

# What could the future of satellite communications hold for us?

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# Overview

- Satellite structural subsystems, network architectures, communication systems, and classifications
- Brief history of satellite communications and their applications
- Scenario and use cases which can benefit from satellite communications in the near future
- Related challenges



# First person to talk about satellite

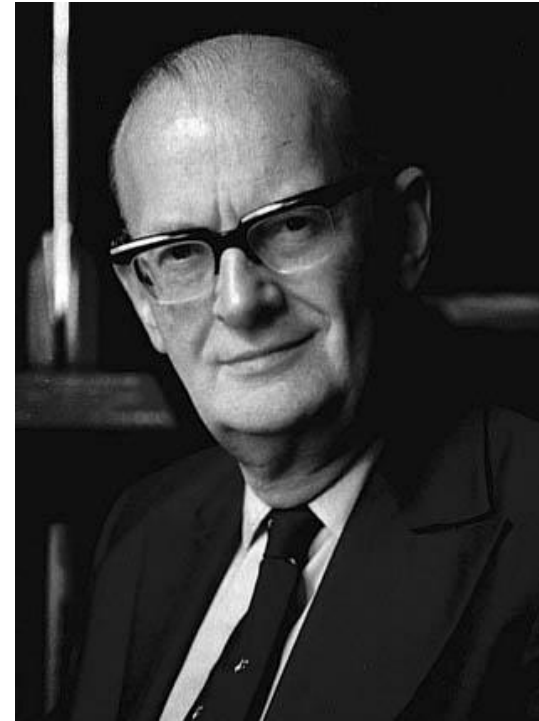
Arthur C. Clarke

**Sir Arthur Charles Clarke** was a British science fiction writer mainly known for the science fiction novel "2001: A Space Odyssey"

When he was a 27-year-old Royal Air Force officer published the paper "Extra-Terrestrial Relays: Can rocket stations give world-wide Radio Coverage?", in October 1945

He was the first one to understand the importance of a satellite with a fixed position relative to a point on the Earth from a communication viewpoint

He wrote: "A true broadcast service, giving constant field strength at all times over the whole globe would be invaluable, not to say indispensable, in a world society"



# First artificial satellite

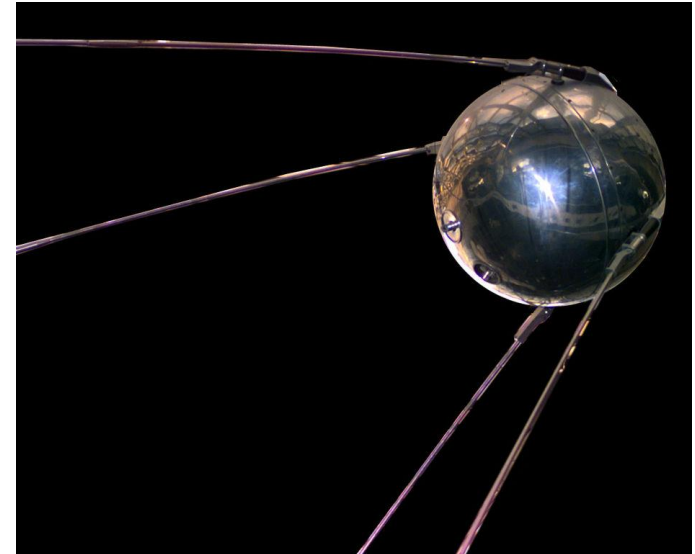
## Sputnik 1

**Sputnik 1** was launched by the Soviet Union on 4 October 1957

It was a 58 cm diameter metal sphere, 83.6 kg weight, with 4 external antennas

It was active in an elliptical low Earth orbit (perigee 215 km, apogee 939 km) for 3 weeks and laid in the space for 3 months before its fall into the atmosphere

It travelled at about 29000 km/h, 1440 orbits completed (96.2 minutes each), 1 Watt power, 20.005 and 40.002 MHz transmission frequency (radio amateur bands)



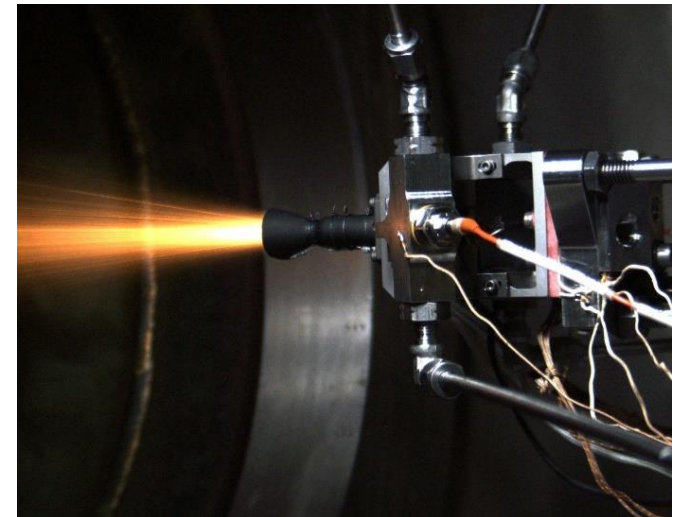
# Satellite hardware system

## Satellite subsystems



**External structure:** the hardware skeleton which defines the shape of the satellite and allows all other hardware components to be merged together

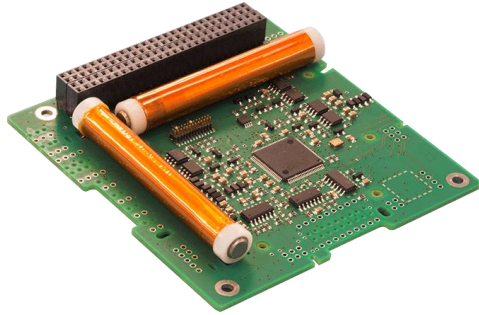
**Propulsion:** thrusters aimed at satellite position keeping, attitude control, reaction control and satellite de-orbiting at mission end. Different kinds of thrusters depending on the satellite weight, such as vacuum arc, colloid, electrospray, pulsed-plasma, which operate with different propellant, such as hydrogen peroxide or hydrazinium nitroformate (HNF) or ammonium dinitramide (ADN)





# Satellite hardware system

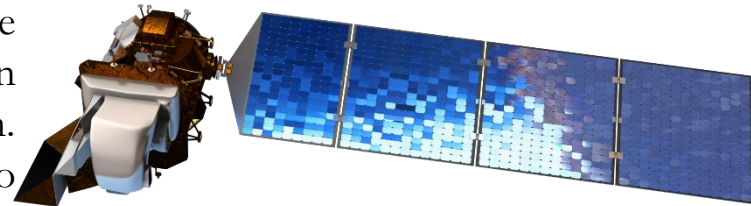
## Satellite subsystems



**Attitude Determination and Control (ADC):** sensors aimed at measuring, maintaining, and adjusting the orientation of the satellite as appropriate for mission requirements but also for power generation and communications

**Electrical Power System (EPS):** manages all aspects related to power generation, storage, conditioning distribution, and conversion. It includes:

- **Solar Panels:** can be fixed or deployable and generate power in all time periods when the satellite is in visibility with the Sun. They can produce from a few Watts to hundreds of Watts. Most used are made of Gallium Arsenide or Silicon
- **EPS card:** distributes all generated energy to all satellite subsystems
- **Batteries:** store the gathered energy to keep active all the subsystems during shadow periods. Most batteries are rechargeable and made of Lithium-Ion or Lithium-Polymer



# Satellite hardware system

## Satellite subsystems



**Command and Data Handling (CDH):** It is the brain of the overall system. It collects mission and science data for transmission, provides the ability to execute received commands, controls the deployment of the antennas and solar panels and provides some measure of robustness in order to cope with failing subsystems

**Data reception/transmission:** allows command and control messages reception and data transmission and reception in the scheduled frequency band. It includes:

- **Transceivers:** include transmitter and receiver combining and sharing common circuitry
- **Antennas:** generate and capture radio waves. They can have different shapes, such as dish or dipole, and size depending on the exploited frequency band



All these subsystems constitute the **primary system**. All other hardware components related to each specific mission goal, such as sensors, camera, high memory storage, ..... constitute the so-called **payload**

# Satellite classification

## by altitude

	Altitude [km]	Orbit time [min]	Speed [km/h]	Radius coverage area [km]	Example
<b>Low Earth Orbit (LEO)</b>	200÷2000	90÷120	28000÷25000	500÷2700	Iridium
<b>Medium Earth Orbit (MEO)</b>	6000÷35786	230÷1400	20000÷11000	5000÷7800	GPS
<b>Geo-Stationary or Geo-Synchronous Earth Orbit (GEO)</b>	35786	1436 (23 h, 56 min, 4 s - one sidereal day)	~11000	~8000	Inmarsat
<b>Highly Elliptical or High Eccentricity Orbit (HEO)</b>	not constant	not constant	not constant	not constant	Molnya

Most orbits are circular (altitude, orbit time and speed are constant)

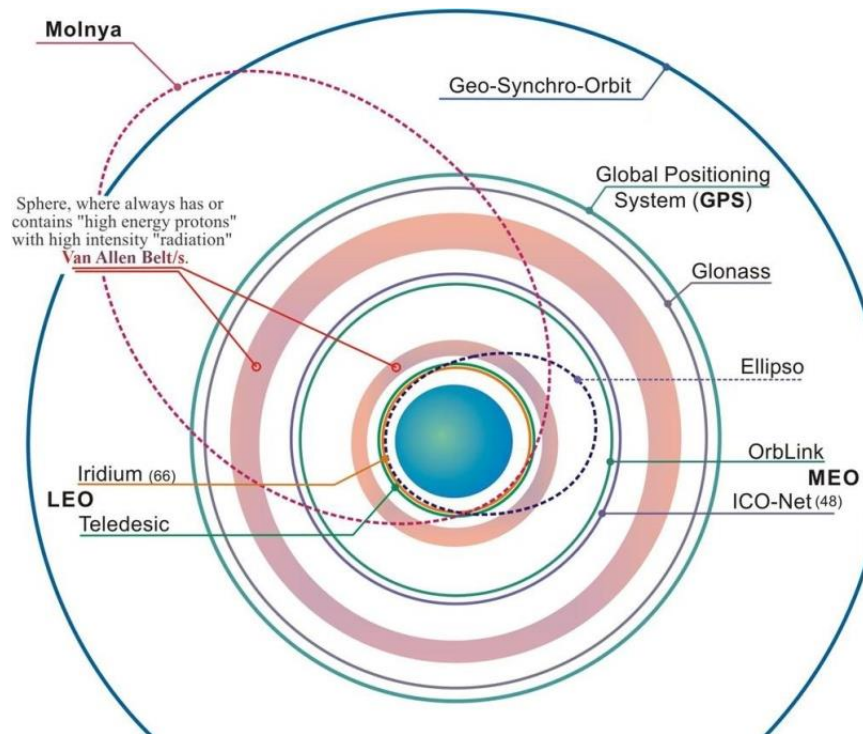
Lower the altitude, smaller the coverage area and faster the satellite

GEO satellites lay in an equatorial plane (Clarke belt orbit) and are fixed points in the sky, while others move faster than the Earth's rotation speed



# Satellite classification

## Satellite orbits



**Van Allen radiation belts** are zones full of energetic charged particles: Inner belt (1000÷6000 km), Outer belt (14500÷19000 km)



# Satellite classification

  
by weight

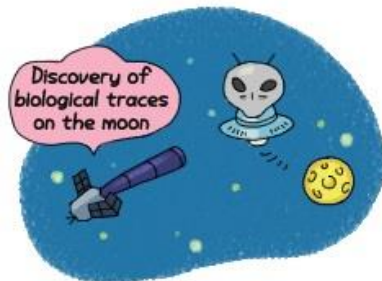
<b>LARGE SATELLITE</b>	 RADARSAT-2	 >1000 kg	 RHINO
<b>MEDIUM SATELLITE</b>	 CASSIOPE	 500-1000 kg	 BUFFALO
<b>MINI SATELLITE</b>	 SCISAT	 100-350 kg	 LION
<b>MICRO SATELLITE</b>	 M3MSat	 10-100 kg	 WOLF
<b>NANO SATELLITE including CUBESAT</b>	 Ex-Altis 1	 1-10 kg   1 kg per unit	 RACCOON   DUCK

# Satellite classification

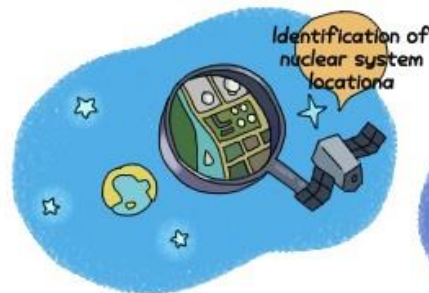
## by mission goals

- Telecommunication (satellite phones, television, Internet, ...)
- Deep space observation
- Surveillance
- Earth observation and monitoring (disaster recovery, weather forecasting, ...)
- Remote Sensing
- GPS/Navigation
- Entertainment and content delivery

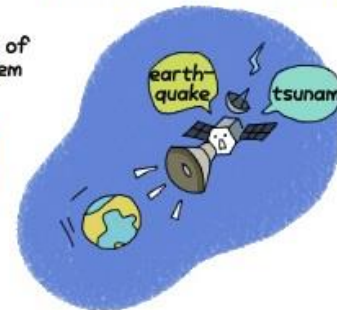
**Deep space observation**



**Surveillance**



**Weather forecasting**



**GPS/Navigation**





# Satellite communications (SatCom)

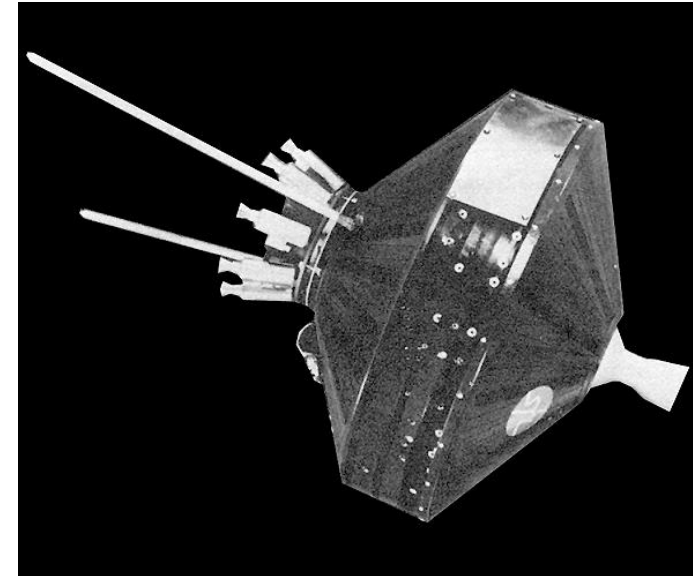
## A brief history

**Pioneer 1** was the first relay communication satellite.

It was launched by NASA on 11 October 1958.

It was intended to orbit the Moon and make scientific measurements, but it just reached an apogee of 113,800 km (less than halfway) and its flight lasted 43 hours.

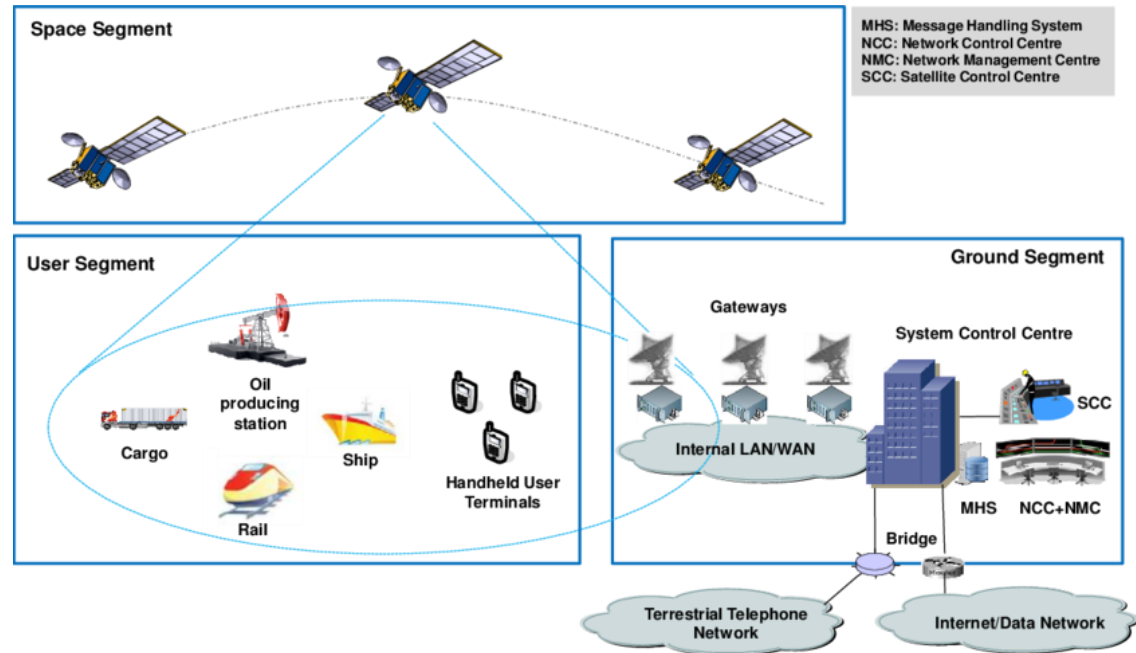
It flew high enough to carry out the proof of concept relay of telemetry across the world, first from Cape Canaveral to Manchester, England; then from Hawaii to Cape Canaveral; and finally, across the world from Hawaii to Manchester.





# Satellite communications (SatCom)

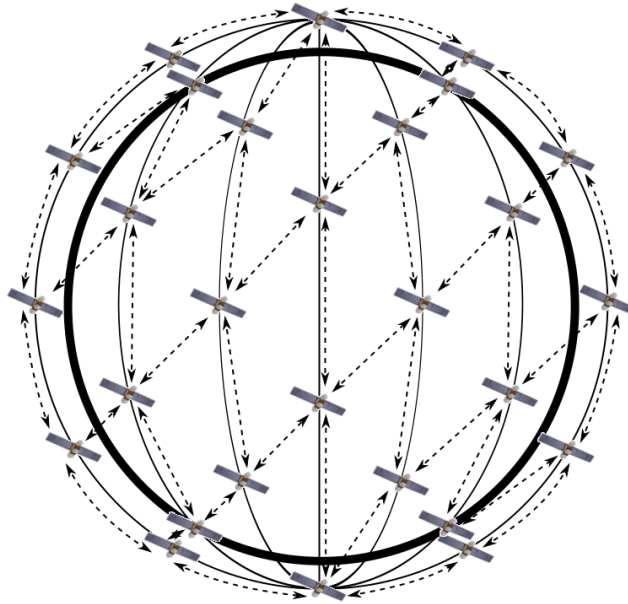
## Network architecture



- **Space segment:** satellite or satellite constellation
- **Ground segment:**
  - **Satellite gateways:** guarantee access to satellites acting as interfaces between satellites and ground infrastructure
  - **System Control Centre:** control and manage satellite network resources and supervise the service provision
- **User segment:** user terminals, both stationary and mobile

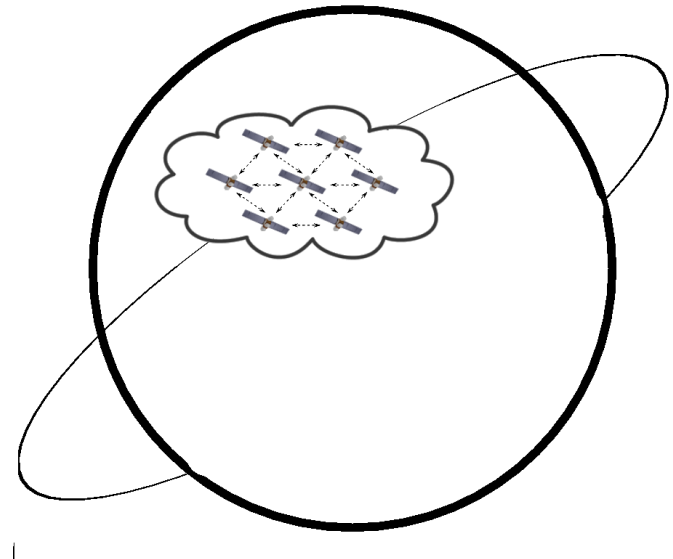
# Satellite communications (SatCom)

## Network topologies



### Constellation

All satellites are equally spaced in the chosen orbital plane (or planes) owing to their sequential deployment. They can cover a greater area, even the entire Earth's surface



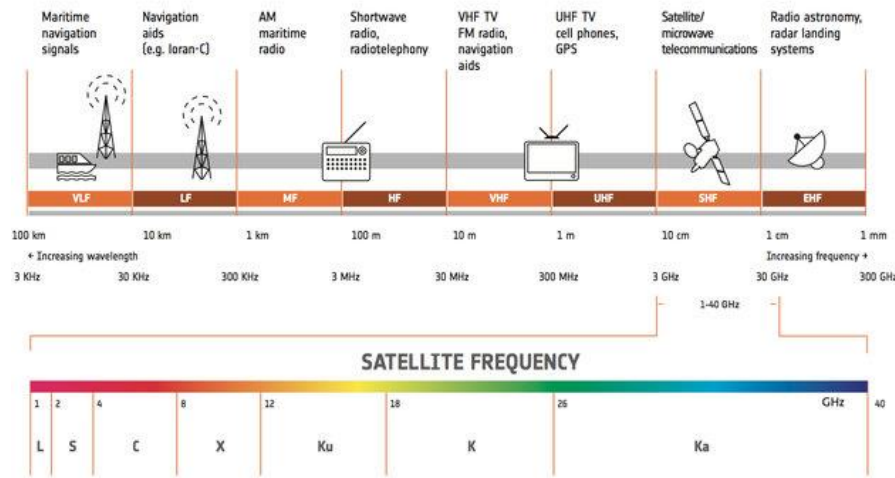
### Swarm

All satellite are very close to each other owing to their rapid deployment one after the other. They can share the available resources (energy, processing power, storage capacity, ...)

# Satellite communications (SatCom)

## Link parameters

- **Transmission rate:** from few kbps to hundreds on Gbps (few Tbps in the near future) depending on the frequency band
- **Attenuation factors:** different kinds of attenuations depending on the transmission frequency, such as gases absorption, antenna misalignment, fading, scattering, ionospheric scintillation, rain



- **Propagation delay** (one-way): from 1 to 140 ms depending on the satellite altitude and elevation angle
- **Loss rate:** high loss rates highly variable depending on a lot of different parameters such as the frequency band

# Satellite communications (SatCom)

## Space environment properties

- **Asymmetric channels:** downlink bandwidths are usually much higher than uplink bandwidths
- **Limited bandwidth:** bandwidth is a precious resource directly connected to cost, energy consumption and frequency allocation. Traffic-intensive protocols and strategies should be avoided
- **Limited computational resources and memory:** protocols and strategies have to be designed in order to minimize the computational resources consumption and require less storage space as possible
- **High propagation delay:** high delays are due to long distances between satellites and ground stations. Protocols which require multiple round-trip times or include timestamps are not well suited for space environment
- **Intermittent connectivity:** there are no persistent connections between satellites and ground stations (except for GEO satellites)
- **Remote location:** there is no physical access to the satellites when are in orbit (both for authorized or malicious users)

# Satellite communications (SatCom)

## Positive aspects

- **Coverage:** satellites can cover the entire Earth's surface
- **Availability:** satellites can always be available providing a persistent service without any disruptions
- **Reliability:** most satellites keep functioning for the entire planned lifetime without irrecoverable damages which make satellites inoperable
- **Group communications:** satellite can forward data to different users located in different geographical areas at the same time owing to their broadcast capability
- **Energy consumption:** satellites are self-sustainable for the energy viewpoint and do not require terrestrial energy sources



# Satellite communications (SatCom)

## Traditional applications: Telephone

The first and historically most important application for communication satellites was in intercontinental long distance telephony

Improvements in submarine communications cables through the use of fiber-optics caused some decline in the use of satellites for fixed telephony in the late 20<sup>th</sup> century

However, satellite phones are still used today in many areas where there is no other kind of telecommunication infrastructure

Satellite phone systems mainly exploit:

- GEO satellites: can only be used at lower latitudes (between 70° N and 70° S). At higher latitudes, the satellite appears at such a low angle in the sky that radio frequency interference from terrestrial sources in the same frequency bands can interfere with the signal
- LEO satellites: the advantages include the possibility of providing worldwide wireless coverage with no gaps. A given satellite is only in view of a phone for a short time, so the call must be “handed off” electronically to another satellite when one passes beyond the local horizon. Depending on the positions of both the satellite and terminal, a usable pass of an individual LEO satellite will typically last 4–15 minutes on average

# Satellite communications (SatCom)

## Traditional applications: Television

Satellite television is a service that delivers television programming to viewers by relaying it from a communications satellite orbiting the Earth directly to the viewer's location

Satellites for television broadcasting are typically GEO satellites of two different types: Fixed Service Satellite (FSS) and Direct Broadcast Satellite (DBS)

FSS use the C-band (4-8 GHz) and the lower portions of the Ku-band (12-18 GHz). They are normally used for broadcast feeds to and from television networks and local affiliate stations (such as program feeds for network and syndicated programming, live shots, and backhauls), as well as being used for distance learning by schools and universities, videoconferencing, and commercial telecommunications

DBS generally operate in the upper portion of the Ku-band even if some recently launched satellites have transponders in the Ka-band (25-40 GHz). DBS technology is used for Direct-To-Home (DTH)-oriented satellite TV services

# Satellite communications (SatCom)

## Traditional applications: Radio broadcasting

Satellite radio offers audio services broadcasted by a communications satellite that can cover a much wider geographical range than terrestrial radio signals

Satellite radio typically uses the S-band (2-4 GHz) in some part of the world (such as North America) while in other parts uses the L-band (1-2 GHz)

The first satellite radio broadcasts occurred in Africa and the Middle East in 1999. Satellite radio subscribers purchase a receiver and pay a monthly subscription fee to listen to programming. They can listen through built-in or portable receivers in automobiles, in the home and office with a portable or tabletop receiver, or on the Internet

# Satellite communications (SatCom)

## Traditional applications: Internet access

Satellite Internet access is Internet access provided through communications satellites

After the 1990s, communication satellites have been used as a mean to connect to the Internet via broadband data connections. This can be very useful for users who are located in remote areas and cannot access a broadband connection or require high availability of services

Modern satellite Internet services are typically provided to individual users through GEO satellites that can offer relatively high data speeds, with newer satellites using Ku-band to achieve downstream data speeds up to 506 Mbit/s

However, the interest of private companies (SpaceX, Amazon, Facebook, ...) in this field is increasing year after year. They planned (and some of them already started) launching hundreds or even thousands of LEO satellites to create a wide satellite constellation able to give access to the Internet to all the people all around the world

# SatCom in the near future

## Fifth Generation of communications (5G)

The fifth generation of mobile communications (5G) is leading to a deep evolution of the telecommunication networks worldwide, characterized by deep changes in the telecommunication infrastructure, new employed technologies, and new emerging use cases

These changes are mainly driven by the envisioned higher number of users/devices which need Internet connectivity with different performance requirements and on the higher number of applications that users/devices can benefit/offer

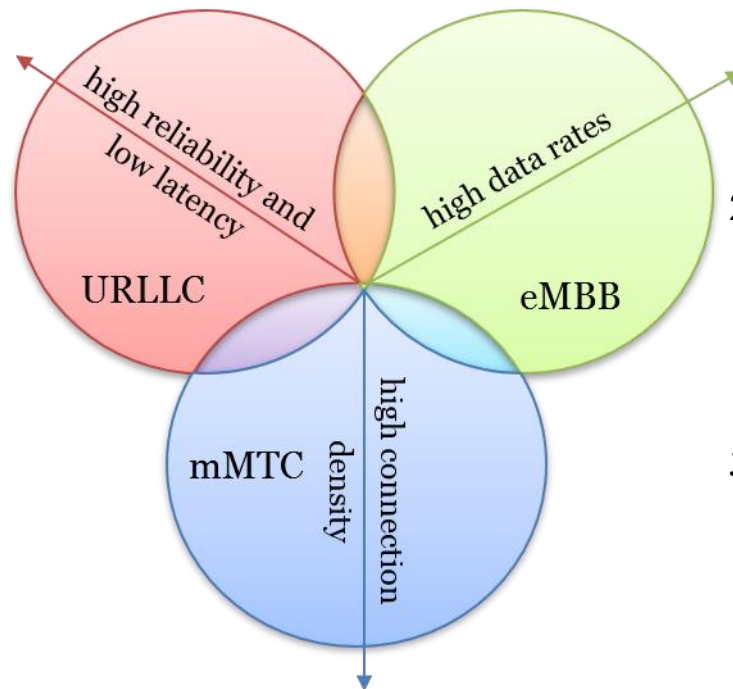
The improvements foreseen in the 5G will go far beyond the simple enhancement of the mobile network and the mobile broadband use case, offering only higher data rates and lower delays. A new set of use cases will emerge and benefit from the new technologies which will be employed in the 5G network, with different performance requirements and technical constraints



# SatCom in the near future

## 5G: Use cases classes

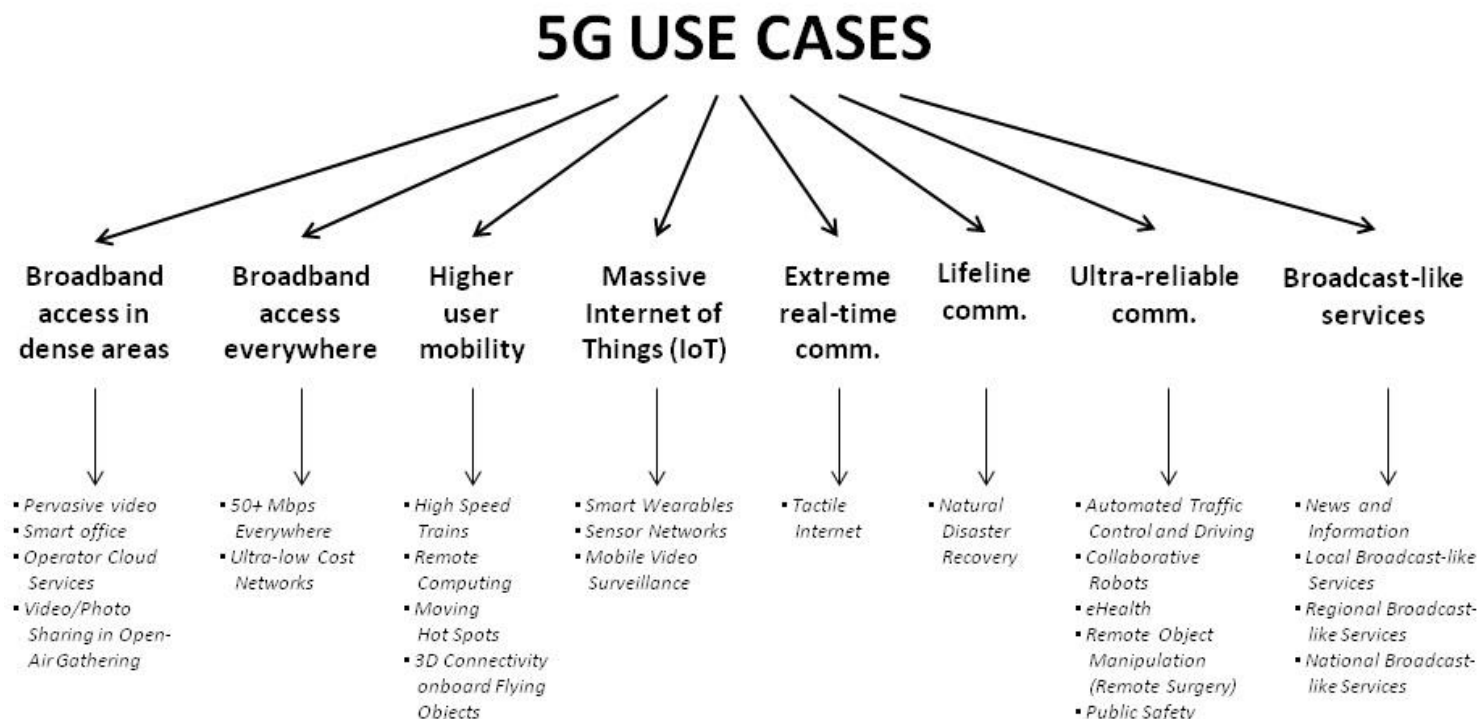
The International Telecommunication Union (ITU) defined 3 principal use case classes in order to group different applications with the same needs in terms of performance requirements:



1. **enhanced Mobile Broadband (eMBB)**: it addresses the human-centric use cases for access to multimedia contents and services, requiring high data rates across wide coverage areas
2. **massive Machine Type Communication (mMTC)**: it is characterized by a very large number of connected devices per square kilometre typically transmitting a low volume of non-delay-sensitive data
3. **Ultra-Reliable Low Latency Communication (URLLC)**: critical communications that require high network availability, low latency, and high reliability, such as remote medical surgery, distribution automation in smart grid, autonomous vehicles, and tactile Internet

# SatCom in the near future

## 5G: Main use cases



# SatCom in the near future

## 5G: Main Connectivity requirements

Offered performance has to be further improved in order to satisfy all users' needs. 3GPP identified the principal performance parameters, called Key Performance Indicator (KPI), that the foreseen 5G framework should accomplish:

- **User Experience Data Rate:** data rate experienced by the users for at least 95% of the covered area and for at least 95% of the time
- **End-to-End latency:** the time between the transmission of a data packet from the source node and the reception of the response packet of the source node
- **Mobility:** system's ability to provide the required service to moving users, considering their possible different speeds and the consequent impact on the services depending on the use case
- **Connection Density:** minimum allowed number of simultaneously active users per km<sup>2</sup>
- **Traffic Density:** minimum supported overall data rates of all connected users per km<sup>2</sup>
- **Spectrum Efficiency:** how efficiently can be exploited the available bandwidth

# SatCom in the near future

## 5G: Secondary Connectivity requirements

- **Coverage:** an almost global coverage is required to the new 5G network in order to reach every corner of the world with the users' guaranteed performance
- **Resource Management:** resource management should be enhanced in order to obtain a more efficient real-time allocation of the available resources
- **Connectivity Transparency:** Internet access should be available through multiple access points in a transparent way to the final users
- **Localization:** users' location knowledge will help offer a proper connectivity service depending on users' current position and movement speed in a 3D space
- **Availability:** the 5G network should offer 99.999% of network availability (percentage of time the network connectivity is available in the targeted area)
- **Resilience:** the 5G network should be able to recover some failures and to offer multiple redundant access technologies
- **Reliability:** the 5G network should guarantee 99.999% reliability rate (ratio between the number of packets successfully received by the destinations and the number of sent packets)

# SatCom in the near future

## 5G: Secondary Connectivity requirements

- **Energy Efficiency:** lower energy consumption should be achieved in order to allow a longer duration and lifetime of the terminals' battery
- **Cost Efficiency:** low-cost network infrastructure equipment and user terminals have to be designed in order to allow the 5G infrastructure employment worldwide
- **Ease of Deployment and Upgrade:** the 5G network should convert as much already existing telecommunication infrastructure as possible, upgrading the necessary existing equipment
- **Flexibility and Scalability:** the 5G network has to be capable of deploying new technologies and solutions afterwards in case of future industrial and research developments
- **Security:** The 5G network has to guarantee user authentication, privacy, encryption, and message integrity for all use cases, dealing with different kinds of malicious threats



# SatCom in the near future

## 5G: Role of satellites

SatCom networks can have a primary role in the future 5G network. Mainly thanks to the ubiquity capabilities, the robustness against physical malicious attacks and natural disasters, and the broadcast/multicast capabilities, SatCom networks can help achieve some of the 5G KPIs allowing Internet connectivity to some users and for some use cases that would not benefit from the expected performance otherwise

The advantages of SatCom networks thanks to their intrinsic features and their possible aims are manifold:

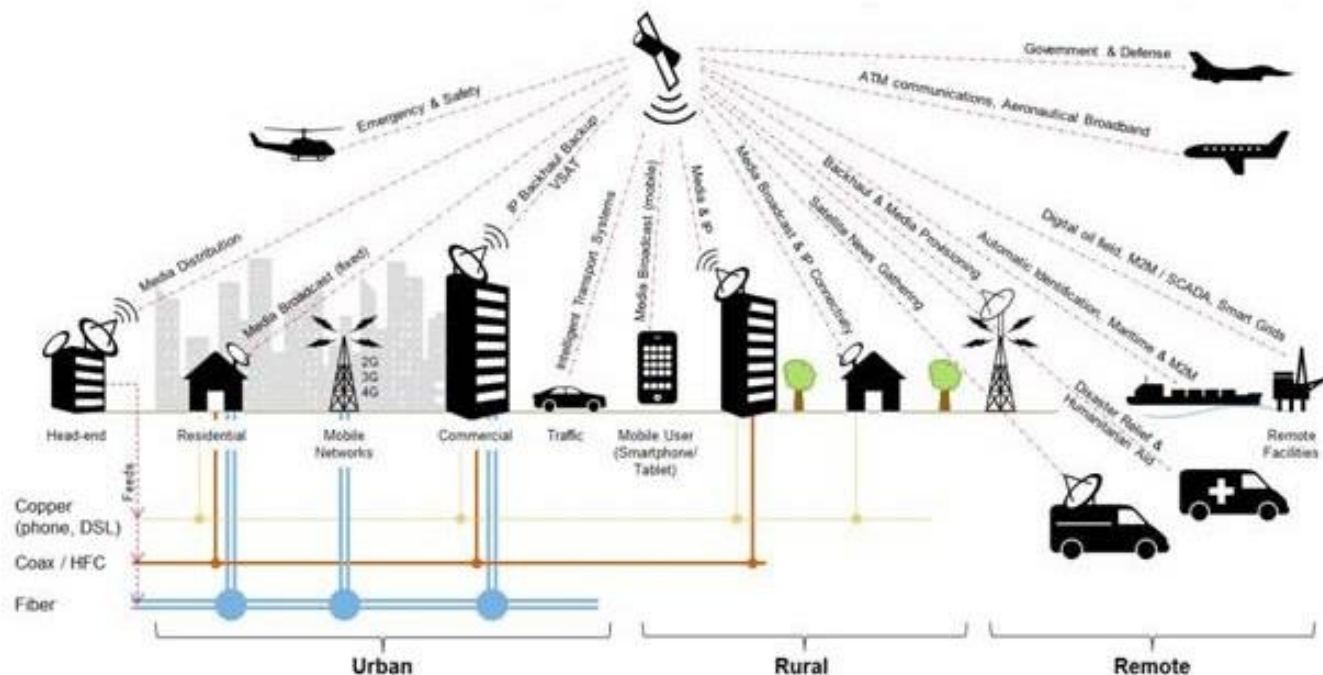
- **Extend Internet access** to people who live in areas without a terrestrial infrastructure, such as rural and remote areas
- **Increase resilience and reliability** of the entire 5G network acting as a backup solution, for example in case of emergency and disaster situations where the terrestrial infrastructure has been damaged
- **Offload the terrestrial network** of data belonging to delay-tolerant applications, such as Internet of Things (IoT) and Machine-to-Machine (M2M) communications, in case of congestion
- **Move data at the edge** of the terrestrial network (nearest to the final users) to decrease the latency and increase the end-users' Quality of Experience (QoE)

# SatCom in the near future

## 5G: Scenarios can benefit from SatCom

Several 5G scenarios can benefit from the large scale employment of huge SatCom networks

These scenarios mainly belong to the eMBB and the mMTC classes due to the high propagation delays and higher loss rates of satellite links which may not be compatible with the high reliability and low latency requirements of the URLLC class



# SatCom in the near future

## 5G scenarios: Broadcast and Multicast

Multiple users can receive different kinds of contents, such as TV or multimedia service delivery, mass delivery of alert messages, and distribution of software updates from the satellites through a single broadcast transmission

In this use case, satellites have access to the user's terminals and can support the 5G terrestrial network distributing contents directly to the user's premises or on-board moving platforms

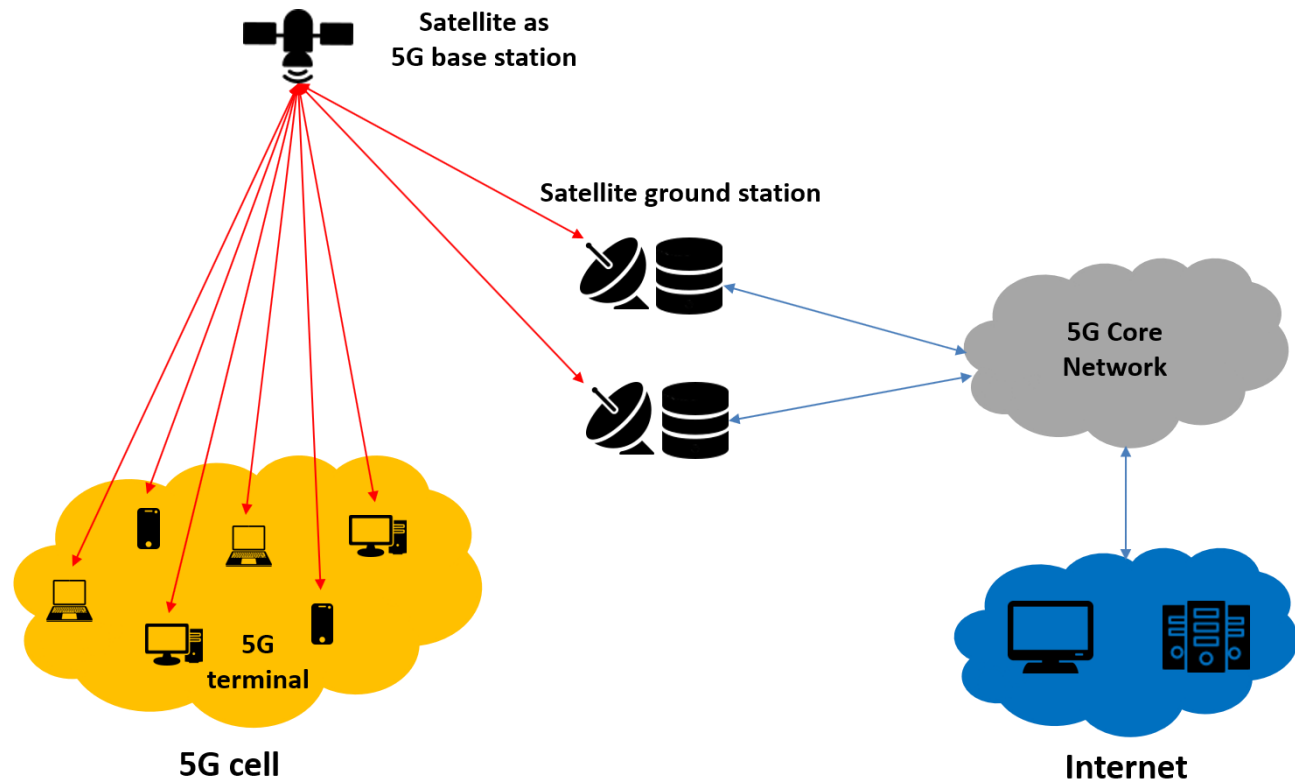
GEO satellites and LEO satellite constellations operating at high-frequency bands are the best options due to the offered high coverage and high bandwidth

# SatCom in the near future

## 5G scenarios: Satellites as access nodes

Satellites can be directly connected to 5G terminals

In this way, satellites act as 5G base stations offering 5G connectivity to a wider coverage area than normal 5G terrestrial base stations

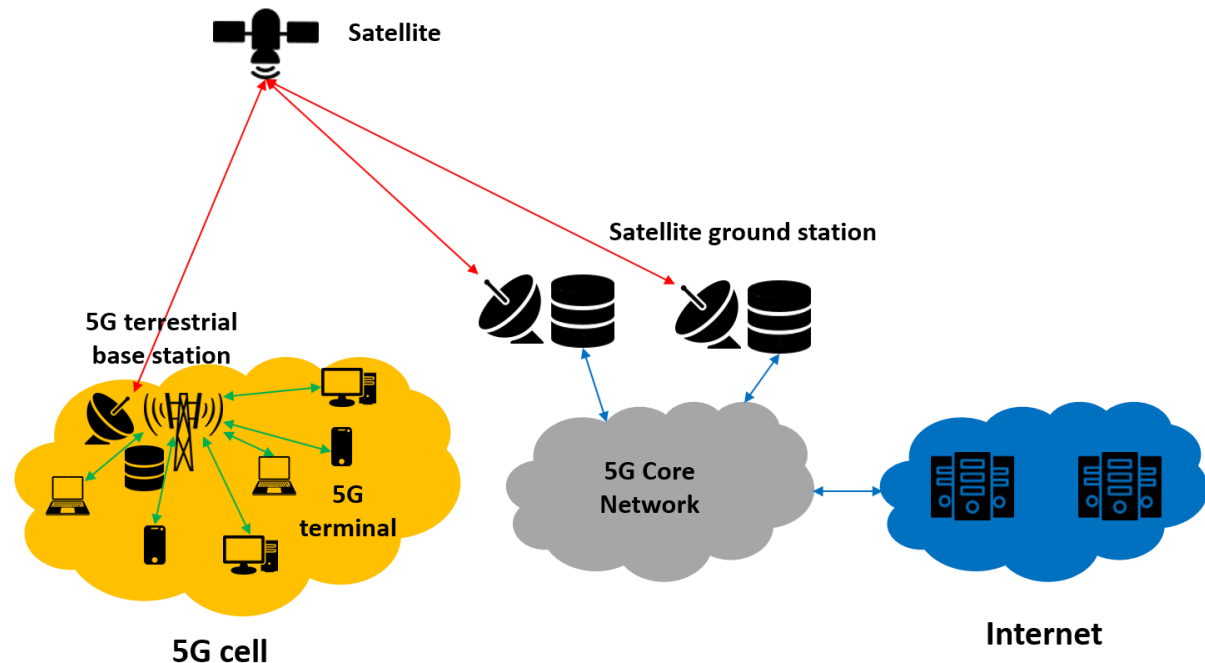


# SatCom in the near future

## 5G scenarios: Backhaul between access and core network

Satellites can be linked between 5G base stations statically deployed in un-served rural and remote areas or on-board moving platforms such as airplanes and ships

In this way, they act as intermediate nodes between the 5G cells and the 5G core network, offering a backhaul solution for all users who are gaining access to the 5G networks in these situations and to all traffic flows which are traversing the network from the edge to the core and vice versa



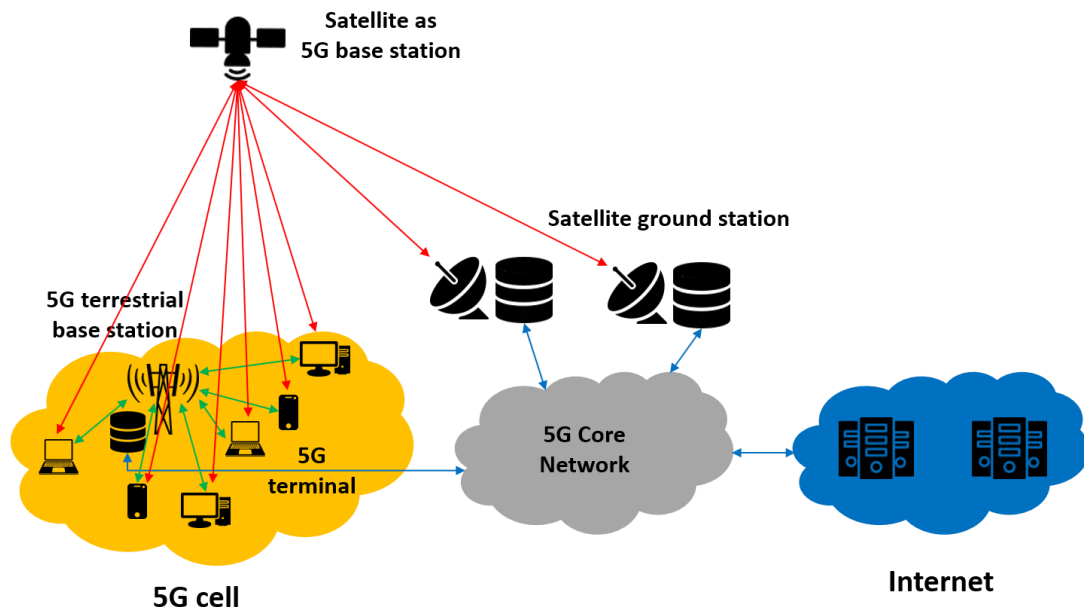


# SatCom in the near future

## 5G scenarios: Multi-connectivity

Users may require exploiting multiple access points belonging to different kinds of network (i.e. terrestrial and satellite ones) to achieve the high data rates required for the broadband services, while the delay-sensitive traffic flows may be routed through the terrestrial network

Multiple connections can be established and kept active simultaneously or activated alternatively depending on the current network conditions and the traffic flow requirements in a transparent way for the final users



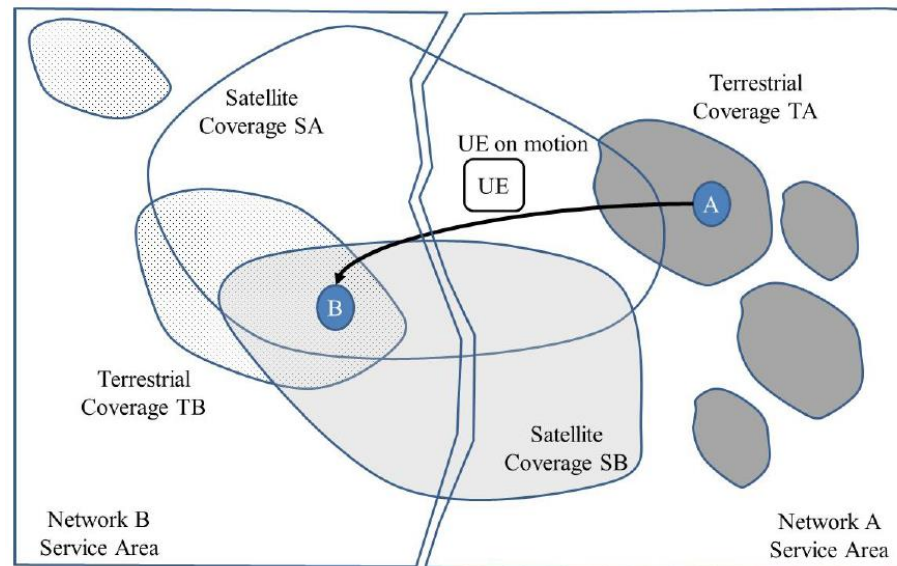
# SatCom in the near future

## 5G scenarios: Satellites to allow service continuity

Satellites can help in performing handover among different access points of the terrestrial network

For example, in case the area covered by the 5G terrestrial network is not homogeneous and users are moving from one terrestrial 5G cell to a shadow area and then back to another terrestrial 5G cell, or the users are losing connectivity to the 5G terrestrial network due to obstacles

In this way, SatCom networks can help increase network coverage and resilience and guarantee service continuity



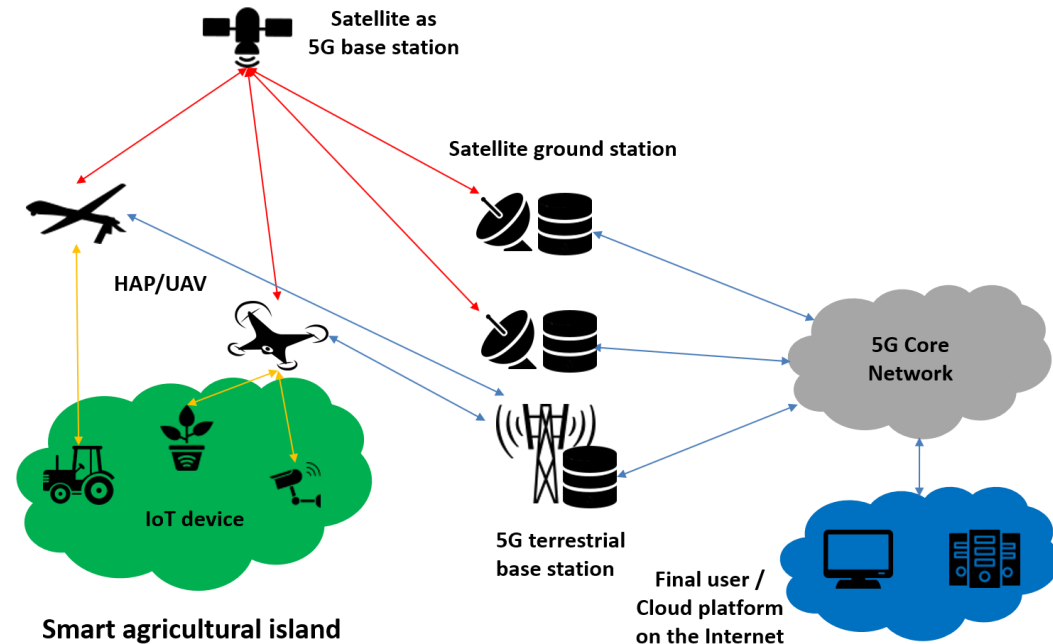
# SatCom in the near future

## 5G scenarios: Internet of Things (IoT) via satellite

Data generated by IoT sensors and destined to the final users connected to the 5G network can be forwarded through satellite links

IoT sensors and actuators can directly access the satellites or through local central entities that act as intermediate nodes offering high storage capacity, high energy availability, and satellite access

In case of direct access, a constellation of LEO satellites would be the best option in order to lower the sensors' energy consumption due to data transmission



# SatCom in the near future

## 5G scenarios: Temporary use of satellites

Satellites can be temporarily involved in 5G communications in case of emergency

They can be exploited to restore 5G connectivity in areas after natural disasters connecting 5G isolated network portions among them and with the 5G core network

Police, firefighters, medical personnel, emergency and rescue teams can exploit satellites to set up local 5G cells to allow them communicating with each other in case the terrestrial infrastructure has been damaged and is not available

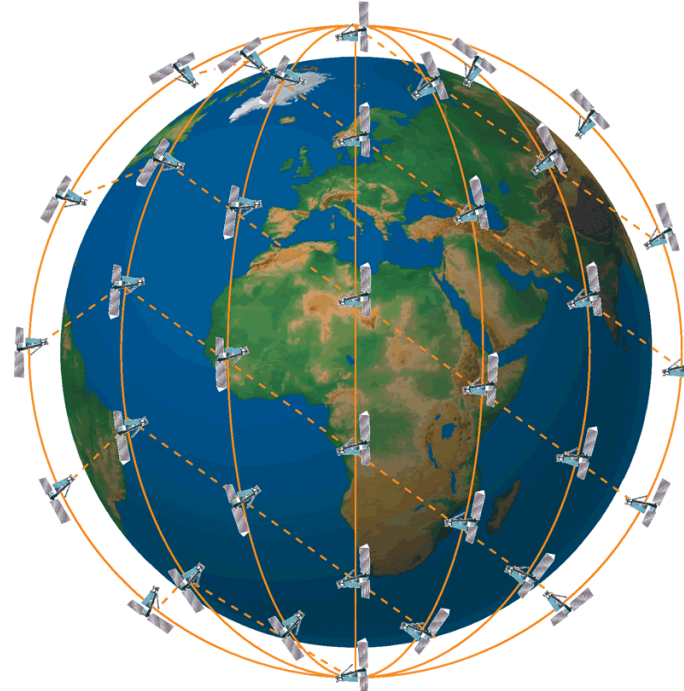
Furthermore, SatCom networks can be employed to relieve temporary congestion situations and overcome temporary failures of the terrestrial network, increasing overall network resilience

# SatCom in the near future

## 5G scenarios: Global satellite overlay

A constellation of LEO satellites where each spacecraft is equipped as a satellite 5G base station and interconnected with other neighbouring spacecrafts via Inter Satellite Links (ISL) can provide direct global access to 5G terminals

Such a type of constellation system would provide an overlay mesh network for users that need long-distance connectivity with high availability and reliability requirements





# SatCom related challenges

## Satellite cyber security: General view

A **system** should be designed having in mind all possible security vulnerabilities in order to minimize them, define proper system requirements and control procedures, employ proper mechanisms to increase the security, and consider proper strategies to be carried out when needed

**Security** can be defined as the process of minimizing the vulnerabilities of assets or resources

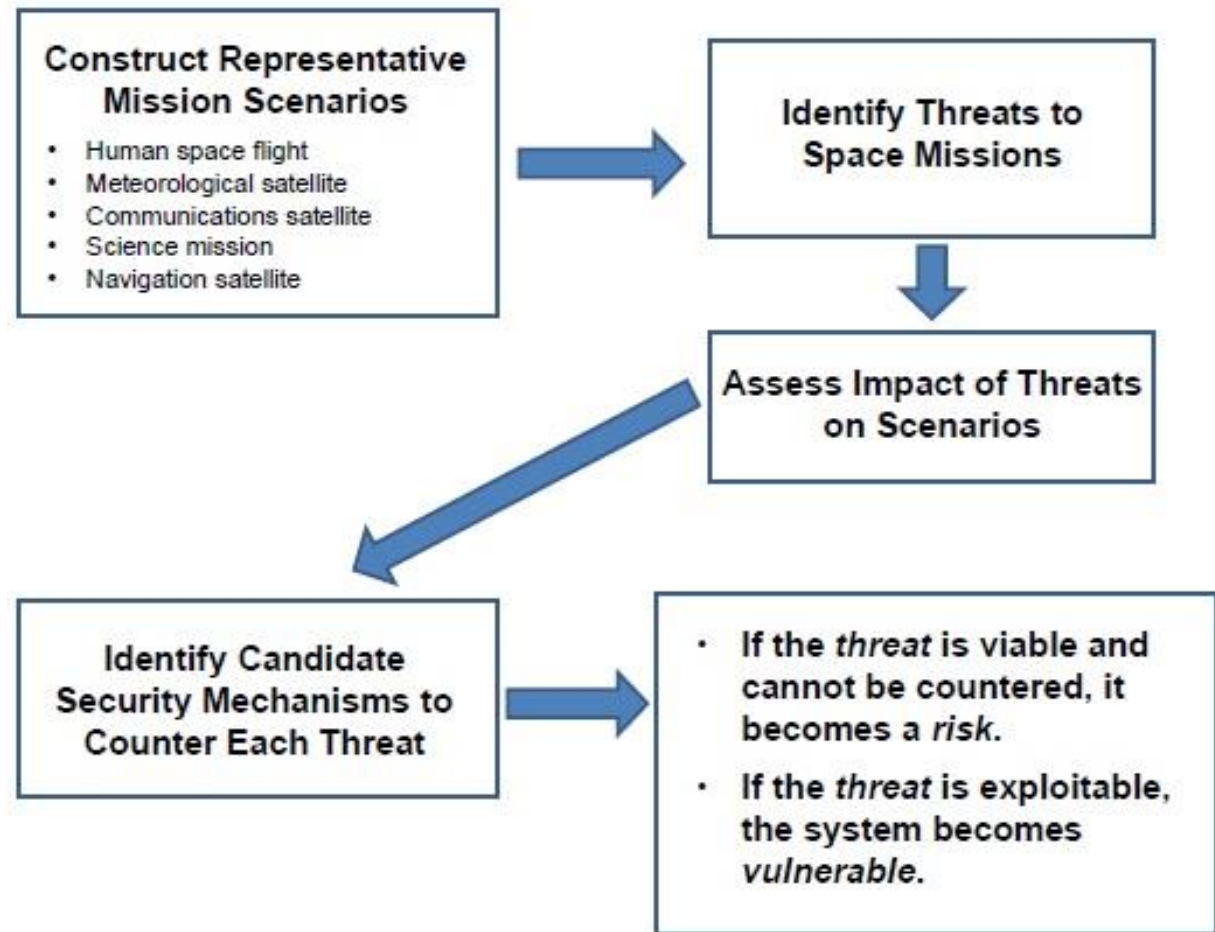
A **threat** is a potential violation of security which may result in harm of systems and organizations

A **threat agent** can be human or non-human, intentional or unintentional, and attempts to harm a physical or logical resource/asset

The **threat assessment** process should assess the vulnerabilities of the system and then establish the likelihood, consequences and cost of realization of each threat

# SatCom related challenges

## Satellite cyber security: Threat assessment



# SatCom related challenges

## Satellite cyber security: Passive attacks

**Passive attacks** do not involve any modifications of the normal system's operations. They are typically accomplished by **eavesdropping/interception** and mainly compromise data confidentiality



In space systems, there are mainly two types of passive attacks:

1. **Tapping on communications links** (wireless or wired)
2. **Traffic analysis** to know information about data travelling through the system, such as source and destination entity and traffic volumes

Passive attacks entail the loss of confidentiality

# SatCom related challenges

## Satellite cyber security: Active attacks

**Active attacks** modify the normal system's operations with different aims and can lead to several different consequences.

Most common active attacks are:

- **Data and commands corruption/modification:** intentional or non-intentional alteration of data
- **Jamming:** attackers interfere with the radio signal in satellite links by injecting noise, by transmitting on the same frequency of authorized transmissions, or by overpowering the original source signal
- **Denial-of-Service (DoS):** attacks that seek to make the attacked system unable saturating its available resources
- **Masquerade:** attackers lie about their true identity or pretend to be authorized entities in order to gain access to the system or to gain greater privileges
- **Replay:** transmissions to or from satellites or among ground segment nodes are intercepted, recorder, and played back at a later time
- **Software threats:** Viruses, Worms, Trojan horses, Spyware, ...
- **Unauthorized access:** attackers exploit intercepted sensitive data such as passwords to take control of the system

# SatCom related challenges

## Satellite cyber security: Potential consequences

If satellite commands were disclosed to unauthorized entities, unauthorized commands could be sent to the satellite, resulting in possible harm or total mission loss

The corruption of satellite telemetry data may lead to unnecessary and potentially dangerous commands from the control station

Unauthorized access may result in the distribution of private information to unauthorized entities

Due to the unbounded nature of satellite links, access to satellites can be prevented at all jamming the transmission/reception frequencies or overloading the network with unauthorized traffic flows

If unauthorized entities gain access to satellite resources, they can hack satellites with different possible consequences, from satellite deviation to prolonged data theft



# SatCom related challenges

## Satellite cyber security: Possible solutions

Different countermeasures can be applied to increase a system's security:

- **Cryptography:** encryption and decryption transform sensitive data (*plaintext*) in less sensitive data (*ciphertext*) and vice versa by using appropriate keys in order to enable unauthorized entities to have access to them
- **Spread Spectrum (SS):** techniques that spread the generated signal in the frequency domains with a certain bandwidth in order to prevent their detection and to increase their resistance to natural interferences, noise, and jamming
- **Data integrity:** schemes that enable receiver users to verify if the received data have not been modified during transmission and allow to authenticate the received data in order to verify the sender identity
- **Firewalls** and **Anti-virus:** softwares that increase the system's robustness against malicious software filtering the incoming traffics in order to block the unauthorized and possibly malicious new traffic connections (firewall) or preventing, detecting, and removing malicious software installed inside the protected network
- **Intrusion Detection System (IDS):** passive solution which analyses the traffic flows travelling across the protected network in order to identify and report unusual behaviours
- **Intrusion Prevention System (IPS):** active solution which inspects traffic flows through the protected network and blocks the ones with malicious data

# SatCom related challenges

## Other challenges

- **Spectrum sharing and Multi-access:** a higher number of communication devices means better management of the available spectrum among communication nodes (terminals, access points, ...)
- **Artificial Intelligence (Machine Learning):** a higher number of services and use cases with different performance requirements means better management of the available network resources
- **Ground segment improvement:** not only a higher number of flying communication satellites is required but also a higher number of ground stations
- **Space debris:** 34 000 objects  $> 10$  cm; 900 000 objects between 1 and 10 cm; 128 million objects between 1 mm and 1 cm (February 2020)
- ...

THANK YOU!  
ANY QUESTIONS?

