



WHITE PAPER

GRAND CHALLENGE 16 - CONNECT AND
SUPPORT EVERYTHING THAT MOVE

Document releases

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List of Acronyms

3GPP	Third Generation Partnership Project
1G	1 st generation
2D	two-dimensional
2G	2 nd generation
3G	3 rd generation
4G	4 th generation
5G	5 th generation
6G	6 th generation
A2A	Air-to-air
A2G	Air-to-ground
A2N	Air-to-network
ADAS	advanced driver assistance systems
ADS-B	automatic dependent surveillance–broadcast
AGV	automated guided vehicle
AI	artificial intelligence
AMR	Autonomous Mobile Robot
APSK	amplitude phase-shift keying
ATC	air traffic control
BPSK	binary phase-shift keying
BS	base station
BVLOS	beyond visual line of sight
C-V2X	cellular-vehicle-to-everything
C2	command and control
C2C-CC	Car 2 Car Communication Consortium
CBTC	communications based train control
CSI	channel state information
CSMA/CA	carrier sense multiple access with collision avoidance
CSMS	cyber security management system
D2D	device-to-device
DDoS	distributed denial-of-service
DSRC	dedicated short range communication
DSSS	direct sequence spread spectrum
DtS-IoT	direct-to-satellite Internet of Things
EASA	European Union Aviation Safety Agency
ECU	electronic control unit
EO	Earth observation
ETSI	European Telecommunications Standards Institute
FAA	Federal Aviation Administration
FANET	flying ad hoc network
GNSS	global navigation satellite system
GPS	global positioning system
GSM-R	global system for mobile communication for railway
GSO	geosynchronous orbit
HAPS	high-altitude platform station

HSR high-speed railway
HUV hybrid underwater vehicle
ICAO International Civil Aviation Organization
IEEE Institute of Electrical and Electronics Engineers
IMT International Mobile Telecommunications
IMU inertial measurement unit
IoT Internet of Things
IoUT Internet of Underwater Things
ISO International Standardization Organization
ITS intelligent transport system
ITU International Telecommunication Union
LDPC low-density parity-check
LEO low Earth orbit
LOS line-of-sight
LoRa long range
LoRa-CSS long range chirp spread spectrum
LoRaWAN long range wide area network
LPWAN low-power wide-area network
LR-FHSS long range frequency hopping spread spectrum
MANET mobile ad hoc network
MEO medium Earth orbit
MIMO multiple input multiple output
NB-IoT Narrowband IoT
NIS2 network and information systems directive
NLOS non-line-of-sight
NR new radio
NTN non-terrestrial network
O-RAN open radio access network
OBU on-board unit
OFDM orthogonal frequency-division multiplexing
OFDMA orthogonal frequency-division multiple access
P2X pedestrian-to-everything
P2N2X pedestrian-to-network-to-everything
PLS physical layer security
QAM quadrature amplitude modulation
QoS quality of service
QPSK quadrature phase-shift keying
RAN radio access network
RNN recurrent neural network
ROV remotely operated vehicle
RRM radio resource management
RSSI received signal strength indicator
RSU road side unit
SAE Society of Automotive Engineers
SAR synthetic aperture radar

SB-DS sensing-based dynamic scheduling
SB-SPS sensing-based semi-persistent scheduling
SSO sun-synchronous orbit
SF spreading factor
SNR signal-to-noise ratio
TDMA time-division multiple access
TN terrestrial network
UAM urban air mobility
UAS uncrewed aircraft system
UAV uncrewed aerial vehicle
UBV underwater bionic vehicle
URLLC ultra-reliable and ultra-low latency communications
USV unmanned surface vehicle
UTC coordinated universal time
AUV autonomous underwater vehicle
UWAC underwater acoustic communications
UWOC underwater optical communications
V2C vehicle-to-cellular
V2N vehicle-to-network
V2N2V vehicle-to-network-to-vehicle
V2I vehicle-to-infrastructure
V2P vehicle-to-pedestrian
V2V vehicle-to-vehicle
V2X vehicle-to-everything
VANET vehicular ad hoc network
VAM VRU awareness message
VBS VRU Basic Service
VDES VHF data exchange system
VHF very high frequency
VHetNet vertical heterogeneous network
VLOS visual line of sight
VRU vulnerable road user
WAVE wireless access in vehicular environment

1 Executive Summary

The incredible advances made in wireless communications in the last few decades make today's connectivity available almost everywhere and also in mobility. In fact, there are general-purpose cellular networks that provide widespread coverage with quality of service; Furthermore, there are specific technologies enabling communications for vehicles, trains, and other mobile objects. However, challenges are still open to obtain a complete coverage really everywhere and to grant a sufficient quality of service for new services to mobile devices of different types. First of all, coverage still needs to be improved, reaching also areas where deploying an infrastructure is not cost-effective or even challenging due to adverse conditions. In addition, mechanisms allowing devices to backup to alternative solutions should be considered when network connectivity is absent or insufficient. Another issue is how to fulfill the increasing demand for throughput, especially when high speed mobility is considered. This white paper first discusses the main classes of mobile objects and the technologies that are being used today for their connectivity, and then elaborates on the research activities that are trying to solve, or at least address, the main open issues.

2 Introduction

Connectivity is today an essential part of people's life and this is the result of innovations brought in the last few decades by the Internet, the world wide web, and wireless communications. As a key player of this process, cellular networks started serving with ubiquitous coverage, first for voice calls and emails, then for entertainment, and increasingly for machine type of communications with stringent requirements in terms of quality of service (QoS).

The promise made by cellular systems was to give connectivity in mobility, everywhere and at any time. This promise has been in large part respected, although still not really everywhere and anytime. More importantly, meanwhile, the requirement has shifted from a simple reachability of people to the willingness to support services with very high demands in terms of data throughput, reliability, and latency.

In parallel to the evolution of cellular systems from the analog voice-based 1st generation (1G) of the '80s to the machine-to-machine 5th generation (5G) that is currently under deployment, other technologies have been developed and used to allow the connectivity of mobile objects with specific requirements. From road vehicles, to trains, to maritime, to flying objects, all have been equipped in the years with some kind of connecting systems that allow operations and control, tailored to the specific needs.

The specificity and limited market impact allowed most of these groups of mobile objects to be connected with systems that until recent years had been sufficient for their scope. For the trains, a specific version of the 2nd generation (2G) of cellular systems, called global system for mobile communication for railway (GSM-R) was specified and used. For maritime critical communications like those related to coverage and reliability, which are of greater relevance than broadband and real-time features, solutions based on low-data-rate terrestrial networks or geo-stationary satellites have been used; however, the necessity of wide broadband services is growing more and more and the support by low Earth orbit (LEO) communications is becoming fundamental. Looking at the air systems, a new generation of flying objects and satellites at various altitudes are being used and require connectivity, with proprietary solutions or new standards under development. When looking at satellites, it is also relevant to note that we can distinguish those that use telecommunications to support their services, from those that have a role as telecommunication elements to improve the network performance. Moving to the industrial environment, automated guided vehicles (AGVs) are also mobile and need connectivity, which is currently provided through corporate Wi-Fi, which may be insufficient for advanced use cases. In addition, another group of mobile objects that has recently received interest is the one for underwater mobility, which have specific communication systems based on either acoustic or optical waves.

A special case is represented by the connectivity for the road vehicles. What is called vehicle-to-everything (V2X) (better discussed later in this document) had in fact gone through huge investments, great promises, and still limited impact on the real life. The main point with road vehicles is probably that the market is huge and it requires agreements between a large number of actors involved. Connectivity on road vehicles allows, in principle, increased safety and improved traffic efficiency, but to be effective it needs that all the vehicles are connected and exchange information with each other. This had produced the definition of more than one solution. However, the need to select only one of them created large debates not yet completely resolved and an overall slowdown in the evolutionary process.

At the same time, on the one hand the requirements of all mobile objects have increased and on the other hand there is a willingness to integrate and harmonize the available solutions in a single large, multi-purpose, and QoS-driven network. Such direction, somehow started with the 4th generation (4G) of cellular systems, was in the intention the core of the 5G but will probably need one further evolutionary step in the 6th generation (6G). Maybe, 6G will be eventually the technology able to provide mobile connectivity everywhere at any time with the needed QoS.

This white paper has the scope to go through the various mobile objects that need connectivity, giving an overview of what is available today, which are the open challenges, and what is expected for the coming years. To this aim, a specific focus on road vehicles is provided in Section 3.1, on vulnerable road users in Section 3.2, on trains in Section 3.3, on maritime systems in Section 3.4, on flying objects in Section 3.5, on satellites in Section 3.6, on autonomous industrial vehicles in Section 3.7, and on underwater vehicles in Section 3.8. Albeit this list cannot be comprehensive, it covers the majority of mobile objects requiring connectivity today.

Then, thanks to the experience and activities of the researchers working in Restart, a vision will be provided about the main aspects that are currently being investigated and will contribute to the next generation of wireless communications for mobile objects. In particular, in Section 4, the role of non-terrestrial network (NTN) is discussed, which aims at exploiting flying objects from low altitude drones to geosynchronous satellites to provide connectivity where terrestrial networks cannot reach. In Section 5, the attention is on direct communications between mobile objects, which can add shorter paths for exchanges between close devices and can cope with coverage holes that may unavoidably remain. Sections from 6 to 8 are dedicated to communication and network aspects; in particular, Section 6 concerns the prospect of using high frequencies considering both the advantages of the greater capacities that can be used, but also the difficulties of managing highly directivity beams in high-speed movement contexts. Section 7 is dedicated to open radio access network (O-RAN) architectures that can be considered as artificial intelligence (AI) native and therefore particularly suitable to manage communications among moving objects in contexts of fast environment variations. Finally, Section 8 is dedicated to security issues.

3 Categories of Mobile Objects

3.1 Road Vehicles

Road vehicles represent the largest sector among moving objects, with the growing market size of connected and automated vehicles already calculated in more than a hundred billions of dollars.¹

The communication systems for road vehicles are normally referred as V2X, including:

- vehicle-to-vehicle (V2V) for the communication between vehicles;
- vehicle-to-infrastructure (V2I) for the communication between vehicles and an infrastructure along the road;
- vehicle-to-network (V2N) or vehicle-to-cellular (V2C)² for the communication between vehicles and a network/cloud server;
- vehicle-to-pedestrian (V2P) if the communication is between vehicles and vulnerable road users (VRUs) including pedestrians.

Recently, also vehicle-to-network-to-vehicle (V2N2V) has emerged, indicating a communication between vehicles that, however, happens through the network.

As a major point to highlight, V2X includes two very different ways of connectivity, as illustrated in Fig. 1. One is connectivity that exploits a network with a large infrastructure, which presently means using cellular systems and corresponds to V2N (or V2C). This type of connectivity can provide in principle a very high level of QoS (high throughput and/or high reliability and/or low latency), with the drawback that coverage is required and with the limits given by the status of standardization and deployment. The other is the direct connectivity between vehicles and other road devices, without the need for network support, corresponding to V2V, V2I, and V2P. This solution grants very fast and localized exchange of information and does not require to be in coverage of a fully deployed network, but hardly grants the QoS of the cellular-based connectivity. These two ways of communicating appear complementary and both necessary in the long term. Hereafter, the two types of V2X are discussed separately, after a premise on the levels of automation.

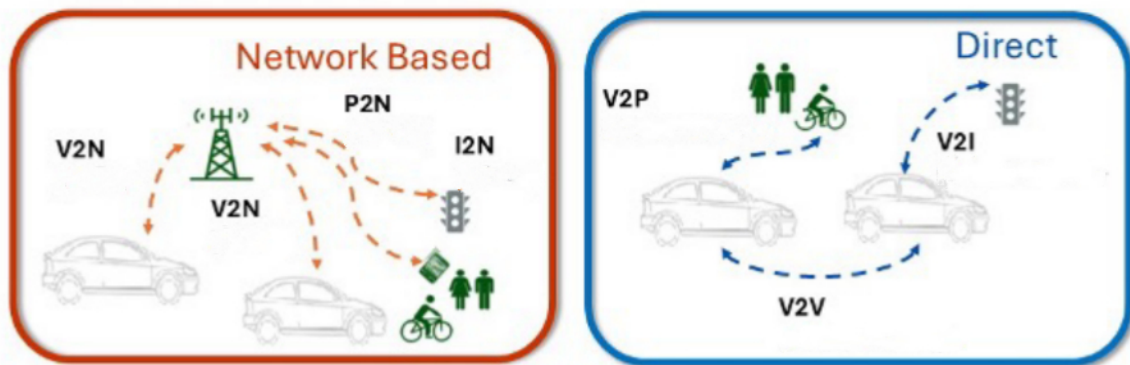


Figure 1: Illustration of the two types of V2X connectivity: network (or infrastructure)-based and direct.

Premise concerning automation. Before entering into the details of the current state of the art for connectivity, let us remark that, sooner or later, vehicles will become autonomous and connected. Vehicles will drive themselves and humans intervention will only be required in particular cases or for specific maneuvers. Automation relies on advanced driver assistance systems (ADAS), and traditional ADAS is based on four primary sensor types: radar, lidar, camera, and ultrasonic short-range sensors. While effective for many applications, these sensors have inherent limitations—they cannot detect pedestrians around corners or alert drivers to hazards beyond their line-of-sight (LOS), just to give basic examples. V2X communication systems emerged to overcome these limitations, providing 360° vision, non-line-of-sight (NLOS) capabilities, extended range, and the possibility of coordination among vehicles.

However, today automation and connectivity are still two aspects that move somehow in parallel and not jointly. When looking at automation, six levels have been defined by the Society of Automotive Engineers (SAE) in [1]:

- L0: Driver only: no automation;

¹Source: <https://www.maximizemarketresearch.com/>

²Note that the “C” in V2C also stands for Cloud.

- L1: Driver assistance: temporarily feet off;
- L2: Partial automation: temporarily hands off;
- L3: Conditional automation: temporarily eyes off;
- L4: High automation: attention off;
- L5: Full automation: human is a passenger.

Automation is moving fast, with most of the cars today including L2 functions and some even reaching initial implementations of L3 or, with robot-taxis in some American and Asian cities, even L4. Based on these levels, two broad categories can be distinguished: Human Assisted Driving (L0-L3) and Autonomous Driving (L4-L5). This distinction has a significant impact on the required QoS, especially when looking at the infrastructure-based type of communications.

Infrastructure-based V2X via cellular networks. Let us discuss the infrastructure-based V2X connectivity separating the cases of human assisted driving (L0-L3 automation) and autonomous driving (L4-L5 automation). In human assisted driving, which also corresponds to what is currently on the road, the vehicle is primarily driven by a human, with technology aimed at simplifying driving through sensing, monitoring, and electronic control units (ECUs) with limited external interaction. Telecommunication networks are mainly required for: communications between the vehicle and the manufacturer or controlling authority (e.g., fleet operator, owner/user); software updates for vehicle systems.

The increasing capacity and features of new intelligent transport system (ITS) produce a significant secondary effect: the reduction of certain vehicle components' life-cycle from several years to potentially just a few months. The "intelligent" components may require frequent software updates, particularly for security patches. Software updates are typically not latency-sensitive and can be downloaded in the background. However, the situation is different when delivering "critical update required" messages during vehicle operations. Software update services must maintain high availability over extended periods. For these services, approximate vehicle position (street/road identification) is usually sufficient, though greater precision would be beneficial to verify if a vehicle is safely parked before installing updates or if it is within range of alternative communication mechanisms like home Wi-Fi.

Another use of connectivity falling in this class is the monitoring for fleet management or for assurance purposes. In these cases, the need is to track the position of the vehicles derived from a global navigation satellite system (GNSS), collected by the remote servers through a cellular system. The collection requires loose real time for fleet management and error free but not real time for assurance, which are not challenging for current cellular networks.

For Level 4 and 5 autonomous vehicles, i.e., when dealing with autonomous driving, several specific systems and technologies are required, which can be very challenging in terms of QoS requirements [2]–[4]. Among the main examples, we can cite the *high-definition map collecting and sharing*, which is a crucial enabler for autonomous driving, allowing vehicles to have a precise and updated vision of the surrounding, and therefore navigate safely and autonomously. These maps involve complex data collection, compilation, content creation, and distribution processes, typically integrated into dedicated digital platforms for autonomous driving services. These specialized maps provide detailed terrain information for precise and secure autonomous operation. The availability of high-definition map services is critical for safety, requiring 99.9% or higher availability and continuous broadband connectivity (4 Mbps uplink, 16 Mbps downlink, with peaks up to 50 Mbps) based on [3].

Another key example is *tele-operated driving*, which involves a remote operator taking control of the vehicle to navigate it safely from the current location to the intended destination. This use case has particularly constrained requirements due to the real-time remote navigation needs. Again based on [3], the requirement can be of almost 40 Mbps in the uplink (assuming 8 Mbps video streaming from 4 cameras using h.264 compression and vehicular sensor data of few Mbps due to tens of objects included at 1 kB/object/100 ms), and large and frequent command messages in the downlink (up to 1000 bytes every 20 ms). In this use case, accurate positioning is also essential for navigating around obstacles and maneuvering through narrow gaps. Latency requirements are directly related to the maximum allowable driving speed, as they depend on the reaction time necessary for remote navigation; at 50 km/h, for example, the vehicle moves 0.27 m within 20 ms, highlighting the critical nature of ultra-reliable and ultra-low latency communications (URLLC).

Summarizing, several critical aspects must thus be considered when looking at the connectivity for autonomous driving systems:

- Coverage must ensure stable and continuous connection, especially in rural or remote areas;
- Handover between cells must be seamless to avoid service disruptions;
- Variations from the coverage under one operation to another and cross-borders operation may be critical;
- Localization and latency are crucial aspects.

Direct V2X without the need of infrastructure. While infrastructure-based communications can serve use cases requiring stringent QoS such as those described in the previous subsection, they have the inherent limitation to require full coverage and they are also inefficient when the information needs to be shared in the close vicinity. If the intent of the vehicle is to inform about the own position and movements, or to share the observed objects, or to coordinate for some maneuver, direct V2X appears as a much more efficient and effective solution.

Wireless technologies for direct V2X are available and have been tested for more than 10 years [5]. However, the enormous impact from an economical perspective and the need for all vehicles to be equipped with the same communication technology, in order to be really connected, has made this sector the arena of a long-standing and not yet fully resolved controversy, with the terrible result that ready-made technologies, capable of saving lives and significantly reducing pollution in cities, have not yet become a concrete part of real life.

Two major solutions have emerged for direct V2X communications. The first solution comes from the Institute of Electrical and Electronics Engineers (IEEE) and is based on the IEEE 802.11p amendment to WiFi, finalized in 2010, representing the first standardized technology for V2X, as an adaption of the IEEE 802.11 Wi-Fi standard for operation in high-speed and dynamic vehicular environments at 5.9 GHz. Its key characteristics include: orthogonal frequency-division multiplexing (OFDM) over channels of 10 MHz, with double symbol duration compared to previous WiFi standards to mitigate delay spread and inter-symbol interference at the cost of halving peak data rates to 27 Mb/s; carrier sense multiple access with collision avoidance (CSMA/CA) for channel access, with mechanisms to prioritize critical messages. This standard, in the years included in the US protocol stack by IEEE and SAE for V2X under the name of wireless access in vehicular environment (WAVE)³ and in Europe by the European Telecommunications Standards Institute (ETSI) under the name of ITS-G5, has been recently improved with the backward-compatible amendment IEEE 802.11bd, published in 2023. This emerging standard incorporates advancements from the WiFi amendments 802.11n, 802.11ac, and 802.11ax. It implements low-density parity-check (LDPC) coding and higher modulation schemes (up to 256-quadrature amplitude modulation (QAM)) while using midamble-based channel estimation to improve performance in high-mobility scenarios. Additionally, IEEE 802.11bd doubles the throughput while maintaining backward compatibility with 802.11p and supports 20 MHz channels to further increase data rates. Furthermore, it integrates positioning capabilities alongside V2X communication, enhancing its applicability in vehicular networks.

The other solution has been developed by the Third Generation Partnership Project (3GPP) and is sometimes called cellular-vehicle-to-everything (C-V2X), although this term is ambiguous and includes different solutions under the same umbrella. More appropriately, within the C-V2X ecosystem, direct communications are supported by two different technologies, which are LTE-V2X sidelink and 5G NR-V2X sidelink (or simply NR-V2X sidelink). Even if the term *sidelink* is what specifically indicates the direct communication (which use the PC5 interface) and differentiates these solutions from the network-based type of communication (which use the Uu interface), hereafter this term will be omitted for the sake of conciseness. The first specifications related to C-V2X technologies were introduced by 3GPP beginning with Release 14, building the LTE-V2X upon the device-to-device (D2D) communications framework available since Release 12. In the physical layer, LTE-V2X employs a variation of orthogonal frequency-division multiple access (OFDMA) called single-carrier frequency-division multiple access (SC-FDMA), considering channels of either 10 MHz or 20 MHz. For resource allocation, LTE-V2X uses two modes: Mode 3, which relies on network-controlled resource allocation via eNodeB, and Mode 4, which enables autonomous resource allocation using a mechanism called sensing-based semi-persistent scheduling (SB-SPS).

3GPP Release 14 established the foundations of LTE-V2X, with incremental improvements in Release 15. Release 16 then marks a major leap with the definition of NR-V2X, which had the intent to address a larger number of use cases. NR-V2X uses OFDMA and renames the two sidelink modes into Mode 1 (which leverages gNodeB for resource allocation) and Mode 2 (which supports autonomous resource allocation). Key physical layer enhancements include flexible sub-carrier spacing (15 kHz, 30 kHz, 60 kHz), LDPC coding with higher modulation (up to 256-QAM), and adjustable pilot signals (called DMRS) for improved channel estimation. At the MAC layer, improvements include expanded communication types (unicast, groupcast, broadcast) and the addition of another mechanism, called sensing-based dynamic scheduling (SB-DS), to cope with messages that are not periodic and with constant size.

Both families have been tested in several international projects, also with large numbers of equipped devices. Among the main challenges that they have to cope with, it is relevant to list:

- **Doppler shift and frequency offset** caused by high relative speeds between vehicles, especially challenging with large messages; this has indeed been mitigated by improved signal design and additional reference signals in the more recent solutions;
- **Radio resource congestion** in high vehicle density scenarios, addressed through intelligent resource selection algorithms; this has been a major topic for research in the last decade when looking at a single channel, but may require new attention if multiple channels are considered [6];
- **Synchronization issues**, especially for out-of-coverage vehicles using LTE-V2X or NR-V2X; synchronization is indeed normally managed through GNSS, which may not always be available (e.g., in tunnels or closed parking lots).

Special use cases at the edge between network-based and direct V2X. While most of the use cases are clearly better served by either network-based V2X or direct V2X, it is worth mentioning that there are a few special ones which could be served by both or may even benefit from the use of both.

³In the US, the solution based on IEEE 802.11p is often called dedicated short range communication (DSRC), even if this is in conflict with the use that in Europe is made of the same acronym. In Europe, in fact, DSRC is used to identify the wireless technologies used for tolling.

One example case where either of the two could be used is the communication with intelligent road infrastructure, such as traffic lights, crossings and streetlights, which may be implemented using V2N or V2I. The connectivity with the roadside infrastructure could be used for example for electronic signal information, or for traffic light real time update. Generally, these applications require low data rates (a few kbps) and, being optimization-based applications rather than safety-critical, moderate service availability levels of 95% may be sufficient. Adding V2V communication, this could be integrated with speed coordination and common start/stop operations, enabling continuous traffic flow, proven to be the most effective way to reduce fuel consumption and CO₂ emissions.

An example where the contribution of both network-based V2X and direct V2X is almost a requirement is instead platooning (for trucks) and chauffeurage (for passenger cars), which represent a special case of continuous traffic flow where groups of vehicles move together in a coordinated manner at the same speed while maintaining very close distances. This application provides several benefits, including constant speeds with reduced inter-vehicle distances, decreased air resistance resulting in lower fuel consumption and CO₂ emissions, and enhanced safety through reduced response times and accident mitigation. As an additional benefit from an implementation point of view, platooning/chauffeurage requires that only the involved cars are connected and do not need a large market penetration. If it is true that direct communications are needed within the group, it is also a major improvement to have a V2N link to enable control or support from remote at least during the operations of group formation, group splitting, and group separation.

Another example where V2N, V2I, and V2V could jointly be used for advanced use case is the intersection management, where coordination between autonomous vehicles and an infrastructure may allow cars to never stop at intersections and thus significantly reducing the road traffic and fuel consumption, as investigated for example in [7].

3.2 Vulnerable road users

In the context of V2X, beyond motor vehicles, a key role is played by what are called VRUs. It is important to clarify that the term VRU does not refer to individuals who are socially or physically more vulnerable (e.g., children, elderly individuals, or people with disabilities or limited mobility). Rather, a VRU is defined as any moving entity that is *inherently* vulnerable in the event of a collision with a motor vehicle. Like other elements of the road environment, VRUs can greatly benefit from connectivity and related services. However, due to their distinct characteristics, they require hardware, software, and communication protocols that are specifically designed for their needs.

Despite the central role of VRUs in the mobility ecosystem, they have only recently been incorporated into V2X frameworks. A relevant example is the dedicated set of standards introduced in Europe by ETSI for VRUs [8]–[10]. These standards define a specific V2X service⁴ for VRUs, known as the VRU Basic Service (VBS), and also introduce four distinct VRU profiles:

- **VRU profile 1** focuses primarily on pedestrians, i.e., road users who are not using any mechanical device for their movement. This category includes pedestrians on sidewalks, children, individuals pushing prams, visually impaired persons guided by dogs, and cyclists walking their bikes.
- **VRU profile 2** covers users of light vehicles, which may or may not be electrically powered. This includes cyclists, wheelchair users, skaters, scooter riders, Segway users, and similar forms of micro-mobility.
- **VRU profile 3** refers to motorcyclists, whose vehicles are capable of reaching speeds comparable to cars, buses, or trucks. According to the standards, motorcycles are considered a special type of VRU because they transmit messages like other motor vehicles, but include a dedicated VRU container to indicate their intrinsic vulnerability.
- **VRU profile 4** concerns animals that may pose a risk to road traffic. This includes pets, farm animals, wild animals, and service animals. While these entities do not have transmission capabilities, they are still considered VRUs when detected by vehicle on-board sensors, and should be identified and signaled accordingly.

Notably, the moving entities described in the four VRU profiles above are not considered VRUs in every context. The classification of an entity as a VRU depends on its *position* and *situation*. For instance, if the entity is inside a building or a vehicle, it is no longer considered a VRU, regardless of its inherent mobility or ability to transmit signals. In such cases, it should neither send nor receive V2X messages. Additionally, when a VRU-profiled entity is located in a pedestrian-only area, where the risk of collision with vehicles is minimal, communication should be *deactivated* or *limited*, unless a vehicle is detected nearby. Full transmission capabilities are only appropriate in *hazardous areas* where vehicle interaction is possible, such as streets, intersections, sidewalks, or bicycle lanes.

Even in areas where regular transmissions are allowed, *transmission mitigation mechanisms* are defined due to the typical behavior of VRUs. When moving in groups (e.g., couples or small clusters), individuals often share similar motion characteristics such as position, speed, and heading. In these scenarios, it is unnecessary for all VRUs to transmit their presence simultaneously. Instead, transmission from some VRUs should be *randomly suppressed* to reduce channel congestion. In the presence of larger groups (typically more than four nearby VRUs with similar motion dynamics) a *VRU*

⁴In the ETSI C-ITS context, a service is a software entity inside a C-ITS station that generates groups of bits, called messages, to be exchanged with neighboring C-ITS devices.

cluster may be formed. Within this cluster, one entity is elected as the *cluster leader*, responsible for broadcasting V2X messages on behalf of the group. The processes of joining or leaving a cluster are managed by the cluster leader, ensuring coordinated communication and reduced redundancy. Regarding the *generation of V2X messages*, the motion patterns of VRUs differ significantly from those of vehicles. As a result, the triggering conditions for generating VRU awareness messages (VAMs) are *not strictly defined* in the standards but are instead offered as flexible guidelines. Whereas vehicles typically transmit V2X messages at intervals between 100 ms and 1 s, VRUs are expected to transmit at intervals ranging from 100 ms to 5 s, depending on situational factors and mobility characteristics.

As for the actual deployment of V2X applications involving VRUs, the field is still largely in the research phase. Most existing studies are simulation-based, with only few of them attempting real-world experimentation [11]–[13]. One of the major obstacles to practical deployment lies in the choice of radio communication technologies. To ensure direct communication between vehicles and VRUs, or among VRUs themselves, dedicated V2X technologies such as IEEE 802.11p, IEEE 802.11bd, LTE-V2X, or NR-V2X (as discussed in the previous section) must be used. However, these technologies currently require dedicated on-board units (OBUs), which are more suitable for installation on vehicles than for use by pedestrians. The most practical device carried by virtually all VRUs is the smartphone, yet as of today, no smartphone manufacturer has announced plans to support native V2X communication technologies. Consequently, an alternative approach involves leveraging existing cellular networks (i.e., LTE or 5G) which are already integrated into smartphones. This would shift the communication paradigm from a direct pedestrian-to-everything (P2X) model to an indirect pedestrian-to-network-to-everything (P2N2X) model. However, this approach introduces challenges, particularly concerning latency. Since data must traverse the cellular network infrastructure, end-to-end communication delays are inherently higher compared to direct P2X communication. This can pose limitations for safety-critical applications that demand low-latency message delivery.

3.3 Trains

In the last decades, the railway infrastructure has been characterized by significant advances, especially thanks to the integration of communication technologies within the core of conventional transport services. In this regard, mobile networks represent a powerful instrument to simultaneously support railway operations and passengers' wireless connectivity. However, the extremely heterogeneous nature of applications and their related QoS requirements has posed new challenges about the harmonization and efficient management of the available resources. Furthermore, due to some criticisms mainly related to coverage, bandwidth scarcity, and latency, the realization of smart railways may not always be achieved by resorting to pure terrestrial systems. So, the investigation of integrated NTN solutions has attracted particular attention since potentially tailored to address the problem of QoS diversification.

Railway scenarios can be organized in 4 categories depending on the achievable speed of the traveling train. Specifically, we have [14]:

- Mainline: also referred to as high-speed railway (HSR), includes long distance paths connecting towns and nations, with traveling speed up to 250 km/h (expected to reach 500 km/h in the very next future).
- Regional: connects cities at medium distances, but with a low-capacity in terms of passengers load.
- Metro/urban: represents a rapid transit transport service operating in urban areas, characterized by limited traveling speed but high capacity; the main services concern traffic monitoring, management, and optimization.
- Freight: regards very long transport distance, with extremely low or null passenger capacity.

In the field of railways, it is possible to define different services and applications which can be related to the pure transport activity, passengers' on-board activity, train facilities and so forth. Rail communication performance is significantly influenced by the environment, that may be characterized by free-space, railway corridors in hilly terrain, tunnel/underground, paths, forest areas, shunting yards and so forth. Moreover, the variability of the scenario represents a further element to be taken into account when implementing solutions for the meeting of requested QoS requirements. In this regard, the Mainline scenario is considered as the most challenging one since voice, video and data traffic must be handled with the train traveling at very high speed. Particularly challenging among these is the exchange of critical videos, which are exploited to support train operations by means of real-time recording to and from the ground side. Typical examples are the automatic obstacle detection, monitoring of doors and gates, and surveillance on platforms. In general, data rates to be provided for video communication ranges from hundreds of kbps to several Mbps, with latency below 100 ms [15]. The variability of QoS requirements depends on the priority of the communication, that is considered as critical when dealing for instance with monitoring issues or very critical when regarding train and passengers' safety. Non-critical data are instead related to general tele-maintenance activities, which do not necessarily require real-time transmission, and other communication to passengers such as public announcement. While the QoS for critical data may be very high as for the case of video, more relaxed requirements characterize non-critical data, especially in terms of latency.

It can be noted that the railway scenario causes very critical challenges for mobile communications, especially with trains traveling at over 300 km/h, with problems due to significant Doppler effect, and frequent handover between cells. Furthermore, it is necessary to take into account the difficulties of signal penetration in metal carriages and the need for

appropriate coverage along the railway line. Thanks to predictive techniques, handover can be improved by exploiting knowledge of the train path. Coverage can be improved with repeaters and antennas located on the trains and along the line and also with NTN networks. Mobile communication systems for railways currently has been mainly based on the GSM-R standard, promoted by International Union of Railways. However, in order to address the increasing QoS demand, significant focus has been given. In this regard, Shift2Rail (S2R) programme, now EU-Rail [16], is the most important european research and industrial initiative on the Future Railway Mobile Communication System (FRMCS) [17]. FRMCS, which involved Technical Committee Rail Telecommunication, ETSI and 3GPP (Release 16 and later) concerning the definition of technologies for communications, spectrum resources assignment and future railway infrastructure realization, is the technology currently planned to progressively substitute the GSM-R. FRMCS is a mission-critical communication also developed in collaboration with the Union Internationale des Chemins de fer (UIC); it ensures secure and reliable voice and data communications between train drivers, rail traffic controllers, signalling and train control systems (e.g., ETCS – European Train Control System) and network infrastructures. FRMCS is still under development and is in large part based on 5G technologies, although also including the possibility to have non-3GPP technologies such as WiFi [18], [19]. FRMCS will be called upon to the effective support of heterogeneous communication services/applications for on-board and/or train-to-ground communications, which are characterized by different QoS, QoE, security/safety and reliability requirements. Railway applications can be grouped into four main categories i.e., (i) signaling for safe train control, (ii) critical voice, (iii) critical video for obstacle detection and monitoring doors inside trains, and (iv) critical data for communications among trains and trackside.

Then the new railway communication systems should be able to support multi-bearers, as well as multi-link communications. The FRMCS is competing with the Adaptable Communication System (ACS) [20]. The ACS is also developed within the EU-Rail project and it is designed in accordance with the Over-the-Top (OTT) view of the communication infrastructure(s). In fact, the ACS goal is to provide connectivity using all the available radio technologies that can be accessed using the IP protocol. This is believed the most natural approach for realizing one-bearer-independent operational rail communication system. The 3GPP 4G/5G technologies are only two of the many radio technologies that can be used by ACS to provide connectivity for railway applications. Different from FRMCS, alternative wireless access technologies can be easily integrated into ACS with no further standardization effort and in a very short time, such as: LEO/medium Earth orbit (MEO) satellites, high-altitude platform station (HAPS), and wireless optical systems. All that is required of these “alternative” bearers is to expose an IP-based interface to allow (secured) access. Urban rail systems, instead, are currently supported by proprietary radio technologies and protocols, which are known as communications based train control (CBTC) systems. The general functional requirements of CBTC systems have been standardized in IEEE 1474.1 IEC 62290.1, which indicates the CBTC system as a continuous, automatic Communication-based train control system utilizing: high-resolution train location determination, continuous high-capacity bidirectional train-to-wayside data communications, and train borne and wayside processors capable of implementing automatic train protection functions, as well as optional automatic train operation and automatic train supervision functions. In Europe, two urban rail ITS CBTC systems are currently used in the ITS band at 6 GHz, one based on direct sequence spread spectrum (DSSS)/time-division multiple access (TDMA), and the other based on IEEE 802.11 with CSMA/CA. It is worth mentioning that the band used by urban rail partially overlaps with the band used by road vehicles, and this is an issue currently being investigated in the ETSI TR 103 580.

3.4 Maritime Systems

A maritime networked system consists of interconnected assets making use of radio-based communications to interoperate. Elements of this environment are: ship stations; search and rescue aircraft; aids to navigation; and satellite service providers. International navigation (including communication aspects) is regulated by the International Maritime Organization (IMO) based in London; IMO encourages standardization, publishes so called “goal-based” standards that are in turn addressed by international standard organizations (notably International Telecommunication Union (ITU), International Standardization Organization (ISO), IEC) in charge of publishing the needed technical specifications. For maritime critical communications like those related to global distress and search and rescue procedures, coverage and reliability are of greater relevance than broadband and real-time features. Furthermore, in the SOLAS convention, duplication of equipment devoted to radio communications during an emergency is required. Therefore, usual communications can be low-rate and non-latency free. Some exemplary communication systems that can be used for the maritime environment are therefore: (i) terrestrial very high frequency (VHF) transmissions making use of DSC technology, which can reach 100 bps (300 kbps in case of VHF data exchange system (VDES)) and quasi-real-time communication; or (ii) geo-stationary satellite links like Inmarsat, which can reach 1.5 Mbps featuring latency in the order of 800 ms due to the propagation delay in the round-trip to the satellite.

In addition to the critical use described above, also broadband communications are used for other purposes. In particular, maritime users (including yacht and luxury boat owners), require connectivity (including access to the Internet) both to consume/offer maritime services and for work and leisure. A strong Internet connection ensures the possibility to communicate with friends and colleagues, as well as access weather and navigation information. The performance requirements differ depending on the activities to be performed. For example, while messaging and emailing have no

strict requirements regarding the latency, a large end-to-end latency can be a problem for real-time applications, such as video streaming and audio and video conferencing. Ubiquitous connectivity is of course an issue when the vessel is sailing the deep-sea; usual communications rely on satellite access and can therefore be costly and limited in performance. The recent spread and evolution of LEO constellations are going into the direction of improving the data rate (up to 150 Mbps) and the latency (reduced to tens of ms) from the original performance offered by geostationary satellites.

Also for the maritime scenario, autonomous motion is being considered as a relevant direction, in particular for autonomous shipping, which refers to the transport of either containers or bulk cargo inside vessels. Different levels of autonomy can be achieved starting from requiring the presence of personnel on board ready to act in case of extraordinary operations, continuing with the remote control from an onshore control center and ending with fully autonomous operations. From the simplest malfunction, such as power failures, to cyber/radio frequency/satellite attacks, automated systems have a certain number of weaknesses. Risks vary depending on levels of automation and degrees of autonomy, with fully autonomous vessels posing a range of particular and entirely new challenges. For a safe navigation, autonomous vessels require the collection, analysis and distribution of a large amount of information coming from the ship itself but also from the control center on shore, and this information should be in real-time. This kind of data must be highly reliable to let the ship evaluate the current situation and decide whether it can handle the operation by itself or the intervention of a human is needed. Moreover, a high-speed broadband connectivity may be necessary depending on the type of information to be shared (e.g., video streams from the cameras installed on the ship that must be shared with the control center on shore). As a matter of example, a radar/AIS plot requires a data rate of 100 kbps while a single LiDAR can require to transmit 1 to 2 Mbps (depending on compression level). Another very stringent requirement is the position accuracy if the ship has autonomous functions inside the port area, as vessels require a high absolute positioning to estimate the relative location of other ships and surrounding objects to avoid collisions. Such positioning accuracy can be offered by satellite navigation services (e.g., global positioning system (GPS)), corrected by local terrestrial references (as in Real Time Kinematics services) as well as by the new generation of 5G networks (from 3GPP R16 onward).

3.5 Flying Objects

This section presents a description of systems requiring connectivity, with respect to flying objects. In this context, flying objects are defined as aerial vehicles capable of changing position within the Earth's atmosphere, including manned aircraft, uncrewed aerial vehicles (UAVs)⁵ (or drones), and urban air mobility (UAM) platforms. Unlike non-terrestrial systems discussed in Section 4, stationary or quasi-stationary platforms, such as HAPSSs, are not considered here; while NTN may involve similar aerial elements, they do so when these elements serve as nodes of the communication infrastructure, such as relays or base stations. In contrast, this section focuses on communication between flying objects and between flying objects and the network, treating them as mobile, active users rather than static components of the system.

Unlike ground or maritime vehicles, flying vehicles operate in a three-dimensional space, often at high speeds and varying altitudes, with communication links extending up to several kilometers. This introduces unique requirements and constraints on communication systems. The communication between flying vehicles is generally referred to as airborne communication. Flying objects engage in multiple communication paradigms depending on their mission profile, altitude, and connectivity requirements. The most common are:

- Air-to-air (A2A): Direct communication between flying vehicles for coordination, collision avoidance, and data exchange;
- Air-to-ground (A2G): Links between flying platforms and terrestrial infrastructure, such as control stations and air traffic towers;
- Air-to-network (A2N): Communication that leverages existing terrestrial mobile networks or satellite infrastructure for broader connectivity.

Within each of these paradigms, it is essential to distinguish between two fundamental types of communication:

- Payload communication: Involves the transmission of data that enhances situational awareness, supports mission objectives, or enables cooperation between vehicles. Examples include sharing sensor data (e.g., video, LiDAR, environmental readings), broadcasting telemetry or position data, or exchanging maps and target coordinates in UAV swarms;
- Non-payload communication: Involves the transmission of commands and control signals that directly govern the behaviour or trajectory of a flying object. These communications are often time-sensitive, low-latency, and mission-critical. Examples include sending piloting commands to a UAV or issuing emergency abort signals.

⁵The acronym UAV was historically defined as unmanned aerial vehicle; however, it has been recently modified to uncrewed aerial vehicles, starting from 3GPP specifications, for two reasons; first, unmanned appears as gender-specific, and therefore not inclusive; second, a human remotely connected may be present, and is indeed normally present for control or supervision.

Maintaining a reliable and secure control link is vital in such cases, as failures may result in loss of the vehicle or safety incidents. In aviation terminology, the data link carrying non-payload information is commonly referred to as the *command and control (C2) link*.

The exchange of payload and non-payload information may occur over the same physical channel or protocol stack, or over separate channels. However, these types of communication often require different prioritization, QoS settings, and redundancy mechanisms to ensure operational safety.

Standardization and regulation bodies. Several organizations play important roles in defining the standards and regulations in the field of air navigation and airborne communication systems. The International Civil Aviation Organization (ICAO) develops global standards and recommended practices to ensure aviation safety, including protocols for communication and surveillance. National and regional regulatory authorities, such as the Federal Aviation Administration (FAA) in the United States and the European Union Aviation Safety Agency (EASA) in Europe, establish rules governing airspace use, UAV operations, and spectrum allocation within their respective jurisdictions. These standards address challenges related to mobility, identification, and potential network interference. The ITU oversees the global allocation of radio frequency spectrum, ensuring consistent and coordinated use of frequencies for aviation communication systems worldwide. Additionally, organizations such as RTCA and EUROCAE develop technical standards for aviation equipment and systems, helping to guarantee interoperability and compliance with safety requirements. In the field of telecommunications, the 3GPP is responsible for developing standards for cellular technologies, including the integration of UAVs into LTE and 5G networks.

Airspace structure and rules for air navigation. To ensure safety, air navigation is governed by a complex framework of rules, procedures, and airspace structures designed to keep aircraft safely separated and coordinated. Airspace is broadly categorized as either controlled or uncontrolled. Controlled airspace is managed by air traffic control (ATC), where pilots must operate under specific instructions and clearances, particularly in busy or high-altitude regions. Air traffic control plays a central role in managing the safe and orderly flow of aircraft. Controllers provide separation between aircraft, issue clearances for specific routes and altitudes, and coordinate takeoffs, landings, and en-route transitions. Uncontrolled airspace allows pilots greater freedom to navigate independently, typically under visual flight rules, without direct ATC oversight. Globally, airspace is further divided into classes, labeled from Class A to Class G, each defining requirements for pilot qualifications, communication obligations, and weather visibility minima. For example, Class A airspace, usually found at higher altitudes, permits only instrument flight operations under strict ATC supervision, whereas Class G airspace represents uncontrolled regions where pilots operate without mandatory ATC services.

Aircrafts do not simply fly in straight lines from one airport to another. Instead, they often follow predefined paths known as airways, sometimes described as air highways. Airways connect navigation aids or virtual waypoints and form structured corridors in the sky, helping to keep aircraft safely separated and organized, particularly in congested regions. These routes have specific names or codes. Waypoints are specific geographic positions, defined by latitude and longitude, used to build and organize flight routes. Each waypoint has a unique five-letter name and serves as an entry or exit point for specific airspace regions. Pilots navigate from waypoint to waypoint along airways, guided by instruments and flight management systems that integrate information from ground-based aids, like VHF omnidirectional range stations, and satellite-based GNSS systems. Vertical separation between aircraft is managed through the use of flight levels, which refer to altitudes measured relative to a standard atmospheric pressure setting. For example, Flight Level 350 (FL350) corresponds to 35,000 feet (10.7 km) above the standard pressure level. There are also directional conventions: eastbound flights typically use odd-numbered flight levels, while westbound flights use even numbers, which helps reduce the risk of head-on conflicts.

Pilots regularly report their positions, request altitude changes, or receive clearances for new routes by communicating with ATC. Traditionally, these exchanges occur via VHF radio, but modern systems allow routine messages to be sent as text, reducing radio congestion and the possibility of mutual communication interference. Surveillance of aircraft positions is accomplished through radar systems, which track aircraft over land and near shorelines. However, radars have limitations in range and coverage, especially over oceans, mountainous terrain, or remote regions, where air traffic control must rely on pilots providing position reports at regular intervals.

Rules for drone air navigation. Unlike traditional aircraft that operate in higher altitudes, civilian drones function under a different set of rules designed to ensure safe operations close to the ground, buildings, and people. Airspace for these vehicles is typically limited to altitudes below 120 meters above ground level to avoid conflicts with aircraft aviation. Regulations often require drones to remain within the pilot's visual line of sight; however, beyond visual line of sight (BVLOS) operations are possible with special authorizations, provided that systems for collision avoidance and reliable communication links are in place. Certain zones, such as areas near airports, over crowds, or around critical infrastructure, are designated as no-fly zones and may be integrated into drone software as geo-fenced regions to prevent accidental incursions. Drones navigate using GNSS, onboard sensors, and flight management systems, allowing them to hold positions or follow pre-programmed routes. Control can be manual via handheld controllers, semi-autonomous through waypoint programming, or network-based using cellular or satellite communication links, especially for longer-range BVLOS operations. With the increasing use of drones, new airspace management frameworks are being developed to handle their integration safely and efficiently. Systems such as U-Space in Europe and the Unmanned Aircraft

System Traffic Management (UTM) initiative in the United States aim to provide services like flight authorizations, real-time airspace information, and conflict resolution, helping drones coexist with other airspace users without overloading traditional air traffic control systems.

Communication technologies and strategies for air navigation. Modern air navigation relies on a range of communication and surveillance technologies to ensure safe, efficient, and coordinated operations for both crewed and uncrewed aircraft. These systems support navigation, collision avoidance, situational awareness, and the integration of air traffic into national and international airspace structures. From a communication perspective, most of these technologies have traditionally employed narrow-band transmissions, as signals need to propagate reliably over long distances. The key technologies relevant to air navigation are:

- **GNSS:** GNSSs allow aircraft to determine their precise position in terms of latitude, longitude, and geometric altitude, as well as synchronize their systems to coordinated universal time (UTC). The precise positioning and timing capabilities of GNSS enable air vehicles to share their real-time location data and facilitate direct navigation between GNSS-defined waypoints. This navigation approach replaces the traditional reliance on ground-based radio beacons, allowing for more efficient and flexible routing, reduced flight distances, and enhanced operational safety. However, GNSS signals can be vulnerable to interference, jamming, or spoofing;
- **VHF:** VHF radio communication has traditionally been the primary means of voice communication between pilots and air traffic controllers in controlled airspace. Operating in the frequency band from 118 MHz to 137 MHz, VHF channels enable line-of-sight communication used for transmitting clearances, instructions, and real-time operational information. However, to reduce the risk of miscommunication between pilots and controllers, VHF voice communication is increasingly supplemented by visual text-based instructions transmitted via other technologies and data links (e.g., controller pilot data link communications (CPDLC));
- **Automatic dependent surveillance–broadcast (ADS-B).** ADS-B is a surveillance technology in which aircraft automatically broadcast their position, velocity, and other data derived from onboard navigation systems. ADS-B enhances situational awareness by enabling both air traffic controllers and nearby aircraft to receive real-time information about surrounding air traffic. Transmissions occur within a 3.5 MHz bandwidth centered around the 1090 MHz frequency, with each aircraft typically broadcasting one message per second. Recently, space-based ADS-B systems have emerged, allowing for global surveillance coverage. In these systems, ADS-B messages transmitted by aircraft are received by satellites equipped with specialized ADS-B receivers that capture the signals directly from the aircraft. The satellites then relay the digitized ADS-B data through dedicated satellite communication links to ground stations, where it is processed and integrated into air traffic management systems;
- **Visual line of sight (VLOS):** VLOS refers to drone operations where the remote pilot maintains continuous unaided visual contact with the unmanned aircraft. Communication in VLOS drone operations relies on a mix of proprietary radio protocols and standardized wireless technologies. Many consumer drones employ IEEE 802.11 Wi-Fi for both telemetry and video streaming, enabling integration with mobile devices. Professional systems often use proprietary RF protocols, operating in the 2.4 GHz or 5.8 GHz ISM bands;
- **Connectivity between airborne platforms and cellular networks:** Connectivity between airborne platforms and terrestrial networks allows air vehicles, including UAVs, to establish communication links beyond VLOS. Such connections can support real-time transmission of telemetry, command and control data, and high-bandwidth payload information such as video streams or sensor data. The 3GPP is actively working on integrating drones as aerial users within cellular networks, leveraging LTE and 5G technologies. This integration is necessary for use cases such as drone delivery. However, recent research suggests that traditional cellular networks may not be ideally suited to provide connectivity to drones, because base station antennas are primarily oriented toward the ground to serve handheld devices. As a result, drones at altitude often rely on connections through the side lobes of the base station’s radiation pattern, which can lead to reduced signal quality and coverage gaps [21]. Similarly, work is ongoing to enable direct A2A communication between flying objects using sidelink; however, this technology, which is designed for short-range terrestrial communications, may need enhancements for proper operations between airplanes or drones [22].

3.6 Satellites

In addition to flying objects such as drones and airplanes, satellites also move above the ground and require connectivity. Here, again, the focus is on satellites that need connectivity for their operations, and not satellites used to provide connectivity, which are instead treated in Section 4.

A particular application for satellites is Earth observation (EO), where they are fundamental actors in the New Space Economy for monitoring and understanding the Earth system. In this context, satellites support a wide range of applications, including remote sensing, environmental monitoring, natural disaster management, precision agriculture, urban planning, maritime surveillance, and climate change research. EO satellites are equipped with a variety of sensors (optical, radar, thermal, and multi-spectral) that enable the collection of high-resolution data across different regions

of the electromagnetic spectrum. These capabilities allow for continuous and systematic observation of Earth's surface, atmosphere, and oceans, providing critical insights for both scientific research and operational decision-making.

Traditionally, EO missions have relied on large, complex satellites such as NASA's Landsat series or ESA's Sentinel missions. These platforms are designed for high performance and long lifetimes, often carrying multiple instruments with advanced capabilities. However, recent years have seen a shift towards smaller, more agile platforms, including small satellites and CubeSats. These miniaturized systems, enabled by advancements in electronics and sensor technology, offer a cost-effective alternative that supports the rapid deployment of large constellations. Such constellations significantly improve revisit times, enabling near-real-time monitoring of dynamic events. While small satellites and CubeSats have inherent limitations in payload capacity, power, and lifetime, their proliferation is transforming the EO landscape by supporting flexible mission designs and lowering barriers to entry for new actors.

Most EO satellites operate in LEO, often in sun-synchronous orbits (SSOs) at altitudes between 600 and 800 km, to maintain consistent illumination conditions for imaging. This orbital configuration allows satellites to revisit the same location at regular intervals, typically every 10 to 16 days, depending on the mission design. For instance, a satellite at 550 km altitude and 98° inclination has an orbital period of approximately 1.5 hours and passes over Turin about four times per day, with each visibility window lasting only a few minutes.

The connection between EO satellites and Earth is traditionally handled by ground stations, with the notable exception of missions using data relay systems.

EO satellites can downlink their data during visibility windows, when they are within line-of-sight of a ground station. This direct-to-Earth transmission approach has several advantages. Links can operate across a wide range of frequency bands, from UHF/VHF to S, X, Ka, and Ku bands, and more recently optical links have also been adopted⁶. Standards such as CCSDS telemetry and telecommand (typically using binary phase-shift keying (BPSK)/quadrature phase-shift keying (QPSK) modulations), DVB-S2X (supporting up to 256-amplitude phase-shift keying (APSK)), and potentially in the future 5G new radio (NR) (with modulations up to 256-QAM as seen in NTN) can be used.

The ground station approach is very effective but has several important limitations. Since LEO satellites move rapidly relative to the Earth's surface, they are only within range of a given ground station for a few minutes per orbit. As a result, latency, defined as the time between data acquisition and its availability on the ground, can often reach tens of minutes. This issue becomes particularly critical in scenarios requiring unscheduled data downloads, such as responses to natural disasters or dynamic events, where delays can severely impact operational effectiveness. Moreover, as the number of LEO satellites grows due to the rise of mega-constellations and EO platforms, ground station networks, despite expanding with more antennas and improved scheduling, face increasing congestion. The limited contact windows and competition for downlink time among multiple operators exacerbate this bottleneck, making it unlikely that the situation will improve without alternative solutions, especially for missions requiring near-real-time data access.

To mitigate these constraints, some missions may employ relay satellites, such as NASA's Tracking and Data Relay Satellite System (TDRSS)⁷ or ESA's European Data Relay System (EDRS)⁸. Relay satellites in geostationary orbit provide near-continuous communication by forwarding data from EO satellites to ground stations in real time. While this approach significantly reduces latency and coverage gaps, it requires more complex and costly onboard communication systems and increases mission costs. NASA is currently preparing to retire its TDRSS, which has provided near-continuous communications for LEO satellites since the 1980s. Instead of replacing it with another government-operated system, NASA plans to rely on commercial providers for space relay services. Companies such as SpaceX, Amazon's Kuiper, and Inmarsat are developing relay solutions to support future missions. This shift aims to leverage private-sector innovation, reduce costs, and ensure more flexible and scalable data delivery to Earth.

Another solution that has recently emerged is the use of LEO mega-constellations, originally deployed to provide broadband Internet access, to serve lower-orbiting LEO satellites. This paradigm, known as mega-constellation satellite services (MCSS), can transform EO satellites into nodes of a space-based network, providing 24/7 availability and sub-second latency thanks to the extensive coverage offered by these mega-constellations. This approach would effectively turn low-orbit Earth observation satellites into fully integrated nodes of a NTN, enabling continuous, low-latency connectivity and unlocking new opportunities for real-time data access and in-space networking. Recent studies confirm that this approach is highly promising, with numerous results highlighting both its feasibility and its impactful potential [23], [24].

3.7 Autonomous Industrial Vehicles

The AGVs assumed a prominent role in industrial application scenarios, typically in the context of intralogistics, movement of raw materials, work-in-process, and finished goods in large factories and production plants, with the goal of ensuring reliable movement, predictable timing and traceable flow. Early AGVs were introduced in the industrial context over 60 years ago [25], and research and development steadily expanded the range of applications and the capabilities of

⁶<https://www.nasa.gov/smallsat-institute/sst-soa/soa-communications/>

⁷<https://www.nasa.gov/mission/tracking-and-data-relay-satellites/>

⁸<https://connectivity.esa.int/european-data-relay-satellite-system-edrs-overview>

AGV over the years [26]. AGVs are typically designed to follow predefined routes, identified using magnetic tape, inductive wires, or reflectors. Additional systems were added in current state-of-the-art in order to improve the coexistence of AGVs in dynamic industrial environments, by enabling accurate positioning and tracking and reliable collision prevention for human-AGV cohabitation in shared environments; such systems include for example laser guidance, computer vision, and wireless technologies. Communications play a key role in the operation of AGVs, as modern deployments are typically coordinated by a fleet manager that optimizes missions, balance traffic at intersections, and integrates with industrial databases for real-time order release and inventory updates. Today, most AGVs are connected via corporate Wi-Fi networks [27]; scalability and reliability issues, related to the presence of congestion, deadlocks, and sudden traffic spikes, call however for the adoption of alternative and possibly complementary technologies. 5G is a prime candidate, with large efforts already in place for the widespread adoption of 5G in industrial scenarios [28]. 5G offers in fact several features suited to improve the performance of AGV deployments, such as the availability of private 5G networks, offering low latency and high reliability, mature support for sidelink/D2D connections, as well as the integration of communications, sensing and positioning currently being investigated both in the research community [29] and in standardization bodies such as ETSI and 3GPP [30]. The introduction of digital models of both industrial and communication components to support efficient operation of AGVs [31], and the integration with edge computing and predictive AI for faster local decisions, dynamic route planning and proactive obstacle detection and avoidance are also being investigated, aiming at closing the gap between traditional AGVs and fully Autonomous Mobile Robots (AMRs) in industrial use cases, opening the way to new application scenarios, such as mixed indoor-outdoor scenarios with seamless transition across different communication and positioning technologies.

3.8 Underwater Vehicles

Interest in underwater vehicles is increasing due to their potential key role in many applications, in both military and civil contexts. Examples include maritime exploration, support for the oil and gas supply chain, and environmental monitoring, eventually leading to the so-called Internet of Underwater Things (IoUT) [32]. Underwater vehicles include a fairly vast class of vehicles, such as remotely operated vehicles (ROVs), hybrid underwater vehicles (HUVs), unmanned surface vehicles (USVs), underwater bionic vehicles (UBVs) and, especially, autonomous underwater vehicles (AUVs), which can tackle specific tasks without requiring the intervention of a dedicated operator [33].

Communication, i.e., how the vehicles share the collected data or coordinate with others, is a critical aspect due to the unique propagation characteristics of the water medium, which then requires a different solution from its terrestrial counterpart. Due to the physical properties of the water, in fact, the leading technologies in underwater are underwater acoustic communications (UWAC) and, more recently, underwater optical communications (UWOC), with few application-specific exceptions, such as magnetic induction (MI). On the other hand, communication and networking are not standardized, with the only notable exception of the JANUS standard [34] proposed by NATO for UWAC, which focuses on the physical and MAC layers.

Both UWAC and UWOC have pros and cons. While UWAC allows to achieve long distances, up to 100 km [35], it has several limitations, such as limited propagation speed (approx. 1500 m/s), it is susceptible to multipath in shallow water, due to the reflection to the seabed and the sea surface, and many environmental interferences, e.g., due to the presence of boat or even marine mammals. Finally, it offers a limited data rate in the order of the tens of kbit/s. On the other hand, UWOC are becoming a valid option as, due to the higher bandwidth, they provide a much higher data rate, from Mbit/s up to Gbit/s [36], [37]. Still, UWOC have several drawbacks with respect to UWAC; to name a few, they suffer of a much more limited range (up to ≈ 100 m) and they are susceptible to water turbulence and solar interference. Thus, when designing new applications, the advantages and disadvantages of these technologies should be considered.

To overcome the limitation of both these technologies, a recent trend is to design hybrid communication systems, often called *multimodal*. The key idea is that the vehicle may dynamically switch from one technology to the other, depending on several factors such as required QoS or environmental conditions; e.g., a vehicle communicating with a buoy may switch from acoustical to optical once it is close enough and vice versa, switch back to acoustic if there are some interferences in the optical channel [38].

4 Non-Terrestrial Networks to Grant Coverage Everywhere

The highly heterogeneous set of mobile objects that require connectivity shares a common issue: connectivity needs to be granted everywhere. Even if the coverage of wireless communication systems has enlarged impressively in the last decades, ensuring that this is possible really everywhere appears challenging. A possible direction for improvement, which is among the main aspects being considered for beyond 5G, is the use of NTN. Indeed, a key aspect of the future of mobile communications is seen in the contribution from NTN, which are anticipated to seamlessly integrate with terrestrial networks (TNs) and related technologies, thus extending the coverage of International Mobile Telecommunications (IMT) systems. These NTN will include spaceborne systems, such as geosynchronous orbit (GSO) and non-GSO orbiting satellites, as well as airborne platforms like HAPs and uncrewed aircraft systems (UASs), also referred to as UAVs [39], [40]. The integration of these technologies is illustrated in Fig. 2 and further discussed in the following.

4.1 Types of NTN Nodes and Motivations

The integration of aerial nodes facilitates the development of a fully cohesive vertical heterogeneous network (VHetNet), as envisioned by the 3GPP in relation to NTN for future 6G scenarios [41]. These networks leverage a three-dimensional architecture to provide seamless connectivity, optimizing coverage and capacity across terrestrial, aerial, and space-based layers. By incorporating multiple network layers, VHetNet can better support moving objects at varying altitudes — such as on-ground vehicles, drones, and aircrafts — ensuring tailored connectivity based on their specific mobility and operational needs. Furthermore, the ability to integrate diverse network nodes in the space, aerial, and terrestrial domains into a unified system improves overall efficiency and adaptability, offering robust connectivity in a wide range of environments.

NTNs include the space segment formed by satellites and the air segment formed by aerial nodes. Concerning satellites, there are three primary types used based on the Earth's orbit, which have different characteristics and therefore different advantages and drawbacks: GSO, MEO, and LEO satellites. GSO satellites maintain a fixed position relative to the Earth's surface, orbiting at an altitude of approximately 3000 km. MEO satellites operate at altitudes between 5000 and 12000 km, while LEO satellites occupy the lowest orbits, typically around 2000 km. Concerning LEO satellites, it is interesting to note that the launch cost reductions and advances in miniaturization have enabled large-scale constellations. For example, SpaceX's Starlink includes over 7000 LEO satellites. Similar initiatives from OneWeb, Amazon Kuiper, China's Hongyan, and Telesat aim to deploy over 20 000 satellites globally. However, the growing number of satellites raises concerns about space debris, with an estimated 330 million objects currently orbiting the Earth [42].

In addition to satellites, integrating terrestrial connectivity also with aerial nodes, such as UAVs or HAPs, offers a flexible and cost-effective solution to extend coverage and capacity to remote areas, providing on-demand connectivity for supporting mobility. Aerial nodes can significantly reduce the deployment costs associated with traditional communication infrastructure in hard-to-reach regions, as they can be quickly deployed and repositioned as needed. While coverage in remote areas typically increases CAPEX and OPEX due to the need for extensive ground-based infrastructure, the

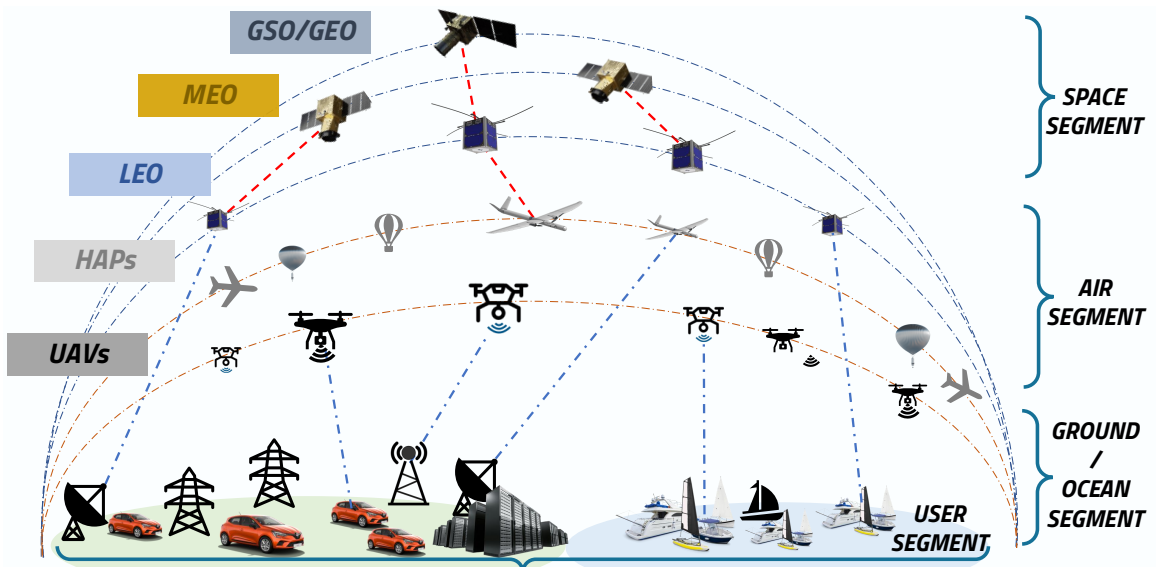


Figure 2: Integration of TNs and NTN segments.

use of UAVs or HAPSs can mitigate these costs, particularly when throughput requirements are limited.

An additional aspect motivating NTN, which cannot be overlooked, is that the deployment of communication networks to support mobility in remote regions faces also the challenge of providing a reliable and sustainable power supply. Efforts to extend the electric grid to remote or challenging areas to support terrestrial communication infrastructures are often unfeasible due to the high cost and physical barriers involved. Establishing reliable power supply lines in such regions may require substantial investment, and in some cases, it may be entirely unrealistic due to rugged terrain, geographic isolation, or lack of infrastructure. An alternative could be to provide dedicated stand-alone energy systems — either fuel-based generators or sustainable energy solutions such as solar panels or wind turbines — which however come with their own set of challenges: maintenance, operational costs, and environmental concerns. A promising solution lies therefore in the use of satellites and aerial nodes, which can provide communication coverage without relying on traditional terrestrial power infrastructure. This solution can in this sense be also seen as promoting environmental sustainability, which is an increasingly crucial aspect [43]. Whereas the advantage is obvious for satellites, it can indeed apply also to aerial nodes: in particular, HAPSs are self-sustainable and can operate efficiently by harnessing renewable energy sources like solar power, ensuring long-term, low-maintenance operations, while UAVs can be charged in remote locations, separate from their operational area, through a shared charging infrastructure that services a wide region. The aerial nodes, by offering on-demand coverage, not only bypass the need for extensive terrestrial power infrastructure but also present a flexible and scalable solution, addressing the unique energy and connectivity challenges posed by remote regions.

In the following, particular attention is devoted to LEO satellites, HAPSs, and UAVs, which represent three of the most relevant categories of NTN nodes.

4.2 LEO Satellite Constellations for Global IoT Connectivity

In the context of connectivity and mobility, LEO satellites are becoming increasingly important for Internet of Things (IoT). In particular, the development of IoT services leveraging LEO satellite constellations has attracted considerable interest from private enterprises, international standardization organizations, and the academic research community [44]. While terrestrial IoT systems already play a critical role in advancing next-generation wireless networks, numerous use cases demand a more global, scalable, adaptive, and robust solution. These include monitoring remote regions, connecting underserved or isolated areas, and enabling intelligent global transportation and asset-tracking systems. Many of these applications involve mobile IoT devices, such as cargo shipments, vehicles, maritime fleets, and other assets that traverse vast and often disconnected geographic regions. Addressing these needs has led to the emergence of the “Internet of Space Things”, a network of interconnected cyber-physical systems that facilitates worldwide connectivity via satellite constellations.

From the perspective of standardization, the 3GPP has championed the adoption of Narrowband IoT (NB-IoT)-based solutions for NTNs. These are tailored to ensure seamless integration with terrestrial cellular systems and provide a framework for extending IoT services to satellite-based platforms. The 3GPP approach emphasizes leveraging existing cellular infrastructure and protocols to maintain compatibility and facilitate global adoption. In parallel, several industry leaders, such as Lacuna Space and EchoStar Mobile, are promoting low-power wide-area networks (LPWANs) utilizing proprietary technologies (e.g., those by Semtech) for direct-to-satellite Internet of Things (DtS-IoT) communications. Among these, a novel communication technology, long range frequency hopping spread spectrum (LR-FHSS), has been introduced specifically to support long-distance, low-data-rate uplink transmissions. By employing rapid frequency hopping, LR-FHSS maintains a link budget comparable to that of long range chirp spread spectrum (LoRa-CSS) while significantly improving network capacity, making it a strong contender for satellite-based communication systems. Simultaneously, the established LoRa-CSS modulation scheme has been enhanced to include new operating frequencies, channel bandwidths, spreading factors (SFs), and data rates, enabling more versatile and efficient satellite IoT solutions [44]. The satellite IoT systems face critical technical requirements, including the ability to serve a large number of users simultaneously, resilience to Doppler effects caused by the high relative velocity of satellites, and the prohibitive link budget. This is further compounded by the necessity for devices to operate at low power to preserve battery life, making system design a challenging yet essential task for enabling reliable and efficient connectivity.

Despite notable advancements in the development and experimental validation of these systems, several critical challenges persist that constrain the full realization of DtS-IoT capabilities in satellite-based communication frameworks. Among the most significant of these challenges are the issues of massive interference and the substantial Doppler shift effects arising from the high orbital velocities of LEO satellites [44]. Current research efforts have predominantly focused on optimizing link budgets, managing latency, and addressing network scalability. However, the Doppler effect, which significantly affects the performance and reliability of DtS-IoT systems, remains underexplored. Promising avenues for future research include comprehensive performance analyses that account for the Doppler effect, as well as the development of advanced prediction and compensation techniques to mitigate its impact. Such studies are essential to improve the operational robustness and reliability of LEO-based IoT solutions. Additionally, a deeper investigation into the uplink capacity limits of DtS-IoT systems is imperative. This includes determining the maximum number or density of devices that can be supported simultaneously under realistic operational conditions, taking into account traffic

dynamics, device mobility, and interference levels. Such insights are critical for identifying scalability thresholds and developing effective resource allocation strategies. Addressing these research challenges will be pivotal to harnessing the full potential of DtS-IoT technologies and achieving global satellite-based IoT connectivity.

4.3 HAPSs for Mobility Support and Sensing Applications

The use of HAPSs holds significant potential for enhancing connectivity for moving objects, such as vehicles, ships, and trains, by providing wide-area, reliable, and adaptable communication coverage. In particular, equipping a HAPS with a 4G or 5G cellular technology base station introduces a versatile and efficient solution to support diverse communication needs, from broadband services to consumers to more challenging QoS-constrained services such as those required by autonomous vehicles and other autonomous mobile objects.

In addition to the coverage improvement that can be provided in specific areas and the capability to operate independently of the electric grid, HAPSs offer a range of additional advantages that make them an ideal solution for providing connectivity to moving vehicles and other dynamic environments. One key benefit is their ability to provide wider coverage than on-ground network nodes, serving areas that are hard to reach with traditional terrestrial networks due to geographic barriers (such as mountains or forests), the complexity of dense urban environments, and the economic limitations of sparsely populated regions. Another point is their ability to flexibly redirect communication resources, which makes them especially valuable for dynamically managing fluctuating connectivity demands like those related to vehicular traffic both in urban and rural settings. Additionally, HAPSs offer significant potential for maritime communications compared to satellites, which are typically used in such scenarios, thanks to a lower latency that improves connectivity for ships and offshore platforms. Similarly, their ability to maintain high-speed, relatively low-latency communication makes them ideal for supporting fast-moving objects such as trains and even aircraft, leveraging their optimal operating altitude—higher than typical flight altitudes but low enough to minimize latency—and geostationary position to provide consistent and reliable connections.

Beyond communications and mobility support, a relevant research direction is the use of HAPSs integrating sensing capabilities, notably through synthetic aperture radar (SAR), to support mobility monitoring and environmental sensing. By sharing the radio signal generated for communication, HAPS-mounted SAR systems can track vehicles, monitor traffic flows, support disaster response, and enhance maritime and border surveillance—without needing separate sensing infrastructure [45]. These capabilities also extend to wildlife monitoring, enabling the tracking of animal movements in remote or protected areas. Compared to satellite-mounted systems, HAPSs require less power to achieve high-resolution sensing and benefit from shorter revisit times, enabling more frequent and detailed observations. Operating in the stratosphere, they offer a balance between coverage and granularity, with the ability to deliver persistent, real-time monitoring across diverse environments and weather conditions. Despite these considerable advantages, important challenges remain, including susceptibility to weather disruptions, the complexity of maintaining seamless connectivity with fast-moving targets, and the need for coordinated integration with terrestrial and satellite networks. Addressing these issues is pivotal to fully leveraging HAPSs for both communications and sensing in dynamic and remote scenarios.

4.4 UAVs for Enhancing Connectivity

In recent years, UAVs are increasingly viewed as potential assets for extending coverage and boosting network capacity. When equipped with mobile base stations (BSs), in fact, UAVs hold significant potential for enhancing mobility support, particularly in urban environments. This is particularly relevant when looking at urban areas where traffic is highly variable and often localized in certain areas, and in this context UAVs can effectively complement fixed terrestrial infrastructure, contributing to a safer and more efficient mobility ecosystem. Their flexibility allows them to be deployed dynamically to address periods of vehicular traffic peaks and to adaptively follow vehicles or VRUs in areas of high density. Furthermore, UAVs are particularly effective in overcoming NLOS challenges, such as those posed by urban canyons or dense building layouts, ensuring uninterrupted connectivity and communication. By providing targeted connectivity where and when it is most needed, these aerial nodes play a fundamental role in enhancing driving safety, especially in complex urban settings where reliable communication is critical. Beyond urban use, UAV-mounted BSs can also find use in rural areas along highways or high-traffic roads to provide additional radio resources that help meet the increased demand associated with critical events, slowdowns due to traffic jams, accidents, or emergencies, thereby enhancing vehicular mobility support.

Despite their flexibility, UAVs are constrained by limited energy autonomy, which can hinder sustained operation in mobility scenarios. While UAVs can be equipped with solar panels to extend battery life, this contribution may not be sufficient to ensure prolonged operation periods as may be required in urban mobility use cases, making it essential to implement effective energy-aware strategies to define optimal trajectories that minimize energy consumption associated with UAV movements and repositioning. Additionally, these strategies should incorporate efficient resource allocation algorithms to dynamically adjust active radio resources (e.g., active beams generated by the aerial BSs) based on vehicle distribution, taking into account their impact on UAV energy usage. These algorithms must balance energy constraints with QoS requirements, ensuring that UAV operations remain sustainable while maintaining connectivity standards and

performance for vehicular communication. A complementary approach to jointly enhance urban mobility and reduce UAV energy consumption, particularly in scenarios with less dynamic traffic distribution, entails the optimization of UAV positioning. By targeting strategic locations, such as building rooftops, UAVs can remain stationary, requiring no energy consumption to maintain their position while providing coverage for critical intersections, especially those impacted by NLOS issues with traditional terrestrial BSs.

5 Direct Communications to Be Always Connected

When considering large networks of mobile devices, it is difficult to expect them to always provide sufficient coverage in all locations and at all times. Even if this were possible (also thanks to the activities on the integration of terrestrial with non-terrestrial networks discussed in Section 4), the use of an infrastructure does not appear as the best solution for the exchange of urgent and contextual information between neighboring nodes. For this reason, what we here call direct communications will become in our view a relevant part of the future mobile networks.

We use the terms *direct communication* to indicate that the mobile nodes communicate to each other without using for this purpose an infrastructure; these terms try to remark some differences with what has been historically called mobile ad hoc networks (MANETs). MANETs, with their subsets represented by vehicular ad hoc networks (VANETs) and flying ad hoc networks (FANETs) among others, have been extensively studied since early 2000, with the aim of creating a set of protocols that realize a network where nodes can exchange information with each other even if the links evolve in time and the path to reach the destination varies quickly. This had led to important activities on the issue of network graph creation, nodes identification, and routing algorithms. In the latest years, especially when looking at the vehicular environment, the approach to communication with mobile ad hoc networks has however in large part changed. From this network-wide perspective that reproduces in mobility what a fixed network does, the attention has moved to the exchange of information between neighboring nodes which in many cases are not even interested in the specific identity of their neighbors. Given the different point of view, we here prefer to avoid the use of ad hoc networking towards the use of direct communications.

The direct communications may involve mobile nodes but also stationary nodes, which use the same protocols and wireless technologies to exchange information locally, with the ultimate goal of cooperating towards some common task. This concept is well explained referring to V2X, which represents in our view the first attempt to create large scale networks of mobile nodes without the use of an infrastructure. Even if cellular communications are viewed as an important part of the connectivity between vehicles and other actors of the transport management, as already discussed in Section 3.1, cars start to be equipped with wireless technologies that enable them to exchange data directly, shortened hereafter as direct V2X.

From the perspective of what type of data is exchanged and which type of use cases can be supported, three phases have been imagined for direct V2X by the Car 2 Car Communication Consortium (C2C-CC): an awareness phase, a collective perception phase, and a cooperation phase [46]. In the awareness phase, the scope is only to make mobile nodes be aware of their neighboring nodes: which type of nodes they are (e.g., a pedestrian or a car or a traffic-light), with which characteristics (e.g., 2 m or 4 m long), and with which mobility conditions (including direction, speed, and so on). The actions based on this awareness are normally independently taken by each vehicle and therefore the degree of cooperation is rather low. In the collective perception phase, each device also shares the view of the surrounding that derives from its sensors: the car or the road side unit (RSU) can be equipped with cameras or LiDARs that scan their proximity and individuate the various objects with their movements, and then can inform about this the other connected nodes. The sharing of additional information improves the awareness beyond the connected devices. Finally, the cooperation phase is where the nodes agree on the operations they will take and coordinate on their implementation. In the V2X domain, this means for example performing safe lane changing or intersection management.

All what discussed for V2X can be in our view extended to the other domains of mobile nodes. Also flying objects, maritime devices, industrial AGVs, and so on, will need awareness of the other nodes, will take advantage of improved perception, and will eventually coordinate in their operations. This requires effort from the research community at various levels. One point to remark is in fact that the wireless technologies and protocols for direct communications require a substantially different design than the other types of networks. For example, they do not normally need to mainly focus on the classical objectives such as high throughput or efficient routing protocols, but need to properly manage fast exchanges between nodes, even when nodes do not know each other; this aspect has a number of implications, such as the need for the use of a common signal structure and common channel, and the implementation of strong distributed security mechanisms. Another notable aspect is that granting reliable communications requires some control on the reciprocal interference that is generated, and this in turn means that the channel occupation needs to be under control in a fully distributed way; the challenge, in particular, is that this needs to be done in a fair way, where the risk that one node takes all the channel and the others stop communicating is avoided.

6 Larger Bands at Larger Carrier Frequencies in High Mobility

High-frequency bands (mmWave and sub-THz) are among the key enablers for ultra-high data rates and low-latency applications, and their adoption is getting particular interest especially in the context of connected and automated vehicles. However, the adoption of the high-frequency bands poses significant technological challenges due to propagation characteristics, which become particularly complex in mobility environments. In that context, in fact, tracking is required in order to allow for the proper antenna steering, but can be very difficult due to the small size of the beams, especially if the object moves at high velocities. This section outlines the key aspects of high-frequency communications in fast mobility.

In the evolution towards 6G mobile networks, enabling ultra-reliable and high-throughput communication for connected and automated mobility demands a radical rethinking of physical layer design, spectrum usage, and link management strategies. One of the fundamental shifts lies in the exploitation of higher frequency bands, beyond those traditionally used in cellular systems. While 5G introduced two main frequency ranges—FR1, spanning sub-6 GHz bands such as 3.6 GHz, and FR2, which includes mmWave bands around 28 GHz—emerging proposals for 6G consider a wider spectrum interval. Of particular interest is the so-called “extended FR2” or upper mid-band FR3 spectrum, located between the original FR1 and FR2. This band promises to offer a compromise between the extensive bandwidth availability of mmWave and the reduced beam directivity and better coverage characteristics of lower frequencies, thereby supporting a more robust and scalable deployment of high-frequency mobile communication.

However, communication at these frequencies is fundamentally challenged by the harsh propagation characteristics of the mobile environment. High-frequency signals suffer from increased free-space path loss and are highly susceptible to penetration loss through common materials, which severely limits signal reachability. Moreover, their propagation is highly directional and strongly dependent on the presence of LOS paths [47]. Obstacles such as buildings or other mobile objects can obstruct LOS and induce deep fading or link outages, particularly in urban scenarios. These conditions make mmWave and sub-THz links inherently fragile and impose stringent requirements on beamforming and tracking mechanisms.

To overcome these issues, directional communication through beamforming becomes essential. Multi-antenna systems, particularly those employing hybrid multiple input multiple output (MIMO) architectures, are crucial to exploit spatial diversity and multiplexing while keeping power consumption and hardware complexity within practical limits. In hybrid architectures, analog beamforming enables the formation of narrow beams with high antenna gain, while digital processing allows for more flexible baseband operations. Nonetheless, directional communication introduces its own challenges, particularly under mobility. The rapid change in the position and orientation of the transmitter or receiver alters the optimal beam direction, necessitating fast and reliable beam tracking mechanisms [48].

Beam management procedures typically involve beam sweeping, measurement, reporting, and refinement. However, these operations introduce non-negligible overhead, especially in high-mobility scenarios, where the beam alignment may become obsolete within a few milliseconds due to dynamic topology changes. The initial access phase — crucial for establishing a directional link — often relies on exhaustive or hierarchical beam training, which can delay connection setup and degrade the quality of service. These latency and reliability issues highlight the need for smarter and faster beam alignment strategies [48].

To address these challenges, position-aided and data-driven beam management approaches have been proposed. Mobile objects equipped with GNSS, inertial measurement units (IMUs), and onboard sensors can estimate their location and share this information with peers and surrounding fixed nodes. By knowing the relative positions, the beam search space can be significantly reduced, enabling direct beam selection without exhaustive sweeping. This approach is particularly effective in V2V and V2I scenarios where frequent exchanges support mutual awareness. Furthermore, the concept of environment-aware beamforming leverages digital maps, road geometry, and 3D environmental models to anticipate likely beam directions [49]. Such knowledge can be embedded into the decision-making process, improving the reactivity and efficiency of the system [48].

In addition to geometric and position-based solutions, statistical and machine learning-based techniques are being explored. These approaches aim to learn from historical beam patterns, mobility traces, and blockage events to predict future beam directions or link quality. Lightweight models can infer optimal beam pairings based on context features such as speed, heading, location, and time of day, reducing reliance on real-time measurements. This enables proactive beam tracking and faster handovers, crucial for maintaining link continuity in dense and dynamic environments.

Nevertheless, even with improved beamforming and tracking, mmWave mobile links remain vulnerable to unpredictable blockage. The dynamic and cluttered nature of mobile environments means that LOS conditions can change abruptly, leading to dramatic signal-to-noise ratio (SNR) fluctuations. To model this behavior, the SNR is often treated as a random variable influenced by path loss, fading, and blockage state. A commonly used model is the weighted mixture of log-normal distributions, where each component represents a specific blockage scenario (e.g., LOS, NLOS by vehicles, NLOS by buildings). This statistical abstraction enables the evaluation of link availability, defined as the probability that the received SNR exceeds a minimum threshold required for reliable communication [47].

To further improve robustness, network-level strategies are also considered. Graph-based models represent the mobile communication network as a dynamic connectivity graph, where edges reflect the probabilistic availability of

links between nodes. This abstraction allows for intelligent routing, relay selection, and path redundancy planning. For instance, intelligent relay nodes — either mobile (other mobile nodes) or fixed — can be dynamically activated to bypass blocked paths, ensuring end-to-end connectivity. These relays can be selected based on predicted channel conditions, trajectories, and local node density, effectively turning the network into a cooperative and resilient system [47].

Interference management and resource allocation also become critical in dense deployments, especially when multiple nodes operate within the same spectrum. Efficient radio resource management (RRM) strategies are needed to dynamically allocate time, frequency, and spatial resources. These strategies must account for the object mobility, channel variability, and the directional nature of links to minimize collision risk and maximize spectrum reuse. Interference mitigation techniques, such as beam nulling, interference-aware scheduling, and power control, are necessary to maintain link quality in complex scenarios such as urban hotspots.

Finally, hybrid and fallback strategies are being explored to improve system-level robustness. For instance, high-frequency links can be complemented by lower-band communications in FR1 or legacy LTE bands. When a mmWave link becomes unavailable due to blockage or misalignment, control or data traffic can be temporarily offloaded to the more reliable sub-6 GHz link. Such integration ensures graceful degradation of service rather than abrupt disconnection. Furthermore, multi-connectivity and interface diversity (e.g., combining for road mobility cellular V2X with Wi-Fi or IEEE 802.11p) can enhance availability and reliability under heterogeneous conditions.

In summary, achieving reliable mobile communication at high frequencies requires a multi-faceted approach combining advanced beamforming, position-aware and learning-based alignment, robust resource management, and cross-layer adaptation. These solutions, together, address the unique propagation and mobility challenges posed by mobile environments and pave the way toward scalable and resilient 6G networks.

7 Mobility and Network Architecture

Modern mobile networks are increasingly challenged by the need to support highly dynamic, latency-sensitive, and heterogeneous use cases. While traditional radio access networks (RANs) have served as the backbone of mobile connectivity, their vertically integrated and static architecture is often inadequate for efficiently supporting highly demanding services such as those envisioned for connected and automated mobile devices. Hereafter, we discuss possible trends for their evolution towards supporting high mobility with high QoS needs, focusing on the specific case of the vehicular scenario due its particular relevance in the near future.

Conventional RANs operate under centralized control, where base stations handle both access and management functions. This results in suboptimal latency performance and bottlenecks, especially in dense environments with large volumes of nodes, such as what happens for connected vehicles in urban areas. The rigidity of static resource allocation mechanisms fails to adapt effectively to fluctuating conditions, such as those happening when there is a sudden change in vehicular density or traffic patterns. Moreover, the frequent handovers required for fast-moving vehicles often lead to connection drops and increased signaling overhead, further compromising the continuity of service. Additionally, traditional RANs lack real-time network intelligence, making them unable of predictive mobility management or proactive link adaptation.

In contrast, the O-RAN paradigm introduces a modular, software-driven architecture designed to overcome these limitations. By disaggregating hardware and software components and exposing open interfaces, O-RAN facilitates the deployment of programmable control logic across various time scales. At the heart of this transformation lie the RAN intelligent controllers (RICs): the non-real-time RIC (Non-RT RIC), responsible for long-term policy enforcement and AI/ML model training; and the near-real-time RIC (Near-RT RIC), which executes latency-critical decisions via dedicated control applications called xApps. These elements enable the implementation of closed-loop control systems capable of adapting to rapid changes in the network environment.

In highly mobile contexts, the advantages of intelligent O-RAN architectures become particularly evident. Distributed control and programmability allow for real-time orchestration of radio resources and mobility strategies. Dynamic network slicing and adaptive scheduling, driven by xApps and rApps, enable differentiated service provisioning across safety-critical and infotainment use cases. Predictive handover strategies can be employed using knowledge of trajectories and historical link performance, reducing service disruptions and improving user experience.

The integration of edge computing and digital twin frameworks further augments the capabilities of O-RAN, enabling proactive network behavior modeling and distributed intelligence. These capabilities pave the way for multi-layered orchestration, where mobile objects, fixed nodes, and cloud services can collaborate in real time to meet service-level objectives.

Looking ahead, the convergence of O-RAN with emerging 6G technologies is expected to unlock new levels of performance and autonomy for highly mobile networks. Sub-THz communication, ultra-low-latency networking, and large-scale machine learning will enable fully self-optimizing networks. Reinforcement learning agents embedded within RICs could adaptively tune the network in response to environmental stimuli, while real-time anomaly detection and trust management will be crucial to ensuring secure and resilient operation in open, programmable environments.

In summary, while traditional RAN architectures face critical limitations in supporting advanced scenarios with highly mobile nodes, intelligent O-RAN frameworks offer a scalable, flexible, and forward-looking alternative. By combining distributed intelligence, programmable control, and AI-driven optimization, O-RAN stands as a key enabler of the next generation of mobile connectivity [50], [51].

8 Mobility and Security: Regulations & Current Research Activity

Having to deal with moving objects may expose the cyber-physical system to security threats that are unique to the mobile scenario, at both a low level, i.e., due to the varying channel conditions, and at a high level, e.g., having to deal with the handover in 5G NR [52]. For communication contexts such as 5G or more specifically V2X, huge effort has been devoted to this issue, and several regulation documents have been published. However, the problem of security has not been addressed for mobility in general. For example it has not been regulated for the JANUS in UWAC or for LEO satellites, where proprietary solutions prevail and no public standards are available. In this Section, we first discuss how regulations tackled the aspect of security in mobility scenarios, taking as an example vehicular communications. Next, we briefly report some of the research activity that is currently being performed.

8.1 Regulations for Mobile User Communications: The Vehicular Communications Case

One of the key objectives of automotive is to increase safety. A possible solution is to exploit the communications with both other vehicles and the environment (e.g., infrastructure, roads, traffic lights pedestrians), as discussed in Section 3.1. A critical aspect is however that these systems may be susceptible to cyber-attacks which, in turn, may lead to safety risks. Due to the different actors that are involved in automotive scenarios and the heterogeneity of devices composing the vehicles and the overall wireless communications environment, several recommendations are present concerning automotive cyber-security. Here, for the sake of brevity, we will only report the ones that are more related to security, safety, and telecommunication aspects [53]–[55]. Potential sources of attacks could come from end devices, untrusted networks, roaming networks, internet application service providers, or insider attacks.

To enable different automotive software/hardware developers to follow the same principles of safety development, the ISO officially released the road vehicles functional safety standard ISO 26262 in 2011 and the second edition in 2019. However, the recent increase in the levels of automation also led to an increase in required interaction with other network elements (e.g., other vehicles, traffic infrastructure, and cloud services), thus making the system complexity, and possible security concerns, escalate [56]. Hence, the ISO/SAE 21434 standard [57] has been recently released to face the challenges regarding vehicles' cybersecurity.

Concerning communication systems, ITU-T recommendation provides security guidelines for different V2X scenarios [57]. Specifically, ITU-T Recommendation X.1372 [58] identifies cyber-security threats, and security requirements to mitigate these threats and describes possible implementations of secure V2X communications. Security issues deal with: i) *identification and authenticity* to authorize access to services and information, ii) *message integrity* to ensure that information is accurate and reliable, iii) *availability* of services and information, iv) *confidentiality and privacy of users*, to protect data and actions from eavesdropping and exploitation and v) *non-repudiation and accountability* of the source of information. In the case of identification, authenticity, and integrity the main threats are message manipulation by an attacker providing false information, credential manipulation allowing access to information without authorization, manipulation of sensor data and information, causing traffic congestion, accidents, etc., and interception of the message and malicious reply in place of the authorized user. In the case of availability, the main threats consist of i) jamming and distributed denial-of-service (DDoS) attacks caused by malicious service requests congesting the channel capacity and so impacting the reliability or availability of V2X services, ii) timing attacks aiming at delaying the delivery of a safety message to other vehicles, and iii) hacking of sensors providing incorrect values determining transient or permanent faults. For confidentiality and privacy issues, the main threats are due to eavesdropping or leaking of personally identifiable information such as identity, position, actions, and trajectories of a user. Finally, for non-repudiation, the main threats may occur if an attacker manipulates the certification database or accesses the private key to a certificate without authorization. More recently, Recommendation ITU-T - X.1383 [59] categorizes the data used in V2X communication into several types, defining the security level of each data type.

As identified in [60], the two fundamental regulations in automotive security are United Nations Regulation No. 155 (UNR155) [61] and No. 156 (UNR156) [62], adopted by the United Nations Economic Commission for Europe (UNECE), which address the cybersecurity management systems for vehicles, aiming to mitigate the increasing threats of cyber attacks in the automotive sector. All the produced vehicles by July 2024 must comply. The Technical Assessment (TA) process under UNR155 involves a thorough evaluation of a manufacturer's cyber security management system (CSMS) by an independent authority or recognized technical service. The CSMS must demonstrate the manufacturer's capability to identify, manage, and mitigate cyber risks throughout the vehicle's lifecycle, focusing on threat detection, incident response, and security measures implementation during the design, production, and post-production stages. A crucial requirement is that the CSMS certification is valid for three years, after which re-certification is necessary to ensure continuous compliance and adaptation to evolving cyber threats. UNR156 complements UNR155 by focusing on software updates and software integrity within vehicles. It has to be pointed out that a fundamental directive for automotive security is also the network and information systems directive (NIS2) that expands the scope of cybersecurity beyond just the vehicle to include the infrastructure supporting vehicle manufacturing and services [57]. It aims to enhance the resilience of critical infrastructures within the automotive sector. Key measures include enhanced cybersecurity protocols for industrial control systems, improved incident response capabilities, and mandatory reporting of significant

cyber incidents. NIS2 affects a broader spectrum of the automotive industry, targeting supply chains, manufacturing plants, and service networks.

The issue of security, especially for satellite networks, is becoming increasingly complex because it involves many players, not just in the telecommunications field. This is why specific recommendations are being developed that follow the satellite throughout its entire life cycle from construction to launch, placement in orbit, and decommissioning, as described by ENISA [63].

8.2 Research Activity on Security for Mobile Communication Scenarios

Specifically concerning vehicular communications, connected vehicles have become vulnerable to malware infections through various entry points such as onboard diagnostic ports, wireless interfaces, and embedded web browsers [64]–[68]. Malware threats in vehicles range from ransomware, causing critical system lockouts, to spyware, compromising driver privacy, and even sabotage, by remotely controlling safety-critical vehicle functions. Traditional security mechanisms such as signature-based malware detection encounter substantial limitations in vehicular applications, primarily due to constraints in onboard resources, real-time performance demands, and the heterogeneous nature of vehicle communication systems. Therefore, advanced cloud-assisted malware defense frameworks have been proposed, leveraging cloud-based capabilities to perform extensive malware analysis, updating vehicle malware detection capabilities remotely, and reducing onboard computational load [68]. Integrating these cloud-assisted malware defenses with physical-layer authentication methods could provide comprehensive, robust protection against emerging security threats in dynamic, resource-constrained vehicular environments.

While many protocols rely on cryptographic solutions for security, a recent trend is to exploit physical layer security (PLS), where the channel itself is exploited to provide, for instance, confidentiality or authentication. PLS-based solutions provide information-theoretic security and are, typically, less energy-consuming than their crypto counterparts. Additionally, the inputs to the security protocols are features that the receiver already computes for different purposes, e.g., the channel state information (CSI) that is used also for equalization. In this context, having to deal with moving users may represent both an issue and an opportunity. Originally, authentication solutions relied on the idea of learning the statistics of the feature associated with the legitimate user, which is in turn related to the user position (e.g., received signal strength indicator (RSSI)). Then, upon reception of a new signal, these features are measured and compared with the expected statistic. However, this kind of approach fails in dynamic scenarios where the channel statistics may change rapidly over time, causing the statistics learned in the first stage to be unrelated to the features measured from the new signals. New solutions are currently being proposed to tackle exactly this issue. The main key idea is to derive a predictor that exploits the past channel measurement to predict the current one. The security test relies then on the comparison between the prediction and the current measurement. To design the predictors, several techniques can be employed, such as Kalman filters and recurrent neural networks (RNNs). Approaches like these have been proposed in many contexts, such as V2X [69], mmWave [70], and UWAC [71].

In specific contexts, the movement itself can be exploited to provide security. For instance, in the satellite communication context, the transmitter's (i.e., the satellite) position and velocity are known a priori to the verifier. Thus, if the receiver is able to obtain its own position and velocity from a different source, such as from a GNSS, it can also derive an a priori estimate of the Doppler shift. Such an estimate can then be used to assess the authenticity of the received signal by verifying whether the measured Doppler matches the estimated one [72].

Finally, challenge-and-response protocols have been proposed in the physical layer security context, where the verifier induces changes in the channel and checks if the response is compatible with the expected change [73]. An example of this can be found in [74], [75], where, after a first stage where the verifier learns a map of possible channel responses, thus learning to map a transmitter position and the corresponding signals, the verifier requests the UAV to move from one position to the other and transmit pilot signals. Then, the verifier authenticates the UAV by checking whether the received signals are compatible with the expected measurements.

9 Conclusion

In this document, we have analyzed the telecommunications aspects affecting a wide range of moving objects, considering both scenarios in which telecommunications are essential for their operation and those in which the objects themselves act as network elements providing coverage, as in the case of non-terrestrial networks.

After introducing in Chapter 2 the main goals of this document, Chapter 3 addresses various categories of moving objects, including road vehicles, vulnerable road users (e.g., pedestrians), trains, maritime, flying objects, satellites, automated guided vehicles for industrial environment, and underwater vehicles. These objects span multiple industrial sectors, such as the automotive and maritime industries, and can deliver an extensive range of services. Enhancing telecommunications for their operation is therefore a critical driver for the development of numerous vertical industries, with significant implications for national industrial policy.

Then, Chapters 4–8 concentrate on broader network aspects. Chapter 4 shifts the focus to moving objects that themselves provide telecommunications services, most of which are part of the non-terrestrial network domain. Chapter 5 examines direct communications between objects, bypassing traditional telecommunications infrastructure, while Chapter 6 explores the role of high-frequency transmissions (from mmWave to sub-THz), which promise transformative capacity gains. Chapter 7 discusses network architectures, particularly O-RAN, whose AI-driven components can dynamically optimize resources and adapt to environmental conditions. Finally, Chapter 8 addresses security considerations, underscoring their importance in complex, interconnected mobility systems.

Our analysis highlights several trends in network evolution, notably the integration of 5G into vehicle operations to overcome limitations of earlier mobile standards. This is evident, for example, in emerging telecommunications standards for rail transport. Operational requirements are also driving the adoption of new frequency bands and AI-based methodologies, signaling emerging needs for 6G.

A key challenge is radio spectrum management, especially spectrum sharing, given the rapid growth in connected objects. At present, most operational communications occur via radio at low frequencies (below 2 GHz), which provide broad coverage even in NLOS conditions. This approach will likely remain essential for basic operations, although coexistence strategies with conventional networks must be defined. However, we must also consider services that will require increasingly greater capacity and therefore the need to use spectrum portions with carriers in the mmWave or even Sub-THz range, although this poses challenges in electromagnetic field management, particularly in maintaining highly directional beams that must track fast-moving objects.

Finally, security must be addressed throughout the entire lifecycle of each object—from manufacturing, to deployment, to operational use, and eventual decommissioning. In the case of satellites, for example, this includes every phase from construction to orbital placement and end-of-life disposal. Inadequate security measures in such an environment could result in catastrophic consequences.

In conclusion, connectivity is now available almost everywhere and at any time. Yet, efforts are still needed to close the remaining coverage gaps; new solutions are essential to enhance service quality, particularly for advanced mobile machine-to-machine use cases; greater harmonization could be targeted to help creating a unified ecosystem capable of evolving to meet future challenges; and above all, security will remain a critical priority, forming the foundation of all next-generation communication systems.

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