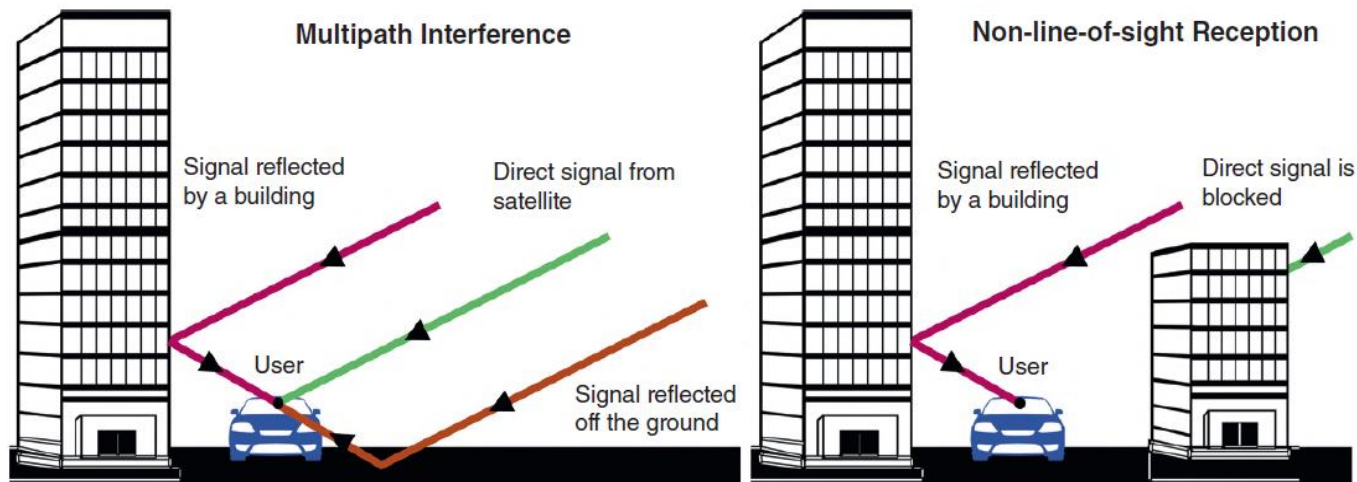
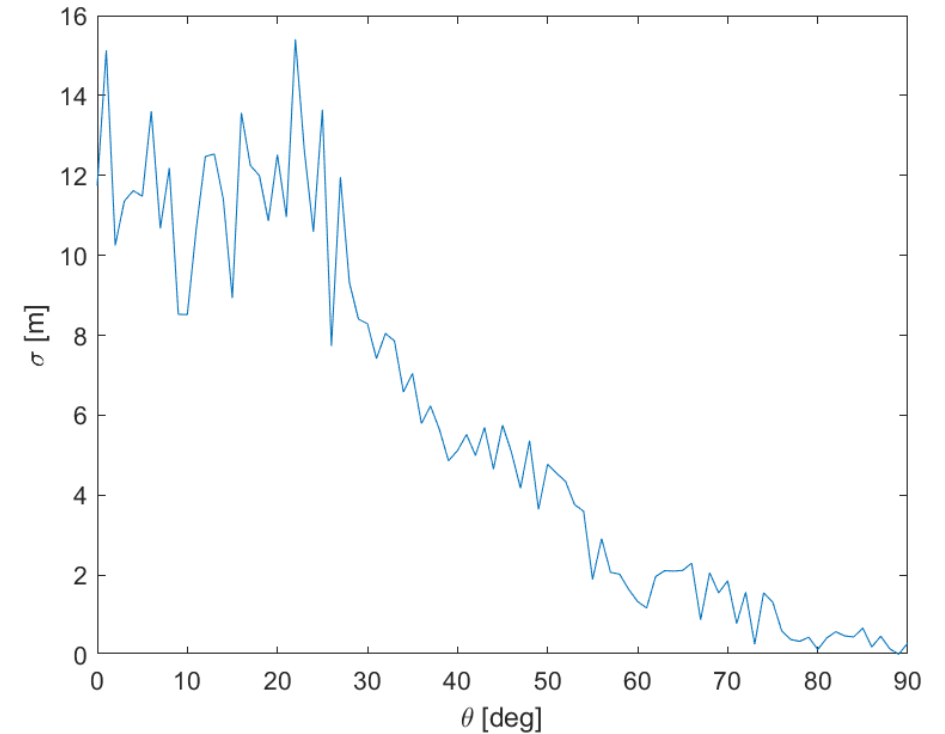


Figure 22.1 Multipath interference and NLOS reception.

Source: Position, navigation, and timing technologies in the 21st Century: integrated satellite navigation, sensor systems, and civil applications. Volume 2. Hoboken, NJ: Wiley : IEEE Press, 2021.



User Equivalent Range Error

- All the errors can be modelled as an iid Gaussian random variable with mean 0 and variance

$$\sigma_{UERE} = \sqrt{\sum_j \sigma_j^2} \quad [\text{m}]$$

- Typical Single Freq. GNSS UERE Budget

Segment	Error Source	RMS Range Error ($2\sigma = 95.5\%$)
Space/Control	Broadcast clock+ephemeris	1.3 m
User	Ionospheric delay	14 m
	Tropospheric delay	0.4 m
	Receiver noise	0.2 m
	Multipath	0.4 m
System UERE	Total	14.1 m

Source: Understanding GPS – Principles and Applications; Kaplan, Hegarty; 2nd Edition; Artech House; 2006

Challenges and future trends

Challenges in JCAP from LEO

- High Doppler shift makes the search window in acquisition larger than MEO satellite. Requiring more processing for acquiring it and higher order in the tracking loops
- Clocks on board LEO satellites are not as accurate as those in GNSS because of the cost per unit. In LEO it is intended a much larger number of satellites and the unit cost should be kept at minimum.
- Intersatellite links are required for communications
- Interference management strategies for large LEO constellation
- No real time LEO-PNT receivers are available in the market at this moment. Only academic works

Future trends

- Seamless communication for the user. It will not distinguish if the user terminal is connected to a terrestrial or a satellite network.
- Improved accuracy, availability and robustness of the PNT service.
- Communication throughput improves by knowing the user location





Thank You!