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A glimpse on the futures of telecommunication networks: From market, technology and regulation trends to strategic foresight

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ABSTRACT

This paper explores the current state, trends, and possible futures of the telecommunication ecosystem in Italy, outlining strategies for development. We adopt a combined methodology, integrating participatory scenario building through the Nominal Group Technique with a structured literature review. The analysis starts from the current situation (Scenario 1) and major transformation trends (Scenario 2) to project two contrasting futures (Scenario 3), providing a rationale for strategic choices.

Various dimensions are considered: market and economic models, technological advancements, and regulatory frameworks, with both European and Italian perspectives. In the market domain, we assess opportunities linked to enabling technologies and digital services built on connectivity. On the technological side, we evaluate the role of network programmability, low-orbit satellites, aerial networks, edge computing, novel materials, and services, while also addressing sustainability and AI integration. The regulatory analysis highlights how evolving policies can impact network evolution and identifies reforms to foster innovation, inclusivity, and industry participation.

From this integrated view, we infer two boundary scenarios for 2040: a utopic one, marked by innovation and inclusivity, and a dystopic one, characterized by digital inequality and stagnation. Finally, we outline strategies and policies to steer the telecommunications ecosystem towards the preferable scenario.

1. Introduction

In recent years, especially after the COVID-19 pandemic, the fundamental role of telecommunication infrastructures has clearly emerged in interconnecting the human, digital, and physical worlds. They enable applications and services across multiple verticals (healthcare, education, industry, agriculture, transport, energy, public administration, commerce, entertainment, finance), ensuring better use of resources and more inclusive access for users. Telecommunication networks thus represent the backbone of the digital ecosystem, a network of interconnected entities (businesses, consumers, governments, service providers) that collaborate through digital platforms to facilitate data exchange and service provision.

Despite this centrality, the telecommunications sector is facing a critical situation worldwide, due to the interplay of several factors: the need for investments to complete the roll-out of innovative technologies, obstacles in deploying new services and business models, and increasing demand on infrastructures already under pressure.

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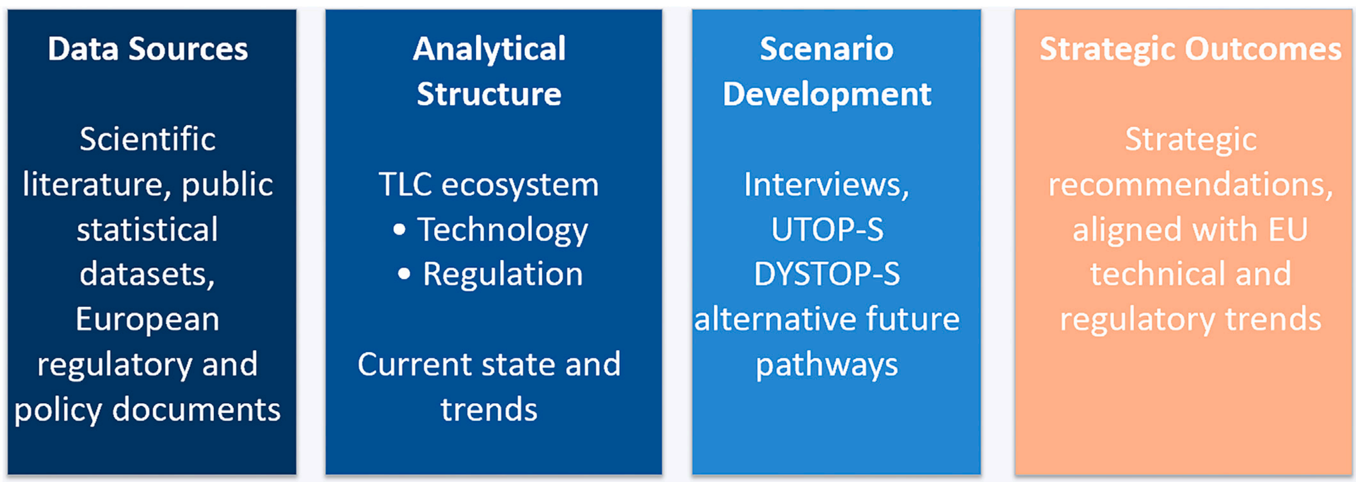


Fig. 1. Methodological framework linking data sources, TLC ecosystem analysis, scenario development (UTOP-S and DYSTOP-S), and strategic recommendations aligned with European regulatory and technological trends.

This paper focuses on the Italian context, where the deployment of ultra-broadband fixed and mobile connections (fiber, FWA, 5G) remains delayed and fragmented, with strong regional disparities. Economic and investment difficulties, declining operator revenues, and challenges in introducing innovative services before full infrastructure modernization are key obstacles. Further issues include a complex regulatory landscape and the limited attractiveness of telecommunications master programs, leading to a shortage of specialized human resources. The Italian perspective is framed against European trends, with comparisons to other countries and EU regulations.

The survival of the traditional telecommunications industry will depend not only on investments for network modernization but also on the ability to seize opportunities in other areas of the digital market, driven by new products and services. Operators will need to adopt innovative business models that capture value from across the digital supply chain.

We present an analysis of the emerging digital ecosystem under technical, market, regulatory, and user dimensions. Our contribution provides analysis and trends that can be interpreted in a Schumpeterian political economics perspective. We present current market structures and regulatory trends, framing telecommunications as an evolving ecosystem where innovation in networks and platforms continuously reshapes competition and value creation. We also review regulatory policies in their current state and future trends, highlighting their relation to technological transformations. Besides, we derive future utopian or dystopian scenarios depending on how technology innovation and regulation coevolve.

1.1. Contributions and novelty

This paper provides a multi-dimensional foresight into the evolution of the telecommunications ecosystem. The core contributions and the novelty of this work are summarized as follows:

- *Methodological Integration*: We combine a literature review with a scenario building methodology involving domain experts. This integration of related work and domain expertise provides a well grounded analysis of the TLC echosystem with a motivated analysis of future scenarios.
- *Multi-Domain approach*: Unlike existing studies that often focus on a single aspect, this work intersects market dynamics, emerging technology (e.g., 6G, 3D integrated networks), and regulatory frameworks, with a special lens on open innovations.
- *Alignment with EU Initiatives*: The research contextualizes national trends (Italy) within the latest European Union strategic frameworks.
- *Strategic Foresight*: We offer a novel perspective on how technical and regulatory aspects are restructuring value creation, and providing actionable strategic foresight for the transition towards innovative TLC ecosystems.

More in detail, in Section 2 we describe our methodology, inspired to the Three Horizons Method: starting from the current state (Scenario 1), identifying trends shaping evolution (Scenario 2), and envisioning long-term scenarios (Scenario 3). In Section 3 we examine the current market and technological state; in Section 4 we analyze the regulatory dimension in Italy and Europe, considering possible impacts of innovative mechanisms. In Section 5 we project two scenarios: a preferable one with growth through innovation and inclusivity, and a dystopic one where current problems deepen, increasing inequalities in access to technology and digital services. Finally, Section 6 discusses policy directions to steer telecommunications towards the preferable scenario.

Overall, the methodology is summarized in Fig. 1.

2. Building scenarios for telecommunications

Adopting strategic foresight methodologies enables telecommunications stakeholders to navigate uncertainties by anticipating market shifts, regulatory changes, and technological innovations (van der Heijden, 2005; Slaughter, 1998), while fostering innovation aligned with evolving demands.

As for the scenario-building, our approach combines a structured literature review with stakeholder elicitation, adopting the Nominal Group Technique (NGT; Delbecq and de Ven, 1971; Van de Ven and Delbecq, 1972). Throughout the paper, we use Scenario 1 (S1 - State-of-the-art), Scenario 2 (S2 - Transition), and Scenario 3 (S3 - Long-term futures) solely as expository labels for the three outputs of the study. Consistent with NGT, we formed a nominal group, that is, a working group in which individuals contribute in the (virtual) presence of one another but do not always interact (Delbecq and de Ven, 1971). These professionals and academics were purposively selected to represent the key domains of telecommunications: network architecture and engineering, cloud and edge computing, AI-driven networking and automation, spectrum and radio systems, cyber-security and data protection, standards and interoperability, economics and market strategy, regulation and governance, user experience and digital inclusion, and sustainability. Participation was voluntary and based on domain expertise. NGT was preferred to alternative consensus methods such as the Delphi technique (Dalkey and Helmer, 1963) because its non-anonymous, time-bounded workflow (i) reduces inhibition across seniority levels, (ii) prevents premature convergence on narrow issues, and (iii) supports rapid idea generation and prioritization (Delbecq and de Ven, 1971; Van de Ven and Delbecq, 1972). Engagement occurred in two formats: in-person workshops and online meetings. In line with good practice (Riley-Bennett et al., 2024), the parallel asynchronous formulation of shared online documents allowed flexibility and instantaneous collection of contributions. All activities were guided by a focal question, formulated to integrate technical, economic, user, and regulatory perspectives:

> "How might the Italian telecommunications ecosystem evolve by 2040 across market/economic models, technical architectures, user perspectives, and regulatory frameworks, and which strategies or policies can steer the system towards a preferable future under conditions of uncertainty?"

While this approach supported broad and rapid input, potential limitations included sampling bias in stakeholder recruitment and bounds on uncertainty quantification; we mitigated these via diversified recruitment.

In the following Sections, we analyze the TLC ecosystem from a twofold point of view, namely (i) Market and technology, and (ii) Regulation; for all cases, we synthesize the current situation (S1), and identify prioritized drivers and trends (S2). Finally, we present the scenario set (S3), which underpins policy implications and robust strategic directions.

3. The TLC ecosystem: Market and technology

Telecommunications are a key enabler of national economic development, as public services, businesses, and industries in all sectors critically rely on fast, reliable, and secure infrastructures. Open innovation practices in telecommunications can reshape firm behavior and performance (Mihailovic et al., 2022). Innovation in next-generation networks provides an ecosystem-level process in which value creation depend jointly on platforms, actors, and regulatory frameworks rather than on isolated firms (Yrjölä et al., 2022). Open interfaces lower entry barriers and stimulate innovation, shifting the regulatory focus from infrastructure control to governance, interoperability, and market power (Bourreau and Lenstra, 2020). Architectural innovations such as Open RAN further intensify these dynamics by restructuring competition, with outcomes shaped not only by market forces but also by geopolitical polarization and divergent telecommunications policy regimes (Laorrojwong and Makarathat, 2024). Against this background, regulatory approaches in 5G and beyond are shown to critically influence innovation trajectories, calling for adaptive, learning-oriented market design under conditions of technological uncertainty and structural change (Bauer and Bohlin, 2022). Herein, we analyze the TLC ecosystem in an evolutionary approach. Specifically, this section presents the current situation (S1) from the perspectives of the TLC market, technology, and services (Section 3.1), and the main trends (S2) regarding market (Section 3.2) and technology (Section 3.3).

3.1. Analysis of current situation (S1)

S1 of the TLC market and technology is analyzed here, with specific reference to Italy. We first consider the TLC market (Section 3.1.1), then connectivity and added-value services (Section 3.1.2, Section 3.1.3), and finally the role of standards (Section 3.1.4).

Table 1
Acronym table.

Acronym	Definition
AAL	Acceleration Abstraction Layer
ACT	Augmented Clinical Tools
ADSL	Asymmetric Digital Subscriber Line
AGCM	Italian Competition Authority (Autorità Garante della Concorrenza e del Mercato)
AGCOM	Italian Communications Authority (Autorità per le Garanzie nelle Comunicazioni)
AI	Artificial Intelligence
AR	Augmented Reality
AWS	Amazon Web Services
BEREC	Body of European Regulators for Electronic Communications
BS	Base Station
BT	British Telecom
CAGR	Compound Annual Growth Rate
CJEU	Court of Justice of the European Union
CPCE	Code des postes et des communications électroniques
DLT	Distributed Ledger Technology
DMA	Digital Markets Act
DSA	Digital Service Act
DSL	Digital Subscriber Line
DWDM	Dense Wavelength Division Multiplexing
ECHR	European Convention on Human Rights
EEA	European Economic Area
EECC	European Electronic Communications Code
EU	European Union
FTTH	Fiber to the Home
FWA	Fixed Wireless Access
FTTC	Fiber to the Cabinet
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
HAP	High-Altitude Platform
IaaS	Infrastructure as a Service
ICT	Information and Communications Technology
IoE	Internet of Everything
IoT	Internet of Things
IP	Intellectual Property
ISO	International Organization for Standardization
ISP	Internet Service Provider
KKR	Kohlberg Kravis Roberts & Co.
LAP	Low-Altitude Platform
LoS	Line of Sight
M2M	Machine-to-Machine
MEF	Ministero dell'Economia e delle Finanze (Ministry of Economy and Finance)
ML	Machine Learning
MPEG	Moving Picture Experts Group
MR	Mixed Reality
NEET	Not in Education, Employment, or Training
NGT	Nominal Group Technique
NLP	Natural Language Processing
NR	New Radio
NRA	National Regulatory Authority
NRRP	National Recovery and Resilience Plan
O-RAN	Open Radio Access Network
Ofcom	Office of Communications (UK Communications Regulator)
OTT	Over-the-Top
PaaS	Platform as a Service
QoE	Quality of Experience
QoS	Quality of Service
PON	Passive Optical Network
PTSD	Post-Traumatic Stress Disorder
RAN	Radio Access Network
RIS	Reflective Intelligent Surface
SaaS	Software as a Service
SDN	Software-Defined Networking
SiC	Silicon Carbide
SMP	Significant Market Power
SPID	Sistema Pubblico di identità Digitale

(continued on next page)

Table 1 (*continued*).

Acronym	Definition
TCA	Trade and Cooperation Agreement
TLC	Telecommunications
UAV	Unmanned Aerial Vehicle
UX	User Experience
VDSL	Very-high-bit-rate Digital Subscriber Line
VR	Virtual Reality
XR	Extended Reality

3.1.1. Telecommunication market

According to AGCOM's 2024 Annual Report (AgCom, 2024), the last five years have brought major shifts in the Italian TLC market. Firstly, after years of stagnation, the sector grew in 2023, supported by fixed-network investments and NRRP funding, reaching a total value of just over 27 billion Euros. This contrasts with a weaker national macroeconomic framework marked by slowed growth and investment. Notably, bandwidth demand increased by 15% CAGR (2020–2023), stressing the need for network upgrades in capacity, resilience, sustainability, security, and edge intelligence. Despite rising traffic, service prices—especially mobile—kept decreasing, reducing operator revenues. In 2023, mobile revenues fell 3%, with average yearly spending per SIM dropping from 131 to 127 Euros. Fixed-network revenues instead grew by 3.9%, driven by ultra-broadband adoption (18.9M lines). Yet, fiber rollout remains below EU Digital Decade 2030 targets, with a slow copper-to-fiber transition. Finally, fixed-network investments reached 3.5 billion Euros, with FTTH coverage expanding to 59.6% of households, mainly in rural "white areas". In contrast, mobile infrastructure investment slowed, particularly in urban "black areas", reflecting reduced operator focus where competition is higher.

3.1.2. Connectivity services

Despite infrastructure progress, the adoption rate of fiber-based services has been slower than expected. AGCOM reports a slight increase in the number of fixed broadband access lines, which reached 18.9 million units in 2023, but migration from older technologies (such as copper) to newer, faster fiber-based solutions remains gradual, with only a 0.1% CAGR over the past three years. The majority of users still rely on DSL and VDSL technologies, though the shift towards high-speed fiber connections is accelerating, particularly in areas with full FTTH availability. Conversely, in terms of volumes of data, the dominant technology is FTTC. Overall, Italy is still lagging behind the EU's Digital Decade target of gigabit connectivity for 100% of households by 2030.

Fig. 2 plots the overall volume of active lines on fixed networks by access technology during the last three years. Most lines are based on technologies that use not only optical fiber but also copper, although these are progressively decreasing from December 2020 to December 2023. ADSL and voice-only lines went from 5.5 and 1.7 million in December 2020 to 2.4 and 1.2 million, showing a clear downward trend. FTTC lines grew marginally from 9.3 to 9.8 million in December 2023, while access based on FWA and FTTH showed the greatest growth.

As for mobile access services, traditionally very dynamic in Italy, AGCOM's data shows that the human SIM segment remains dominant. The mobile network infrastructure covers nearly the entire population, with 99.8% of Italian residents having access to 4G LTE services. Meanwhile, 5G networks are rapidly expanding, now covering over 65% of the population. However, there is significant regional variation, with major urban centers seeing a more robust 5G rollout compared to rural or less densely populated areas. Despite a 3% reduction in revenues from mobile services in 2023, largely due to declining prices, the number of active mobile lines continues to grow modestly. Moreover, the adoption of M2M SIMs is gaining traction. From a user point of view, it is evident that customers have been increasingly opting for mobile data plans that prioritize affordability. This trend has led to a reduction in average spending per human SIM. The uptake of 5G services is still in its early stages, with consumer interest growing, but limited by device availability and pricing.

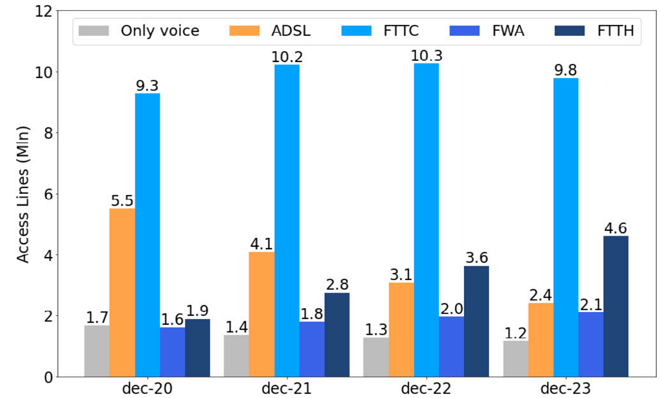


Fig. 2. Fixed Access Volumes by technology during the last three years (Dec. 2020 - Dec. 2023) (Millions).

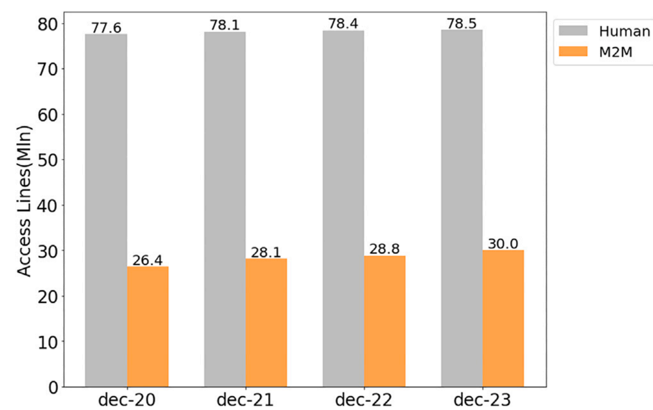


Fig. 3. Mobile Access Volumes by usage during the last three years (Dec.2020–Dec. 2023) (Millions).

Fig. 3 shows the mobile market dynamic: the lines for human use undergo only a marginal increase, going from 77.6 million in December 2020 to 78.5 million in December 2023, while the M2M lines go from 26.3 million to 30 million during the same survey interval, resulting in an almost constant total volume of lines.

3.1.3. Added-value services

At the national and international level, the telecommunication sector shifts from providing basic connectivity services by pervasive network infrastructures to integrating additional functionalities -cloud/edge computing, data storage, security primitives, IoT, and AI-. Fig. 4 shows that the overall value chain is given by three different interacting components, which add *enabling services* and *digital services* on top of the connectivity services.

Service provisioning spans from the vertically integrated operator, managing all services built on top of connectivity, to the full separation scenario, where connectivity providers are independent of digital services providers and act rather as an enabling element of the digital service value chain. The Italian situation has been traditionally characterized by the presence of vertically integrated operators, offering a wide range of value-added services like cloud/edge computing, IoT, and AI, and security solutions, including advanced portfolios of services as IaaS, PaaS, and SaaS solutions made available to enterprises and public institutions. Services range from private, public, and hybrid

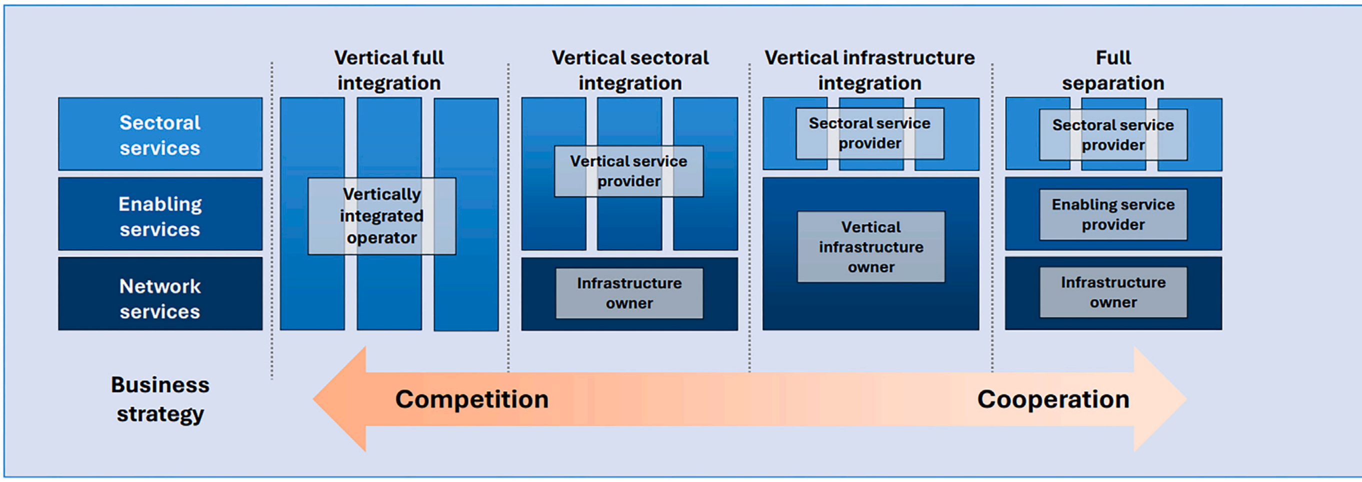


Fig. 4. The competitive alternatives for telcos.

cloud environments to disaster recovery and data storage solutions. Moreover, vertically integrated operators leveraged their global scale to develop IoT platforms or cybersecurity solutions able to respond to local heterogeneous needs. The situation is now evolving towards a more fragmented scenario. The recent split of TIM into different companies and the case of an important player like Open Fiber (focusing purely on deploying and managing fiber optic infrastructure) demonstrate the presence of wholesale-only providers in Italy. In addition to vertical integration and full separation, Italy also has examples of hybrid models, where partnerships between operators and third-party providers (with high levels of specialization in different sectors) are common. This collaborative approach allows telcos to maintain control over connectivity while outsourcing or co-developing specific digital services.

According to the last annual report by Anitec-Assinform (2024), the increasing success of digital services, developed on the last level of the telecommunication value chain, is enabling strong progress on digital transformation in Italy. Customer satisfaction in the telecommunication markets (Gazi et al., 2024). Developing trajectories of SME (Al-Karkhi, 2024). ICT and e-government induce a decrease in government corruption (Lee et al., 2018), Cooperation and competition effects (Kwon et al., 2020). ICT fosters entrepenheurships (Gomes and Lopes, 2022). IT contribution to innovation (Majid Gilani and Faccia, 2021). Digital technology for sustainability (Elfaki and Ahmed, 2024).

Financial Services represent one of the most successful ones. Banks and insurance companies are leading the digital shift, with AI and blockchain technologies playing a fundamental role in service definition, customer experience reform, and risk management. The digital transformation in these sectors is accompanied by a decline in physical branches and a shift to omni-channel service models.

A similar deep transformation involves the *Manufacturing and Energy* sectors: these industries are focusing on the digital monitoring and control of their traditional assets (either in terms of production systems or distribution energy grids) for supporting improved decision systems and predictive maintenance. The services are enabled by IoT and AI solutions, as well as cybersecurity primitives devised to prevent unauthorized access to physical resources.

Digital services are also affecting the *Public Administration services*. Initiatives such as SPID, AppIO, and PagoPA reflect the growing importance of digital identity platforms and a Mobile First approach, aimed at making public services more accessible and efficient for citizens.

Finally, another important sector worth mentioning is the *Healthcare* sector, which is growing thanks to the exploitation of telemedicine and AI for improving patient care, cybersecurity for safeguarding sensitive health data, and cloud services for data management and sharing.

Digital services based on the so-called *platforms*, devised to facilitate interactions between multiple user groups, are also transforming significantly the relevant markets. Indeed, these types of services are based on the creation of a digital intermediary between some providers of facilities in the real world and the users. Digital intermediation allows the reduction of transaction costs and support of service optimizations enabled by data-driven algorithms. Moreover, it creates a multi-sided market, where two groups of users (the facility providers and the facility consumers) multiply the opportunities for increasing the service value as the population of each group grows. In such a context, traditional industries are increasingly displaced from their coordinating role and many Italian companies (especially small and medium-sized) struggle to compete. As a result, there is a growing push for digital transformation across industries, as well as new challenges for regulatory bodies and policymakers.

3.1.4. Role of standards

Telecommunication standards are essential to the growth of the communications market. Network Standards also reflect the market, regulatory, technical, and user needs and expectations of different stakeholders in the network scenario. As such, they continuously evolve to adapt to both technological advancements and the changing requirements of the market and society.

Telecommunications Standards have an impact on different dimensions. First of all, standards enable a transparent and competitive market for network products and services, allowing for multivendor sourcing and economies of scale. Standards also create value for the network industry by enabling the licensing of IP, which is essential for implementing the standards. Standards can also help address the regulatory requirements and challenges that network operators and service providers face in different regions and countries. Standards are also strictly related to the policy decisions and actions of governments and regulators, such as spectrum allocation, network security, and data privacy. Standards drive the continuous evolution and improvement of network technologies by motivating participation, collaboration, and competition from a diverse set of companies and experts. Standards also respond to the changing and increasing demands and preferences of network users, such as higher data rates, lower latency, better coverage, and more applications.

As for any country, telecommunication standards are essential for the development and growth of the Italian telecommunication industry and market.

Besides promoting the adoption and implementation of the latest European and international standards (e.g. 5G), so that compatibility, interoperability, and innovation in the Italian network infrastructure and services are ensured, Italy can leverage telecommunication standards as a driving force for innovation by promoting the participation of national industries in the standardization process and its active contribution, both at the regional and global level. Influencing the direction and outcome of the standards is pivoting to protect and promote the Italian interests and values in the telecommunication sector. This can be obtained by:

- supporting and fostering the research and development of new and emerging technologies, such as AI, edge computing, and quantum communications, not only in academia but also in industry. Innovations in these fields can enhance the performance, security, and efficiency of the network systems and applications, and create new market opportunities and value propositions.
- encouraging and facilitating the collaboration and cooperation among the different stakeholders in the telecommunication scenario, such as network operators, service providers, equipment manufacturers, regulators, academia, and users, to share best practices, exchange information, and create synergies and partnerships.
- educating and informing the public and the policymakers about the benefits and challenges of telecommunication standards, and the role and responsibility of Italy in the global telecommunication community.

As part of its 5G rollout, Italy recently increased its electromagnetic emission limits, which had previously been stricter than in many other European countries. This regulatory change is crucial for enabling the widespread deployment of 5G networks. Higher limits allow for more powerful transmissions, which improve network coverage and capacity, especially in dense urban areas. This change is aligned with European electromagnetic exposure guidelines, balancing public health concerns with the need for next-generation connectivity.

3.2. Market trends (S2)

The main trends affecting telecommunications from a market perspective are reviewed in this Section. Emerging market models are outlined in Section 3.2.1. User-centric services are addressed in Section 3.2.2. The evolution of the operator role and the survey of telecommunications ecosystems is highlighted in Section 3.2.3. Innovative services, with emphasis on Extended Reality applications, are the focus of Section 3.2.4.

3.2.1. Emerging market models

To overcome the current market stagnation of connectivity services, traditional telecommunication companies are trying to find new opportunities in added-value services and, in particular, in the so-called digital enabling services. Digital enablers have been grouped into distinct clusters, categorized based on their expected market value (by 2027) and CAGR to describe their growth potential. Each enabler in the map is reported based on its size, which represents the economic value associated with it in 2026, as in Fig. 5.

Cluster I: Cloud Computing – Leading the Market. Cloud computing stands out as the dominant enabler, occupying the largest market share (22%) with a significant CAGR of 20%. This growth is largely driven by the increasing adoption of cloud-based solutions that enable faster deployment of digital services, cost-effective configurations, access to constantly updated technologies, and improved scalability. In this cluster, hyperscalers — global cloud giants, like AWS, Microsoft Azure, and Google Cloud — are playing an important role and transforming the relationships with telecom operators, from vendor-client interactions to collaborative partnerships. On one side, telecom operators can rely on hyperscalers to avoid on-premise infrastructures for selling cloud services, as well as for exploiting in turn cloud-native architectures for their networks, thus achieving more flexible and dynamic service

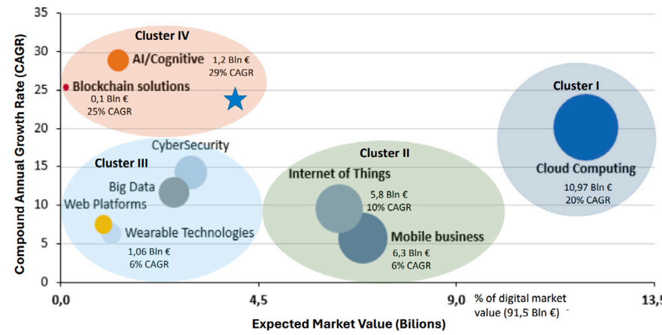


Fig. 5. Clusterization of the digital market by its dimensions, market value, and growth rate (represented by the CAGR).

delivery; on the other side, hyperscalers can leverage telecommunication networks to extend their cloud services closer to end-users, improving latency and performance—key factors in sectors such as IoT, autonomous vehicles, and real-time analytics. Moreover, for smaller telecom operators or those with limited resources, Telecom-as-a-service offerings from hyperscalers provide a way to compete more effectively.

Cluster II: IoT and Mobile Technologies – Stable Growth. Cluster II encompasses the IoT and mobile technologies, which represent a notable 13.2% of market share, with a moderate CAGR of 8%. IoT, in particular, is expected to grow significantly due to its vast range of applications, from smart cities and smart grids to automotive and biomedical industries. The economic value of IoT is driven by its ability to transform traditional industries by improving efficiency and creating new business models. Meanwhile, mobile technologies continue to expand, fueled by the increasing number of connected devices and their integration into business operations, particularly in sectors such as maintenance, workforce training, and customer experience management.

Cluster III: Big Data – Supporting Emerging Models. Big Data services, despite their smaller market share, play a critical role in enabling companies to become data-driven organizations. These services support strategic decision-making, cost containment, and supply chain visibility. Big Data is also essential for enabling new business models, such as *servitization*, where companies shift from selling products to offering services based on the insights derived from data analytics. Although the current growth rate is modest, Big Data remains an integral enabler for future business transformations.

Cluster IV: AI – High Growth Potential. Cluster IV features enablers with the highest growth rates (averaging a 27% CAGR), though their current market share is relatively small (1.4%). Leading this cluster is AI, which has experienced a significant acceleration, particularly with the adoption of generative AI tools and applications such as NLP. Large companies have started investments in AI, while smaller firms remain in the experimental phase. AI-driven applications are increasingly being used for predictive analytics, anomaly detection, and intelligent process automation in industrial and business environments. AI-powered recommendation systems have become indispensable in e-commerce, enhancing customer journey insights and anticipating user needs. The growing use of robotic and intelligent process automation further demonstrates AI's potential to drive efficiency and innovation across various industries.

3.2.2. Towards user-centric digital services

One interesting trend for the definition and evaluation of digital services is the shift from a traditional focus on infrastructures and network performance towards a user-centric perspective. In other words, while traditional services were focused on delivering basic internet access, measured by technical parameters such as speed, latency, and QoS, now the trend is evaluating connectivity based on how it enhances the end-user's lifestyle. We consider two use cases representative of these shifts.

Indoor connectivity in smart homes The indoor connectivity market is growing rapidly. According to a recent research by Plume IQ, in each household, we have on average 17.1 connected devices, with Europe leading the growth at 12.8% annually. This surge in connected devices has some implications for changing user demand for connectivity, which is now viewed as an enabler for smart homes. Several factors require a rethinking of how connectivity is delivered indoors, taking into account that: (i) the indoor environment is under the user's control, with limited configuration possibilities left to providers of connectivity services; (ii) several actors and heterogeneous technologies coexist for producing and consuming data in the home environment; (iii) users prioritize ease and comfort over technical superiority (e.g., fiber optics), often unwilling to deal with installation inconveniences.

Indeed, since the value of smart home services depends on the QoE (e.g., frequency and number of hours of use of connected TVs, optimize electricity consumption, and intelligent management of lighting and security services) end users very often do not recognize the advantage of an entire fiber connection. Moreover, connectivity providers are not incentivized to advertise fiber services, because they achieve the same revenues (substantially aligned prices) while incurring higher costs.

In such a scenario, the survival of the traditional operators is related to the ability to make agreements and market their services in bundles with those offered by OTTs. OTTs are moving towards the higher levels of the supply chain, as represented in the figure, i.e., not limiting themselves to offering ancillary services to connectivity, but rather by going up to the higher levels to participate in the offer of premium services and those specific to smart homes.

Edge cloud The demand for real-time, low-latency services (such as IoT, streaming, and AI-driven applications) is driving the need for localized data centers or edge data centers. These smaller, distributed units are positioned closer to end-users, enabling faster processing and enhancing service quality. In this context, telcos have a unique opportunity to capitalize on their existing infrastructure (e.g., pervasive transport and access networks, as well as distributed power supply systems) for offering edge cloud solutions integrated into their networks and creating new revenue streams (in terms of "edge as a service", vertical solutions, managed services, system integration). Edge cloud solutions can support the high demands of modern applications while offering competitive advantages in latency, scalability, and sustainability. Indeed, companies are increasingly resorting to the ability to collect and automate data processing for improving the customer experience, as well as for security reasons, or even for improving business processes and decision support systems.

The demand for co-location services offered by the telecommunications operators is already growing. According to a recent research carried out by the consultant Analysys Mason, after several years of investments in new skills, technologies, and partnerships, operators are starting to record growth rates in business delivery above 30% in 2023. Consequently, the opportunity to exploit investments in already available assets to address the business market can make them fuel new revenue streams through the supply of services such as edge cloud and IoT, in several physical infrastructures such as smart grids or vehicular networks.

3.2.3. Evolution of operators and ecosystems

The telecommunications scenario is undergoing a dual transformation characterized by significant economic-financial contractions and rapid technological innovation. These changes are predominantly affecting vertically integrated operators, which deal with both the infrastructure and the service provision. Due to high fixed costs and shrinking revenues, some operators are considering the separation of their infrastructure business units to better focus on value-added activities targeting end customers.

A case for such a separation is with the TIM Group in Italy, where the fixed network has been separated into a new entity, the wholesale company FiberCop, acquired by the American fund KKR. The new TIM will serve as a retail company, integrating all business and consumer service units and potentially the mobile network. There are several technical aspects to be faced. The first relates to the technical feasibility of a genuine and complete network separation and the exposure of infrastructure to service providers capable of competing in the market. Fixed network infrastructure has evolved over time, driven by technological advancements and considerations related to the enhancement of existing assets like the copper network. This historical context can complicate the separation process and impact the competitiveness of the resulting entities.

The operational separation must address challenges such as interoperability, network management, and quality of service. Effective separation requires robust systems to manage these aspects, ensuring that service providers can operate independently while maintaining high service standards. This involves investments in new technologies and processes that support the seamless integration and operation of separated network entities.

The second question concerns the long-term sustainability of the emerging business models. The creation of a new entity dedicated to infrastructure management requires careful consideration of market dynamics, regulatory implications, and the potential impact on service innovation and delivery. From a strategic perspective, the separation of fixed network infrastructure can drive innovation by allowing operators to focus on core service offerings. This specialization can lead to the development of new services and business models tailored to specific customer needs. For instance, the separated entities can invest in advanced technologies like 5G, AI, and edge computing, enhancing their service portfolios and competitiveness in the market.

3.2.4. Innovative user interfaces and services

One of the major challenges in selling advanced connectivity services (e.g. 5G or 6G) to users is that, in many cases, they do not perceive tangible benefits from the enhanced capabilities, such as higher capacity and lower latency, compared to 4G. To change this trend, it is necessary to promote innovative connectivity services, such as immersive communications, able to directly tie network performance to user experience. The popularity rise of XR applications, due to advances in visualization and interaction techniques, improvements in software, program interfaces, and tracking methods, and advances in XR hardware, can be seen as a signal in this direction.

XR may integrate real and virtual elements, including AR, MR, and VR. Milgram et al. (1995) conceptualized the XR spectrum within the framework of the reality-virtuality continuum. A wide range of industries have had the opportunity to apply XR to their processes (Cárdenas-Robledo et al., 2022). The independent 'portable XR' has significant potential; however, further technical advances are needed to improve and deliver more efficient and powerful XR experiences (Akyildiz and Guo, 2022). Innovative services XR are expected to provide a productive environment for video/audio services, enriched by text, synthetic data, immersive experience, 3D data, and ambiance visualization. Key XR use cases include: (i) virtual meetings or events where holographic projections replace standard video calls, offering a deeper sense of presence; (ii) immersive gaming, where latency and high data rates are critical to delivering real-time interaction and seamless environments; (iii) remote collaboration with AR tools that integrate 3D models into physical spaces, aiding industries like architecture, design, and manufacturing; (iv) holographic interactions. XR services can impact different sectors, like the entertainment industry, e.g., for gaming, or online commerce, e.g., for shopping interactivity or assistance. Herein, we will focus on two general application frameworks, deemed especially relevant for their social impact, namely the adoption of XR in education or training programs and in initiatives for social inclusion. The choice of these areas stems from the consideration of their social relevance, as well as the growing recognition of the transformative potential of XR technologies in enhancing learning experiences and enabling the overcoming of certain real-world barriers.

In the field of education, in particular, Kašela et al. (2021) point out that XR applications are mainly implemented in the field of natural sciences, especially mathematics, astronomy, and biology, but also in relation to geography and history, especially for the reconstruction of cities or events using VR technology. Therefore, XR services for training are extremely promising, since they enhance sensorial and embodied experiences, providing scaffolded learning points that cater to individual needs. XR environments can facilitate self-directed experiential learning (heutagogy), making complex knowledge more accessible (Jagatheesaperumal et al., 2024). Furthermore, this technology can be used in areas that are difficult to access physically (Alazmi and Alemtairy, 2024). Fernandes et al. (2023) reviews the state of the art on immersive learning frameworks, whereas (Wu et al., 2023; Wang et al., 2022) revises the architecture of the scenarios for learning purposes. XR offers unprecedented support for demonstration-based training (Bayro et al., 2023). Barteit et al. (2021) and Curran et al. (2023) demonstrate how the adoption of XR technologies in the training of future medical practitioners leads to improved performance over time due to induced immersion and presence.

Besides, XR supports advanced information visualization (Liu et al., 2022b), provides virtual field trip experiences in hardly reachable environments (Horota et al., 2022), and extreme conditions (Wheeler et al., 2021). Burian et al. (2023) shows how XR can offer a realistic, immersive experience that, when integrated with ACT, can enhance training outcomes and provide real-time guidance during non-routine tasks, diagnostic, and therapeutic procedures.

XR learning and training ameliorate results for autistic students in terms of autonomy, human–computer interaction, and sense of presence (Gu et al., 2022). A special aspect of training by XR concerns the production and availability of immersive, interactive storytelling, leading to a virtual theater kind of service. In Jiang et al. (2022), Webb et al. (2024), the authors propose an objective evaluation of the quality of experience in VR theater. VR theater can distract the audience with respect to the story, but it can improve their engagement, providing an overall better perceived quality due to the interactions and movements. In Hagler et al. (2022), the authors examine different technological solutions for virtual theater, highlighting practical difficulties in navigation and associated impairments in the quality of experience; this study also confirms that the affordance of the services also plays a major role in the service quality. In Navarathna et al. (2017), the authors focus on predicting the appreciation of video content based on affective gesture detection.

Furthermore, XR services may be adopted to foster inclusion. With its ability to tailor experiences to the needs of the target audience and project goals, XR technology represents an innovative tool for developing accessibility solutions. Teng and Gordon (2021) discusses whether VR can support Transition into society; studies on US incarcerated women identified a high rate of mental health issues during captivity and high-frequency recidivism after prison. The authors realized a community-based design of the VR service to train women with respect to possible stressful situations associated with the reentry process. Teng and Gordon (2021) also stresses the importance of community-based design. Other studies prove that ICT overcomes isolation in prison (Ertl et al., 2019), and VR job interview simulation improves the employment rate after release (Smith et al., 2023). Moreover, Almohamed et al. (2019) shows that XR technologies can be used to help refugees overcome conditions of PTSD, find information on the go, overcome cultural differences, and fit into a new culture. Ligthart et al. (2022) observe that although the adoption of extended reality from the therapeutic framework allows stepwise, controlled challenges, forensics poses ethical and legal problems. The XR application can facilitate reintegration. It provides support for decision-making; still, it can change user feelings and ideas, posing an ethical and legal dilemma.

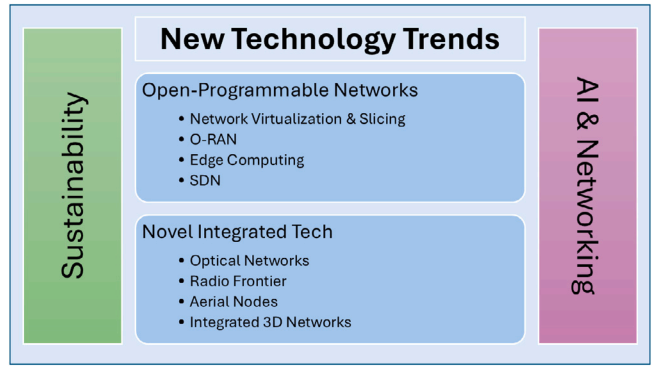


Fig. 6. Emerging technology trends in networking. The figure highlights the interplay between **Sustainability**, **AI & Networking**, and two key domains: *Open-Programmable Networks* and *Novel Integrated Technologies*.

A user-centered approach is necessary to integrate XR services with human rights. Furthermore, XR can support the inclusion of special needs people as in the project described in De Luca et al. (2023), where a social hub was built, leading to creativity stages. Virtual museum implementation and stage play by virtual augmentation have been experimented with. Virtual learning community models have been positively exploited and described in Stuart et al. (2023). For neurodivergent people, XR solicitation may be very stressful, and the design should be adapted to special needs (Lukava et al., 2022). Creating accessible VR experiences for individuals with special needs, including those with visual, audio, or motion impairments, poses significant challenges, and the main issues revolve around the diverse range of user requirements and the need to ensure developers are equipped to cater to these unique needs.

More generally, XR UX raises issues related to the affordances of technologies, such as the limited field of view, the search for eye contact, the poorly immersive auditory experience, and social aspects (Çöltekin et al., 2020)—as well as the motivations for adopting these technologies (Chuah, 2018; Salmi et al., 2017), and the expected motivations. In addition, three possible barriers have to be taken into account in relation to the deployment of XR services: financial (cost of visors), sensory (overstimulation, dizziness, nausea, fatigue, and headaches), and technical (poor hardware calibration) (Saredakis et al., 2020). At a higher cognitive level, XR's impact on users' emotions is recognized to be potentially high (Bampouni et al., 2023), and it is currently under investigation (Tabbaa et al., 2021; Krugliak and Clarke, 2022).

3.3. Technology trends (S2)

Recently, telecommunication networks' technologies evolved from an agnostic bit-transport infrastructure to a heterogeneous communication and computing environment, integrating many vertical applications. In this section, we sketch the key technological drivers of the evolution, potentially impacting on future scenarios. A visual summary of the Section appears in Fig. 6.

3.3.1. Towards programmable and open network

Traditionally, telecommunication networks have relied on specialized hardware and closed software, implementing specific data and control operations with a monolithic design. Network services were offered as an integral part of the equipment, and interoperability was achieved by following strict industry standards.

Conversely, network programmability (Anerousis et al., 2021) allows deploying and connecting general-purpose equipment, which changes behavior and data operations by running a "program" indicated by a centralized remote controller. Programs are built by composing instructions, supported by the equipment according to its internal (closed) design and exposed as open interfaces to network operators and third parties.

The concepts of network programmability and control/data plane separation date back to the 1960s and 1970s, when the telephone network started its transition to digital, and progressively emerged with increasing success in various network segments. Different network aspects are becoming programmable: (i) the data forwarding operations between nodes, where OpenFlow represents the first successful programming model (Miguel-Alonso, 2022), based on the match/action abstraction, able to radically change the design of switches and routers; (ii) the flow controlling operations, including firewalls, inspection, and load balancing functions (Alsaeedi et al., 2019), which rely on software programming models to be executed on standard servers; (iii) the baseband operations of radio BSs, which can be centralized and migrated to datacenters, by exploiting innovative disaggregated architectures and interfaces for the RAN (Giannopoulos et al., 2022); (iv) the scalable provisioning of network resources, which is decoupled by the physical availability of the hardware, thanks to the concept of network virtualization and slicing (Afolabi et al., 2018), Foukas et al. (2017). Different abstractions of network functions and elements, leading to different programming models, have emerged so far according to the required trade-offs between flexibility and execution efficiency of the programs, as well as vendors' needs for closed platforms. Usually, programmability has a cost in terms of performance; hardware acceleration abstractions (i.e., AALs) are needed for efficiently supporting the set of instructions exposed in the open interface.

SDN is a paradigm-breaking trend (Hakiri et al., 2014; Nisar et al., 2020), that is making obsolete the idea of protocols and changing the role of standards towards the definition of network programming interfaces and operating systems. This trend, consolidated in the wired domain, is now involving the wireless domain as well (Guan et al., 2021), with the emergence of O-RAN. O-RAN has the goal to open the RAN components, which are currently provided by a limited number of vendors and seen by the operators as black boxes. The idea is to expose disaggregated software-based components for supporting RAN operations and connecting these modules through open standardized interfaces (Polese et al., 2023). Open interfaces allow operators to onboard different equipment vendors, thus opening the RAN system to smaller players and integrating intelligent, data-driven control schemes. O-RAN principles have the potential to drastically change the design, deployment, and operations of the next generations of cellular networks. Moreover, they enable new approaches to network security. Indeed, the possibility of overcoming the vendor's lock-in, improving the visibility of RAN performance, or running control programs for security analysis and threat identification can make future networks more robust, resilient, and trustworthy. Beyond the current disaggregation of the RAN, the next frontier in 6G research involves the transition towards AI-Native Radio Access Networks (AI-RAN). While O-RAN focuses on open interfaces, AI-RAN embeds AI/ML directly into the physical and MAC layers to enable real-time, autonomous optimization of radio resources, predictive beamforming, and self-healing capabilities, effectively making the network "intelligent by design" (Hexa-XII Consortium, 2024).

The last two decades have witnessed a further structural trend in network architecture design: the inception and growth of the cloud, aiming at stacking huge amounts of storage and computing resources under centralized control in data centers, so as to provide flexibility and on-demand elasticity for a wide variety of applications. The pendulum has moved back again in the last few years, especially in the framework of the deployment of 5G and the evolution towards 6G, entailing edge computing as a central element of new networking paradigms. The key idea is shifting substantial storage and computational power close to final users, especially in the context of mobile networks, thus providing high performance, energy saving on battery-dependent devices, and extra computational power for specific operations. The edge computing paradigm stems from the well-established content-delivery network evolution. Since the rise of widespread multimedia streaming services, providers have strived to sustain an adequate QoS on the Internet for their final users, moving the most popular content in each area close to final users. The content replication facilities are provided by several companies, providing small-scale data centers scattered in the access networks. Edge computing leverages this approach, broadening the range of applications and services with respect to mere multimedia streaming. Few examples are the support of IoE, integrating technologies as AI, blockchain, and microservices, for massive connectivity of devices (Kong et al., 2022), remotely controlled personalized healthcare (Chen et al., 2024), support to Intelligent Transportation System services and automated driving (Gong et al., 2023), and industrial automation (Sharma et al., 2024).

The advent and expansion of edge computing are boosted by the coupling with AI-supported applications, from natural language processing functions to personalized services, to image processing and generation, to automated driving, to mention but a few examples. Distributing AI across the network and bringing it close to final users opens up the opportunity for massive AI-based applications and data-driven approaches in a pervasive perspective (Duan et al., 2023b,a). AI-supported applications may require massive computational power and storage, and are not necessarily suited for running on-board mobile devices. An interesting multi-objective optimization can be searched for to trade off energy consumption, delay, and accuracy of application output.

Europe is lagging behind other actors (e.g., USA and China) in the edge computing market, with a market value sized in several tens of millions USD in 2023, but expected to grow up to a hundred million USD by the early 2030s (BIS-Research, 2024). A braking factor in the development of these technological paradigms lies with the highly fragmented company scenario in Europe for network operators, as well as the lack of strong and large over-the-top players based in Europe. Most developments of AI-based applications and technology are driven by big non-EU companies. Other relevant concerns, which are carefully considered by EU institutions, have to do with security and privacy, which have special profiles when meeting with edge computing technology (Mao et al., 2023). However, edge expansion could also open up opportunities for new actors in the telecommunications and service market. If properly driven by regulation, the development of edge-based technology revamps the importance of local communities, socio-economic local organizations, and small to medium enterprises, well rooted in their own neighborhood.

3.3.2. Novel and integrated networking technologies

Communications media on which current networking technology is built are well-established: copper wire and radio since the XIX century and optical fiber since 70's of the XX century. The quest for larger bandwidth, more reliability, and new deployment environments and applications is however, relentless. Optical networks are by now an established reality, grounded on powerful DWDM systems and a vast array of optical components (R. Ramaswami, 2010). More recent trends are towards wireless optical systems and the application of reconfigurable optical networks to the design of new generation data centers (Ben Yoo, 2022). The fundamental advantage of optical networking is the ability to carry huge amounts of data through analog wavelength multiplexing and switching, thus escaping the electronics bottleneck as clock rates grow. Optical networks are also preferable from a sustainability and security point of view. This is a well-established technology that has been extended beyond the core Internet to the access network through PON. Still, optical technology finds new areas of application, e.g., underwater network (Guo et al., 2022). This is yet another increasingly emerging trend, namely the extension of networking coverage to extreme and hostile environments, such as in underwater communications (Jiang, 2021) and ad-hoc networks of moving objects, e.g., UAVs, robots, vehicles, or massive constellations of satellites (Al-Hraishawi et al., 2023; Mahboob and Liu, 2024).

Radio communications are dominating the networking scenario in the access network, as well as in specialized applications, such as the already mentioned satellite networks, but also for maritime and aerial communications, down to body area networks. A frontier of radio communications is the extension of usable frequencies to extremely large values, starting off with a 5G boost towards bandwidth above 6 GHz, e.g., with mmWave communications. This trend is pushing towards the so-called THz communications paradigm (Serghiou et al., 2022). The twelve decades of usage of radio waves for communications have witnessed an unstoppable growth of used frequencies, motivated mainly by the quest for larger bandwidth and unallocated spectrum portions for new services. The Newfoundland of radio communications is the THz bandwidth. This frequency range is the cornerstone of the Integrated Sensing and Communication (ISAC) paradigm, a key 6G pillar identified in EU initiatives like Hexa-X II. ISAC enables the network to function as a high-resolution radar, allowing for simultaneous data transmission and environmental mapping, which is essential for future autonomous systems and smart city infrastructures (Liu et al., 2022a). Besides offering very large bandwidths, due to the very small wavelength, THz technology is rejoining two mainstreams that used to march closely but are quite separated between them: communications and remote sensing (Chaccour et al., 2022; Jiang et al., 2024; Liu et al., 2022c).

Yet another rising technology for empowering wireless communication is based on RISs (Gong et al., 2020). New materials are being studied whose reflectivity properties can be controlled and changed according to the desired directivity of the radio beam. Although this technology implies deploying such active material panels in the propagation environment, it is shown to boost communication performance, at least over local range distances. As a matter of example, an application to visible light communications is reported in Aboagye et al. (2023).

Public institutions are part of this progress in that spectrum usage is regulated in most advanced countries. Given the geo-political fragmentation of the EU, it is critical that spectrum usage be faced in a consistent way in different countries, in a holistic socio-economic European perspective. Also, the role of unlicensed spectrum should be carefully evaluated.

Although not specifically tied to a specific communication medium, it is worth mentioning the rise of the quantum Internet paradigm. Quantum key establishment protocols have been investigated and experimented long since over the last two decades. More recently, quantum computing is getting closer to becoming a practical reality. The convergence of quantum technology for communications and computing is pointing at a full-blown networking infrastructure exploiting quantum physics as its cornerstone (Zhang et al., 2024; Li et al., 2024). The implications of such directions are hard to predict as of now. Most probably, the dawn of a quantum Internet, if it exists research labs to turn into an industrial reality, will not replace the "traditional" Internet, at least from a short-medium perspective.

As for integrated 3D networks, a few remarks are in order. Wireless communications have traditionally ensured global coverage worldwide thanks to the integration of two complementary systems: ground networks and satellite networks. Ground networks, characterized by low access delays and cost-effectiveness, provide robust connectivity in urban and suburban areas but are inherently vulnerable to disasters, infrastructure damage, and installation limitations (e.g., in mountain regions or oceans where back-hauling links and BSs are difficult to deploy). Conversely, satellite networks extend coverage to remote and underserved areas, offering broadband connectivity where ground networks falter, with higher costs and limited performance.

A recent trend in these integrated wireless networks is represented by the introduction of a further intermediate level, in which aerial nodes (UAVs, aircraft, balloons, etc.) are deployed between satellite and terrestrial BSs, thus creating an integrated space-air-ground architecture (Liu et al., 2018). The idea is to use the air segment to enhance the capacity in terrestrial areas with high service demands for disaster recovery, or for providing broadband coverage in rural areas at low cost, by means of HAPs & LAPs. Although several recent projects have focused on the deployment of integrated systems, such as the Global Information Grid (Hubenko et al., 2006), or aerial systems such as Loon (Kaur and Randhawa, 2018), many design aspects still need to be fully investigated. Indeed, the time-variability of the network architecture, the heterogeneity of physical layer technologies, the limitations of each infrastructure layer, together with non-technical factors such as consumer readiness and regulatory aspects, need to be properly addressed. These networks also require a high level of self-organization capabilities, together with specific solutions for resource allocations, mobility management, multicast routing, and inter-layer optimizations.

A very innovative aspect of these systems is represented by the deployment and integration of UAV-based nodes, which, on one side, can significantly enhance cellular networks with aerial BSs, but on the other side, require reliable connectivity for coordination and control. The former aspect, pioneered by academia, advocates the usage of UAV-based BSs for disaster assistance, border surveillance, or hotspot events, given that UAVs carrying a radio access node can be promptly dispatched, cheaply maintained, and easily maneuvered. The second aspect, strongly considered by the standardization fora (NR Rel. 17 (3GPP, 2019), NR Rel. 18 (3GPP, 2021)), triggered a parallel stream of research that aims at supporting UAV-based end-devices through cellular networks. Guaranteeing good coverage to these end devices is currently a challenge, as ground cellular BSs are typically down-tilted, with a limited 3D coverage on the height dimension. In other words, UAVs are only reached by upper antenna sidelobes and experience sharp signal fluctuations. Moreover, flying above buildings, UAVs receive and transmit LoS signals, potentially interfering with a plurality of cells (Geraci et al., 2022).

In such a scenario, innovative solutions for spectrum monitoring and allocations can be envisioned for improving spectrum utilization, especially on the third (novel) dimension. Challenged include both the space-air and the air-ground segments, where different frequencies and technologies are currently used. Apart from the integration of multiple-band systems, it is important to exploit navigation data and routing information of mobile infrastructure nodes to achieve optimal spectrum utilization (Si et al., 2015). Ultimately, spectrum sharing and innovative coexisting schemes between aerial, space networks, and ground networks will be necessary. In this scenario, cognitive radio technology, extensively studied in the past but with scarce adoption in real networks, can play a role in dealing with a more dynamic spectrum allocation. Since aerial network nodes are far from the ground, spatial isolation can facilitate spectrum reuse; however, the absence of obstacles in the air links can extend the interfering area with other aerial nodes. This requires exploiting methods for controlling the transmitter power and beam angle, as well as for pervasive monitoring of the spectrum utilization along three dimensions (Wang et al., 2020) with innovative infrastructures.

To support these high-bandwidth applications, 6G necessitates a shift in Spectrum Management. This includes moving from static licensing to dynamic, automated spectrum sharing and the exploitation of "extreme" frequencies. Efficiently managing the interference between terrestrial, aerial (UAV), and satellite layers in a 3D architecture requires real-time, AI-driven coordination of spectrum assets to ensure global connectivity without service degradation.

3.3.3. Improving network sustainability

Telecommunication networks are experiencing a dramatic increase in energy consumption and overall carbon footprint, due to the increasing traffic volumes and pervasiveness of the access infrastructures (Lorincz et al., 2019a). Currently, it is estimated that the industry accounts for 3% to 4% of global CO_2 emissions, about twice that of

Table 2
Overview of the EU digital ecosystem: current state and emerging trends.

EU digital ecosystem

(S1) Current regulations

- Asymmetric regulation: ex ante obligations to ensure non-discriminatory access to essential facilities and network elements.
- EU evolution: Digital Services Act (DSA) and Digital Markets Act (DMA) introduce preventive duties for online platforms and gatekeepers.
- National snapshots:
  - **UK**: post-Brexit continuity of telecom asymmetries; diverging path on data protection.
  - **France**: balancing national-security driven data retention with fundamental rights; ISP liability recalibrated under DSA.
  - **Italy**: abuse of economic dependence for digital platforms; strengthened AGCM powers on mergers in digital markets.

(S2) Trends

- Data governance: shift from possession to sharing (B2B, B2G); open-data debates and co-regulation models.
- Network structure & competition: discussion on functional/ownership separation and net-neutrality approaches.
- Digital rights: privacy and freedom of expression reinterpreted under EU and national reforms.
- Perspectives:
  - **Operators**: more contestable, fairer markets.
  - **Consumers**: equal access to adequate digital services.
  - **Public administrations**: harmonization and standardization to reduce territorial inequalities.

civil aviation. With the current trends of growth in traffic volumes, fiber optic networks, and cellular sites, the industry's share will further increase unless investments in energy efficiency and more sustainable technologies can offset this trend (Lorincz et al., 2019b). Emissions derive mostly from purchasing energy and heat for the infrastructure (with the so-called scope 2 emissions), as well as from downstream and upstream activities connected to the telecommunication industry, which account for the energy consumption of suppliers and service providers. In the past few years, most telecommunication companies have declared that they should assume responsibility for their Scope 3 emissions, for example, by demanding transparency into their suppliers' footprint (Friedrich et al., 2021). In this scenario, there are several levels at which technological advances can improve network sustainability: from the device/sub-system level to the network integration level, up to the end-to-end service level.

At the device level, the usage of innovative semiconductor technologies, such as Gallium Nitride (GaN) and SiC, allows the design of energy-efficient components (Collaert, 2024). Development of more efficient hardware involves many different components, from analog/digital converters, optical converters, and mixers, to graphene-based photo-detectors, low-noise and low-power amplifiers, and, in general, low-energy front-end transceivers able to work at the emerging mm waves or optical bands. Moreover, another interesting trend is the integration of small-scale energy harvesting technologies (Ku et al., 2015) (like solar cells or piezoelectric generators) or wireless charging systems for developing battery-less devices able to work as end devices in heterogeneous applications (Rahmani et al., 2023).

At a sub-system integration level, innovative and efficient elements for future networks include programmable antenna systems (Chaloun et al., 2022) able to exploit signal backscattering and reflective intelligent surfaces (Zhu et al., 2025), ultra-low-power nodes, equipped with a wake-up radio interface for managing the sleeping states in a trigger-based logic, energy-efficient channel coders specialized for ultra-reliable and low-latency communications, and all-optical processing solutions. Moreover, it is important to integrate probes for measuring energy consumption in different sub-systems, together with the other usual performance metrics.

At a network level, several research works consider the problem of designing more efficient RANs (Zhu et al., 2025). Indeed, an approach based on powering cellular sites using energy harvested from renewable energy sources such as wind, solar, fuel cells, or a combination of these energy sources significantly contributes to the improvement of wireless network efficiency. Moreover, dynamically controlling the activation/deactivation of the BS can further improve the overall efficiency. Apart from the RAN, AI-driven network orchestration can be extended for dealing with energy optimization, by steering opportunistically the network traffic, or by selecting different security and network functions (Lu et al., 2020). More flexible and efficient network management is improving the network adaptability, without specialized hardware, by also reducing hardware obsolescence and reuse. Another emerging direction is based on the exploitation of edge computing for processing data closer to the source to reduce the energy required for long-distance data transmission. Improving coexistence between multiple technologies and service providers by means of infrastructure sharing can improve circularity and reduce e-waste.

Network sustainability is challenged by resource draining by heavy, high-demanding services, such as XR and AI services. XR services - e.g., XR calls and streaming- present technical challenges that range over aspects like acquisition, interaction, rendering, streaming, buffering, and the pivotal role of 5G networks in enhancing XR experiences (Gapeyenko et al., 2023). XR data compression techniques leverage the user's point of view by tiling the overall scene into smaller data packets and discarding parts not visible to the user. Ongoing efforts in ISO MPEG span XR compression and multiplexing XR data: the search is open for compact metadata formats, including timed media, APIs for network-assisted rendering, and tools for retrieving either pre-encoded 3D data or content dynamically generated during playback. Future developments anticipate large-scale, client-specific streaming, tailoring traditional media presentation descriptions on a per-session basis through manifests for personalized services. Trending developments address compression techniques for XR volumetric video (point cloud) or short sequences used in social networks, as well as network-based media processing at the edge based on appropriate encoding metadata. Finally, other innovative MPEG trends cover smart contracts for digital rights management protocols, and deep neural network-based video coding for unified handling of natural and synthetic data.

These developments involve both network signaling and edge computing devoted resources, posing peculiar sustainability challenges (Theodoropoulos et al., 2022) still to be explored.

3.3.4. Intelligence and networking entanglement

AI is prominently driving the development of new features and applications in many disparate fields, thanks to its apparent ability to extract meaning out of the wealth of data produced by humans and machines (e.g., in the framework of the Internet of Things). AI offers a valuable tool to tame the complexity associated with new societal living models, including smart cities, intelligent transportation, smart grids, and industrial automation. AI is a broad field, covering several different specialized areas, ranging from knowledge representation to probabilistic reasoning, semantics, and machine learning. As of today, ML stands out as the most relevant of these areas for telecommunications. ML is already having a big impact in enabling machines to learn from data, with or without the supervision of humans. An astonishing improvement in ML capabilities has come in the last decade from the inception of deep neural network algorithms. The amazing achievements of ML tools have raised a huge hype of interest and expectations on their potential to improve information and communication technologies.

ML and AI in general are already deeply affecting the way technical problems are addressed, specifically those concerning communications and networking, e.g., in the design of 5G/6G networks (Kaur et al., 2021; Noman et al., 2023). As a matter of example, effective network slicing calls for very sophisticated mechanisms to configure and orchestrate network resources (e.g., virtual machines, network interfaces) where and when they are needed. The increasing level of complexity of networked systems management pushes towards increasingly automated solutions to cope with the volume of data and resources to be dealt with. The aim is to guarantee a high level of resource exploitation and to keep network management costs within affordable bounds. Here, AI and ML can play a significant role (Phyu et al., 2023).

All network architecture layers offer examples of fruitful applications of ML algorithms as well. To mention some areas where ML-based approaches have been proposed for networks, we refer to beamforming, dynamic spectrum sharing, multiple access control, routing, resource allocation, congestion control, proactive caching, and security. Also, the reverse is true since there is an active field of research and experimentation on what networks can do to assist and empower ML algorithms, e.g., with reference to real-time data collection, support of learning in the edge cloud, and distributed/federated learning.

AI, and specifically Machine Learning, is expected to play a major role in all of those areas, especially in cases where there is a model deficit, i.e., it is not known how to state an optimization model, or a model statement leads to an infeasibly complex problem (e.g., because of many involved parameters). As pointed out in Zappone et al. (2019), coexistence can be expected between model-based and data-driven approaches. Maintaining a hybrid approach allows us to leverage decades of model-based know-how accrued in the communications and networking fields, while at the same time keeping the door open to getting benefit from powerful data-driven deep learning algorithms in those cases where enough data can be collected cheaply.

Within the early developments of Shannon's seminal works, Shannon and Weaver identified three levels of communication (Shannon and Weaver, 1949):

1. transmission of symbols (the technical problem);
2. semantic exchange of transmitted symbols (the semantic problem);
3. effect of semantic information exchange (the effectiveness problem).

Shannon deliberately focused on the technical problem in his seminal paper (Shannon, 1948). This enabled him to derive a rigorous mathematical theory of communication based on probabilistic models, which has, insofar, underpinned the whole development of information and communications technology. AI and ML offer the opportunity to move forward towards the semantic and effectiveness levels, as drivers in the design of new communications and networking systems (Calvanese Strinati and Barbarossa, 2021). This will require full integration of knowledge representation systems, ML, and goal-oriented communications, leading to what is often referred to as the semantic communication paradigm (Chaccour et al., 2024; Trevlakis et al., 2024; Getu et al., 2024). Communication and network systems could be tailored to exactly what is the relevant information needs to be transmitted to fulfill the desired goal, with the desired level of effectiveness.

In this respect, a critical open issue arises considering the tremendous impact of standardization as a cornerstone of technological evolution, interoperability, and an open market enabler. Designing systems in a modular way and putting them together to build complex networks appears to clash against goal-oriented semantic communications, which is inspired by a holistic approach, where the whole system design revolves around a specific goal and is carefully carved to fit that goal. How to exploit the potential of semantic communications enabled by deep learning algorithms (in general, by AI), while preserving the flexibility and modularity of networks, is a big open issue in our view.

4. The TLC ecosystem: Regulation

In this section, we offer an in-depth overview of current regulations (S1) and trends (S2) impacting information and communication technologies in Europe, with a focus on Italy and similar countries, for comparative purposes. The overall Section structure is sketched in Table 2.

4.1. Analysis of current situation (S1)

4.1.1. The european answer to the digital ecosystem

Over time, the emergence of "digital ecosystems" has innovated EU regulation,[1] in particular, in the regulation of telecommunications. We describe, firstly, the asymmetric regulation originally established for telecommunications and, secondly, the new forms of atypical asymmetry.

Traditional asymmetric rules (De Minico, 2012; Clarich and Cassano, 2009; Amato, 2005) are subsidiary to competition law and aim to create "the preconditions of a competitive marketplace rather than substituting regulation for competition" (Breyer, 1982). A relationship of subsidiarity results from this setting: asymmetric rules, according to Breyer (1982) are "necessary when antitrust cannot successfully maintain a workably competitive marketplace, and rely on the essential facility doctrine. This elaboration is meant to address cases characterized by the following circumstances. Firstly, a firm is both a leader in an "upstream" market and a competitor in the "downstream" (or retail) market. Secondly, the dominant undertaking has exclusive control of an essential structure, i.e., a means necessary for rivals to compete in the market. Thirdly, competitors do not have the possibility to duplicate the essential structure for technical, environmental, or economic reasons. In these instances, rules intervene to prevent market abuses. More precisely, those who monopolize the "upstream" market can hamper competition in the retail market simply by denying rivals access to essential facilities. As abuse is inherent in this system, restorative antitrust remedies have proved to be insufficient to ensure a competitive and fair market. Consequently, the threshold of protection needs to be anticipated, i.e., measures have to be applied on a precautionary basis, before the competitive offense occurs. Such precautionary measures

[1] A remark on regulatory trends for OTT operators is in order. While hyperscalers supply cloud infrastructure and platform services to enterprises, OTT firms provide digital services directly to end users; some companies operate simultaneously as OTTs and hyperscalers. OTT operators are addressed within the EU regulatory framework on telecommunications, digital data, and digital services, including the Digital Services Act (DSA) and the Digital Markets Act (DMA). The DSA operates downstream along the value chain, targeting digital services provided to end users and affecting OTT operators as actors in downstream or retail markets, e.g., through obligations of transparency, accountability, and user protection on OTT online platforms. The DMA addresses market power and structural risks associated with operators designated as gatekeepers, and targets OTT firms that extend their activities upstream through vertical integration, thereby occupying positions of intermediation and control within digital ecosystems. In this Section, mainly focused on asymmetric regulation and competition, OTT operators are implicitly addressed, and assimilated either to retail market actors under the DSA framework or to vertically integrated intermediaries under the DMA framework, depending on the level(s) of the digital value chain in which they operate. In this context, net neutrality and universal service are seen as asymmetric regulatory instruments primarily binding connectivity providers, while OTT operators largely benefit from these safeguards without assuming equivalent access, coverage, or interoperability duties.

must redress the imbalance and thus impose obligations on the party that stands to benefit alone. Indeed, asymmetric rules are defined as a unilateral discipline as they only provide obligations to one part of the relationship: the incumbent. They tend to normatively simulate a situation of perfect competition, in which the incumbent does not discriminate between operators in the "downstream" market but grants everyone equal conditions of access to its network (Amato, 1992). For example, the dominant party is burdened with an obligation to conclude contracts allowing its competitors to use its facilities under the same conditions as those reserved for its own business divisions. As proof of the accessory relationship, this system does not exclude the enforcement of the ordinary antitrust remedies in certain cases where (and after) distortive conducts nevertheless occur. In the same way, economic tests in TLC law are similar to the ones provided in antitrust law. This asymmetric pattern is the ideal model originally provided by the EU regulation in the TLC sector (Directives 2002/19/CE and 2009/140/CE).

Along with technical development, new EU legislation has been added to the existing asymmetrical one. We particularly refer to two significant Regulations: *Digital Service Act* and *Digital Market Act* (Unver, 2024; Zhang, 2023; Koenig, 2024). The former is meant to counter information monopolies in online platforms, despite its field of application still seeming to be controversial (see June 27, 2023 – Zalando/Commission, T-348/23). The latter is a general preventive discipline for online markets, restraining gatekeepers to avoid the degeneration of dominance into abuse. Some early examples of DMA implementation are offered by the recent EU Commission non-compliance investigation. In particular, the initiative has concerned "Alphabet's rules on steering in Google Play and self-preferencing on Google Search, Apple's rules on steering in the App Store and the choice screen for Safari, and Meta's 'pay or consent model'". The measure shows its closeness to asymmetric regulation in the TLC sector, notwithstanding the different methods adopted by DMA to assess dominance. In particular, DMA identifies operators with Significant Market Powers through a relative presumption, susceptible to being contested by appropriate evidence (even if a 'diabolical' one). Under the same Act, gatekeepers are obliged, to a certain extent, to give access to their own search engine data to competitors owning other search engines. This measure goes in the right direction, as it would benefit competitors by lowering a significant barrier to entry. At the same time, it is a balanced measure because it does not impose an excessive burden on the incumbent: data are non-rival goods and can be used simultaneously by several actors. Consequently, the Act is also consistent with the European Commission's Data Strategy (COM/2020/66 final), which is supposed to encourage the sharing of data between companies to increase the competitiveness of the entire system.

Now, we focus on national law systems that raise different questions. In particular, we will focus on asymmetric rules in the UK system; fundamental rights issues in the French system; and antitrust problems in the Italian system. Notwithstanding this, we acknowledge that these problems are partially the same in the 27 States.

These topics have a transversal issue in common: data governance. Based on both human and economic rights protection, the EU Data Strategy stems from the need to create pro-competitive data alliances, mainly through business-to-business sharing, in order to create European Data Spaces. The strategy is also meant to support the individual and collective dimensions of privacy (De Tullio, 2016), deriving from the interconnection of each individual's information in the processing of big data. These rights are currently affected by concentrations in online markets. In this light, we analyze internal rules in the three systems – the UK, the French, and the Italian – and the EU regulation, including the Data Governance Act and the proposed Data Act into account (see below).

4.1.2. Looking at relevant UK issues concerning asymmetric rules

As is known, the UK has long been a member of the EU. It is interesting to have a look at regulations enforcing EU Directives before Brexit from the EU for two reasons. (1) The UK has been the first country in the EU to rule the competitive market in the TLC sector. From 1984, Oftel, the Independent sector authority, applied some ex-ante regulations to improve competition in the telecommunication market (De Bijl and Peitz, 2002; La Spina and Majone, 2000). However, only in 2003, also thanks to the push from the EU reforms, that we had a real transformation in telecommunication markets. First of all was created a new authority, Ofcom, with new duties (which has substituted the precedent regulatory authority by the Ofcom Act 2002). Indeed, the English political decision-maker noticed the permanence of the failure of the market, which still had bottlenecks. At that time, a duopoly had been created, formed by BT, the vertically integrated telecoms incumbent, and Mercury, the only new entrant. Nevertheless, this market situation was not sufficient to guarantee consumer satisfaction. Hence, rules imposed ex-ante remedies on BT to ensure that its competitors could obtain access to parts of BT's network that they could not fairly replicate due to enduring economic bottlenecks. In particular, the English regulator observed that BT had SMP in 14 wholesale markets and 16 retail markets. In the wholesale markets, BT had an obligation to supply an SMP wholesale product at a regulated price under non-discriminatory terms. According to Ofcom's review, discrimination in these markets emerged as a core issue. Indeed, Ofcom (after a public consultation in 2004) has been regulating the functional separation of the incumbent in the TLC market. However, the functional separation of BT, although it improved competition, was not sufficient to overcome the bottlenecks in the wholesale and retail markets. Therein, BT has continued to be the SMP company (De Minico, 2008; Curwen and Whalley, 2008). It is important to underline that Great Britain, from 2016, has started the exit from the EU after the referendum in which the leave position won. Now, all EU regulations in the UK will apply – but not the DSA and DMA – because they have been transposed into domestic law. Thus, the UK government can unilaterally change these rules without incurring penalties from the Commission. (2) Looking at the fundamental right protection of personal data, the UK has had a different approach from the first period of Brexit until today. It is important to underline that the data protection regulation in Great Britain is more complex than in the past because, in the last three years, the English Government and Parliament have ruled many times on this issue. The UK Data Protection Act 2018 was the first source before the final Brexit transition period. After the UK TCA stipulated in December 2020, each of the parties enjoys a different and independent "right to regulate". Great Britain transposed an amended version of the GDPR into domestic law, creating the UK GDPR through amendments to the UK Data Protection Act 2018. Hence, the UK has a very wide scope for internal data protection, also because the Charter on Fundamental Rights is not a part of the EEA legal system and the countries of the EEA are not obliged to adhere to it or adopt it into their national systems. It is important to stress that in the UK, the only safeguard of data protection results from Article 8 of the EU Charter of Fundamental Rights, whose wording only refers to the right to privacy. Additionally, according to the Human Rights Act 1998, the Courts should interpret legislation in a way that protects ECHR rights "so far as possible". So, the principle is generally applied less protectively because it is impossible to give an extensive or teleological interpretation (Erdos, 2022). However, for the data flow between the UK and the EU, the UK has to follow the adequacy criterion. The UK on June 28th, 2021, was granted the status of EEA member, and it was recognized by the Commission Implementing Decision of 28.6.2021 pursuant to Directive (EU) 2016/680 of the European Parliament and of the Council on the Adequate Protection of Personal Data by the UK. Hence, personal data can flow freely from the EU to the UK, but it is necessary that Great Britain guarantees the equivalent level of protection safeguarded at the EU level. In the UK, according to the Adequacy Decision of the European Commission, the data protection system is based on the same rules that were applicable when the UK was a Member State of the EU. The UK has completely incorporated the principles, rights, and obligations of the GDPR and the Law Enforcement Directive into its post-Brexit legislation. In particular, the Commission approved the Adequacy Decision because, above all, in the field of data access from public authorities, principally to protect national security, the UK legal system has adopted a very strong model of protection of privacy. Indeed, the collection of data by intelligence authorities is generally subject to prior authorization by an independent judicial body. Any measure needs to be necessary and proportionate to what it intends to achieve. Moreover, if a person is believed to be subject to unlawful surveillance, it is possible to bring an action before the ad hoc Tribunal named Investigatory Powers Tribunal (Mc Cullagh, 2022). The peculiarity of Adequate Decision lies also in the rule that provides for a sunset clause; therefore, it expires automatically after four years, precisely on June 27th, 2025 (Celeste, 2021). Moreover, at the moment, the government intends to repeal the GDPR and the UK GDPR with a new proposal, the Data Protection and Digital Information Bill. The Bill is expected to reduce human rights protection because it is more flexible on cookie utilization, allows greater use of automated decision-making, and replaces data protection officers with “senior responsible individuals”. In addition, the reform endows the Government with the power to interfere in the citizens’ personal sphere through the Information Commissioner. The regulatory authority (Information Commission Office) may apply stricter sanctions in the case of a data breach. More specifically, Clause 5 clarifies that “legitimate interests” can be used as a lawful basis for direct marketing, while it removes the “balancing test” for some important public interests. In the same clause, the most significant (and dangerous) innovation is that the Secretary of State has broad powers to amend data protection laws via statutory instruments, without adequate scrutiny by Parliament. Clause 9 changes the regime of Subject Access Requests, allowing the denial of access by public authorities or bodies. Knowing who uses which data, and in which manner, is an important way for people to exercise their rights to privacy and non-discrimination. Without these notices, it becomes very difficult to exercise data protection rights when personal information has been used unlawfully. Moreover, the Bill introduces a new regime applicable to automated decision-making. It is important to underline that the UK massively utilizes AI, especially in the public sector. In Clause 14, there is a presumption of legitimacy of automated decisions also against the will of individuals, and there is no exception regarding profiling; in that way, Article 22 of GDPR is reframed. Finally, Clause 20 proposes, in an unclear way, an Assessment of High-Risk Processing which, compared to the UK GDPR, has fewer requirements for recording information or processing operations. Thus, in many cases, authorities handling data will not have to perform a thorough consideration of whether the processing is necessary and proportional. These changes put at risk the Adequacy Decision with the EU, which, as mentioned before, will expire in June 2025 because the UK does not ensure an adequate level of data protection (Tozer, 2024; Erdos, 2024).

4.1.3. Looking at relevant French issues concerning fundamental rights

Concerning France, several normative acts compose the French TLC normative framework. Indeed, the main act is Ordinance n. 2021-650, which is the transposition of the Directive (UE) 2018/1972 of 11 December 2018 establishing the European Electronic Communications Code and amending existing provisions of the CPCE, even adding new ones to it. In this framework, at least two issues of great interest for the constitutionalist emerge; indeed, the third one could be interesting, but just as an in-depth analysis for the future. The first (and the most interesting) issue concerns the relationship between data retention, GDPR, and French anti-terrorism legislation. The prohibition of systematic content retention is established by Law n. 2001-1062 of 15 November 2001, codified under article L.34-1 of the CPCE. The French Anti-Terrorism Act (Law n. 2006-64 of 23 January 2006) expanded data retention provisions, granting police access to retained data and extending obligations to entities like internet cafés, hotels, and restaurants offering internet access. Decrees n. 358-2006 (26 March 2006) and n. 2012-436 (30 March 2012) specified the obligations of operators in retaining and anonymizing traffic data. These obligations apply to all electronic communications network operators and service providers. State refunds cover costs incurred by operators. In a 6 October 2020 judgment, the CJEU (C-511/18, C-512/18, C-520/18) ruled that general and indiscriminate data retention must be limited to what is necessary for national security, with intelligence service access subject to prior review by an independent authority or judge. In CE, Ass., 21 Apr. 2021, n. 3930922, the Conseil d’Etat endorsed the generalized and undifferentiated retention of connection data due to perceived national security threats. Does this comply with European law? The second issue concerns the content-related liability of ISPs. Generally, France’s civil and criminal law system and Court interpretations of codified norms absolve telecommunications operators and ISPs from content-related liability on numerous occasions. Nevertheless, ISPs may face obligations to limit access to specific websites to a certain extent. Article L.32-3-3 of the CPCE shields telecommunications operators and ISPs from civil and criminal liability for transmitted content. They can only be held accountable if: (i) they solicited the communication; (ii) they chose the communication’s recipient; or (iii) they selected or altered the transmitted content. How high is the risk of censorship by ISPs, which remain private entities? To what extent does French law protect freedom of expression?

4.1.4. Looking at Italian answers to competitive problems

In Italy, the focus on the market power of the undertaking that provides digital platform services had already been demonstrated by the amendments that Law No. 118 of 2022 made to Article 9 of Law 192/98, regulating the abuse of economic dependence. This amendment introduced a simple presumption of economic dependence where an enterprise uses the intermediation services provided by a digital platform that plays a decisive role in reaching end users or suppliers, including in terms of network effects or data availability (Bougette et al., 2019; Tombal, 2020). The notion of abuse of economic dependence between two enterprises set forth in Article 9 of Law 192 of 1998 (a provision that, although placed within the scope of the Subcontracting Law, is generally considered applicable to all vertical relationships of duration) occurs when one of them is in a situation that results in an excessive imbalance of rights and obligations in business relationships and the other one has no real possibility of finding satisfactory alternatives on the market. In contrast to the case of dominance, in the case of economic dependence, the dominant power is relative to one firm. More in detail, it must result in an excessive imbalance of rights and obligations with respect to a firm that has no real prospects of changing its supplier. This can mean that there are no alternatives or that the existing alternatives are not economically viable for the dependent firm. Indeed, the latter might not be able to afford the investments needed to comply with the supplier’s requirements or to operate with a new supplier (Borzilo, 2021; Osti, 1999). The simple presumption provided for digital platforms results in a reversal of the burden of proof so that it is up to the platform to prove the absence of economic dependence. However, if the presumption is not overcome, it must then be ascertained whether the “dominant” firm has committed abuse. An abuse may be realized, for example, by imposing unjustifiably onerous or discriminatory contractual conditions, arbitrarily terminating existing business relations, or refusing to deal. Pursuant to the new version of Article 9 of L. 192/98, abusive practices by digital platforms may also consist of providing insufficient information or data concerning the scope or quality of the service provided; requesting undue unilateral services not justified by the nature or content of the activity performed; adopting practices that inhibit or hinder the use of a different provider for the same service, also by applying unilateral conditions or additional costs not provided for in the contractual agreements or existing licenses. The approach is quite different from the DMA. Indeed, the DMA aims to maintain contestability and fairness in digital markets for the benefit of commercial and end users through the obligations imposed on the gatekeeper. Instead, the discipline of abuse of economic dependence intervenes ex post facto by sanctioning abusive behavior in inter-subjective relations (Colangelo, 2023; Scalzini, 2022). It is certain, moreover, that civil and administrative sanctions against abuses of economic dependence incentivize correct conduct in contractual relations between the digital platform and users. This effect will also concern the sharing of data and information, as demonstrated by the precautionary measures adopted by the AGCM in its order of 20 April 2023 in case A558 Meta/Siae. In addition, the Annual Competition Law of 2022 (Law No. 118 of 5 August 2022) substantially changed the powers of the AGCM on the assessment of mergers affecting digital markets. In particular, as a part of the assessment test, Art. 6 l. 287/90 has provided that the authority "may assess the anticompetitive effects of acquisitions of control over small-sized companies characterized by innovative strategies, including in the field of new technologies". Furthermore, in Art. 16 of l. 287/90, Paragraph 1 bis was inserted, which now allows the authority to assess mergers that do not meet the thresholds of Art. 16 if there are concrete risks for competition in the national market, or in a relevant part of it, also taking into account the detrimental effects on the development and diffusion of small enterprises characterized by innovative strategies.

4.2. Trends (S2): issues, trends and perspectives

The creation of the digital ecosystem, which is present rather than potential, will entail at least three types of consequences: on the network, on the status of digital rights, and on data governance. We examine the network issue with respect to Italy, but the situation in this Country is clearly indicative of a critical point affecting the former dominant – now the vertically integrated operator – of each European Country. Consequently, a common argument can be made on remedies, from the least intrusive, such as corporate separation, to the most drastic, e.g., forced separation of the network from the service management business. Of course, this common reasoning will consider national differences regarding the status of the new network owner: private or public.

4.2.1. About data issues

In light of the aforementioned trend towards data sharing – emerging in the EU and Italian discipline on abuse of economic dependence – we can observe that new obligations and incentives to business-to-business sharing are being introduced. Hence, there is a shift from a "possessive" approach to a disclosure of information. This change is expected to open new issues concerning the effectiveness of this new asymmetric measure. Indeed, we can question whether a competitive marketplace can be guaranteed by the sole accessibility of the data facilities belonging to the dominant actor, the semi-exclusive owner of the data asset. We will try to answer this question through our research. The analysis of EU antitrust decisions will highlight potential symptoms: if abuses of dominance through data are continuously declared, the cause is probably that asymmetrical rules have failed to ensure that gatekeepers comply with the rules of competitive fair play. The highlighted regulatory trends also allow further reflections on data sharing. Namely, we investigate whether we are still under a regime similar to a Freedom of Information Act – i.e. disclosure under specific and motivated request – or we are heading towards a general rule of open data, where data are made publicly available in a machine-readable format and without restrictive licenses, so that this information can be used, modified and shared by anyone for any purpose, even in the absence of a "qualified interest" (The Open Definition, in http://opendefinition.org/). In that sense, the Data Act proposal should be observed closely, as it provides some specific and exceptional obligations of businesses to government data sharing (De Tullio, 2023; Chu, 2022; Ducuing and Margoni, 2022), which might be the premise for a future disclosure of data from undertakings to netizens in general. In light of the above issues, we can conclude that data governance is an expression of a more general regulatory question involving the choice between concurring normative sources: self-regulation and binding rules. In this dilemma, we support co-regulation as a third way between the former and the latter. In this framework, private power has to be regulated by respecting the correct order between public and private interventions. Namely, self-regulation has to follow, while the initial political direction needs to be entrusted to public representatives. Indeed, political choices are not delegable to private individuals (Craig, 2003). More in detail, the heteronomous framework should precede self-regulation by providing not only criteria and principles but also a sufficiently prescriptive minimum of rules of conduct; 'private interests governments' (De Minico, 2015, 2023) should then be in charge of the implementation of such a framework.

4.2.2. EU ecosystem trends

Regarding the UK, DMA and DSA have no relevance after Brexit. As a result, one of the key issues in scholarly debates remains whether Ofcom should enforce the ownership separation of BT. The Communication Act of 2003, which currently regulates the TLC sector, does not grant such power. Furthermore, the complex history of Brexit has created uncertainty regarding how the UK's competition and regulatory Authorities could enforce structural separation under the European framework for telecoms regulation. After Brexit, EU regulations are enforced as domestic law. According to amendments to the European regulatory framework, consolidated into the EECC, which was due to be implemented in the UK by December 21, 2020, voluntary commitments of a structural nature will be given legally binding force. However, mandating structural separation would likely require new legislation, which would be an internal rule without any connection to past EU regulations. As mentioned earlier, following Brexit, EU Regulation is upheld as domestic law. Currently, the second key issue revolves around the regulation of net neutrality. It is important to recall that the EU introduced the net neutrality rule for the first time in Regulation 2015/2120, which is complemented by BEREC Guidelines. These guidelines were essential for clarifying certain rules outlined in the Act and, above all, to fill in the loophole present in the Regulation. After Brexit, Ofcom introduced new principles on the Net Neutrality Review contained in the Statement (published October 26th, 2023), in contrast with the BEREC signs. Synthetically and differently from EU guidelines, the Ofcom position is inspired by the new USA approach to Net Neutrality, which started during Trump's Presidency. According to the NRA Statement, ISPs can offer premium quality retail offers; ISPs can develop new 'specialized services'; ISPs can use traffic management measures to manage their networks, and zero-rating offers will be allowed. In the next months, Ofcom will publish guidelines to indicate in which way ISPs can enforce this Statement. In conclusion, we evaluate the dynamic evolution of the EU legal system and national examples in Europe, endeavoring to align the traditional TLC rules with the new ones in pursuit of homogenous regulation for digital ecosystems. Regarding data protection, the approach in the UK after Brexit is moving apart from the EU, in a diametrically opposite direction. In fact, the Data Protection and Information Bill will amend the GDPR and the UK GDPR to the detriment of user safeguards, favoring businesses and public authorities. This approach will call into question the Adequacy Decision approved by the European Commission, which may not renew the Agreement in 2025. We will have to await the final approval of the Bill and its implementation by the Government, which may intervene with statutory or soft law instruments, such as guidelines. It will depend on the scope of the rules introduced through secondary or soft legislation and the degree of discretion granted to public authorities. It will vary depending on the specific provisions and decisions made by competent authorities. In this case, the Commission may still disapprove of the use of secondary regulation or non-legally binding instruments, especially when the discretion of government or other public authorities interferes too widely with data protection. Indeed, the use of such sources would be contrary to the EU principle of the rule of law regarding the protection of fundamental rights. The Commission could impose, albeit not as directly as in the past, compliance with the principles contained in the Charter of Fundamental Rights. Paradoxically, the UK, after Brexit, can operate in the telecommunication market without following anticompetitive or asymmetric rules, while more stringent enforcement of EU rules will be in place concerning personal data protection (Mc Cullagh, 2023).

As for the French Ecosystem trends, the following remarks are in order. Regarding the proposed issues, concerning fundamental rights within the French legal framework, some noteworthy trends emerge. (1) The decision rendered on April 21, 2021, by the Council of State is certainly one of the most important of recent years. Presented in the Assembly of the litigation, it closes (temporarily?) a chapter opened in 2014 concerning the question of how sensitive the balance between the protection of privacy and the research and prosecution of the perpetrators of criminal offenses is. Given the sensitivity to maintaining the current legal regime, the Government requested the State Council to trigger an ultra vires control. What is it? The Government thus invited the Council to monitor and then found that the CJEU had exceeded the limits of its competencies with those under the jurisdiction of the Member States under the Treaties. In doing so, the Council was asked to set aside the jurisprudence of the CJEU, which would have constituted a major upheaval in the legal order. This form of monitoring has already been implemented in Germany. However, the Council refused the ultra vires control requested by the Government, thus averting a judicial conflict. On the other hand, it relied on French constitutional law and then on the Quadrature du Net judgment to circumvent certain principles set out by the CJEU in its various judgments, a fine exercise of balance. To this end, the Council introduces its decision, solemnly affirming the primacy of the Constitution. Nevertheless – and this is the remarkable ability of this decision – the Council of State does not implement this safeguard clause, certainly not to open a front with the CJEU. Indeed, it will rely on the Quadrature du Net decision to ultimately preserve the retention and use of connection data in most judicial investigations. However, the CJEU's decision is respected if it is justified by a threat to national security. In particular, the Council of State notes that "France faces a threat to its national security (...). This threat is not only predictable but also current. This threat stems first from the persistence of a high-profile terrorist risk, as evidenced in particular by the fact that six successful attacks occurred on national soil during the year 2020, resulting in seven deaths and eleven wounded. Two new attacks have already been foiled in 2021. The Vigipirate plan was implemented at the 'Emergency attack' level between 29 October 2020 and 4 March 2021 and then at the 'Enhanced security-risk attack' level from 5 March 2021, attesting to a permanently high level of terrorist threat on the territory". The use of the national security criterion, therefore, makes it possible to safeguard access to connection data in the context of judicial investigations. However, this solution can only be temporary. The Council recalls that the existence and persistence of this national security threat must be subject to periodic review under the supervision of the administrative judge. If this national security threat disappears, data retention and access to judicial investigations will disappear. This solution certainly helps maintain, in part, the current regime and advance the draft E-evidence regulation. In the short term, the Council of State requires the Government to repeal the regulatory framework for the preservation of metadata within six months. In the medium and long term, substantial changes in French criminal procedure must also be considered. These amendments will likely affect several articles of the Code of Criminal Procedure: as recently Matthieu Audibert affirmed (Audibert, 2021), it is necessary to modify several provisions of the Code of Criminal Procedure to bring them into line with the indications of the Council of State. To this aim, amendments to sections 60-1, 60-2, 77-1-1, and 99-3 of the Code of Procedure should be considered. The judgments of the CJEU and the Council of State have been followed by a legislative intervention which, although it made some significant corrections under the algorithm technique, at the same time, inserted elements that question the new balance of this issue. In the doctrine's opinion, the legislator has, paradoxically, modified certain conditions of use of the technique with the law n° 2021-998, introducing new imbalances. These aspects concern the extension of the field of connection data that can be analyzed automatically to URL addresses and the strong restriction of access to administrative documents relating to algorithmic processing implemented by the intelligence services, which tends to deprive citizens of an opportunity to control these tools (Labbay, 2023). Listening to the voice of the doctrine that has pointed out these persistent shortcomings, it will perhaps be possible to restore a framework that conforms to constitutional principles and the protection of rights, even more homogeneous with the principles of European law. (2) Regarding the second issue, there have been several regulatory changes that are likely to necessitate the French legislature to reconsider the overall system concerning the liability of Internet Service Providers (ISPs). With respect to the provision of CPCE L. 32-3-3 (introduced by Law 2004-669) governing the liability of the service provider, changes have occurred in various directions. On the one hand, there has been a shift and complexity in the role of the provider, which is no longer a mere neutral intermediary but plays an "active" role in the content reaching users through the network. On the other hand, the European response to this altered factual framework has come through the DSA, which came into force on 17 February 2024. In Chapter II, from Art. 4 onwards, the DSA distinguishes between three main activities of the Internet services intermediator: "mere conduit", "caching", and hosting. The identification of offenses has been defined as "imperfect" and, even in this changed regulatory framework, the doctrine continues to regard the criminal responsibility of the ISP as a "real mystery" (Besse, 2023). France is currently debating numerous draft laws to align the internal regulatory framework with European standards, as DSA introduces enhanced controls and sanctions. To facilitate the application of the DSA within the EU, the text requires each Member State to appoint a digital services coordinator to oversee intermediary service providers and ensure proper implementation of the relevant regulations. In France, the bill aimed at securing and regulating the digital space includes certain provisions to align French law with the requirements of the DSA. Notably, the text proposes the appointment of Arcom as the coordinator for digital services. Regarding the sanctioning powers of Arcom, the bill incorporates the limits outlined by the DSA. This bill successfully passed its first reading in the Senate on July 5, 2023, and later in the National Assembly on October 17, 2023. The assessment of fundamental freedoms will thus be conducted only upon completion. Only when the full picture is available will it be possible to ascertain whether ISPs have assumed the role of private censors due to the responsibilities they are entrusted with?

4.2.3. Perspectives on a substantial equity objective

The present discussion can be concluded with some prospective analyses. Indeed, perspectives are the ultimate goal of the discipline under review, which aligns with the objective of substantive equality. These perspectives can be articulated in three distinct but connected directions, corresponding to three market actors: operators, consumers, and the public administration. (a) The analysis prompts the question of whether asymmetrical regulations in the telecommunications sector serve as an effective tool for achieving the objective of equality. In this context, the constitutional concept of the principle of equality in the Italian legal system aims not only to prevent discrimination among individuals but also to promote substantive equality. Examining European legislation, one could argue that it aims to achieve this objective by imposing more stringent obligations on former telecommunications incumbents. This approach seeks to level the playing field for all operators, ensuring that the network of the former incumbent is accessible to those who do not own telecommunications networks (De Minico, 2015). However, an examination of case law reveals that asymmetrical network access rules do not effectively replicate a truly competitive market. Therefore, the most recent European rules have been enacted, which provide for network separation and ownership unbundling. However, in any case, this separation is based on a consensual basis. Conversely, an optimal outcome would only be achieved if the network relies on a neutral third party, as has been attempted to be pointed out above. Nevertheless, a broader examination, extending beyond the telecoms market, reveals how this objective permeates the digital single market. Indeed, the recent rules established by the Digital Market Act are noteworthy in this regard. The regulation, similarly to what happens in the TLC sector, imposes ex-ante obligations on the gatekeepers of the digital market, namely the intermediaries between the demand and supply of online services through their platforms, who serve as "the important entry point for providers to reach the end user". The objective stated in Art. 1 of the regulation is to establish a fair and manageable market, benefiting not only businesses but also end-users. The first example of a Decision to open proceedings against some gatekeepers, for their violation of Artt. 20 and 29, can be read in the press release. Whether this will also inspire other markets within the Union remains to be seen. Nevertheless, there is considerable focus on the theme of equality, as enshrined in Article 3, paragraph 2 of the Italian Constitution. This principle arises not only to prevent differential treatment among operators with varying positions in the market but also in the more intricate endeavor of striving to provide equal opportunities to all operators. The objective is to establish the prerequisites for a contestable and, therefore, fairer market for end consumers as well (De Minico, 2023). Moreover, European efforts to ensure substantial equality in the sector extend beyond this aspect and also encompass another dimension: the relationship between the service provider and the users. In particular, the European Commission's recent White Paper "How to master Europe's digital infrastructure needs?", issued on 21 February 2024, aims to enhance submarine infrastructure cables to achieve a digital single market for telecommunications, thereby ensuring a truly level playing field among operators. Indeed, the White Paper addresses the challenges and opportunities for the EU in deploying future connectivity networks, providing scenarios for enhancing the security and capacity of such facilities. It emphasizes the need for uniform strengthening of digital infrastructures across Europe. Indeed, the issue in the digital sector lies in the necessity for a unified market for electronic communication networks and services. Currently, there exist as many markets as there are Member States. Consequently, market conditions significantly differ from each other in terms of both supply and demand. There is significant fragmentation and, consequently, a pressing need to harmonize regulations. This fragmentation is also evident in the market structure, leading to an unequal cross-border provision of digital services that distorts the market. Consequently, some players lack network coverage or sufficient network quality. In essence, this creates inequality among citizens, where only some can access digital services while others cannot. This issue represents the divide between the pursuit of substantive equality among operators and the concern for end consumers. (b) The issue, which challenges substantive equality by granting access to networks and related services to only some users while marginalizing others, has been exacerbated by the COVID-19 pandemic and further intensified by ongoing war crises. In such circumstances, asymmetric rules regarding substantive equality should particularly come into play. They aim to prevent those who have little from having even less and enduring all the adverse effects of a crisis. Nevertheless, observation of practice reveals the opposite scenario: a market in which crises exacerbate social inequalities. This situation is also underscored in a recent Recommendation on Secure and Resilient Submarine Cable Infrastructures (C(2024) 1181/3). (c) However, when considering the last actor involved in the market, the public administration, it also bears responsibility for ensuring substantive equality. Significant inequality in the retail market can also impact the relationship between the public administration and citizens because digitization has revolutionized the way public administration operates, now offering many services online. Hence, only those with knowledge and access to the net can avail themselves of these services. Consequently, it is necessary to standardize and harmonize the market across all Member States by implementing equal regulations that enable all public administrations to provide services to citizens, avoiding territorial inequalities, as is already the case, for example, in the mobile telephony sector. Likewise, specific administrative authorities must implement ad hoc, rapid, and efficient procedures to enable administrations to swiftly proceed with authorizations. In this context, the issue also arises regarding the ownership of data belonging to private entities. Indeed, it is necessary to ensure circulation and pooling of data, as we tried to highlight in para. 3.1. This issue raises the question of whether and how to make data held by the public administration available and standard. This is an essential prerequisite for guaranteeing citizens' fundamental and economic freedoms (Cremona, 2023). Finally, the issue of substantive equality (De Minico, 2024), as has been highlighted (para. 3.1.), also affects the issue of data sharing, where the objective is to ensure broad accessibility and sharing of personal data, both in the private and public sectors, in a way that is functional to the proper consolidation of the single market and instrumental precisely to guaranteeing citizens' fundamental freedoms. In conclusion, there is a pressing need to harmonize the digital sector as a whole, ensuring universal digital services that are adequate and accessible to all, including consumers with lower incomes. This approach will enable the achievement of the objectives of substantive equality while upholding democratic constitutional principles.

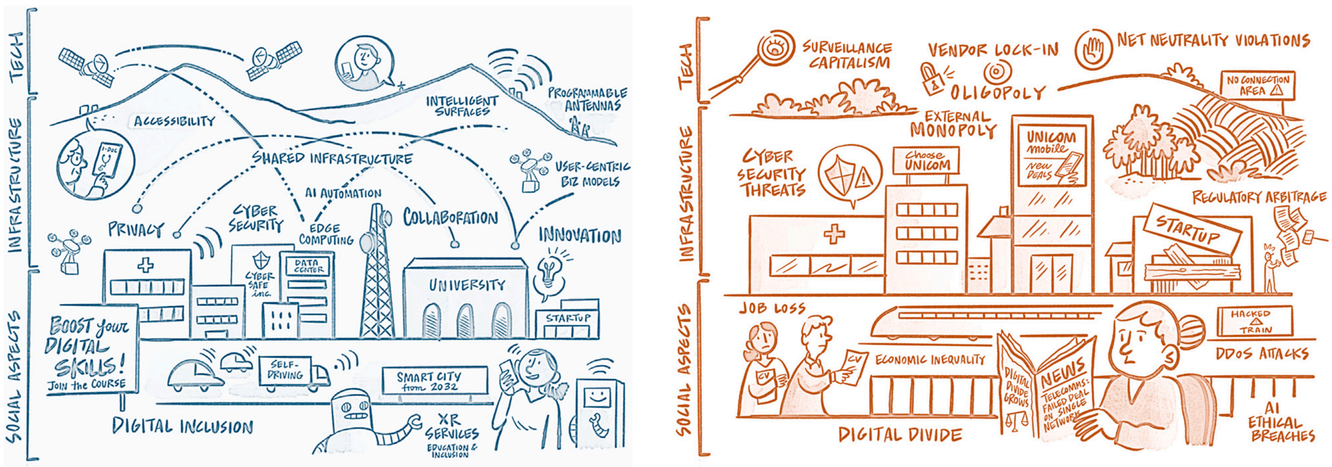
Looking ahead, the evolution of the European digital regulatory framework will likely be driven by three converging dynamics. First, the consolidation of a genuine Digital Single Market will require deeper harmonization of rules across Member States, reducing fragmentation in network governance and digital services provision. Second, the balance between innovation and protection will push regulators to refine mechanisms of co-regulation, where public authorities set binding principles while private actors operationalize them under supervision. Third, the governance of data will increasingly move from sectoral to horizontal models, expanding obligations for interoperability, portability, and open access while safeguarding fundamental rights. These developments suggest that the next phase of regulation will not simply adjust existing asymmetries but rather design a comprehensive architecture for fairness, contestability, and inclusiveness in Europe's digital ecosystem—an architecture capable of addressing the dual imperative of competitiveness and substantive equality.

5. The TLC ecosystem: Next steps

In this Section, we address future scenarios (S3) and highlight key steps to drive the telecommunications sector towards the preferable future scenario.

5.1. Future scenarios (S3)

The herein presented scenarios are shaped by both the trends discussed in the previous sections and strategic interviews conducted with telecommunications experts. By leveraging above mentioned insights into market dynamics, technological advancements, and regulatory frameworks, we explore the divergent visions that may influence the future of telecommunications in the next decade. Without loss of generality, we refer to the Italian case. Several scenarios can be built to elicit informed strategic planning by strategic foresight. For instance, the scenarios may differ in terms of urban concentration versus rural development. Similarly, they may reflect varying levels of integration among European operators. For the sake of compactness, we consider here two opposite scenarios for the general telecommunications industry, labeled as Utopian Scenario (UTOP-S) and Dystopian Scenario



(a) UTOP-S (b) DYSTOP-S

Fig. 7. Illustration of (a) UTOP-S and (b) DYSTOP-S futures. In this exercise, we mark possible futures for the positioning of the generalized telecommunications industry. The UTOP-S future (a) envisions a collaborative and innovative future for the Italian telecommunications industry, driven by shared infrastructure, accessibility, and user-centric business models. Key advancements such as AI automation, edge computing, and robust cybersecurity foster efficiency and trust, while inclusive initiatives like digital skills training and XR services bridge the digital divide, positioning the industry as a catalyst for equitable growth. Dystop-S Future (b) envisions a fragmented future dominated by external monopolies, vendor lock-in, and net neutrality violations. Infrastructure inequalities deepen the digital divide, economic disparity grows, and societal trust is eroded by surveillance capitalism and cybersecurity threats. While some actors may benefit from this environment through regulatory arbitrage or monopolistic strategies, the overall positioning of the industry is marked by stagnation and vulnerability.

(DYSTOP-S). In either scenarios, specific actors could find beneficial or detrimental aspects- e.g., a specific entity can benefit of acquisition by a foreign corporation, but this may have negative consequences on the country wide ecosystem.

5.1.1. UTOP-S future

In UTOP-S future of telecoms, the sector flourishes by delivering cutting-edge digital services that are seamlessly integrated into the physical environments experienced by users. At home, on the road, in farms and factories as in hospitals, the telecommunications infrastructure acts as a conduit for innovative solutions customized to meet diverse needs.

A Dynamic and Collaborative Ecosystem A single network operator offers an open platform to new players, which provides innovative digital services.

Sharing infrastructure, operators significantly reduce costs and foster innovation. The open platform promotes collaboration among universities, research institutions, startups, and established companies, with a focus on the development of 5G infrastructure, IoT, AI, cloud computing, and cybersecurity solutions.

Policies for promoting Effective Collaboration Among Telecom Operators. Regulatory incentives, as those discussed in Section 4.2.3 support these collaborative efforts, leading to more efficient and extensive network expansions and technology upgrades, thus enhancing the overall quality of service.

Policies for Accessibility and Digital Inclusion Comprehensive policies drive the expansion of broadband infrastructure nationwide, bridging the digital divide and promoting digital inclusion. The single network operator model helps achieve this by mandating that basic telecommunication services remain affordable and accessible, particularly in rural and underserved areas.

Subsidized access programs are developed, providing discounted internet access and low-cost devices to low-income families, seniors, and underserved communities. These programs are a collaborative effort between the public and private sectors, ensuring that everyone has the opportunity to participate in the digital economy.

Promoting Digital Literacy Digital literacy is addressed as a national priority, with campaigns aimed at improving digital skills among various groups, including NEETs, women re-entering the job market, and older adults. Blended learning courses are offered to equip individuals with essential digital skills, empowering them to engage fully in the digital landscape.

Leveraging Emerging Technologies Adoption and enhancement of emerging technologies are pivotal in transforming the telecommunications sector. The deployment of 5G and 6G networks smartifies urban environments, supports autonomous vehicles, and enables remote healthcare services.

Integrated AI and machine learning optimize network efficiency and automation, improving decision-making. Predictive maintenance and real-time network adjustments are standard practices, ensuring reliability. IoT infrastructure supports smart city initiatives and industrial automation. Edge computing enables applications such as AR and remote healthcare to function seamlessly by reducing latency and improving real-time data processing.

Enhancing Cybersecurity In the interconnected environment, investments boost advanced cybersecurity technologies, including AI-driven threat detection and blockchain for secure transactions, to protect network integrity and user data. National cybersecurity standards are established, providing a robust framework for safeguarding digital assets.

Strengthening Regulatory Frameworks Telecommunications services incorporate privacy by design, ensuring the highest standards of privacy and data protection. Data minimization practices are strictly enforced, and user consent mechanisms are transparent and easily understandable. Robust encryption and regular security audits protect against unauthorized access and data breaches.

Mandatory performance reporting and service quality assessments ensure transparency and accountability among telecommunications companies. Clear pricing and data handling practices are required, fostering consumer trust and fair competition. Public participation in regulatory processes ensures that consumer interests are represented and addressed.

Robust Consumer Protection Strengthened consumer protection laws prevent unfair practices by means of penalties for non-compliance and corrective action requirements for enforcing adherence to regulatory standards. Public–private partnerships drive innovation and expand digital services, with incentives such as tax breaks or grants for spectrum allocation and infrastructure investments.

5.1.2. DYSTOP-S future

In the dystopian vision of telecommunications sector future, monopolistic/oligopolistic practices stifle innovation, limiting service diversity. In a fragmented market, a few large players control access, pricing, and technological advancements. This concentration of market power leads to a telecommunications environment that is neither equitable nor innovative.

Monopolistic Control and Stifled Innovation The telecommunications monopolies and oligopolies hinder innovation and reduce the diversity of services offered. These dominant players exert substantial control over pricing and service options, making it difficult for smaller companies to enter the market and compete. A single network operator lacks, and each major player maintains its own infrastructure, leading to inefficiencies, environmental impact, and increased costs ultimately passed on to consumers.

The monopolistic environment limits the incentive for these companies to innovate or improve their services. With reduced competition, there is little pressure to invest in new technologies or expand service offerings, leading to a stagnation in technological progress.

Increased Economic Inequality and Digital Divide Economic inequality exacerbates access issues, creating a significant digital divide across the country. High costs for basic telecommunications services put them out of reach for lower-income individuals and rural communities, disadvantaged by limited infrastructure investment in their areas. As a result, these populations remain disconnected or reliant on subpar services, hindering their ability to participate in the digital economy and access essential online resources.

Educational disparities are exacerbated as affluent households gain better access to digital tools and high-speed internet, while those in lower-income brackets struggle to afford these necessities. This imbalance perpetuates a cycle of inequality, where only the privileged can fully benefit from digital advancements. Initiatives aimed at promoting digital literacy and providing subsidized access are insufficient and poorly implemented, failing to bridge the gap effectively.

Security Vulnerabilities and Cyber Threats The telecommunications infrastructure is increasingly vulnerable to cyber threats, with frequent data breaches, DDoS attacks, and IoT device exploits. The lack of robust regulatory frameworks and proactive security measures leads to widespread vulnerabilities that are easily exploited by cybercriminals. Both consumers and businesses experience unreliable service and frequent disruptions, eroding trust in telecommunications providers.

Due to insufficient investment in cybersecurity, the risks associated with emerging technologies such as IoT and AI remain inadequately managed. Critical infrastructure, including hospitals and public services, faces heightened risks from cyber attacks, endangering public safety and national security.

Job Losses and Social Impacts The rapid adoption of automation and AI results in significant job losses within the telecommunications sector. AI-driven processes replace many operational roles, leading to widespread unemployment and economic hardship for displaced workers. This displacement disproportionately affects low-skilled workers and marginalized communities, exacerbating social inequality.

Automation leads to a skills mismatch, where the demand for high-tech expertise grows while opportunities for those without such skills diminish. Reskilling programs are inadequate, leaving many workers without the necessary training to transition into new roles. This results in increased economic hardship and mental health issues among the affected workforce, further straining social services and community support systems.

Poor Regulation and Compliance Issues Poorly regulated technology exacerbates these problems, with compliance issues and legal liabilities becoming major concerns. Inadequate regulatory frameworks lead to non-compliance, fostering lax cybersecurity practices and vulnerabilities in telecommunications networks. Legal liabilities stemming from data breaches, privacy violations, and consumer protection violations can result in litigation and fines.

Reactive regulatory approaches fail to timely address emerging threats and challenges. Delayed responses to technological issues and insufficient consumer protection measures undermine trust in telecommunications providers. This uncertainty and lack of proactive regulation hinder innovation, as companies are reluctant to invest in new technologies without clear guidelines and protections.

In conclusion, this dystopian scenario is a grim picture of monopolistic control, economic inequality, security vulnerabilities, job losses, and poor regulatory oversight. Addressing these issues requires proactive regulatory frameworks, investments in digital inclusion, and a balanced approach to competition and innovation to ensure a more equitable and innovative telecommunications environment. Figs. 7(a) and 7(b) show a graphical summary of the above described limit S3 scenarios.

A remark is in order. Regarding scope, the study conducts detailed analysis and scenario development for Italy and then situates the findings within the broader European regulatory context, addressing the long-term evolution of technology, markets, and regulation up to 2040. Methodological limitations mainly stem from the exploratory and qualitative design. The expert-based sample, composed of telecommunications specialists (see Appendix), enhances the identification of strategic opportunities but may introduce sample bias. These limitations do not materially affect the results, as the use of expert-driven scenario building and the Nominal Group Technique aims to structure and explore alternative futures under high uncertainty rather than to produce probabilistic forecasts or statistically generalizable outcomes.

5.2. Discussion

The two extreme scenarios form a basis for a discussion of the most needed policy and strategy of the sector.

Firstly, in UTOP-S Future, the telecommunications sector is a cornerstone of its digital economy, characterized by dynamic innovation, widespread accessibility, enhanced security, and strong regulatory frameworks. The successful realization of the single network operator drives economic growth and creates a more inclusive and prosperous society.

To navigate towards the preferred scenario of a dynamic, inclusive, and innovative telecommunications sector, a series of strategic policy actions shall be adopted, based on emerging trends and evolving user needs. Strategic recommendations, based on current trends, are summarized in Table 3 and detailed in the following:

1. Focus on User-Centric Business Models: Embrace business models that prioritize the end user's needs and adapt to their evolving lifestyle habits. By providing seamless indoor and outdoor connectivity, operators can enhance user satisfaction and engagement. A user-oriented approach can drive adoption, reflecting the common trend that emphasizes user-centric service delivery.
2. Leverage Growth in Home Automation: promote interoperability and standardization of smart home devices. Encouraging strategic partnerships between telecommunications providers and home automation companies can create efficient integrated solutions that enhance convenience and efficiency for users while significantly improving the quality of life for users. This strategy aligns with the significant growth prospects observed globally, in Europe, and nationally.
3. Support Data Center Expansion: support the significant growth trend recorded in the data center market over the past five years through favorable policies and incentives. Robust and scalable data center infrastructures handle increasing data volumes and support AI and IoT emerging technologies.
4. Promote Network Programmability: support the development of open interfaces and standardized protocols. This approach allows network operators and third parties to efficiently deploy applications, fostering service innovation to meet the dynamic consumers' needs.

Table 3
Strategic foresighting: UTOP-S and DYSTOP-S futures and informed strategic steps.

UTOP-S	DYSTOP-S	Steps
Dynamic and Collaborative Ecosystem, Leveraging Emerging Technologies	Monopolistic Control and Stifled Innovation	Promote Network Programmability, Support Data Center Expansion, Encourage Edge Computing, Explore Integrated 3D Networks
Strengthening Regulatory Frameworks, Policies for promoting Effective Collaboration Among Telecom Operators	Poor Regulation and Compliance Issues	Facilitate Infrastructure and Service Separation, Ensure Effective Unbundling of Networks
Policies for Accessibility and Digital Inclusion, Promoting Digital Literacy, Robust Consumer Protection	Increased Economic Inequality and Digital Divide, Job Losses and Social Impacts	Focus on User-Centric Business Models, Leverage Growth in Home Automation, Address Energy Consumption and Sustainability, Foster Testbed-Driven Innovation, Support XR Services for Education and Inclusion
Enhancing Cybersecurity	Security Vulnerabilities and Cyber Threats	Address Security Issues from Technological and Regulatory Perspectives, Invest in Optical Networks

5. Encourage Edge Computing: promote the deployment of edge computing infrastructure, bringing storage and computational power closer to users. Operators can provide high-performance, energy-efficient services that enhance user experiences, especially in mobile networks. This shift is crucial for achieving high performance and energy savings.
6. Invest in Optical Networks: support the deployment of wireless optical systems and reconfigurable optical networks, for designing next-generation data centers which can significantly improve network performance and reliability.
7. Address Energy Consumption and Sustainability: implement policies aimed at reducing the energy consumption and carbon footprint of telecommunications networks. Encouraging the use of renewable energy sources, energy-efficient technologies, and sustainable practices can help mitigate the environmental impact of increasing traffic volumes.
8. Harness the Power of AI: promote the integration of AI across various aspects of the telecommunications sector to improve network management and enhance customer service by extracting valuable insights from users' and devices' data mining.
9. Explore Integrated 3D Networks: Invest in research and development of integrated networks, which can offer enhanced connectivity and performance, leading to cutting-edge telecommunications applications.
10. Foster Testbed-Driven Innovation: Encourage the use of testbeds, living labs, and sandboxes to validate and refine emerging technologies and services. This approach can accelerate innovation, particularly in digitalization, energy, and manufacturing, by providing real-world environments for experimentation and development.
11. Support XR Services for Education and Inclusion: Leverage XR technologies to enhance educational and inclusive services. Promoting XR applications can help bridge gaps in access to quality education and provide immersive experiences that support learning and social inclusion.
12. Facilitate Infrastructure and Service Separation: Consider policies that support the separation of infrastructure within telecommunications business units. This approach can help operators focus on value-added activities and adapt to economic-financial fluctuations, ensuring sustained innovation and service quality. The telecommunications ecosystem is undergoing significant economic-financial contractions and rapid technological advancement.
13. Ensure Effective Unbundling of Networks: Monitor and support the unbundling process of network assets, such as the sale of NETCO shareholdings. Ensuring transparent and fair practices in these corporate operations can foster a competitive environment and enhance network accessibility and efficiency. The current unbundling efforts need careful oversight to ensure effective implementation and to safeguard potential market monopolization.
14. Address Security Issues from Technological and Regulatory Perspectives: Pursue security from the point of view of regulation and privacy protection, as well as incentive technology developments, such as the continuous development of secure protocol stacks in programmable networks or the adoption of inherently resilient technologies as optical networks.

Let us observe that, this notwithstanding, other key driving factors, not investigated in depth here, can be considered, such as the impact of an EU-wide cooperative industrial framework, and the role of the different stakeholders, which may have interdependencies as well as conflicts of interest, as described in Simon et al. (2023). Still, the indications provided by these strategic recommendations indicate how the telecommunications sector, especially from an Italian perspective, could achieve a balanced and forward-looking development, aligning with current trends and technological advancements while ensuring broad accessibility and innovation. An extension to more nuanced scenarios where the conflicts and trade-offs are further investigated is left for future studies. Finally, a few remarks are in order from a wider, European-level perspective. The European sector suffers from national fragmentation and a smaller number of users compared to global competitors (Letta, 2024). Strategic steps have been devised in Draghi (2024), and include, at the regulatory level, defining EU-level markets, embedding innovation and investment commitments into merger rules, and shifting from ex-ante national regulation to ex-post competition enforcement. At a technical level, measures as licence harmonization, creation of a European standard body for APIs and edge computing, and supply chains secured by prioritizing trusted suppliers can definitely bend the path towards a future development of the telecommunication sector.

In Table 3, we identify the main informed strategic steps leading to the UTOP-S future. It is worthy noting that a set of current EU initiatives explicitly address the strategic step towards UTOP-S. We summarize the main initiatives in Table 4, where we highlight that

Table 4
Current initiatives leading towards UTOP-S.

UTOP-S	Strategic step	Current initiatives
Dynamic and Collaborative Ecosystem, Leveraging Emerging Technologies	Initiatives accompanying technological evolution	European Parliament and Council of the European Union (2022a), European Commission (2016, 2024, 2020)
Strengthening Regulatory Frameworks, Policies for promoting Effective Collaboration Among Telecom Operators	Technical–regulatory paths and techno-economic effects	Body of European Regulators for Electronic Communications (2024), European Commission (2025b), 5G Infrastructure Public Private Partnership (2016), European Parliament and Council of the European Union (2018, 2021, 2023, 2024a)
Policies for Accessibility and Digital Inclusion, Promoting Digital Literacy, Robust Consumer Protection	EU regulatory roadmap and open innovation dynamics	West and Bogers (2014), European Parliament and Council of the European Union (2022f, 2023, 2019, 2022b,e), European Commission (2016), European Parliament and Council of the European Union (2022a, 2024b), Teece (2010), Zott et al. (2011), European Parliament and Council of the European Union (2022), European Union (2022), Yi et al. (2022), European Parliament and Council of the European Union (2016), Parliament and of the European Union (2024), Cave (2022)
Enhancing Cybersecurity	Security issues across the ICT ecosystem	European Commission (2025a), European Parliament and Council of the European Union (2022c, 2024b, 2019), NIS Cooperation Group (2020), European Commission and High Representative of the Union for Foreign Affairs and Security Policy (2020, 2025, 2023, 2025), European Parliament and Council of the European Union (2023d, 2022b)

they (i) have been developed in parallel to technology development, (ii) have both technical and economical effect, (iii) shape a road to open innovation, and (iv) pursue security in ICT ecosystems. In the following, we review these initiatives, a few of which have already been mentioned in Section 4, from the point of view of their strategic impact towards the UTOP-S future.

I. Initiatives accompanying technological evolution

Strategic, EU-wide digital targets (European Parliament and Council of the European Union, 2022a) link connectivity objectives, including gigabit and 5G coverage, with cloud and edge uptake, cybersecurity, and digital public services. This trajectory matches the technology development (European Commission, 2016) for spectrum assignment, deployment targets, cross-border corridors. Large-scale digital infrastructure imply (European Commission, 2024) investment analyses, and raise scale issues in fixed and mobile connectivity, as in cloud and edge capacity. Deployment in dense urban areas benefits of harmonization (European Commission, 2020) of the small cells, characteristics for lighter deployment, reduced administrative barriers to densification, and wider 5G capacity expansion.

II. Technical–regulatory paths and techno-economic effects

In TLC open development, technical evolution and market structure are closely intertwined, producing mixed technical and economic effects. Consistent application of the EU telecom framework (Body of European Regulators for Electronic Communications, 2024) addresses competition, consumer protection, net neutrality, infrastructure rollout, and emerging issues such as fiber migration or future network models. Connectivity networks investments (European Commission, 2025b) shall address scale, consolidation, copper switch-off and fiber migration, cross-border services, and governance role, with effects across market actors. On open innovation side, the 5G Infrastructure Public Private Partnership (5G Infrastructure Public Private Partnership, 2016), combining industrial policy and research funding, strengthens technology maturation and EU role in global standards, while de-risking early innovation with implications for market entry and deployment timing. A stable core framework (European Parliament and Council of the European Union, 2018) for market power, spectrum, access and interconnection, and consumer protection, shapes investment incentives and competitive dynamics, particularly for fiber and 5G rollout. Recovery and Resilience Facility (European Parliament and Council of the European Union, 2021) moves public funding towards connectivity and digital infrastructure, accelerating capital expenditure where national plans prioritize these areas, while procurement rules and conditionality influence project design and risk allocation. Horizontal measures increasingly affect telecoms ecosystems, regulating IoT data portability, cloud switching, and edge architectures (European Parliament and Council of the European Union, 2023), or addressing strategic material dependencies and supply resilience (European Parliament and Council of the European Union, 2024a), possibly affecting procurement costs for due diligence and reporting obligations.

III. EU regulatory roadmap and open innovation dynamics

European digital policy co-evolved with technology, setting boundary conditions for open innovation in ICT-intensive by knowledge flows, collaboration, and value capture (West and Bogers, 2014). From an open-innovation perspective, the policies (European Parliament and Council of the European Union, 2016, 2022f, 2023) constrain personal and industrial data access and reuse, enabling sharing arrangements and data-space architectures. Compliance and verification requirements in collaborative development and third-party dependencies (European Parliament and Council of the European Union, 2024b, 2019, 2022b,e) support the governance of distributed R&D and supply chains. The 5G Action Plan and the Digital Decade Policy Programme (European Commission, 2016; European Parliament and Council of the European Union, 2022a) promote collaborative experimentation, pilot diffusion, and coordinated deployment. Enhanced interoperability and data-sharing frameworks (European Parliament and Council of the European Union, 2019, 2024b) raise returns to broader external search, while increase coordination costs due to heightened security certification and resilience obligations. Platform governance and transparency (European Parliament and Council of the European Union, 2022; European Union, 2022) shift bargaining power and coopetitive strategies between telecom operators and large platforms, in turn favoring open innovation links. Data portability and cloud-switching provisions (European Parliament and Council of the European Union, 2023; Teece, 2010) increase the strategic relevance of edge–cloud–network integration for value capture. At the macro level regulation redirects innovation incentives towards trusted and interoperable technologies (Callegari and Nybakk, 2022), while at the micro level resilience requirements raise contracting and monitoring costs (Williamson, 1985; European Parliament and Council of the European Union, 2019, 2022e). Openness in the telecommunication ecosystem (Yi et al., 2022) leverages integration capabilities and modular architectures (Dahlander and Gann, 2010; West and Bogers, 2014). Also public-sector interoperability initiatives increase returns to standardized interfaces and reference architectures (European Parliament and Council of the European Union, 2016, 2022f; Parliament and of the European Union, 2024), and legal harmonization potentially reduces innovation complexity (Cave, 2022). Political-economy in platform regulation and critical-infrastructure security (European Parliament and Council of the European Union, 2022,b) affect outcomes of telecom operators and new entrants by reshaping bargaining power, data access, interoperability, and value capture, e.g. due to compliance costs.

IV. Security issues across the ICT ecosystem

ICT security spans technical cybersecurity and resilience, economic security, and strategic dependencies. The resilience in the face of geopolitical and technological turbulence [European Commission, 2025a]encompasses robust digital infrastructure, trusted supply, and security-by-design. Beyond cyber controls, resilience strengthening (European Parliament and Council of the European Union, 2022c) mandates minimum continuity planning requirements that integrate physical and cyber risk management and map interdependencies, including digital assets. Lifecycle cybersecurity requirements (European Parliament and Council of the European Union, 2024b) for products with digital elements directly affect telecom supply chains such as network equipment and embedded software; EU-level certification schemes (European Parliament and Council of the European Union, 2019) assure conformity evidence affect procurement and cross-border trust. The EU 5G Toolbox (NIS Cooperation Group, 2020) establishes a coordinated set of mitigation measures for 5G risks, e.g. supplier risk, governance, and technical controls across core and RAN domains; policies shift towards security-by-design and closer cooperation for critical connectivity ecosystems (European Commission and High Representative of the Union for Foreign Affairs and Security Policy, 2020). Furthermore, telecommunications and digital infrastructure are economically strategic assets exposed to external dependencies. The risk-based approach (European Commission and High Representative of the Union for Foreign Affairs and Security Policy, 2023) focuses on competitiveness, protection, and partnerships, with direct implications through supply-chain risk management (equipment, semiconductors, and advanced technologies), investment screening, and controls of dual-use capabilities. Strategic dependencies such as chips, cloud, subsea infrastructure and critical components, require diversification, monitoring, and assurance in expansion and sourcing decisions (European Commission and High Representative of the Union for Foreign Affairs and Security Policy, 2025). Semiconductor ecosystem and security of supply (European Parliament and Council of the European Union, 2023d) affects telecom network equipment availability, edge computing capacity, and long-term resilience of the digital infrastructure supply chain. An EU-wide baseline (European Parliament and Council of the European Union, 2022b) for cybersecurity risk management, incident reporting, and oversight across critical sectors, includes obligations on governance, resilience, and supply-chain controls for telecom operators and key suppliers. The integrated regulatory regime leads to telecom security outcomes depending on network controls, certified assurance practices, critical-entity resilience planning, and strategic dependency management.

Table A.5
Survey questions for building the Horizon 3 scenarios.

MARKET	How could the competitive landscape of telecommunications in Italy evolve to foster greater dynamism and innovation? In what ways could accessibility and digital inclusion be promoted through initiatives in the telecommunications sector? How could the emergence of monopolies or oligopolies limit innovation and the provision of diversified telecommunications services in Italy? How could the increase in economic inequality affect access to telecommunications services and digital inclusion in Italy?
TECHNOLOGY	Which emerging technologies could contribute to improving the efficiency and reliability of telecommunications networks in Italy? How could technological innovation promote greater security and data protection within the telecommunications ecosystem? What are the potential threats to the security of telecommunications networks in Italy in a context of increasing cybercrime and computer vulnerabilities? How could automation and artificial intelligence lead to job losses in the telecommunications sector, resulting in negative social impacts?
REGULATION	How could privacy regulations and data protection be strengthened to ensure user trust in the services offered? What regulatory measures could promote transparency and accountability among telecommunications companies towards Italian consumers? What are the potential consequences of poorly regulated technology in the telecommunications sector, including compliance issues and legal liability? What could be the consequences of a reactive regulatory approach rather than a proactive one in the context of telecommunications in Italy, considering potential emerging risks and threats?

6. Conclusion

The study has examined the Italian telecommunications ecosystem by integrating expert-based scenario building with a structured review of technological, market, and regulatory developments. The combined analysis has clarified how current conditions and major transformation trends could evolve into two contrasting futures for 2040, highlighting the strategic choices at stake. Assessments of market dynamics, enabling technologies, and regulatory trajectories — framed within both Italian and European contexts — show how innovation, sustainability, and AI integration may either accelerate progress or widen existing gaps. The resulting boundary scenarios, one inclusive and innovation-driven and the other marked by stagnation and digital inequality, provide a structured basis for strategic orientation. Building on these insights, the paper identifies policy and industry measures that can guide the ecosystem towards the preferable pathway and align national actions with emerging European regulatory and technological directions.

CRediT authorship contribution statement

Giovanni Emanuele Corazza: Writing – original draft, Methodology, Conceptualization. **Ilaria Rinaldi:** Writing – original draft, Methodology, Writing – review & editing. **Irene Coletto:** Writing – review & editing. **Mario Mirabile:** Writing – review & editing. **Sara Mazzarella:** Writing – original draft, Investigation. **Francesca**

Parasecolo: Investigation. **Andrea Baiocchi:** Writing – original draft, Investigation, Writing – review & editing. **Stefania Colonnese:** Writing – review & editing, Writing – original draft, Investigation. **Paola Panarese:** Investigation. **Mert Yildiz:** Writing – review & editing, Writing – original draft, Formal analysis. **Cristina Costa:** Data curation. **Giovanna De Minico:** Writing – original draft, Methodology. **Fulvia Abbondante:** Investigation. **Maria Francesca De Tullio:** Investigation. **Maria Chiara Girardi:** Investigation. **Stefania Parisi:** Investigation. **Stefania Serafini:** Investigation. **Ilenia Tinnirello:** Writing – original draft, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giovanni Emanuele Corazza, Ilaria Rinaldi, Irene Coletto, Mario Mirabile, Sara Mazzarella, Francesca Parasecolo, Andrea Baiocchi, Stefania Colonnese, Paola Panarese, Mert Yildiz, Cristina Costa, Giovanna De Minico, Fulvia Abbondante, Maria Francesca De Tullio, Maria Chiara Girardi, Stefania Parisi, Stefania Serafini, Ilenia Tinnirello report financial support was provided by the European Union - Next Generation EU under the Italian National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3, partnership on "Telecommunications of the Future" (PE00000001 - program "RESTART") in the Net4Future project. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Survey methodology

The scenario-building process was inspired by the Three Horizons framework, which was adopted as an organizing logic rather than as a rigid procedural method. The scenario-building process was inspired by the Three Horizons framework, which was adopted as an organizing logic rather than as a rigid procedural method. In this study, Horizon 1 is informed by the analysis of the current state of the telecommunications ecosystem presented in the preceding sections of the paper, Horizon 2 stems from the identification of emerging trends and drivers across market, technological, and regulatory dimensions. Horizon 3 is constructed by synthesizing the insights through a forward-looking expert elicitation process.

As for the construction of the two scenarios, a few remarks are in order. Generally speaking, the Nominal Group Technique is a forecasting method that elicits expert judgments through individual idea generation and controlled group discussion, producing consensus-based future assessments. As a preliminary study, we carried out the scenario building by surveying the 20 faculty members, and domain experts, who contributed to the study of Horizon 1 and 2, inviting them to reflect on Horizon 3 developments of their studies, through targeted question referring to long-term challenges, opportunities, and policy levers. In order to reflect the relevant topics addressed in the paper, the survey was organized in three sections, related to (i) market, (ii) technology, (iii) regulation. For these topics we posed questions aimed at devising possible actions and trends, and reported in Table A.5.

The survey was carried out online. After collecting the results, we skimmed 110 answers to extract more relevant observations, we ranked them on the base their frequency of occurrence, identifying the main topics, while still accounting also for minority observations in our final scenarios descriptions. Finally, the expert insights were integrated with the literature review, the analysis of the current system and the emerging trends to inform the construction of the two boundary future scenarios, representing alternative long-term configurations of the telecommunications ecosystem. The surveying study was further extended to a larger set of experts, with in presence and online interviews to identify further leading topics and provide an extended study of Horizon 3. The results of these studies fall out of the scope of this paper, which balances contribution about the three horizons; their detailed analysis is left for future work.

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