Partnership Research Program: Scientific Studies on Connectivity – Knowledge Synthesis

I. Introduction

In an era of unprecedented digital transformation, connectivity is the cornerstone of economic growth, social progress, and the advancement of artificial intelligence (AI). Reliable internet access and advanced communication technologies are no longer optional; they are essential drivers of productivity and innovation across key sectors such as education, healthcare, and smart infrastructure. Yet, remote and underserved areas of Québec still face connectivity barriers, constrained by geographical and economic challenges.

Recognizing these persistent barriers, the Government of Québec has introduced the *Partnership Research Program: Scientific Studies on Connectivity – Knowledge Synthesis*. This forward-thinking initiative not only aims to enhance high-speed internet coverage and next-generation communication services but also drives the development of emerging technologies through policy-driven investments and infrastructure optimization. By fostering technological innovation and spurring economic growth, this program aspires to secure Québec's competitive edge in the rapidly evolving global digital landscape.

Despite these concerted efforts, critical obstacles remain. These include insufficient investment in research and development, inefficiencies in infrastructure coordination, and concerns over the equitable distribution of technological benefits [1]–[3]. Preserving Québec's leadership in the international digital economy requires a balanced approach that advances cutting-edge solutions while safeguarding broader societal interests. Through an in-depth analysis of **technological advancements** and **societal impact**, this study aims to fortify Québec's strategic objectives and pave the way for sustained inclusive growth.

II. Technological

In the context of global digital transformation, connectivity technologies have become a pillar for enabling efficient communication and seamless data exchange. Innovative technologies are redefining the future of this field by addressing growing demands for speed, coverage, and reliability.

A. *What are the emerging technologies in the field of connectivity?*

Emerging connectivity technologies are advancing in wide-area communication, intelligent optimization, short-range communication, and future network architectures, enhancing coverage, efficiency, and adaptability. This section explores their strategic importance and potential to drive connectivity advancements.

1) Wide-Area Communication

Low Earth Orbit (LEO) satellite networks enhance global connectivity, particularly in remote and underserved regions where terrestrial networks are insufficient. Operating at 500 to 2,000 kilometers [4], LEO satellites provide low latency (20–40 ms) and high-speed communication [5], supporting applications such as telemedicine, financial transactions, and real-time navigation. Their constellation-based deployment ensures redundancy and reliable coverage across vast areas [6].

Meanwhile, 5G and 6G networks are transforming wide-area communication with high bandwidth, ultra-low latency, and massive connectivity. 5G, driven by extensive small cell deployment, supports speeds of 100 Mbps to 1 Gbps [7]. In Canada, Québec is at the forefront of 5G expansion, fostering smart cities and autonomous vehicle ecosystems [8]. Looking ahead, 6G will further enhance global connectivity through terahertz (THz) communication and sub-millisecond latency [9], with initiatives like Hexa-X and Telesat exploring its potential to bridge connectivity gaps [10], [11].

2) Short-Range Communication

Short-range communication technologies are evolving to meet increasing demands for high-speed, low-latency, and interference-resistant connectivity in localized environments. Wi-Fi 7, the next-generation

WLAN standard, introduces 320 MHz channels, 4096-QAM modulation, and multi-link operation (MLO) to significantly enhance throughput and network efficiency [12]. With speeds exceeding 40 Gbps, Wi-Fi 7 is poised to support data-intensive applications such as real-time VR and industrial automation.

Meanwhile, Li-Fi, a visible light communication (VLC) technology, is emerging as a complementary alternative to radio-frequency-based wireless networks. By leveraging LEDs for high-speed optical transmission, Li-Fi achieves speeds surpassing 100 Gbps, while offering reduced electromagnetic interference and enhanced security [13]. Its potential applications span hospitals, aircraft cabins, and high-density urban environments, where RF-based networks face limitations.

3) Intelligent Optimization

Intelligent optimization is revolutionizing network management by enabling real-time adaptability, efficient resource allocation, and predictive analytics. AI-driven networks leverage machine learning and deep learning to enhance traffic management, optimize spectrum utilization, and dynamically adjust network parameters [14]. In 5G and emerging 6G networks, AI-powered self-optimizing mechanisms improve latency, reliability, and energy efficiency, making networks more resilient to dynamic conditions.

A key enabler of intelligent optimization is network slicing, which allows networks to be partitioned into multiple virtual segments tailored to specific applications, from ultra-reliable low-latency communication (URLLC) to massive IoT connectivity [15]. Meanwhile, holographic beamforming enhances wireless efficiency by intelligently directing signals based on user movement and environmental factors [16]. These technologies, driven by AI, are shaping the future of autonomous and self-optimizing connectivity systems, ensuring seamless, high-performance communication across diverse applications.

4) Future Network Architectures

Future network architectures are evolving to enhance intelligence, adaptability, and real-time optimization. Digital Twin Networks (DTN) have emerged as a transformative technology, accurately mapping physical networks into virtual spaces for improved resource allocation and topology optimization [17]. In LEO satellite and 6G networks, DTN constructs comprehensive network views, simulating scenarios to improve connectivity and operational efficiency [18], [19]. Its adaptability spans industries, including healthcare, manufacturing, and telecommunications, enabling real-time adjustments to dynamic environments.

Expanding on this, Human Digital Twin (HDT) integrates smart healthcare, personalized services, and human-machine interaction [20]. By virtually modeling physiological and behavioral states, HDT enables seamless connectivity between humans, devices, and networks [21], [22]. Aligned with Québec's emphasis on AI and edge computing, our research explores how HDT enhances resource distribution and intelligent algorithms, advancing smart cities and remote healthcare solutions [23].

B. What is the potential of satellite technologies and their evolution prospects over a 1-to-10-year horizon?

Satellite technology is poised for significant advancements over the next decade, driving global connectivity, economic feasibility, and seamless integration with terrestrial networks. Over the 1-to-10-year horizon, key innovations—including laser inter-satellite links (LISLs), multi-orbit collaboration, and AI-driven network optimization—are set to reshape the satellite industry, enhancing performance, flexibility, and cost-effectiveness.

1) Current Landscape and Technological Foundations

Geostationary Earth Orbit (GEO) satellites, enabled by High Throughput Satellite (HTS) technology, continue to support navigation, weather monitoring, and high-bandwidth fixed-region communications [24], [25]. Meanwhile, Medium Earth Orbit (MEO) satellites play a critical role in positioning, timing, and navigation systems such as GPS, Galileo, and GLONASS [26].

However, the most transformative developments have occurred in Low Earth Orbit (LEO) satellite networks, which are rapidly expanding due to their low latency and high coverage density [27]. LEO constellations are particularly beneficial for Québec's northern communities and resource development areas, where traditional terrestrial infrastructure is economically unviable.

2) Technological Advancements and Future Performance Gains

Over the next five to ten years, the evolution of satellite networks will be driven by three major technological breakthroughs:

- **LISLs**: By enabling high-speed optical communication between satellites, LISLs will reduce reliance on ground stations, lower latency, and significantly increase network capacity and reliability [28]. Starlink V1.5 satellites have already begun leveraging LISLs to ensure stable global coverage, even in regions lacking ground infrastructure [29].
- **Multi-Orbit Collaboration (LEO-MEO-GEO)**: Over the next decade, integrated satellite architectures will become more dynamic, enabling real-time adjustments to coverage and capacity based on geographic and demand-driven factors [30].
- **AI-Driven Satellite Network Optimization**: Machine learning algorithms will dynamically optimize satellite routing, spectrum allocation, and network load balancing, leading to higher efficiency and more adaptive coverage across orbits [31].

These advancements will enable seamless high-speed, low-latency communication, ensuring global, flexible, and resilient connectivity solutions for both urban and remote environments.

3) Economic Viability and Deployment Feasibility

The economic case for satellite deployment is strengthening, particularly in regions where fiber-optic networks are prohibitive due to challenging terrain and extreme weather. LEO satellite constellations, exemplified by Starlink [29], have demonstrated industrial success by delivering low-latency, high-speed broadband to underserved areas, reducing dependence on extensive ground-based infrastructure [28]. In high-latitude regions like Québec, expanding satellite connectivity not only addresses communication gaps but also drives economic growth by supporting resource industries, smart infrastructure, and remote business operations. By enabling stable digital access for enterprises and public services, satellite technology plays a crucial role in fostering regional development, innovation, and long-term economic resilience.

4) Market Projections and Growth Potential

The satellite industry is poised for significant growth over the next decade, with global satellite capacity supply projected to increase by 30% by 2033, driven by the continued dominance of LEO satellite networks in global broadband expansion. The cumulative revenue of the global space industry is expected to reach $1.7 trillion by 2032, largely fueled by demand from remote and hard-to-reach areas [32]. Within Canada, Québec's unique geographic and economic positioning presents a strategic opportunity, as LEO networks expand to support northern resource sectors and Indigenous communities, bridging connectivity gaps in underserved regions.

5) Seamless Satellite-Terrestrial Network Integration

The next decade will see the emergence of a fully integrated satellite-terrestrial network, where LEO, MEO, and GEO satellites seamlessly converge with fiber-optic and cellular infrastructure, creating a unified communication ecosystem. GEO satellites will support high-bandwidth applications such as telemedicine and disaster response, while LEO satellites will enable low-latency services for real-time remote operations and cloud computing. Additionally, AI-driven multi-orbit switching will allow devices to intelligently transition between satellite and terrestrial networks based on real-time demand, ensuring seamless connectivity across diverse environments and optimizing network efficiency.

C. What are the best technologies to support the current and future connectivity needs of the population, including businesses, in terms of connectivity?

As the demand for seamless, high-speed, and reliable connectivity continues to grow—driven by smart cities, data-intensive industries, and the push for inclusivity—transformative technologies are essential to meet diverse needs and environments. Connectivity requirements vary significantly across urban centers, rural and remote communities, and industries. Addressing these needs effectively requires tailored technologies and solutions for each segment:

1) Urban Users

Urban areas are defined by their high population density, well-developed infrastructure, and increasing reliance on high-speed, reliable connectivity to support their dynamic ecosystems. These regions face growing demands driven by smart city initiatives, data-intensive applications, and the expanding use of Internet of Things (IoT) devices in daily life. Key technologies include:

- **5G and 6G Networks**: Ultra-fast 5G networks are transforming urban connectivity, enabling autonomous vehicles [8], AR/VR, and large-scale IoT deployments [33]. For Québec, advancing 5G infrastructure is vital to fostering innovation and economic growth. Looking ahead, investment in 6G technologies, including terahertz communications and AI-driven optimization [9], will position Québec as a leader in digital connectivity and smart city development.
- **Wi-Fi 7**: As demand for high-speed wireless access grows, Wi-Fi 7 provides an essential complement to cellular networks, delivering improved spectral efficiency, reduced congestion, and ultra-fast indoor connectivity. Its multi-link operation (MLO) and enhanced modulation schemes make it ideal for dense urban environments, ensuring low-latency communication in office buildings, transportation hubs, and public spaces [12].
- **Li-Fi**: Utilizing light waves instead of radio frequencies, Li-Fi offers an alternative for secure, high-speed data transmission in bandwidth-constrained environments [13]. Its ability to function in RF-sensitive areas such as hospitals, aircraft cabins, and industrial automation makes it a strategic addition to urban networks, reducing spectrum congestion while enhancing data privacy.

2) Rural and Remote Communities

Rural and remote areas face connectivity challenges due to sparse populations, vast distances, and high fiber deployment costs. In Québec, 50/10 Mbps access covers 76.88% of rural areas vs. 99.74% in urban regions, with First Nations reserves at 66.70%, highlighting a persistent digital divide [1]–[3]. Key technologies to address these gaps include:

- **LEO Satellite Networks**: LEO satellite networks provide broad, stable, and low-latency coverage, making them ideal for addressing connectivity challenges in Québec's rural and remote regions [5]. By investing in LEO deployment and advanced technologies like inter-satellite laser links, Québec can bridge the digital divide, enable access to essential services such as telemedicine and online education, and support economic growth in underserved areas.
- **Multi-Orbit Satellite Systems**: Multi-orbit satellite systems ensures reliable connectivity across urban, rural, and remote areas [30], fostering economic growth and bridging the digital divide while positioning Québec as a leader in advanced communications.

3) Business Users

Businesses, from small enterprises to large industrial players, rely on secure, high-performance, and efficient networks to support their operations and drive growth. Technologies tailored for business users include:

- **Digital Twins**: Digital Twin technology relies on high-speed connectivity to create real-time virtual replicas of physical assets, enabling precise monitoring and process optimization. For Québec, it offers a path to boost innovation and efficiency in key industries, driving economic growth.

- **AI-driven Networks**: AI-driven networks optimize traffic management, resource allocation, and adaptability, ensuring efficient, low-latency, and reliable connectivity for industrial automation, cloud computing, and digital services. As businesses increasingly depend on real-time data, AI-powered networking will be essential for delivering scalable and high-performance solutions.

D. To what extent will it be necessary to continue investments in terrestrial infrastructure considering the rapid evolution of satellite and other emerging technologies?

Amid the rapid transformation of global communication technologies, the rise of satellites and other emerging innovations presents both unprecedented opportunities and challenges for the development of digital infrastructure. For Québec, striking a strategic balance between terrestrial infrastructure and cutting-edge technologies is not only pivotal to shaping the future of its digital economy but also crucial for securing its position in the global technology landscape.

1) Complementarity of Terrestrial and Satellite Technologies

Satellite technologies, such as low Earth orbit (LEO) satellites, offer significant advantages in providing connectivity to remote or underserved areas, particularly in Québec's northern regions where terrestrial infrastructure is costly or challenging to deploy [27]. However, satellites face limitations in handling high-density urban traffic and low-latency applications due to bandwidth constraints and inherent delays. As a result, in Québec's urban centers and industrial hubs, terrestrial networks—particularly fiber and 5G infrastructure—remain essential components of the province's connectivity strategy.

2) Technological Limitations and Transitional Needs

Although satellite technologies are advancing rapidly, they still face technical limitations that prevent them from fully replacing terrestrial infrastructure. For example, satellite networks struggle to meet the demands of large-scale device connectivity, high reliability, and low-latency requirements [34], which are critical for industrial applications and smart city initiatives in Québec's urban and suburban regions. Until these technologies achieve greater maturity, terrestrial networks will remain essential to supporting the province's economic growth and technological innovation.

3) Québec's Strategic Priorities

For Québec, continued investment in terrestrial infrastructure not only addresses the immediate connectivity needs of urban and industrial sectors but also lays a solid foundation for the integration of future technologies. In the short term, investment should prioritize terrestrial networks, as urban centers and industrial users require robust and reliable connectivity. Mature terrestrial systems, such as existing 5G and upcoming 6G networks, provide higher data rates and lower latency compared to current satellite offerings [9], [33]. According to the Canadian Radio-television and Telecommunications Commission (CRTC), expanding access to high-speed internet is a key priority for fostering economic growth and ensuring equitable access to digital services across all regions [35].

Looking ahead, rapid technological advancements may significantly reshape the telecommunications landscape. Emerging satellite technologies, including LEO, MEO, and GEO networks, are poised to offer competitive speed and reliability, potentially challenging terrestrial services [28], [30]. Moreover, the sustainability advantages of satellite networks, such as reduced environmental impact and global coverage capabilities, are likely to gain increasing importance. Given Québec's vast geography, adopting a hybrid approach that combines terrestrial networks with satellite technologies is a highly efficient way to achieve province-wide digital connectivity while meeting the diverse needs of different regions.

E. Should aluminum (or other materials) be preferred over steel for the construction of terrestrial cellular sites to accelerate construction, reduce costs, and address extreme weather events?

In the construction of modern telecommunications infrastructure, material selection transcends technical decision-making to encompass strategic considerations of construction efficiency, economic feasibility, and environmental adaptability. Within the context of Québec's commitment to advancing both digital transformation and sustainable development, optimizing the choice between aluminum and steel for terrestrial cellular sites holds profound implications—not only for accelerating deployment but also for enhancing network resilience and reducing operational costs.

1) Material Properties

Aluminum is lightweight, corrosion-resistant, and easier to transport and handle, making it particularly suitable for regions with high humidity, high salinity (e.g., coastal areas), or areas where transportation costs are significant. Its malleability allows for easier on-site assembly, potentially accelerating construction timelines [36], [37]. Steel offers superior tensile strength and load-bearing capacity, making it an ideal choice for sites exposed to strong winds, heavy snow, or seismic activity. Galvanized steel can resist corrosion effectively, though it may require more maintenance in highly corrosive environments [38].

2) Cost Considerations

The initial cost of aluminum is typically higher than steel [39]. However, its lighter weight significantly reduces transportation and installation expenses. Over the long term, aluminum's low maintenance in corrosive environments may offset its higher upfront cost. Steel, by contrast, has a lower initial cost but may require additional anti-corrosion treatments and ongoing maintenance in harsh environments, which could increase its total cost of ownership over time.

3) Material Suitability by Region

Steel's higher strength makes it better suited to withstand extreme weather conditions such as hurricanes or heavy snow, both of which are relevant to the climate in certain regions of Québec. Therefore, in urban or suburban areas requiring high load-bearing capacity, steel is likely the more appropriate choice for cellular site construction. Conversely, in remote regions, corrosive environments, or scenarios demanding rapid deployment, aluminum's lightweight, corrosion resistance, and ease of handling make it a more advantageous option.

4) Deployment Efficiency

The lightweight nature of aluminum enhances its transportability and ease of handling, enabling streamlined and efficient construction processes. This advantage is particularly significant for Québec, given the province's vast and diverse geography, including remote and northern regions where traditional infrastructure deployment can face considerable challenges. This supports the province's goals of accelerating network expansion, bridging connectivity gaps, and fostering economic development through resilient telecommunications infrastructure.

5) Sustainability

Aluminum is highly recyclable and environmentally friendly, though its production is energy-intensive [40]. For Québec, prioritizing materials with high recyclability aligns with the province's commitment to sustainability and reducing environmental impact, particularly as it seeks to balance industrial growth with its ambitious climate goals.

F. How can the maximum territory be covered with high-quality signals at the best cost?

Maximizing territory coverage with high-quality signals while ensuring cost efficiency requires a strategic blend of technologies, tailored deployment, and resource optimization to adapt to diverse geographical and demographic conditions.

1) Multi-Technology Integration

Combining Multi-Orbit Satellite Systems and 5G/6G technologies establishes a robust and comprehensive network infrastructure. Multi-Orbit Satellite Systems, encompassing both low and medium Earth orbit satellites [30], ensure foundational connectivity for remote and underserved regions, effectively bridging the digital divide. Meanwhile, 5G and 6G technologies provide high-speed, low-latency connectivity in urban centers and densely populated areas [9], [33], enabling advanced applications and fostering innovation.

2) Dynamic Resource Allocation

Incorporating advanced network optimization algorithms, such as genetic algorithms, particle swarm optimization, and reinforcement learning [41], can enhance the deployment of base stations and satellite systems. These algorithms optimize placement based on factors like population density, geographic constraints, and traffic demand, ensuring efficient coverage, reduced latency, and optimal resource allocation.

3) User Demand Analysis

Conducting detailed analyses of user demand across regions is essential for identifying areas with high and low connectivity needs. By leveraging digital twin technology, user behavior can be accurately simulated and analyzed, offering valuable insights to support network optimization [42], [43]. These insights enable more informed decision-making, helping to prioritize infrastructure investments and optimize technology deployment strategies, ultimately achieving an optimal balance between cost and coverage.

4) Partnerships

Encouraging partnerships between businesses and local governments to jointly invest in infrastructure development can significantly enhance connectivity. For example, companies can take responsibility for maintaining and managing LEO satellites within their areas of expertise, enabling cost-sharing for launch and maintenance while ensuring high-quality service across various sectors. Such collaborative efforts effectively expand satellite communication coverage, particularly in remote and hard-to-reach regions, fostering greater accessibility and efficiency.

5) Phased Deployment Strategy

A phased deployment strategy reduces costs by prioritizing high-need areas first, such as remote communities and key industrial zones, before gradual expansion. This approach optimizes resource allocation, minimizes financial risks, and allows for continuous improvements, ensuring efficient and sustainable connectivity expansion.

III. Social Impacts

A. Are the social impacts of connectivity well-documented?

The social impacts of connectivity are well-documented, particularly in driving economic growth, education, and healthcare. However, gaps remain in addressing the digital divide and understanding long-term societal effects. In Québec, connectivity is vital for bridging regional disparities and enhancing public services, though challenges persist in ensuring equitable access and leveraging new technologies.

1) Well-Documented Social Impacts

In Québec, connectivity has driven significant advancements across education, employment, and healthcare. Initiatives like the Digital Campus program have equipped schools with digital tools and resources, enhancing classroom engagement and learning outcomes. Universities such as Concordia University have expanded online courses, enabling students from remote regions, including Indigenous communities in northern Québec, to access quality education without relocating [44], [45].

In employment, connectivity has facilitated remote work and digital skills development, particularly during the COVID-19 pandemic. Flexible work arrangements adopted by companies in Montreal have allowed employees to maintain productivity, while programs launched by the Commission des partenaires du marché du travail provide digital skills training, enabling rural residents to access job opportunities previously out of reach [46].

In healthcare, telemedicine networks have connected patients in remote areas with healthcare providers through virtual consultations, reducing the need for long travel and improving access to essential medical services [47]. By enabling timely consultations, telemedicine has also contributed to better health outcomes and reduced the strain on overburdened healthcare facilities.

2) Areas Requiring Further Exploration

While many social impacts of connectivity are well-documented, certain areas remain underexplored. For example, the long-term psychological and societal effects of pervasive digital connectivity, such as digital addiction, mental health challenges, and changes in interpersonal dynamics, require further investigation. These aspects are critical to understanding the broader implications of a hyper-connected society.

In addition, the impacts of emerging technologies like 6G, LEO satellites, and digital twins have yet to be fully documented. Questions surrounding privacy, equity, and the societal shifts caused by these innovations highlight the need for comprehensive research to ensure their benefits are maximized without unintended consequences.

3) Québec's Unique Context

As a province with vast rural areas, remote northern regions, and dynamic urban centers, Québec provides a unique setting for examining how connectivity transforms societies in diverse contexts. In urban areas like Montréal, the role of connectivity in driving innovation, economic growth, and public services is well-documented, showcasing the benefits of advanced infrastructure and technologies. However, in rural and northern regions, including Indigenous communities, the societal impacts of connectivity—such as improving access to education, healthcare, and economic opportunities—remain less thoroughly documented, particularly in addressing regional disparities and preserving cultural heritage.

Moreover, Québec's strong Francophone identity and distinct cultural dynamics add further complexity to how connectivity shapes societal outcomes. While these unique factors demand tailored strategies, limited research has been conducted on the role of digital tools in supporting cultural sustainability, social cohesion, and inclusivity across the province's diverse communities.

B. Does connectivity help reduce social inequalities, or does it accentuate them?

Social inequality remains one of the most pressing challenges of modern society. Connectivity, as a driving force of the digital age, offers a transformative pathway toward building a more equitable social structure. By breaking down barriers of geography and access to information, connectivity creates new opportunities for resource distribution and broader participation, particularly for marginalized groups.

1) Access to Opportunities

Connectivity significantly enhances opportunities for residents in remote areas by providing broader access to digital resources. In education, platforms like École en réseau[1] allow students in remote and Indigenous communities in Quebec to access quality teaching through online courses and virtual classrooms, breaking geographic barriers. In healthcare, telemedicine has become a critical development in northern Quebec. Initiatives such as the Réseau québécois de la télésanté[2] enable residents to access professional medical support via digital health tools and virtual consultations without the need for long-distance travel.

In employment, connectivity opens new possibilities for remote communities. For example, agricultural and artisanal producers in northern Quebec can market their products nationally and globally through e-commerce platforms. Additionally, the rise of remote work enables residents to participate in the knowledge

[1] École en réseau, https://eer.qc.ca/

[2] Réseau québécois de la télésanté, https://telesantequebec.ca/

economy and secure well-paying jobs without relocating to urban centers.

2) Economic Development

By promoting the digital economy, connectivity has created new sources of income and development opportunities for remote and economically disadvantaged communities. In Quebec, the digital economy is revitalizing underdeveloped regions in various ways. For example, local e-commerce platforms like Maturin[3] provide opportunities for showcasing and selling agricultural and specialty products, helping rural producers reach a broader customer base.

In addition, the rise of remote work has brought entirely new employment opportunities to residents in remote areas. In recent years, the Quebec government has supported infrastructure development, significantly improving network coverage in rural and remote areas. This has enabled residents in these regions to participate in knowledge-intensive industries or provide professional services through remote work without having to leave their hometowns.

3) Social Inclusion

High-quality communication technologies play a significant role in enhancing social inclusion by bringing marginalized groups closer to mainstream society. On one hand, social networks provide a platform for vulnerable groups to participate in social activities, express their opinions, and establish connections. On the other hand, online support networks make it easier for individuals with disabilities, senior citizens, and other vulnerable groups to access psychological support, medical consultations, and career guidance. Additionally, governments and nonprofit organizations, such as through initiatives like Canada's Digital Charter [48] program in Canada, employ digital tools to foster social inclusion by offering online skills training programs that enable disadvantaged groups to better adapt to the digital age.

4) Information Equity

Connectivity ensures equal access to information, from government policies to market trends and cultural resources, helping disadvantaged groups stay informed. It bridges the information gap for remote and low-income communities while enabling marginalized groups to participate in knowledge-sharing and innovation, empowering them as contributors to societal progress.

C. How can connectivity foster scientific, economic, and social development?

Connectivity is a transformative driver of progress, empowering Quebec to enhance scientific collaboration and resource integration, foster economic innovation and high-value employment, and revolutionize access to education and social services. By addressing immediate demands while paving the way for a sustainable and inclusive future, connectivity emerges as a foundational pillar for holistic development in the region.

1) Scientific Development

Connectivity is the cornerstone of modern scientific progress, breaking down barriers to collaboration and enabling institutions to pool their expertise and resources seamlessly. In Quebec, this interconnected infrastructure empowers researchers to tackle complex, multidisciplinary challenges with transformative potential. For example, initiatives like the Canadian Institute for Advanced Research (CIFAR)[4] foster global partnerships that drive innovation in critical domains such as health and environmental science. Similarly, Concordia University's collaborative projects on climate resilience (C-CCAL)[5] demonstrate how connectivity unlocks impactful scientific breakthroughs. By facilitating access to vast datasets and state-of-the-art research tools, connectivity accelerates discovery and propels advancements in areas of global importance.

[3] Maturin, www.maturin.ca
[4] CIFAR, https://cifar.ca/
[5] C-CCAL, https://www.climatechangeadaptationlab.ca/

2) Economic Development

Connectivity has reshaped Quebec's economic landscape, fostering a vibrant tech ecosystem that competes globally. High-speed internet access enables startups to innovate and scale, creating a fertile environment for entrepreneurship. This connectivity not only drives the growth of emerging businesses but also attracts investment and talent to the region. For example, Mila, the Montreal Institute for Artificial Intelligence, has become a global hub for AI research, with its partnerships accelerating the commercialization of cutting-edge technologies in sectors like healthcare and natural language processing. By enabling businesses to access international markets and attract foreign investments, connectivity fuels innovation, generates high-value jobs, and strengthens Quebec's economic competitiveness.

3) Social Development

Connectivity has transformed access to education and social services in Quebec, particularly benefiting underserved communities. By integrating online learning tools, students in remote areas, including Indigenous communities, can now access high-quality educational resources that were previously out of reach [44]. This advancement fosters educational equity by ensuring that all students, regardless of geographic location, have the opportunity to succeed. Moreover, digital platforms like Service Quebec have streamlined access to government services, allowing residents to efficiently apply for permits and access social support. These innovations promote greater civic engagement while ensuring that marginalized communities receive the assistance they need, thereby enhancing inclusivity and social well-being.

D. Are there specific impacts on First Nations and northern communities?

Connectivity has the potential to transform the lives of First Nations and northern communities by addressing longstanding challenges of isolation and limited access to resources. In these regions, digital technologies serve as a bridge, enabling access to essential services, preserving cultural heritage, and fostering economic opportunities.

1) Positive Opportunities

Connectivity empowers Indigenous and northern communities to access essential services, including telemedicine, online education, and government programs. Telemedicine, in particular, plays a critical role in these regions by enabling residents to consult medical specialists remotely, eliminating the need for long-distance travel and significantly enhancing access to healthcare services.

Digital platforms serve as powerful tools for Indigenous communities to safeguard and celebrate their languages, traditions, and stories. Groundbreaking initiatives like FirstVoices[6] leverage technology to document and revitalize Indigenous languages, ensuring the preservation of cultural heritage for future generations. Similarly, Sandra Cespedes' visionary "Eagle and the Condor" project exemplifies the transformative potential of digital equity, empowering Indigenous communities with cutting-edge technological solutions to bridge historical divides and foster cultural resilience in the digital age [49].

Connectivity has created new opportunities for economic activities such as e-commerce and remote work, enabling Indigenous communities and residents of remote areas to access broader markets. For instance, local crafts and agricultural products can be sold nationwide and even globally through e-commerce platforms, improving economic conditions.

2) Ongoing Challenges

Despite improvements in connectivity, many Indigenous communities and remote regions still lack reliable internet access. For example, in northern Canada, some communities experience internet speeds far below the national average, and others lack broadband coverage entirely [50]. The absence of infrastructure limits these communities' ability to fully participate in the digital economy.

Some Indigenous communities face challenges in adopting digital technologies, particularly among older

[6]FirstVoices, https://www.firstvoices.com

adults and those with lower levels of education. A lack of digital skills hinders their ability to leverage opportunities in e-commerce, remote work, or online services.

Many digital tools and platforms fail to adequately support Indigenous languages and cultural contexts, creating additional barriers for these communities when using technology. The needs and perspectives of Indigenous people are often overlooked in the design of technological solutions.

Due to geographic isolation and long-standing social exclusion, some communities may be skeptical about the introduction of new technologies and lack trust in their implementation. Cultural mistrust and historical experiences of exploitation can lead to reservations about adopting digital technologies.

REFERENCES

[1] Innovation, Science and Economic Development Canada, "Canada's connectivity strategy," 2019. [Online]. Available: https://ised-isde.canada.ca/site/high-speed-internet-canada/en/canadas-connectivity-strategy

[2] Canadian Radio-television and Telecommunications Commission, "Broadband fund: Closing the digital divide in canada," 2025. [Online]. Available: https://crtc.gc.ca/eng/internet/internet.htm

[3] O. of the Auditor General of Canada, "Connectivity in rural and remote areas: Internet coverage report," Government of Canada, 2023. [Online]. Available: https://www.oag-bvg.gc.ca/internet/English/parl_oag_202303_02_e_44205.html

[4] G. Sebestyen, S. Fujikawa, N. Galassi, and A. Chuchra, *Low Earth Orbit Satellite Design*. Springer, 2018.

[5] I. Leyva-Mayorga, B. Soret, M. Röper, D. Wübben, B. Matthiesen, A. Dekorsy, and P. Popovski, "LEO Small-Satellite Constellations for 5G and Beyond-5G Communications," *IEEE Access*, vol. 8, pp. 184 955–184 964, 2020.

[6] S. Cakaj, *LEO Coverage*. John Wiley & Sons, Ltd, 2022, ch. 5, pp. 103–119. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119899280.ch5

[7] Shivendra Panwar, "Breaking the Latency Barrier," IEEE Spectrum, 2020. [Online]. Available: https://spectrum.ieee.org/breaking-the-latency-barrier

[8] Société de l'assurance automobile du Québec, "In an Autonomous Vehicle," SAAQ, 2024. [Online]. Available: https://saaq.gouv.qc.ca/en/road-safety/modes-transportation/autonomous-vehicles

[9] L. U. Khan, I. Yaqoob, M. Imran, Z. Han, and C. S. Hong, "6G Wireless Systems: A Vision, Architectural Elements, and Future Directions," *IEEE Access*, vol. 8, pp. 147 029–147 044, 2020.

[10] Hexa-X Consortium, "Deliverable D5.3: Final 6G architectural enablers and technological solutions," Hexa-X, 2023. [Online]. Available: https://hexa-x.eu/wp-content/uploads/2023/05/Hexa-X_D5.3_v1.0.pdf

[11] Telesat, "Telesat Lightspeed: Resilient, assured global communications," Telesat, 2023. [Online]. Available: https://www.telesat.com/wp-content/uploads/2024/01/Telesat-Lightspeed-Defence.pdf

[12] C. Chen, X. Chen, D. Das, D. Akhmetov, and C. Cordeiro, "Overview and performance evaluation of wi-fi 7," *IEEE Communications Standards Magazine*, vol. 6, no. 2, pp. 12–18, 2022.

[13] H. Haas, "Lifi: Conceptions, misconceptions and opportunities," in *2016 IEEE Photonics Conference (IPC)*. IEEE, 2016, pp. 680–681.

[14] N. A. Khan and S. Schmid, "Ai-ran in 6g networks: State-of-the-art and challenges," *IEEE Open Journal of the Communications Society*, vol. 5, pp. 294–311, 2024.

[15] X. Foukas, G. Patounas, A. Elmokashfi, and M. K. Marina, "Network slicing in 5g: Survey and challenges," *IEEE Communications Magazine*, vol. 55, no. 5, pp. 94–100, 2017.

[16] X. Hu, R. Deng, B. Di, H. Zhang, and L. Song, "Holographic beamforming for leo satellites," *IEEE Communications Letters*, vol. 27, no. 10, pp. 2717–2721, 2023.

[17] Y. Wu, K. Zhang, and Y. Zhang, "Digital Twin Networks: A Survey," *IEEE Internet of Things Journal*, vol. 8, no. 18, pp. 13 789–13 804, 2021.

[18] B. Mao, X. Zhou, J. Liu, and N. Kato, "Digital Twin Satellite Networks Toward 6G: Motivations, Challenges, and Future Perspectives," *IEEE Network*, vol. 38, no. 1, pp. 54–60, 2024.

[19] T. T. Bui, L. D. Nguyen, B. Canberk, V. Sharma, O. A. Dobre, H. Shin, and T. Q. Duong, "Digital Twin-Empowered Integrated Satellite-Terrestrial Networks Toward 6G Internet of Things," *IEEE Communications Magazine*, vol. 62, no. 12, pp. 74–81, 2024.

[20] S. D. Okegbile, J. Cai, and C. Yi, "Concept of Human Digital Twin: An Introduction," in *Human Digital Twin: Exploring Connectivity and Security Issues*. Springer, 2024, pp. 3–15.

[21] S. D. Okegbile, J. Cai, D. Niyato, and C. Yi, "Human digital twin for personalized healthcare: Vision, architecture and future directions," *IEEE network*, vol. 37, no. 2, pp. 262–269, 2022.

[22] J. Chen, C. Yi, S. D. Okegbile, J. Cai, and X. Shen, "Networking architecture and key supporting technologies for human digital twin in personalized healthcare: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 26, no. 1, pp. 706–746, 2023.

[23] S. D. Okegbile, H. Gao, O. Talabi, J. Cai, C. Yi, D. Niyato, and X. Shen, “Fles: A federated learning-enhanced semantic communication framework for mobile AIGC-driven human digital twins,” *IEEE Network*, 2025.

[24] ltjon, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis, “Satellite Communications in the New Space Era: A Survey and Future Challenges,” *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 70–109, 2021.

[25] A. Kyrgiazos, B. G. Evans, and P. Thompson, “On the Gateway Diversity for High Throughput Broadband Satellite Systems,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 10, pp. 5411–5426, 2014.

[26] J. Matar, M. Rodriguez-Cassola, G. Krieger, P. López-Dekker, and A. Moreira, “MEO SAR: System Concepts and Analysis,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 58, no. 2, pp. 1313–1324, 2020.

[27] R. Wang, M. A. Kishk, and M.-S. Alouini, “Ultra Reliable Low Latency Routing in LEO Satellite Constellations: A Stochastic Geometry Approach,” *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 5, pp. 1231–1245, 2024.

[28] A. U. Chaudhry and H. Yanikomeroglu, “Laser Intersatellite Links in a Starlink Constellation: A Classification and Analysis,” *IEEE Vehicular Technology Magazine*, vol. 16, no. 2, pp. 48–56, 2021.

[29] M. Jackson, “SpaceX Starts General Rollout of Starlink’s Inter Satellite Lasers,” ISPreview, 2021. [Online]. Available: https://www.ispreview.co.uk/index.php/2021/09/spacex-starts-general-rollout-of-starlinks-inter-satellite-lasers.html

[30] X. Qin, T. Ma, X. Zhang, Y. Wang, H. Zhou, and L. Zhao, “Ultra-Dense LEO-MEO Constellation Integrated 6G: A Distributed Hierarchical Mobility Management Approach,” *IEEE Transactions on Wireless Communications*, vol. 24, no. 1, pp. 323–339, 2025.

[31] J. Pi, Y. Ran, H. Wang, Y. Zhao, R. Zhao, and J. Luo, “Dynamic Planning of Inter-Plane Inter-Satellite Links in LEO Satellite Networks,” in *ICC 2022 - IEEE International Conference on Communications*, 2022, pp. 3070–3075.

[32] Analysys Mason, “Space,” Analysys Mason, 2025. [Online]. Available: https://www.analysysmason.com/what-we-do/capabilities/space/

[33] M. Agiwal, A. Roy, and N. Saxena, “Next Generation 5G Wireless Networks: A Comprehensive Survey,” *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1617–1655, 2016.

[34] Y. Li, H. Li, L. Liu, W. Liu, J. Liu, J. Wu, Q. Wu, J. Liu, Z. Lai, and F. Guojie, “Fractal Rosette: A Stable Space-Ground Network Structure in Mega-Constellation,” 2021. [Online]. Available: https://arxiv.org/abs/2105.05560

[35] Canadian Radio-television and Telecommunications Commission, “Communications Market Reports,” CRTC, 2024. [Online]. Available: https://crtc.gc.ca/eng/publications/reports/PolicyMonitoring/

[36] J. Davis, *Corrosion of Aluminum and Aluminum Alloys*. ASM International, 1999.

[37] M. F. Ashby, *Materials Selection in Mechanical Design (Fourth Edition)*. Butterworth-Heinemann, 2011.

[38] R. W. Revie, *Uhlig’s Corrosion Handbook (Third Edition)*. Wiley, 2011.

[39] W. D. J. Callister and D. G. Rethwisch, *Materials Science and Engineering: An Introduction (Tenth Edition)*. Wiley, 2018.

[40] F. A. Almalki, S. H. Alsamhi, R. Sahal, J. Hassan, A. Hawbani, N. Rajput, A. Saif, J. Morgan, and J. Breslin, “Green IoT for eco-friendly and sustainable smart cities: future directions and opportunities,” *Mobile Networks and Applications*, vol. 28, no. 1, pp. 178–202, 2023.

[41] H. Zhang, H. Wang, Y. Li, K. Long, and A. Nallanathan, “DRL-Driven Dynamic Resource Allocation for Task-Oriented Semantic Communication,” *IEEE Transactions on Communications*, vol. 71, no. 7, pp. 3992–4004, 2023.

[42] A. E. Onile, R. Machlev, E. Petlenkov, Y. Levron, and J. Belikov, “Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review,” *Energy Reports*, vol. 7, pp. 997–1015, 2021.

[43] R. Aluvalu, S. Mudrakola, U. M. V, A. Kaladevi, M. Sandhya, and C. R. Bhat, “The novel emergency hospital services for patients using digital twins,” *Microprocessors and Microsystems*, vol. 98, p. 104794, 2023.

[44] Gouvernement du Québec, “Ressources numériques pour le réseau de l’éducation,” Québec, 2025. [Online]. Available: https://www.quebec.ca/education/numerique/ressources-numeriques/ressources-numeriques-reseau-education

[45] Concordia University, “Online courses at concordia university,” CU, 2025. [Online]. Available: https://www.concordia.ca/academics/online-courses.html

[46] Future Skills Centre, “FSC establishes $20 million partnership with CPMT to support workforce development in Quebec,” FSC, 2024. [Online]. Available: https://fsc-ccf.ca/engage/workforce-development-in-quebec/

[47] N. Mohammadzadeh, S. Rezayi, and S. Saeedi, “Telemedicine for Patient Management in Remote Areas and Underserved Populations,” *Disaster Medicine and Public Health Preparedness*, 2022.

[48] ISED, “Canada’s Digital Charter,” Goverment of Canada, 2021. [Online]. Available: https://ised-isde.canada.ca/site/innovation-better-canada/en/canadas-digital-charter-trust-digital-world

[49] S. Cespedes, “Eagle and the Condor Project: Promoting Digital Equity with Indigenous Communities,” CU, 2024. [Online]. Available: https://www.concordia.ca/ginacody/about/equity-diversity-inclusion/awards.html

[50] J. Turner, “Bridging the Gap: Unraveling the Digital Divide (DDN2-A26),” Goverment of Canada, 2024. [Online]. Available: https://www.csps-efpc.gc.ca/tools/articles/digital-divide-eng.aspx