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WWRT

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From the Desk of the Editor-in-Chief

Dr Sudhir Dixit
Editor-in-Chief



Welcome to the fifth issue of *Wireless World Research and Trends* (WWRT) magazine. In the two years since our launch in 2024, WWRT has earned strong engagement from a diverse readership – thought-provoking op-eds from experts worldwide, technology and standards articles for practitioners in networking and communications, and in-depth papers for researchers and academics. Thank you for your continued interest and endorsement of the magazine.

This issue features two opinion articles and five full-length papers.

The first opinion piece, “Trends for the Wireless World” by Mikko Uusitalo, offers a window into the future of communications from Nokia’s perspective, highlighting key accomplishments of the Hexa-X project. The second, “Vision of a Future-Ready Enterprise Campus Network” by Sures Ramadass, Asyraf Mohammad, and Vallikkannu Nagappan, examines the real-world requirements and practical considerations of production enterprise networks.

In the first full-length article, Dixit argues that 6G (IMT-2030) represents a fundamental rearchitecting of wireless systems beyond 5G’s capabilities. The paper proposes a four-layer 6G architecture – Intelligent RAN (I-RAN), AI-Native Core (ANC), Semantic Communication Plane (SCP), and Non-Terrestrial Network (NTN) Stratum – unified by cross-cutting AI/ML orchestration and zero-trust security, and grounded in the Hexa-X use case taxonomy, its eight architecture principles, and the 5G PPP functional reference model. The article also offers a North American perspective, examining the central role of the ATIS Next G Alliance (NGA) in shaping a coherent regional 6G vision.

Mekuria and Banda then present a sustainable digitalization framework for rural entrepreneurial ecosystems, advancing UN and IEEE goals to connect underserved communities by 2030. Their rural-urban social network (RUSN) ecosystem introduces two interventions for digital inclusion and affordable connectivity, addressing affordability, sustainable business models, and co-creation of ICT services with local communities – validated through a proof-of-concept digital entrepreneurship ecosystem

(DERE) tested across four South African sites, alongside policy and regulatory recommendations.

In the third article, Shruthi Koratagere Anantha Kumar et al. examine why the digital divide persists despite the centrality of connectivity to education, healthcare, and economic opportunity. The article explores infrastructure, usage, and demand gaps alongside space-air-ground integrated networks (SAGIN), and unpacks the market drivers – supply, demand, macroeconomics, technology, and policy – that widen the divide, along with the stakeholder interdependencies needed to close it.

The fourth article, by Telang, tackles a practical challenge in modern user equipment (UE): as devices adopt multiple switchable antenna panels and simultaneous TN/NTN connectivity – including LEO satellite links – existing uplink selection schemes fall short, relying on downlink proxies, network-delegated decisions, or transmit-power-only optimization. The paper proposes a fully autonomous, UE-side selection framework built on a five-component energy cost function, driven entirely by on-device sensing, with a forward-looking extension for NTN links using satellite ephemeris and hysteresis-based switching control.

The fifth and final paper, by Nasralla, Munir, and Farman, presents a compact, dual-band MIMO antenna for resilient 5G vehicular communications. Built on a $25 \times 10 \times 0.51 \text{ mm}^3$ RO4350B substrate and operating across 8–11 GHz and 24–34 GHz, the design achieves peak gains up to 5.99 dBi and 6.4 dBi, over 90% efficiency, and better than –19 dB isolation – with experimental validation confirming strong performance for advanced driver-assistance systems (ADAS), vehicle-to-everything (V2X), and high-data-rate vehicular applications.

We hope you find this issue both engaging and illuminating for the opportunities ahead. As always, we welcome proposals from those interested in guest-editing a future special issue.



Trends for the Wireless World

Mikko A. Uusitalo

Abstract: This article presents trends for the wireless world from the perspectives of Nokia Bell Labs based on recent Nokia blogs as well as from the already finalized European level 6G Flagship Hexa-X-II.

Keywords: 6G, AI, Hexa-X-II, ML, Wireless communications.

1. Advancing Connectivity for the AI Supercycle

New capabilities based on artificial intelligence are reshaping many aspects of society in a profound way. This certainly includes wireless world and connectivity as well. Artificial intelligence is entering a transformative multi-decade phase known as the AI supercycle, where it will become integral to all industries and technologies, driving exponential innovation and economic growth through pervasive automation and data optimization, as described in [1] and continued as follows: AI supercycle is defined by three ongoing shifts:

- AI Inference diffusion from centralized LLMs to more distributed multi agent systems
- Compute expansion: a step-change in demand for capacity, optimized for AI-specific workloads, and distributed closer to the endpoint
- Network evolution: the move to deterministic, high-capacity, low-latency networks that allow AI to work everywhere, not just in the cloud.

Once these three shifts converge, AI becomes a general-purpose technology that drives long-term growth across the entire economy. If the cloud era was about centralising compute, the AI supercycle is about distributing intelligence everywhere the real world operates, across devices, machines, networks, and industries [1].

Secure, advanced connectivity infrastructure is an integral enabler of AI innovation, connecting intelligence across the world's devices, the network edge and data centers [2]. Radio access networks (RAN) and AI are converging into AI-RAN. Here AI and RAN workloads can run on a shared platform. This enables moving inferencing from AI factories to the network edge, providing new capabilities.

Boundaries between physical, digital and human worlds will be blurred. Physical AI [3, 4] is the integration of artificial intelligence into physical machinery. This enhances the capacity of real time interaction by machines, such as robots or autonomous systems, including vehicles and other advanced devices and gives them more capacity to perceive, reason and interact, via loops including perception, decision, and action. This requires of course connectivity and especially improvements in connectivity: low latencies for control signals as well as large-volume uplink video with strict latency requirements. Connectivity becomes an integral part of intelligence. This is also a monetization opportunity.

Network acts in additional ways as a distributed nervous system, part of the intelligence [3]. AI over the network does not happen from connectivity perspective as it might be perceived by many users as just responses received based on prompts sent. Requirement for the traffic behind the scenes is bidirectional, latency-sensitive, and context-aware. Inference is placed at the edge to reduce round-trip delay, preserve privacy, and optimize resource utilization. Communication between AI agents forms dynamic service graphs that evolve in real time.

Networks not only transmit information, but also create information that can be used in the intelligence that the networks are part of. Examples of this include metadata on the state of the network in order to recognize any needs for actions or network usage patterns informing about the state of the society using the network. In the physical space new opportunities come from different forms of physical sensing that network can carry out. Integrated sensing and communication (ISAC) is a prime example of this.

6G is the first generation of cellular communications in which AI has been taken into account from the very beginning of the design at all layers of the network, starting from the physical layer of the radio. During the time of 6G research and development, AI has become more and more central. 6G is the first generation in which communication is deeply integrated with sensing and computing. Networks will be able to sense, coordinate, decide and act in real time.

AI-driven experiences are interactive and bursty, leading to similar requirements for the connectivity [5]. Therefore, networks need to be designed for tail behavior and adaptability and not any more for the busy hour. This requires coordinated intelligence end-to-end across RAN, core, access, transport, and the automation, agentic control, intent, and governance layers above, not siloed optimization [5]. Need to prepare for this and additional other changes in traffic requirements, emerging faster than the traditional changes from one generation to the next, creates a critical mismatch: a demand profile evolving at software speed colliding

Nokia Bell Labs

E-mail: Mikko.uusitalo@nokia-bell-labs.com

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with an architectural model that moves at generational speed. Solution is a programmable platform with the right acceleration, and an operating model that can evolve at software speed. A recent Nokia blog [6] presents this challenge and provides the solution via three core architectural shifts: programmability and performance at scale, decoupling innovation from hardware via a Hardware Abstraction Layer (HAL) and intelligence in the decision loop.

A HAL allows a Radio Access Network to become a programmable platform with an execution and a learning domain [6]. The separation into domains allows stable operation combined with continuous innovation.

The distribution of AI systems across devices, cloud infrastructure, edge platforms as well as wireless and fixed networks raises an architectural challenge [7]. Current networks were designed to transport data reliably, not to coordinate intelligence dynamically. Therefore, new network architectures will need to support seamless coordination across these distributed environments, consolidating processing, connectivity and intelligence into a unified fabric rather than isolated layers. So, the challenge is enabling intelligent systems to operate reliably, dynamically and at scale across complex interconnected environments.

2. Generation Game and the Hexa Projects

Mobile networks have developed through generations from 1G to 5G. Research work for 6G started end of last decade. Academic research was soon followed by industrial research. European level Flagship project Hexa-X started January 2021 to create joint industrial and academic basis and momentum for 6G. It was followed by the second European level 6G Flagship Hexa-X-II, which ended summer 2025. Hexa-X and Hexa-X-II have had wide societal, economic and scientific impacts at global scale.

Planning for the new generation starts from studying trends and visions and then creating use cases that cannot yet be realized fully with currently available technologies. At the start of the ITU process towards IMT-2030, the next generation, Hexa-X was invited to make a keynote. When 3GPP ramped up use case work for 6G, output from Hexa-X-II was in central role in the joint European level input as 5 out of the 6 representative use cases were prepared, presented, and accepted in 3GPP. See more on Hexa-X-II use cases in Figure 1 and from [8].

Objective of Hexa-X was to lay down the intelligent fabric of technology enablers connecting human, physical, and digital worlds. This reflected the vision of the three worlds to be connected. As human needs were in the center focus, human world was separated from the physical world. This is not in contradiction with the needed balance between humans and their environment – on the contrary, sustainability was a central theme through Hexa-X and Hexa-X-II. Hexa-X outcome is well summarized in [9]. Hexa-X-II continued extending and refining the vision and the use cases, developing the needed technical enablers and building the E2E system view of 6G. Hexa-X-II results have been well summarized in [10] and [11].

As the objectives for 6G were recognized to be much richer than for previous generations, Key Values and related Key Value Indicators were introduced as well as new analysis methods related to them [8,12].

Hexa projects had wide interactions with global initiatives through e.g., workshops inside Europe (EC, 6G-IA, SNS-JU project, national initiatives) as well as in other continents, like US (Next G Alliance) and Asia (IMT-2030 PG, B5GPC/SGMF/XGMF, 5G/6G Forum, ETRI, ITRI, IITH). Hexa projects were a key contributor in European level white papers, including 2 on 6G overview, sustainability, KPIs and KVs.

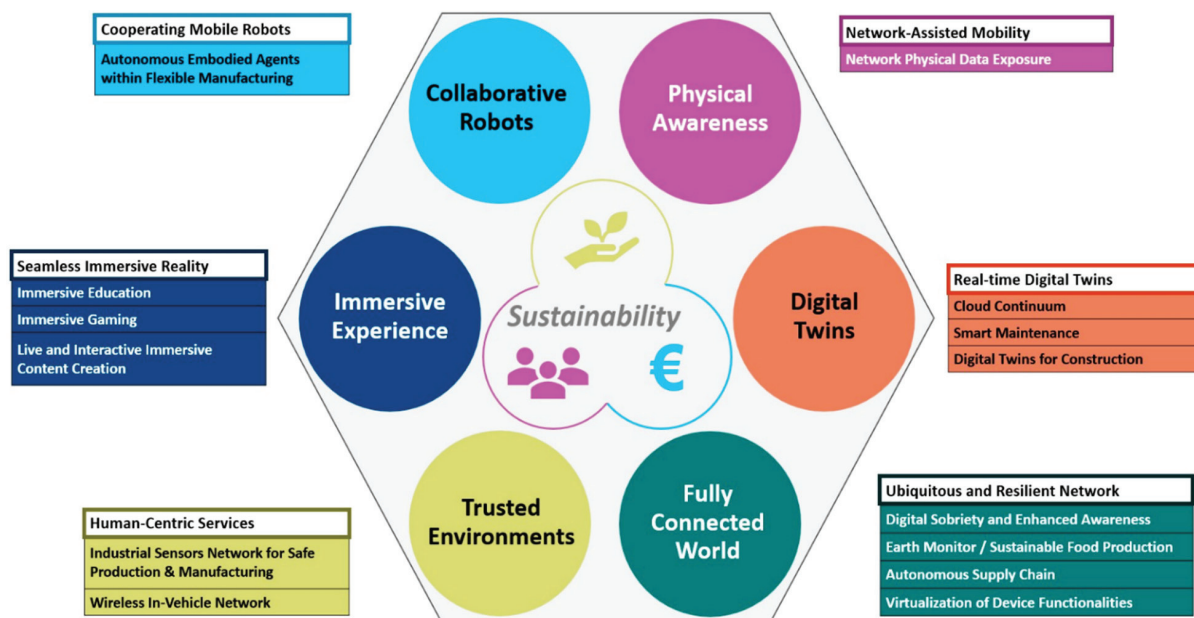


Figure 1.
Hexa-X-II's use cases and use case families.

In addition, the projects created more than 300+ publications and co-created 2 books [10,13].

Hexa-X-II projects made around 290 std contributions. Due to the contributions to ETSI, Hexa-X-II received an ETSI award June 2026 at the EUCNC & 6G Summit.

WiTaR (Women in Telecommunications and Research) started from Hexa-X and continued to be supported by Hexa-X-II and many others with more than 30 projects having joined to support the activity.

Hexa projects did create an early vision for 6G, made important impacts based on the use case work, introduced key values and key value indicators, more than 100 technical enablers to address the new needs based on the vision and use cases as well as a 6G E2E system view including architecture. Hexa projects did emphasize the fundamental role of AI in creating 6G – the first generation for which AI has had an important role throughout all the layers of the network. Hexa results were disseminated via more than 300 publications as well as around 290 contributions to standardization.

Currently the momentum in 6G creation has shifted from research to standardization and productization. It remains to be seen that how many of the results of research can be turned into commercially successful features bringing added value to the society.

References

- [1] Nokia blog, The AI supercycle explained [Online]. (Accessed on 2026, May 18th). Available: <https://www.nokia.com/artificial-intelligence/the-ai-supercycle-explained/>, 2026.
- [2] P. Mahajan, Beyond the innovation horizon: Advancing connectivity in the AI era, Nokia blog [Online]. (Accessed on 2026, May 18th). Available: <https://www.nokia.com/blog/beyond-the-innovation-horizon-advancing-connectivity-in-the-ai-era/>, 2026.
- [3] O. Sunay and P. Mahajan, When AI becomes physical: The network as a distributed nervous system, Nokia blog [Online]. (Accessed on 2026, May 28th). Available: AI-Native Networks: Distributed Nervous System, 2026.
- [4] H. Viswanathan, Physical AI: Redefining RAN and telco monetization, Nokia blog [Online]. (Accessed on 2026, May 28th). Available: Physical AI isn't "just more traffic" I Nokia, 2026.
- [5] P. Mahajan and O. Sunay, From voice to video to AI-shaped traffic: Why network architecture must evolve at software speed, Nokia blog [Online]. (Accessed on 2026, May 28th). Available: Why AI-native traffic demands a new network architecture, 2026.
- [6] P. Mahajan, O. Sunay, A. Ed and D. Urbaniak, AI-RAN: Bringing software-speed innovation into the radio network, Nokia blog [Online]. (Accessed on 2026, May 28th). Available: AI-RAN: Bringing software-speed innovation into the radio network | Nokia.com, 2026.
- [7] D. Bourse, M. A. Uusitalo and H. Viswanathan, AI-native 6G is now the industry direction, Nokia blog [Online]. (Accessed on 2026, June 18th). Available: AI-native 6G is now the industry direction I Nokia, 2026.
- [8] E. Ramos (Ed), Deliverable D1.4 6G value, requirements and ecosystem, Hexa-X-II deliverable [Online]. (Accessed on 2026, June 21st) Available: doi: 10.5281/zenodo.15772634, 2025.
- [9] M. A. Uusitalo et al., "6G vision, value, use cases and technologies from European 6G flagship project Hexa-X," IEEE Access, vol. 9, pp. 160004–160020, 2021.
- [10] M. A. Uusitalo, P. Rugeland, M. R. Boldi and A. Nimr (Eds.), *6G to Build a Sustainable Future*, Wiley, 2026.
- [11] M. A. Uusitalo et al., "Towards environmentally, socially and economically sustainable 6G – Key findings from the European Flagship Hexa-X-II", accepted for *ITU Journal on Future and Evolving Technologies*, 2026.
- [12] A. Jain et al., "Knowledge graph-based approach for sustainable 6G end-to-end system design," accepted for *IEEE Open Journal of the Communications Society*, 2026.
- [13] Ö. Bulakci et al., *Towards Sustainable and Trustworthy 6G: Challenges, Enablers, and Architectural Design*, now Publishers, 2023.

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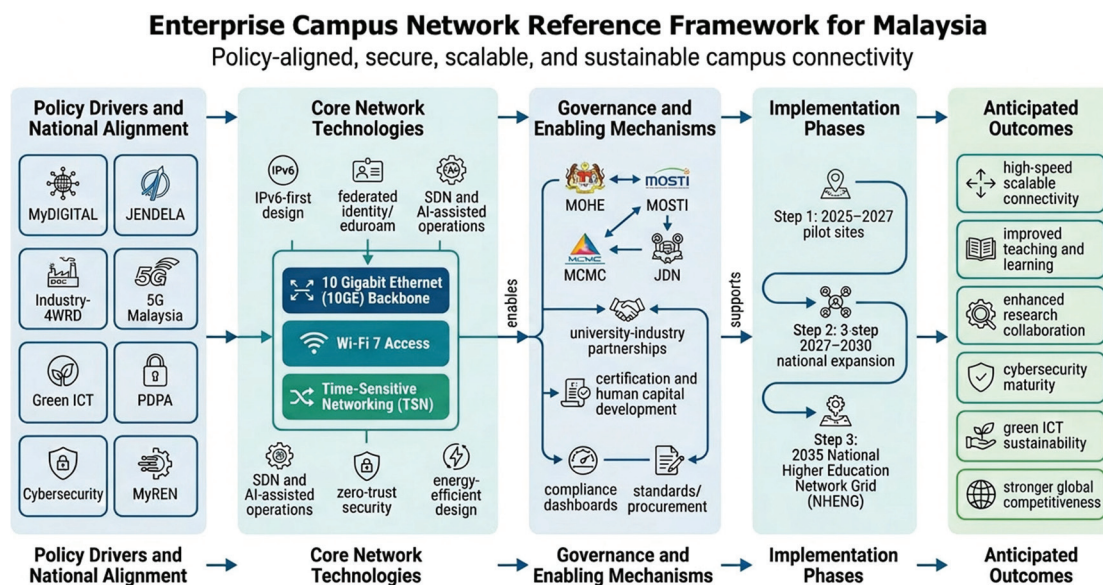
Biography



Mikko A. Uusitalo is Head of Research Department Radio Systems Research Finland and Nokia Bell Labs Finland Site Lead. Mikko is the Chair of the Board of the Nokia Foundation. Mikko was leading the European 6G Flagships Hexa-X and Hexa-X-II. He obtained a M.Sc. (Eng.) and Dr.Tech. in 1993 and 1997 and a B.Sc. (Economics) in 2003, all from predecessors of Aalto University. Mikko has been at Nokia since 2000 with various roles, including Principal Researcher and Head of International Cooperation at Nokia Research. Mikko is a founding member of the CELTIC EUREKA and WWRF. Mikko has been nominated among Nokia top inventors six times, Mikko's H-index is 40+ and i10-index 100+. Mikko has more than 230 granted patents. In 2020 Mikko received the Cross of Merit of the Order of White Rose from the President of Finland. Mikko has and has had numerous board and advisory positions in many important groups in the industry, academia or government side.

Vision of a Future-Ready Enterprise Campus Network

Sureswaran Ramadass^{1,}, Muhammad Asyraf Mohamad Naim², Vallikkannu Nagappan³, Nor Ashidi Mat Isa⁴ and Karen Morgan⁵*



Cellular and fixed networks have quietly become the nervous system of modern universities and enterprises. Yet many so-called “campus networks” are still engineered as best-effort LANs rather than as strategic digital infrastructure. As research, teaching and administration increasingly depend on cloud, AI and real-time applications, the enterprise campus network (ECN) must be treated as critical infrastructure requirement, and not just as an IT project. The reference framework diagram above portrays the strategic journey for modernizing enterprise campus networks, balancing high-level policy mandates with concrete technical and operational requirements. For Campus Networks in Malaysia, it moves from foundational policy drivers such as MyDIGITAL and JENDELA, through to specific architectural imperatives like

10GE backbones, Wi-Fi 7, Enterprise 5G and Net5.5G, and IPv6 Enhanced and IPv6-First designs. By connecting these technologies to essential governance structures and through a phased, multi-year implementation plan, the framework provides a clear path toward achieving long-term outcomes. Among the desired outcomes include high-speed scalable connectivity, improved educational research collaboration, cybersecurity maturity, and green ICT sustainability, among others.

What we ask of future ECNs

In today’s environment, a production-grade, future-ready ECN is defined less by technical features and more by the experience it delivers. In practice, six requirements consistently emerge across universities, research institutes and large enterprises:

- **High performance:** predictable multi-gigabit throughput in the backbone and low latency to applications, even during peaks,
- **Consistency:** users experience the same quality of service whether they are in lecture halls, labs, hostels, or remote campuses, with uniform policies rather than ad hoc exceptions.
- **Scalability:** the network can grow from thousands to tens of thousands of endpoints, sensors and services without requiring disruptive redesigns every few years.

¹Head of Department, Medical Informatics, RCSI & UCD Malaysia Campus (RUMC) Chairman, APAC IPv6 Council

²Director for Training & Consultancy, IPv6 Forum Malaysia

³Chief Secretary & Senior Advisor, APAC IPv6 Council

⁴Chief Digital Officer, University Sains Malaysia

⁵President & CEO, RCSI & UCD Malaysia Campus (RUMC)

E-mail: asyraf@ipv6forummalaysia.my

*Corresponding Author

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- **Energy efficiency:** each generation should lower watts per bit and favour designs that minimise over-provisioning, supporting national Net Zero and green ICT targets.
- **Security:** zero-trust principles, fine-grained segmentation and strong identity security underpin every connection, protecting both operational continuity and research assets.
- **Privacy and isolation:** policy-driven separation between student traffic, research flows, operational technology (OT) and guest access, aligned with data protection and sectoral regulations.

These requirements must be met simultaneously. It is no longer acceptable to trade security for convenience, or performance for energy savings; instead, the design challenge is to be optimised across all the six axes mentioned above.

Open and Future-Proof Technology Choices

The good news is that the technology building blocks for future-ready ECNs already exist and are mature. The question is how to combine them in ways that are cost-effective, open and backwards-compatible, while avoiding unnecessary vendor lock-in.

10 Gigabit Ethernet backbones. For most universities and large enterprises, 10 Gigabit Ethernet (10 GE) is now the practical minimum for core and distribution, with clear upgrade paths to 40/100 GE where research or intercampus flows demand it. Within Malaysia's recent campus upgrades, which often see implementations of IPv6 Enhanced technology for addressing, backed by Enterprise 5G and Net5.5G designs for high speed end point infra, including fibre-to-the-room (FTTR) models delivering up to 2.5 Gbps per endpoint shows that such backbones and end connectivity are not just aspirational but well into implementation stages [1,2].

Wi-Fi 7 as the campus edge. The transition from Wi-Fi 5/6 to Wi-Fi 7 (IEEE 802.11be) brings multi-link operation, 320 MHz channels and better deterministic behaviour which are critical for dense lecture halls, hybrid classrooms and AR/VR-based teaching. Malaysia is already piloting AI-optimised Wi-Fi 7 in public universities, and more than 13,000 access points have been deployed nationwide as part of a phased plan towards 32,000 Access Points [3-5].

Time-Sensitive Networking (TSN). TSN extends Ethernet with time synchronisation and scheduled traffic, enabling precise control for robotics labs, smart manufacturing testbeds and biomedical instrumentation. Early TSN pilots in research networks globally, and Malaysia's own plans for testbeds at MIMOS and MRANTI, point to TSN as a key differentiator for research-intensive campuses [6,7].

IPv6 Enhanced and IPv6-First, identity-aware networks. Campus networks that remain IPv4-centric will struggle to scale securely. An IPv6-first posture, combined with federated identity (such as eduroam/eduGAIN) and robust RADIUS/SAML integration, enables per-user and per-device policy, seamless roaming and cleaner segmentation across institutions [8,9]. SRv6, Network

Slicing, IFIT and IPSec are futuristic IPv6 features which will change the landscape.

Software-defined operations. Software-Defined Networking (SDN), streaming telemetry and AI-assisted operations are no longer optional "nice to have" features. An inherent feature within Enterprise 5G and Net5.5G technologies, they are essential for managing tens of thousands of endpoints, dynamically adjusting RF conditions, and spotting anomalies before they become outages. Malaysia's first AI-powered Wi-Fi 7 deployments demonstrate how AI-O&M can reduce mean time to detect and repair while sustaining classroom SLAs [5,10].

The unifying thread is openness: architectures should be grounded in global standards like IEEE, IETF and ISO, with clear interoperability across vendors. This is what makes an ECN future-proof, i.e. the fact that new generations of hardware or software can be introduced incrementally without redesigning the entire network.

Why Policy and Governance Matter as much as Technology

Even the best technical design will fail if it is implemented as a one-off project without proper policy backing. A national ECN framework provides the glue that aligns campus-level decisions with long-term public goals.

Malaysia's Enterprise Campus Network Policy Guide situates campus networking squarely within national digital transformation agendas such as the Malaysia Digital Economy Blueprint (MyDIGITAL), JENDELA, Industry4WRD and 5G Malaysia [11,12]. By defining strategic goals, target beneficiaries and expected outcomes, it positions universities as anchor nodes in a wider national digital fabric, not isolated IT islands.

Policy also ensures regulatory compliance by design. Personal data protection (PDPA), national cybersecurity guidance, spectrum allocation for Wi-Fi 7 in the 6 GHz band, and government cloud interoperability requirements all shape how ECNs can be architected and operated [7,11,13,14]. Embedding these requirements early avoids a familiar pattern where technically successful pilots later hit legal or regulatory roadblocks.

Finally, governance clarifies who owns what. Lead ministries, regulators, research networks and campus CIOs each have defined roles in steering investment, setting minimum baselines (for example, 10GE-ready cores and Wi-Fi 7 in high-density zones), and monitoring performance through national dashboards [11,15]. Without this shared governance, campuses may drift into fragmented procurement and inconsistent security implementations.

Malaysia's Higher Education ECN Journey

Malaysia's higher education sector offers a concrete example of how ECN principles translate into practice. The national research and education network (MYREN) already links universities, polytechnics and teaching hospitals, forming the backbone for high-speed academic traffic [16]. Recent policy efforts build on this foundation to standardise campus architectures and close gaps between early adopters and lagging institutions. It is also one of the first IPv6 only networks to be implemented in the world.

Wireless modernisation is one visible front. Government-funded programmes have deployed more than 13,000 access points (APs) across public university campuses, with a target of approximately 32,000 APs by 2027, and some campuses achieving 80–100% Wi-Fi coverage. [3–5] At Universiti Malaya, an AI-driven Wi-Fi 7 pilot demonstrates how multi-link implementations using 6 GHz spectrum and AI-based RF optimisation can sustain multi-gigabit performance in dense academic settings [5, 10].

Backbone upgrades are progressing in parallel. UPM Bintulu, for example, has implemented a CWDM-based FTTR design delivering 2.5 Gbps per endpoint, while research-intensive institutions such as Universiti Sains Malaysia are securing 100 Gbps international R&E links through partnerships like ARENA-PAC [1, 17]. These designs are explicitly engineered to scale towards TSN-enabled labs and high-throughput AI workloads [6, 17].

Smart classrooms and hybrid learning environments form the third pillar. At Universiti Teknologi Malaysia, smart classroom pilots integrate high-quality AV, edge compute, managed Wi-Fi and secure collaboration, showing how the ECN becomes the teaching and learning substrate rather than just a connectivity layer [18]. Similar initiatives across campuses support the Ministry's projections that hybrid models will dominate by 2030, provided that network performance and reliability keep pace [19].

Together, these projects illustrate the ECN vision in action: a converged, high-performance fabric that supports research, teaching, operations and industry collaboration while remaining aligned with national policy and regulation.

What Really Works in Production ECNs

Across deployments and case studies, several patterns consistently separate successful ECN implementations from those that under-deliver.

- Architect for 10GE (and beyond) from day one: Even if initial traffic can be served on lower line rates, designing the core and distribution for dual-redundant 10 GE rings with clear upgrade paths avoids costly retrofits later [1, 11].
- Treat Wi-Fi 7 as a system, not just an access point. RF design, AI-assisted optimisation, identity integration and adequate wired backhaul must be planned together; otherwise, the wireless edge simply exposes backbone bottlenecks [3, 5, 10].
- Invest in people and operations: Certification programmes for campus network engineers, centralised NOCs/SOCs and shared playbooks are as important as hardware. Skills gaps in SDN, automation and TSN can quickly become the limiting factor [7, 11, 15].
- Standardise architectures and procurement: Common reference designs, RFP templates and security baselines reduce fragmentation across campuses and simplify federation via MYREN and eduroam [8, 9, 11, 15].
- Measure what matters: National dashboards that track uptime, latency, Wi-Fi health, TSN performance, security incidents and energy usage turn ECN performance into a visible, managed KPI rather than an invisible background service [15].

Equally important are the recurring pitfalls that often derail ECN ambitions:

- Fragmented, campus-by-campus procurement that prioritises short-term discounts over long-term interoperability, leading to incompatible management tools and duplicated effort.
- Designing purely for peak performance while ignoring energy and sustainability targets, resulting in over-provisioned, under-utilised infrastructure that is politically and financially hard to defend [12, 20].
- Treating cybersecurity as an afterthought, bolted onto an otherwise completed network, rather than embedding zero-trust, segmentation and ISO/IEC 27001-aligned controls into the initial architecture [13, 14].
- Underestimating migration and user technology upgrades, especially for legacy OT, lab equipment and AV systems. This oversight can turn otherwise sound designs into disruptive projects that lose campus buy-in [6, 18].
- Piloting advanced features such as TSN or private 5G without first securing sufficient backbone capacity, spectrum coordination and operational readiness, leading to fragile proofs-of-concept that cannot be scaled [6, 7, 17].

Towards Trusted, Green and Intelligent Campus Fabrics

A future-ready enterprise campus network is not defined by a single technology generation. It is the result of deliberate choices: embracing open standards, designing for evolution, aligning with national policy, and investing in the people who will operate increasingly intelligent infrastructures.

Malaysia's ECN journey in higher education shows that even in resource-constrained environments, it is possible to combine 10 GE backbones, Wi-Fi 7, TSN and AI-assisted operations into a coherent, policy-backed roadmap [1–3, 5, 6, 11].

As more countries confront similar challenges, the core lesson is simple: treat the campus network as critical infrastructure, and it will repay the investment in enterprise or research output, teaching quality, resilience and global competitiveness.

References

- [1] UPMKB first Malaysia's public university to adopt CWDM technology for network infrastructure – 17 Feb 2025. <https://www.theborneopost.com/2025/02/17/upmkb-first-malaysias-public-university-to-adopt-cwdm-technology-for-network-infrastructure/>.
- [2] Malaysia Enterprise Campus Network Policy Guide 2025 – Executive Summary and Section 3.1.
- [3] “Over 13,000 Wi-Fi access points installed at public universities nationwide: Fahmi” – 10 Jun 2025. https://newswav.com/article/over-13-000-wi-fi-access-points-installed-at-public-universities-nationwideA2506_JVvDht.
- [4] “Over RM 600 million allocated to improve WiFi access at public universities” – 21 Jan 2025. <https://www.bernama.com/en/newsp.php?id=2385115>.
- [5] “TP-Link to equip Universiti Malaya with Malaysia's first AI Wi-Fi network” and related Wi-Fi 7 launch coverage – 17 Oct 2024. <https://www.nst.com.my/business/corporate/2024/10/1121182/tp-link-equip-universiti-malaya-malaysias-first-ai-wi-fi-network>.
- [6] “Comprehensive Review on Time Sensitive Networks with a Special Focus on Its Applicability to Industrial Smart and Distributed Measurement Systems” – 19 Feb 2022. <https://pmc.ncbi.nlm.nih.gov/articles/PMC8879530/>.

- [7] MIMOS Smart Manufacturing Intelligent Service Platform (SMISP) and MRANTI 5G Innovation National Testbed. <https://www.mimos.my/portfolio/smart-manufacturing-intelligent-service/>; <https://www.mosti.gov.my/wp-content/uploads/2023/08/26-12-Jun-2023.pdf>.
- [8] eduroam hits a new record – 8.4 billion authentications in 2024 – Jan 2025. <https://eduroam.org/eduroam-hits-a-new-record-8-4-billion-authentications-in-2024/>.
- [9] GÉANT Compendium 2023 and eduroam Support Organisations Status Report 2023–2024.
- [10] UM launches Malaysia's first AI-powered Wi-Fi 7 technology – 17 Oct 2024. <https://www.businesstoday.com.my/2024/10/17/tp-link-k-empowers-um-with-first-ai-powered-wi-fi-7-inmalaysia/>.
- [11] Malaysia Digital Economy Blueprint (MyDIGITAL) and associated Enterprise Campus Network Policy recommendations.
- [12] National Energy Policy 2022-2040 – Ministry of Economy, Malaysia. https://ekonomi.gov.my/sites/default/files/2022-09/National_Energy_Policy_2022-2040.pdf.
- [13] CyberSecurity Malaysia principles and guidelines; MyCERT incident coordination resources. <https://www.cybersecurity.my/>.
- [14] Government cloud services and interoperability guidelines (MyGovCloud, JDN). <https://www.malaysia.gov.my/portal/content/31183>.
- [15] Malaysia Enterprise Campus Network Policy Guide – Governance and monitoring framework (Sections 5 and 8.3).
- [16] MYREN – Malaysian Research & Education Network. <https://www.myren.net.my/>.
- [17] "USM Partners with ARENA-PAC to Launch Malaysia's 100 Gbps Research and Education Network" – 26 Sep 2024. <https://soi.asia/usm-partners-with-arena-pac-to-launch-malaysias-100gbps-research-and-education-network/>.
- [18] "Universiti Teknologi Malaysia and Cisco redefine learning with smart classroom transformation" – 6 Feb 2024. <https://www.digitalnewsasia.com/business/universiti-teknologi-malaysia-and-cisco-redefine-learning-smart-classroom-transformation>.
- [19] "Malaysia's AI-Driven Education Landscape: Policies, Applications, and Comparative Insights for a Digital Future" – 2025. <https://arxiv.org/html/2509.21858v1>.
- [20] Malaysia Enterprise Campus Network Policy Guide – Green ICT and sustainability sections (Sections 2.1.5, 7.4 and Annex 10.1).

Biographies



Sureswaran Ramadass is Head of Medical Informatics Department at RCSI & UCD Malaysia Campus (RUMC). He is also the Chairman of the APAC IPv6 Council, IPv6 Forum Academy and the IPv6 Forum Malaysia. He is also the Vice-Chair of NIDA and has supported ITU as a Subject Matter Expert (SME) in IPv6. He is also involved as an SME for IPv6 and Cybersecurity

for MCMC, Malaysia. He has a distinguished career spanning next-generation networking, IPv6, cybersecurity and multimedia conferencing. He has led many IPv6 initiatives globally and numerous national and regional steering roles related to IPv6 deployment, education and certification. His academic highlights include being awarded the Tokoh Negara (National Laureate) for Innovation and commercialisation, the WWRF Fellow award and the National Innovation award by the Prime Minister (twice). He has graduated over 20 PhD students and awarded over USD 15 Million in numerous research grants.



Muhammad Asyraf Mohammad Naim is a digital transformation professional and technology strategist, and currently serves as Director for Training & Consultancy for IPv6 Forum Malaysia. He is a key contributor to IPv6 and 5G capacity-building initiatives in the region, and has helmed national and regional roles including the National IPv6-only Adoption Task Force Capacity Building Working Group and the MCMC NEXUS Application Validation. He has led projects spanning national-level IPv6 strategic roadmaps, sovereign digital infrastructure planning, policy analysis and development, and AI governance. His background combines technology strategizing, stakeholder engagement, and project leadership, with a portfolio of research and whitepapers in the domain of IPv6, 5G, Artificial Intelligence and data governance.



Vallikkannu Nagappan is Chief Secretary of the APAC IPv6 Council and a regional coordination and capacity-building professional with strong experience in IPv6 programme operations, stakeholder engagement and compliance support. In her current role, she manages council operations, coordinates regional meetings and partnerships, supports IPv6 audit and compliance assessments, and contributes to the development of best-practice frameworks that advance IPv6 adoption across the Asia Pacific. She holds qualifications in information technology and finance, and holds additional project management and IPv6 certifications, reflecting her blend of technical coordination, organisational leadership and training expertise.



Nor Ashidi Mat Isa is Professor at the School of Electrical and Electronic Engineering, and Chief Digital Officer at Universiti Sains Malaysia (USM), where he has served since 2003. His expertise covers artificial intelligence, intelligent systems, image processing, biomedical engineering, intelligent diagnostic systems, machine learning and algorithms, with research interests in medical diagnostic systems, image enhancement and reconstruction, neural network architectures, metaheuristic algorithms, segmentation, feature extraction, and intelligent clustering. He has published extensively in Web of Science-indexed journals, including papers in IEEE Access, Applied Soft Computing, Pattern Recognition, and Artificial Intelligence, and his work reflects longterm contributions to image analysis, medical imaging, and computational intelligence. Among his recent achievements include being recognised as the Top 2% Scientists for the Category of Citation Impact in Single Calendar Year 2019 & 2020 from Stanford University, as well as Top Research Scientists Malaysia (TRSM) from Akademi Sains Malaysia (ASM) in 2020.



Karen Morgan is President & CEO of RCSI & UCD Malaysia Campus (RUMC), one of Southeast Asia's leading international medical universities. She is a Professor of Health Psychology and a Fellow and former President of the European Health Psychology Society. She holds a PhD in Health Psychology from RCSI, a Master's in Social and Organisational Psychology from UCD, and a Postgraduate Certificate in Medical Education from Newcastle University. Before joining RUMC, she served as Director of Perdana University Royal College of Surgeons in Ireland School of Medicine (PU-RCSI) in Kuala Lumpur, and earlier worked as a change management consultant with Accenture on major government projects in the UK and Ireland. She is also a founding member of WomenEd Malaysia. With over 20 years of experience in health professions education, institutional quality assurance, and research capacity building, she brings institutional leadership perspectives on how future-ready digital infrastructure underpins research collaboration, hybrid learning, and organisational excellence in the higher education sector.

Towards a Unified 6G Network Architecture: Principles, Layers, and Key Enabling Technologies

Sudhir Dixit

Abstract: Sixth-generation (6G) wireless networks – formally designated IMT-2030 by the ITU – will require a fundamental rearchitecting of how wireless systems are conceived, standardised, and operated. Motivated by application classes that 5G cannot serve, this paper proposes a four-layer 6G network architecture comprising an Intelligent RAN (I-RAN), an AI-Native Core (ANC), a Semantic Communication Plane (SCP), and a Non-Terrestrial Network (NTN) Stratum, unified by a cross-cutting AI/ML orchestration plane and a zero-trust security framework. The paper draws on the Hexa-X use case taxonomy (HEX-D13) [1], the eight architecture principles of HEX-D51 [2], and the 5G PPP functional reference model [3].

Keywords: 6G network architecture, Hexa-X, IMT-2030, I-RAN, AI-Native Core, NTN, Semantic communications..

1. Introduction

The evolution from 5G to 6G is not an incremental upgrade – it will require a generational rearchitecting. The ITU IMT-2030 framework (Recommendation M.2160, 2023) [4] sets a capability envelope qualitatively and quantitatively different from any previous generation: peak data rates exceeding 1 Tbps, air interface latency below 100 μ s, a hundredfold improvement in energy efficiency per bit, and native AI integration across every network layer. Five structural gaps in 5G motivate this rearchitecting: no native AI, insufficient programmability, incomplete cloud-nativity, no continuum orchestration, and sustainability treated as an afterthought rather than a foundational constraint.

This paper addresses each gap through a coherent four-layer architecture illustrated throughout with figures. Sections 2–5 establish the motivating context: use cases, why 6G is needed, structural gaps, and design principles. Sections 6–7 present the three reference architecture views from Hexa-X and the 5G PPP Working Group. Section 8 proposes the four-layer architecture with deep dives into each layer. Section 9 compares it with 5G. Section 10 analyses four open research challenges. Section 11 concludes.

Basic Internet Foundation, Oslo, Norway & University of Oulu, Oulu, Finland

E-mail: sudhir.dixit@ieee.org

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2. 6G Use Cases and Application Drivers

Figure 1 reproduces the Hexa-X HEX-D13 use case taxonomy [1], which organises 6G applications into six families around the convergence of the physical, digital, and human worlds. These families provide the inputs to the requirements that ITU has defined for the 6G architecture that must be satisfied.

Robots to Cobots

Consumer robots, AI partners, interacting and cooperative mobile robots, flexible manufacturing, and situation-aware device reconfiguration. A cobot (collaborative robot) is a robotic system designed to operate safely in close proximity to human workers, allowing them to share the same workspace. The defining requirements are ultra-reliable low-latency communication (URLLC) at density levels beyond 5G capability, deterministic latency guarantees, and distributed sensing to support real-time collaborative autonomy.

Telepresence

Fully merged cyber-physical worlds, mixed reality co-design, immersive sport events, and merged reality games and work environments. These applications require multi-Gbps bidirectional video streams with sub-millisecond synchronisation between endpoints – a throughput and latency combination that exceeds 5G's capability by more than an order of magnitude, and which requires semantic compression at the network layer to be bandwidth-feasible.

Massive Twinning

Digital twins for manufacturing, immersive smart cities, and the Internet of Tags (IoTa) designed for passive tracking using technologies of RFID and NFC. Digital twins are persistent, real-time computational mirrors of physical entities and environments. Sustaining them at scale – a city, a supply chain, a national infrastructure – requires continuous, low-latency telemetry from millions of sensors, edge computing resources co-located with physical assets, and a network fabric capable of supporting planetary-scale data flows with deterministic quality of service.

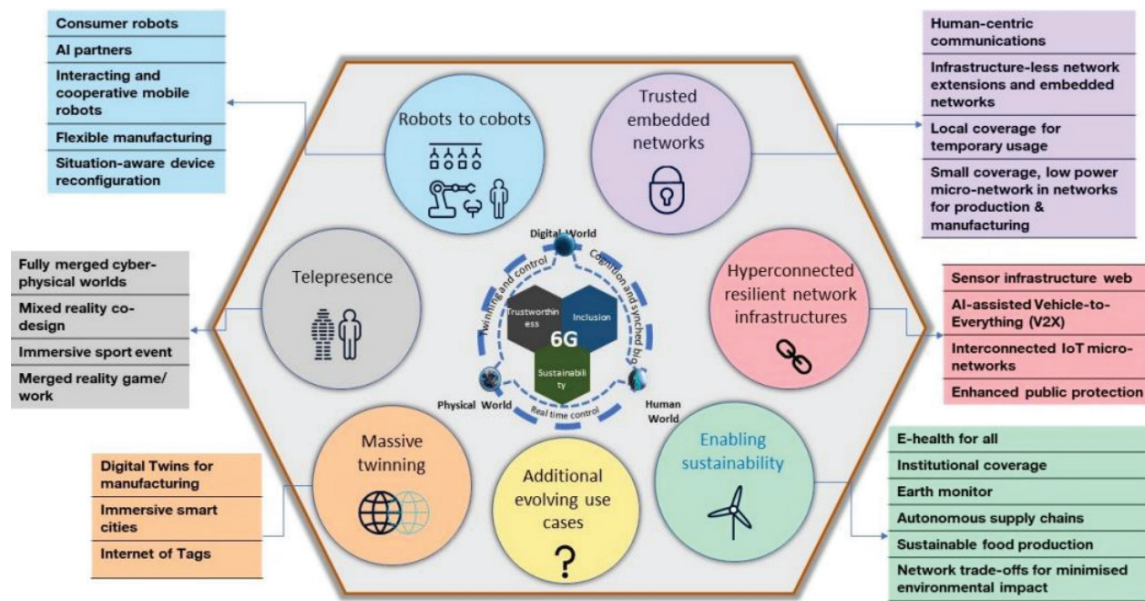


Figure 1.
Families of 6G use cases [1].

Hyperconnected Resilient Infrastructures

Sensor infrastructure webs, AI-assisted Vehicle-to-Everything (V2X), interconnected IoT micro-networks, and enhanced public protection systems [6]. These require the 6G network to act as a sensing and inference platform, not merely a connectivity conduit – integrating radar-like environmental sensing directly into the radio access network through integrated sensing and communications (ISAC).

Trusted Embedded Networks

Infrastructure-less network extensions, local coverage for temporary usage, and small, low-power micro-networks for production and manufacturing. These require 6G to function without fixed infrastructure – in disaster recovery, remote industrial, and tactical military contexts – using non-terrestrial networks (NTN) and device-to-device relay architectures as primary means to connect with the data network.

Enabling Sustainability

E-health for all, institutional coverage, earth monitoring, autonomous supply chains, sustainable food production, and network functionality for crisis resilience. This family collectively establishes that 6G must serve not just the richest markets and most profitable verticals, but must be affordable, energy-efficient, and globally deployable – making sustainability not an add-on requirement but a core architectural constraint.

3GPP, “TR 22.870” has also studied the use cases and requirements for IMT-2030 [5]. From a North American perspective, the ATIS Next G Alliance (NGA) has played a central role

in articulating a coherent 6G vision for the region. Established in 2020 by the Alliance for Telecommunications Industry Solutions (ATIS), the NGA brings together more than 80 member organisations spanning operators, equipment vendors, chipmakers, government agencies, and academia to develop a coordinated roadmap for 6G leadership. The Alliance aims to establish North American preeminence in 5G evolution and 6G development. Its work focuses on creating a comprehensive national roadmap, influencing government policy, and driving rapid commercialization of beyond 5G, including 6G, technologies. More specifically, its foundational “Roadmap to 6G” [7], published in 2022 and updated since, identifies six audacious goals addressing North America’s priorities in standardisation, R&D, spectrum policy, sustainability, and supply chain resilience. The NGA’s National 6G Roadmap Working Group has subsequently published North American 6G Roadmap Priorities, identifying nine representative use cases – spanning immersive communications, connected intelligence, and resilient infrastructure – that directly inform the use case taxonomy discussed in Section 2 of this paper [7]. The NGA has also produced targeted technical reports on ISAC channel modelling in the 7–24 GHz mid-band range, spectrum needs assessments, and component technology white papers covering antennas, RF circuits, and transceivers. Taken together, this body of work establishes that the architectural shifts proposed in this paper – AI-native design, ISAC integration, Open RAN, and post-quantum security – are fully consistent with North American industry priorities and the NGA’s roadmap for achieving global 6G leadership.

3. Why 6G? The Case for Rearchitecting

Early work on 6G began in the Finnish 6G Flagship project in year 2018 [8]. Around the same time, other interesting papers were published articulating the 6G vision and requirements [9–11],

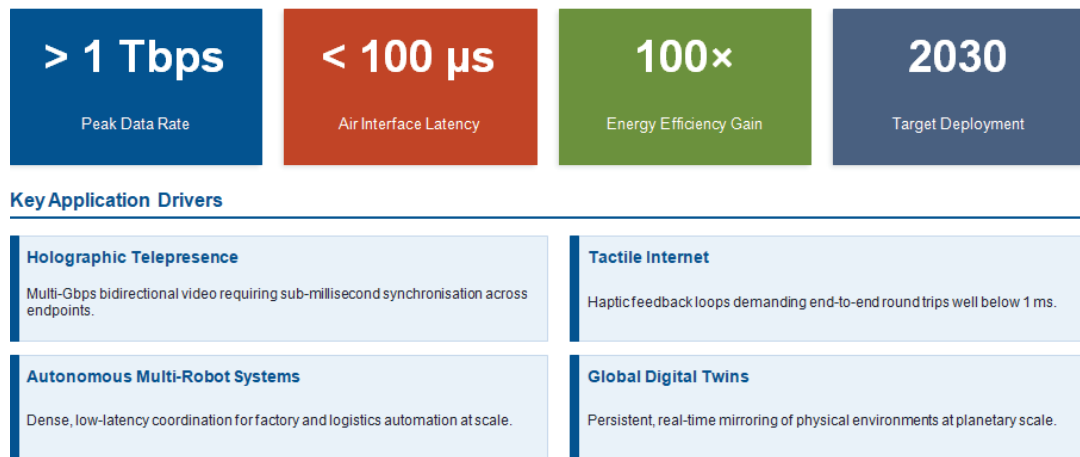


Figure 2.

Why 6G? Four IMT-2030 headline targets – >1 Tbps peak data rate, <100 μs air interface latency, 100× energy efficiency gain, 2030 commercial deployment – and four key application driver families: Holographic Telepresence, Tactile Internet, Autonomous Multi-Robot Systems, and Global Digital Twins. Adapted from [4].

including discussions on whether 6G is needed beyond 5G [9]. ITU continued the momentum on 6G, by now called IMT-2030, and summarized the four headline targets and the four principal application driver families as depicted in Figure 2.

4. Structural Gaps From 5G to 6G

There are five structural gaps in 5G that 6G must close – each representing a dimension in which 5G is fundamentally, not merely quantitatively, insufficient.

- **Enabling AI and Agentic AI** – 5G has no native AI. 6G must embed autonomous, goal-directed AI inference in every network function from the outset. This would enable more automation, self-learning, cost reduction, and increased efficiency.
- **Programmability** – 5G's Open RAN and network slicing do not provide closed-loop policy generation. 6G must be fully programmable from radio to application layer.
- **Cloud-native softwarisation and service-based architecture** – 5G softwarisation is partial, particularly in the RAN. 6G requires complete softwarisation to the radio edge to enable open source implementation, programmability, faster configuration/changeover, faster upgrades and operational efficiency.
- **Continuum Orchestration** – 5G cannot seamlessly orchestrate across device, edge, cloud, and NTN. 6G must treat these as a unified compute-communication fabric.
- **Cross-cutting concerns** – sustainability, trustworthiness, cybersecurity, and regulatory compliance must be first-principles architectural constraints in 6G, not post-deployment overlays.

5. Architectural Design Principles

The Hexa-X deliverable HEX-D51 establishes eight guiding principles for 6G architecture design [2]. These principles function as an evaluation lens: every architectural decision must be assessed

against them, and any decision that violates more than one principle without compelling justification should be reconsidered. Table 1 summarises the eight principles.

Two principles deserve particular emphasis in the context of the proposed architecture. Principle 2 – AI for full automation – implies that the network intelligence is not an xApp or an external optimiser but an intrinsic property of every network function: session management, handover control, interference coordination, and security enforcement are all AI-driven from initial design, not retrofitted. Principle 8 – network simplification – is a counterweight to the complexity that the preceding principles tend to add: the architecture must be measurably simpler to operate than 5G, or it will remain a research artefact rather than a commercially deployable system.

6. High Level View of the 6G System Architecture

The Hexa-X high-level architecture view (HEX-D13) [1] organises the 6G system into three horizontal strata and two vertical cross-cutting dimensions, as illustrated conceptually in Figure 3. The three strata are:

- **Infrastructure Layer** – the physical and virtualised compute, transport, and radio infrastructure spanning extreme/far edge, edge cloud, and central cloud, together with non-terrestrial assets (LEO satellites, HAPS, UAVs).
- **Network Service Layer** – the set of network functions (control plane, user plane, management plane) exposed through an Exposure Framework and Integration Fabric. This stratum is explicitly multi-tier: functions may run at any edge or cloud location, and the Exposure Framework provides a unified northbound interface regardless of function placement.
- **Application Layer** – vertical service providers access the network through the Exposure Framework, running application instances that span the use case families of Section 2, from immersive smart cities to AI-assisted V2X to fully merged cyber-physical worlds.

Table 1.

6G architecture design principles [HEX-D51] [2]	
Principle	Description
1 – Exposure of capabilities	Well-defined northbound APIs enable vertical service providers to programmatically consume network capabilities, decoupling application logic from network implementation.
2 – AI for full automation	The network manages itself autonomously through embedded AI/ML inference engines; human operators declare intent rather than configure parameters.
3 – Flexibility to different topologies	The architecture operates identically in dense urban, rural, aerial, maritime, and satellite environments without topology-specific customisation.
4 – Scalability	From a handful of devices to trillions of connected objects, the architecture scales horizontally without redesign.
5 – Resilience and availability	Self-healing network functions, geographic redundancy, and automatic failover ensure continuity under hardware failures, cyber-attacks, or natural disasters.
6 – Servicebased exposed interfaces	All inter-function communication uses standardised, loosely coupled service-based interfaces – enabling independent evolution and multi-vendor deployments.
7 – Separation of concerns	Management, control, and user plane functions are cleanly separated, allowing independent scaling, updating, and policy enforcement at each plane.
8 – Network simplification	6G must be measurably simpler to operate than 5G – fewer parameters, more automation, and reduced total cost of ownership – enabling global reach including low-income markets.

The two vertical cross-cutting dimensions are: Management and Orchestration with AI/ML (left axis), which operates continuously across all three strata with CI/CD (Continuous Integration/Continuous Delivery/Deployment) pipelines enabling live network updates; and Security (right axis), which implements a multi-layer security stack including physical layer security, privacy-enhancing technologies, quantum security, AI/ML security, distributed ledger technologies, and trust foundations. The critical architectural insight from this view is that both AI/ML orchestration and security are pervasive system properties – not components at any single layer – and the architecture must be designed accordingly.

7. Proposed 6G Reference Architecture -- Functional View

The 5G PPP Architecture Working Group’s functional reference model (from Working Party documentation) further decomposes the Network Service Layer into a Security Stratum, Network Intelligence Stratum, Sensing Stratum, and Network Stratum, each running vertically through the Management Plane, Control Plane Network Functions, User Plane Network Functions, and

Infrastructure [3]. This functional view makes the separation of concerns explicit (Principle 7) and shows how the Sensing Stratum – representing integrated sensing and communications – is a first-class architectural element in 6G, not an application-layer overlay as in 5G. Figure 4 shows the 5G PPP Architecture Working Group’s functional reference model [3], which decomposes the Network Service Layer into four vertical strata running through all horizontal planes.

The Network Intelligence Stratum – the AI/ML engine – continuously optimises every function. The Security Stratum enforces security at every plane, not only at the perimeter. The Sensing Stratum makes ISAC a native architectural element: the same physical-layer waveform simultaneously carries user data and performs environmental sensing, localisation, and radar-like ranging. The Sensing Stratum outputs are consumed both by applications (autonomous vehicles, digital twins) and by the network’s own resource management functions.

8. Proposed Four-Layer Architecture

Building on the principles and high-level views, we propose organising the 6G architecture into four functional layers, each with well-defined responsibilities, northbound APIs to the layer above, and southbound service consumption from the layer below. A cross-cutting AI/ML orchestration plane and a unified data fabric span all four layers. Figure 5 shows this stack with the layers numbered 1 (bottom) to 4 (top), with the AI/ML orchestration plane as a vertical strip and the Unified Data Fabric plus Zero-Trust Security Framework as a horizontal base. Figure 6 provides detailed deep dives into each layer’s key functions.

The sub-100- μ s latency target enables haptic feedback loops in the tactile internet – human reflexes operate at approximately 10 ms, and realistic haptic response requires network round trips well below this threshold. The 100 $\times$ energy efficiency target addresses the unsustainable energy trajectory of globally deployed wireless networks. The 2030 commercial target is driven by the competitive strategies of Korea (targeting 2028), Japan, China, and others, as detailed in the WWRF 6G Global Pathways position paper (under development).

Layer 1 -- Intelligent RAN (I-RAN)

The Intelligent RAN extends the 5G Open RAN paradigm [17] along three dimensions. First, the functional split between the Distributed Unit (DU) and Central Unit (CU) is made dynamic and context-aware: latency-sensitive processing migrates toward the edge in real time based on traffic conditions, interference state, and application requirements, without manual reconfiguration. This dynamic split is enabled by a federated learning-capable Near-Real-Time RAN Intelligent Controller (Near-RT RIC), which hosts xApps that train interference coordination and handover prediction models across base stations without centralising raw channel data – preserving user privacy while maintaining system optimality.

Second, Reconfigurable Intelligent Surfaces (RIS) are managed as first-class network elements under the RAN controller, not as external accessories. RIS panels – large arrays of passive reflective elements – enable passive beamforming with

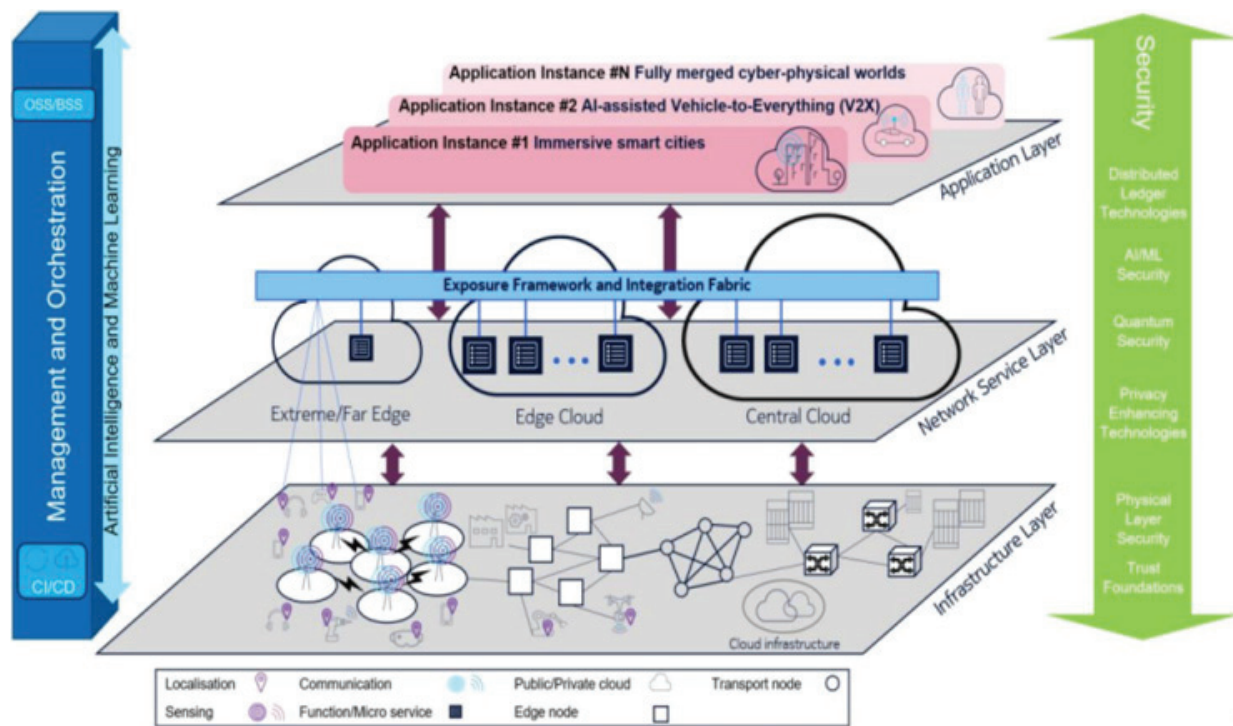


Figure 3.
High-level view of the 6G architecture [1].

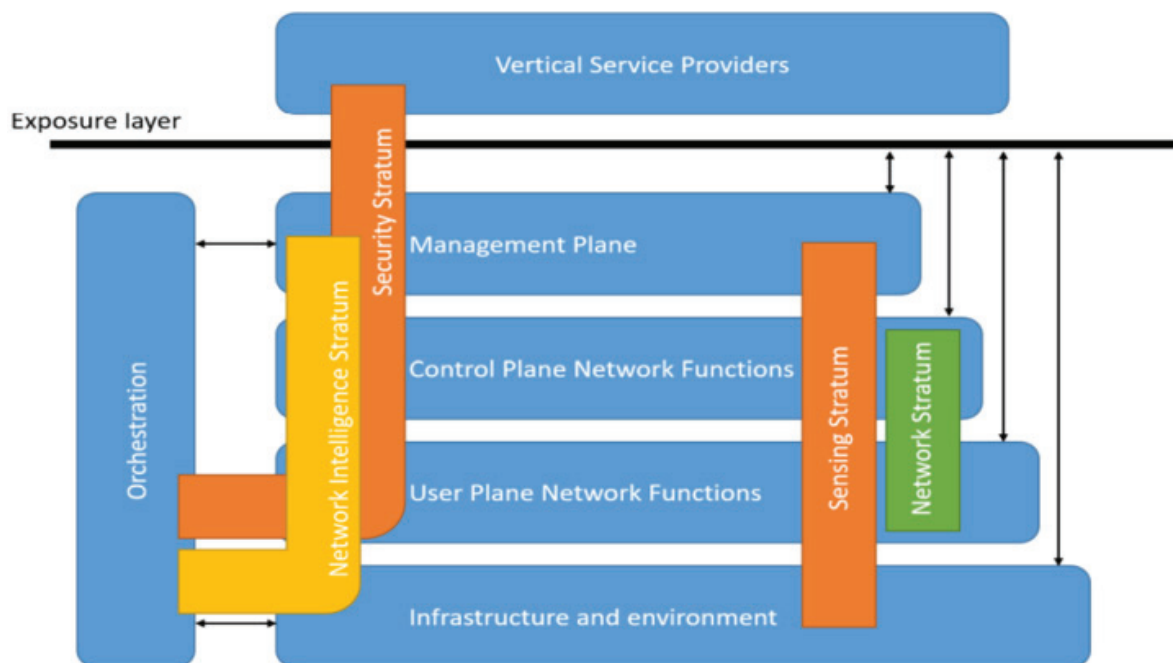
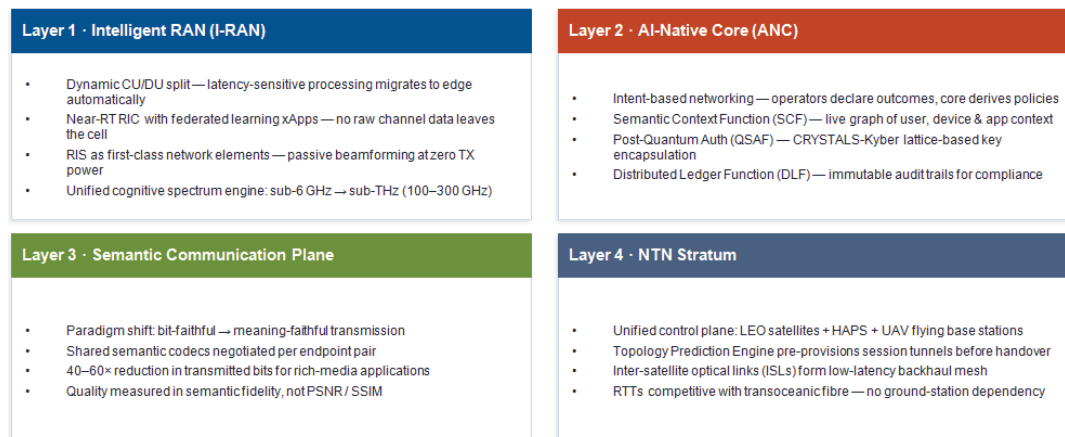


Figure 4.
Proposed 6G reference architecture – functional view [3]. Four vertical strata – Network Intelligence Stratum, Security Stratum, Sensing Stratum, and Network Stratum – run through the Management Plane, Control Plane Network Functions, User Plane Network Functions, and Infrastructure. The Exposure Layer provides northbound access to Vertical Service Providers. Orchestration with CI/CD runs on the left.

**Figure 5.**

Proposed 6G four-layer architecture stack. Layer 1 (navy): Intelligent RAN (I-RAN) – dynamic CU/DU split, federated learning RIC, RIS, sub-THz spectrum engine. Layer 2 (orange): AI-Native Core (ANC) – Semantic Context Function, CRYSTALS-Kyber auth, intent-based networking. Layer 3 (olive): Semantic Communication Plane – 40–60× bit reduction, semantic codecs. Layer 4 (slate): NTN Stratum – LEO/HAPS/UAV, Topology Prediction Engine, ISL backhaul. Cross-cutting: AI/ML Orchestration Plane (vertical) and Unified Data Fabric + Zero-Trust Security Framework (horizontal base).

**Figure 6.**

Layer deep dives. I-RAN: dynamic CU/DU split, federated learning Near-RT RIC xApps (no raw channel data leaves the cell), RIS as first-class elements (passive beamforming at zero TX power), cognitive spectrum engine sub-6GHz through sub-THz (100–300 GHz). ANC: intent-based networking, Semantic Context Function (SCF), Post-Quantum Auth via CRYSTALS-Kyber (QSAF) [12, 13], Distributed Ledger Function (DLF). SCP: bit-faithful to meaning-faithful paradigm shift, shared semantic codecs, 40–60× bit reduction [14, 15], semantic fidelity metrics. NTN Stratum: unified LEO+HAPS+UAV control plane, Topology Prediction Engine [16], intersatellite optical links, RTTs competitive with transoceanic fibre.

zero transmission power, extending coverage into blind spots and improving spectral efficiency without adding interference. Treating them as native network functions allows the AI/ML orchestration plane to include them in system-wide resource allocation.

Third, the I-RAN’s spectrum management engine spans the full 6G spectrum range: sub-6 GHz for coverage, millimetre-wave (24–100 GHz) for capacity, and sub-terahertz (100–300 GHz)

for peak-rate hotspot scenarios. It should be noted that the most essential spectrum is in lower part of FR3 (Frequency Range 3), like 7–8 GHz as well as around 6 GHz. Sub-THz and mm-wave are not central at least not in the beginning of 6G, due to the “terahertz wall” of severe physical and technical hurdles, such as extreme path loss, short range, water absorption, health/biological effects. A unified cognitive engine arbitrates access based on real-time propagation sensing enabled by ISAC – the same waveform

serves both communication and environmental sensing simultaneously, providing the network with a continuous, high-resolution map of the radio environment.

It is to be noted that the efforts required for the optimization of radio layer functions is going to add complexity in the higher layers of the four-layer architecture. Since the spectrum is a critical resource, intra-layer (radio-layer) design and optimization is extremely important. In addition, because the same waveform can be used for sensing and communication, etc, this results in the need to develop MAC layer enhancements caused by the massive sensing. Such an enhanced MAC layer would have to be capable of managing heavy load of sensing packets (passive and active sensing) coming from the “surrounding” targets in high density environments. The timely availability of this information would be essential for tuning AI mechanisms.

Layer 2 -- AI-Native Core (ANC)

The AI-Native Core departs from the 5G Service-Based Architecture by embedding AI inference engines directly into network functions, rather than post-hoc optimisation through external controllers. The defining paradigm shift is intent-based networking: operators and vertical applications declare outcomes (e.g., ‘ensure 99.999% reliability for this surgical robotics slice’) and the core autonomously derives and enforces the necessary policies across session management, UPF placement, and mobility without human configuration.

Three new network functions are central to the ANC. The Semantic Context Function (SCF) maintains a live knowledge graph of user, device, and application context – a structured, queryable representation of who is on the network, what they are doing, and what the network knows about their environment. This graph is the substrate for AI-driven policy generation. The Quantum-Secured Authentication Function (QSAF) implements lattice-based key encapsulation mechanisms standardised by NIST – specifically the CRYSTALS-Kyber algorithm (FIPS 203, ML-KEM) [12, 13] – providing authentication that is secure against both classical and quantum adversaries [12]. The Distributed Ledger Function (DLF) maintains an immutable, tamper-evident audit trail of network events and policy decisions, supporting regulatory compliance requirements across jurisdictions without requiring a centralised trusted authority.

Layer 3 -- Semantic Communication Plane (SCP)

The Semantic Communication Plane is the most architecturally novel layer of the proposed stack. It represents a fundamental shift in what the network transmits: from bit-faithful reproduction of source signals to meaning-faithful transmission of communicative intent. In the SCP paradigm, a video conferencing application need not transmit full pixel streams; instead, the SCP negotiates a shared semantic codec with the remote endpoint – a learned model that both parties agree encodes the relevant features of the communication – and transmits only the semantic content, with the receiver reconstructing a photorealistic representation locally.

The SCP interposes between applications and the transport network as a managed service layer, allowing the network

operator to compress, prioritise, and reconstruct information at the semantic level. Quality of service is measured not in PSNR or SSIM – signal-fidelity metrics inherited from information theory – but in semantic fidelity: did the receiver understand the intent of the communication? Initial projections, consistent with results reported in [14, 15], suggest 40–60× reduction in transmitted bits for rich-media applications with no perceptible quality degradation. At 6G scale – billions of simultaneous high-bandwidth sessions – this reduction is not merely commercially attractive but is arguably a necessary condition for meeting the energy efficiency targets of IMT-2030.

Layer 4 -- NTN Stratum

Global 6G coverage – including the remote, maritime, and aerial environments required by the use case families of Section 2 – cannot be achieved by terrestrial base stations alone. The NTN Stratum integrates Low Earth Orbit (LEO) satellite constellations, High-Altitude Platform Systems (HAPS), and Unmanned Aerial Vehicles (UAV) acting as flying base stations into a single, unified control plane. Integration is not merely an interconnection of separate systems: NTN nodes are managed as first-class network elements by the same control plane that manages terrestrial base stations, with seamless handover between segments.

One of the critical enabling innovations for the NTN Stratum is the Topology Prediction Engine (TPE), which anticipates satellite visibility windows and handover events – using orbital mechanics, atmospheric models, and real-time traffic state – and pre-provisions session continuity tunnels before they are needed. This eliminates the handover latency spikes that are the principal quality-of-service problem in current LEO systems [16]. Inter-satellite optical links (ISLs) form a low-latency backhaul mesh between satellites, reducing reliance on ground stations and enabling round-trip times competitive with transoceanic fibre for data paths that cross oceans or poles.

Cross-Cutting Elements

Three mechanisms operate across all four layers. The AI/ML Orchestration Plane provides a hierarchical intelligence controller: at the RAN level, Near-RT RIC xApps handle sub-second resource allocation; at the core level, a Non-RT RIC provides network-wide policy; and at the system level, a global orchestrator balances load across terrestrial and non-terrestrial segments using reinforcement learning for long-horizon optimisation and transformer-based anomaly detection for real-time fault isolation. The Unified Data Fabric exposes standardised APIs for telemetry collection, model training, and inference – with differential privacy mechanisms ensuring that sensitive data never leaves its origin domain. The Zero-Trust Security Framework mandates continuous device authentication, microsegmentation of network slices, and hardware-rooted trust anchors (e.g., TPM 3.0) at every layer, eliminating the implicit trust relationships that are the principal vulnerability in current mobile network designs. Microsegmentation of network slices is a Zero Trust security technique that further segments broad, virtualized network slices into smaller, strictly isolated security zones down to the individual workload or service level [18].

Table 2.

6G vs. 5G: eight-dimension architectural comparison		
Parameter	5G	Proposed 6G
Peak Data Rate	20 Gbps	>1 Tbps
Air Interface Latency	1 ms	<100 μ s
AI Integration	Post-hoc, external	Native & embedded
Coverage	Terrestrial + limited NTN	Unified terrestrial + NTN
Security	EAP-AKA / 5G-AKA	Post-quantum + zero-trust
Communication Model	Bit-faithful	Semantic/ goal-oriented
Energy Efficiency	Baseline	100 $\times$ improvement per bit
Spectrum Bands	Sub-6GHz + mmWave	Sub-6/mmWave/ sub-THz

9. Architectural Comparison with 5G

Table 2 compares the proposed 6G architecture with 5G NR / 5G Core across eight dimensions. The qualitative shifts are architecturally more significant than the quantitative ones.

The quantitative dimensions – peak data rate, air interface latency – are well-established in the IMT-2030 framework. The qualitative shifts are architecturally more significant. The change in AI integration from post-hoc to native fundamentally changes the operational model: 6G networks are not configured, they are trained. The change in communication model from bit-faithful to semantic changes what the network’s service boundary is: in 5G the network delivers bits; in 6G the network delivers meaning. The change in security from EAP-AKA to post-quantum plus zero-trust reflects not an incremental hardening but a change in threat model – one that accounts for the cryptographically relevant quantum computers that are expected to be operational before 6G reaches end of life [13, 19]. These qualitative shifts interact: semantic communication requires AI to generate and decode semantic codecs; AI requires zero-trust security to prevent adversarial manipulation of training data; zero-trust security requires the Distributed Ledger Function (DLF) to maintain tamper-evident audit trails. The four layers are not independent – they are architecturally coupled.

10. Open Research Challenges

Figure 7 summarises the four open research challenges alongside the architecture’s key takeaways and some near-term validation opportunities to build confidence in the paradigm shift from 5G to 6G.

10.1 Semantic Codec Standardisation

The Semantic Communication Plane requires cross-industry agreement on a shared semantic codec interface – the protocol by which two endpoints negotiate a joint learned model for encoding

and decoding communicative intent. This requires consensus on ontologies: the structured vocabulary of concepts and relationships that the codec uses to represent meaning. No such standard exists. The problem is deeper than a naming convention: different application domains (healthcare, automotive, manufacturing) have different semantic structures, and a codec that performs well in one domain may fail catastrophically in another. Research challenges include domain-adaptive semantic codecs, adversarial robustness of learned encoders, and objective quality metrics that capture semantic fidelity independently of signal-level measures such as PSNR or SSIM [14, 15]. This work is planned to be done by ETSI ISG.

10.2 NTN Topology Prediction at Orbital Scale

The Topology Prediction Engine must operate with high fidelity across constellations of thousands of LEO satellites – each moving at approximately 7.5 km/s relative to the ground, with inter-satellite geometry changing continuously. At this scale, the prediction problem is not tractable with classical orbital mechanics alone: atmospheric drag variations, satellite manoeuvres for collision avoidance, and traffic-dependent routing decisions all introduce stochastic perturbations that must be modelled probabilistically. Research challenges include large-scale graph neural networks for orbital topology prediction, handover decision policies under uncertainty, and the design of session continuity protocols that tolerate prediction errors without service interruption [16]. While each NTN will have its own TPE, it is unclear whether there is a need for an overarching TPE as well.

10.3 Post-Quantum Cryptography Compute Overhead

CRYSTALS-Kyber (ML-KEM, FIPS 203) introduces key encapsulation operations that are computationally more expensive than the elliptic-curve Diffie-Hellman operations used in 5G-AKA. For 6G authentication at scale – where a single base station may simultaneously authenticate thousands of devices following a power-up event or NTN handover – this overhead must be absorbed without degrading authentication latency below the 100 μ s air interface target. Research challenges include hardware acceleration architectures for lattice-based cryptography at base station scale, lightweight variants of ML-KEM for constrained IoT devices, and hybrid classical/post-quantum authentication protocols that allow graceful migration from legacy 5G credentials [13, 19].

10.4 Federated Learning Convergence in Heterogeneous RAN

The I-RAN’s Near-RT RIC uses federated learning to train xApps across base stations without sharing raw channel data. In practice, the data distributions across cell sites are highly heterogeneous and non-independent-and-identically-distributed (non-IID): urban macro-cells see different traffic patterns, channel conditions, and interference topologies than suburban micro-cells or industrial private networks. Standard federated averaging algorithms have poorly understood convergence properties under non-IID conditions, particularly when the number of participating

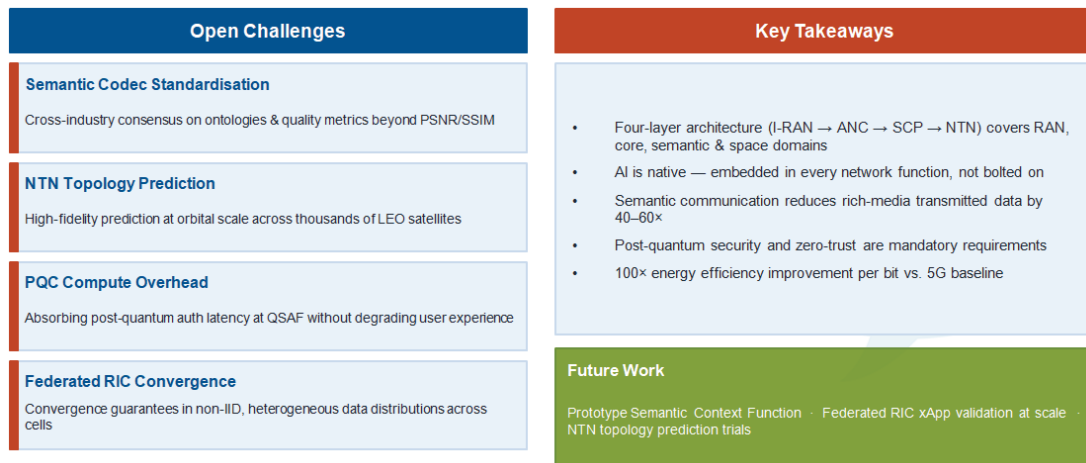


Figure 7.
Challenges and conclusions.

nodes is large and communication rounds are rate-limited by the RIC's near-real-time constraint. Research challenges include federated optimisation algorithms with provable convergence guarantees under non-IID data, privacy-preserving gradient aggregation mechanisms, and adaptive client selection policies that balance convergence speed with communication cost [20, 21].

11. Conclusion

This paper has proposed and analysed a unified four-layer 6G network architecture – Intelligent RAN, AI-Native Core, Semantic Communication Plane, and NTN Stratum – designed to satisfy the six Hexa-X use case families and the eight HEX-D51 design principles while closing the five structural gaps left by 5G, all in conformance with the requirements set out by the ITU. The architecture is distinguished by four qualitative shifts from 5G: post-hoc to native AI; bit-faithful to semantic communication; unified TN-NTN coverage; and perimeter-based to zero-trust security. These shifts are mutually reinforcing and architecturally coupled, forming a coherent system rather than a collection of independent improvements. This reinforcing coupling is the result of: semantic communication requires native AI; native AI requires zero-trust security; zero-trust security requires the distributed ledger infrastructure of the AI-Native Core.

The architecture is grounded in three established reference frameworks: the Hexa-X high-level layered view (HEX-D13), the functional decomposition of the 5G PPP Architecture Working Group, and the eight design principles of HEX-D51. These have in turn guided the ITU to define the IMT-2030 requirements. Its four open research challenges – semantic codec standardisation, NTN topology prediction, post-quantum cryptography compute overhead, and federated RIC convergence – define the engineering agenda that must be resolved before 2030 commercial deployment. Progress on each will require close coordination between 3GPP standardisation, ITU-R spectrum work, and academic research communities should benefit from the kind of cross-regional collaboration that the WWRF and its member organisations are uniquely positioned to facilitate.

Future work will focus on prototype implementation of the Semantic Context Function within an open-source 5G core, experimental validation of federated Near-RT RIC xApps under realistic non-IID traffic distributions, and the design of a hardware-accelerated QSAF compliant with the FIPS 203 ML-KEM standard.

References

- [1] Hexa-X Consortium, “Deliverable D1.3 – Hexa-X Use Cases and Requirements (HEX-D13),” EU Horizon 2020, 2022.
- [2] Hexa-X Consortium, “Deliverable D5.1 – 6G Architecture Principles and Design (HEX-D51),” EU Horizon 2020, 2023.
- [3] 5G PPP Architecture Working Group, “View on 6G Architecture, v2.0,” 5G Infrastructure Association, 2023.
- [4] ITU-R, “Framework and overall objectives of the future development of IMT for 2030 and beyond,” Recommendation ITU-R M.2160, ITU, Geneva, 2023.
- [5] 3GPP, “TR 22.870 – Study on use cases and requirements for IMT-2030,” Release 20 Study Item, 2025.
- [6] Samsung Research, “The Next Hyper-Connected Experience for All: A White Paper on 6G,” 2020 (updated 2022).
- [7] ATIS Next G Alliance, “Roadmap to 6G: Building the Foundation for North American Leadership in 6G and Beyond,” ATIS, Washington, DC, 2022 (updated 2024–2025). [Online]. Available: <https://nextgalliance.org>.
- [8] University of Oulu 6G Flagship, “White Paper on 6G Networking,” 6G Research Visions No. 6, 2020.
- [9] David K. and Berndt H., “6G vision and requirements: Is there any need for beyond 5G?,” IEEE Vehicular Technology Magazine, vol. 13, no. 3, pp. 72–80, September 2018.
- [10] Andrews, J. G. et al., “What will 5G be?,” IEEE JSAC, vol. 32, no. 6, pp. 1065–1082, 2014.
- [11] IMT-2030 (6G) Promotion Group, “6G Vision and Candidate Technologies White Paper,” MIIT, China, 2021 (updated 2024).
- [12] NIST, “Module-Lattice-Based Key-Encapsulation Mechanism Standard (ML-KEM),” FIPS 203, 2024.
- [13] Bos, J. et al., “CRYSTALS-Kyber: a CCA-secure module-lattice-based KEM,” IEEE EuroS&P, pp. 353–367, 2018.
- [14] Qin, Z. et al., “Semantic communications: principles and challenges,” IEEE Communications Magazine, vol. 61, no. 3, pp. 26–32, 2022.

- [15] Shi, J. et al., "Semantic communication systems for speech transmission," *IEEE JSAC*, vol. 39, no. 8, pp. 2434–2444, 2021.
- [16] Del Portillo, I. et al., "A technical comparison of three LEO satellite constellation systems," *Acta Astronautica*, vol. 159, pp. 216–225, 2019.
- [17] O-RAN Alliance, "O-RAN Architecture Description v07.00," Technical Specification, 2023.
- [18] Olli Mammel, et al, "Towards Micro-Segmentation in 5G Network Security," *European Conference on Networks and. Communications (EuCNC)*, Athens, 2016.
- [19] Bernstein, D. J. and Lange, T., "Post-quantum cryptography," *Nature*, vol. 549, pp. 188–194, 2017.
- [20] McMahan, B. et al., "Communication-efficient learning of deep networks from decentralised data," *AISTATS*, vol. 54, pp. 1273–1282, 2017.
- [21] Li, T. et al., "Federated learning: challenges, methods, and future directions," *IEEE Signal Processing Magazine*, vol. 37, no. 3, pp. 50–60, 2020.

Biography



Sudhir Dixit is Co-Founder and COO of the Basic Internet Foundation in Oslo, Norway, where he also heads US operations.

He is also a Docent at the University of Oulu, Finland. Previously, he co-founded Skydoot, Inc. in Davis, California (2015–2017) and was its CEO, and spent five years at Hewlett-Packard Enterprise Services as Distinguished Chief Technologist, CTO for Communications and Media Services in the Americas, and Director of HP Laboratories India. Earlier in his career, he held engineering and leadership roles at BlackBerry, Nokia, NSN, and NYNEX (now Verizon Communications).

A prolific figure in the IEEE community, Dixit serves as Co-Chair of the Connecting the Unconnected working group in the IEEE Future Networks Initiative; WG 6G Chair, and Vice Chair for Americas at the WWRF, where he is also the Editor in Chief of the WWRF magazine, *Wireless World Research and Trends*. He has served as a technical editor of *IEEE Communications Magazine* and was on the editorial board of *IEEE Spectrum*. Dixit has published eight books and holds 21 U.S. patents.

A Life Fellow of the IEEE, IET and IETE, Dixit holds a Ph.D. from the University of Strathclyde, Glasgow, an M.B.A. from the Florida Institute of Technology, an M.E. in Electronics from BITS Pilani, and a B.E. in Electrical Engineering from MANIT, Bhopal.

Sustainable Digitalization & Connecting the Unconnected

Fisseha Mekuria^{1,} and Laurence Banda²*

Abstract: This paper presents a framework for sustainable digitalization and entrepreneurial ecosystems for rural areas. Innovation on sustainable ICT technologies to realize affordable broadband connectivity for rural and underserved communities is a crucial component of the effort to achieve the aim of “leaving no one behind by 2030” as championed by the United Nations and the IEEE “connecting the unconnected” initiative. Sustainable digitalization and broadband connectivity requires the creation of a digital entrepreneurial rural ecosystem (DERE) described in to sustain the broadband connectivity infrastructure, develop innovative services and benefit the local rural communities. The paper describes a rural urban social network (RUSN) ecosystem and two interconnected interventions necessary to achieve digital inclusion with rural communities as a vehicle to achieve affordable connectivity and sustainable digitalization. A definition of the framework for sustainability and its application to the RUSN ecosystem partners and components is described. Important concepts including affordability of broadband services, sustainable business models and co-creation of relevant ICT services involving beneficiary rural communities are presented. The sustainable digitalization framework is presented as a proof of concept on rural SMEs and the DERE digital entrepreneurship ecosystem and tested on four sites deployed in South Africa. Discussions on regulatory and policy interventions to enable sustainability and the business models for the DERE ecosystem partners are presented.

Keywords: Digital entrepreneurial rural ecosystem (DERE), rural urban social networks (RUSN), sustainable digitalization, connecting the unconnected, emerging digital technologies.

Introduction

The research and development work described in the INGR-IEEE-CTU report-2024 [1], aiming to connect the unconnected is a vital component of the sustainable digitalization drive by society and industry. In this paper this is extended by a digital entrepreneurial rural ecosystem (DERE) [2], which aims to promote digital inclusion by accelerating the deployment of innovative and affordable

digital broadband connectivity solutions and an entrepreneurial ecosystem. This is achieved by building a framework for sustainable digital business enterprises, which is expected to accelerate ICT service creation and a digital innovation ecosystem for rural communities. The long term objective of any related digital sustainable transformation initiative should be to develop an Africa-wide digital connectivity and accelerator program in the short run and to facilitate a continent-wide digital connectivity and entrepreneurial ecosystem (ES) in the long term. The DERE ecosystem model incorporates frameworks to assess and implement the model to enable co-creation with local communities and possible uptake in regional African countries. The specific objectives of the described DERE model is to achieve the following outcomes:

1. Support the development of an enabling telecom regulatory environment, including capacity building in networking for sustainability for national telecom regulators and relevant aspects of emerging wireless standards, spectrum innovation technologies, and associated business ecosystems.
2. Strengthen the digital SME ecosystem existing in rural communities (e.g., accelerator labs and innovation hubs). This is aimed to develop innovative ICT services and inclusive business models for the different layers of digital connectivity and for affordable rural network innovation.
3. Enable broadband network innovation and the concept of networking for sustainability. This is to support internetworks powered by green energy technologies to facilitate affordable broadband and digital inclusion for the rural and underserved population.
4. Promote a three-pronged approach to ensure sustainability, complementing existing networks and integrating new network technologies such as 5G which are expected to propel development of 4th Industrial Revolution (4IR) services.
5. Identify synergetic opportunities for emerging network technologies (such as AI in wireless/mobile communication and software defined networks) to facilitate rural and underserved communities to benefit maximally from digital transformation, especially in driving sustainable economic development and a network of rural ICT SME businesses.

Sustainable connectivity and digitalization is one of the tools for socioeconomic change and sustainable development in emerging economy countries, that will assist in tackling unemployment, poverty, and income inequality [1–3]. Research shows ICT services could enable sustainable development in many sectors of the economy. An International Telecommunications Union

¹Sustainable Digitalization Research Centre (SDRC), Malmö University, Sweden

²University of South Africa, Pretoria, South Africa

E-mail: fisseha.mekuria@mau.se

*Corresponding Author

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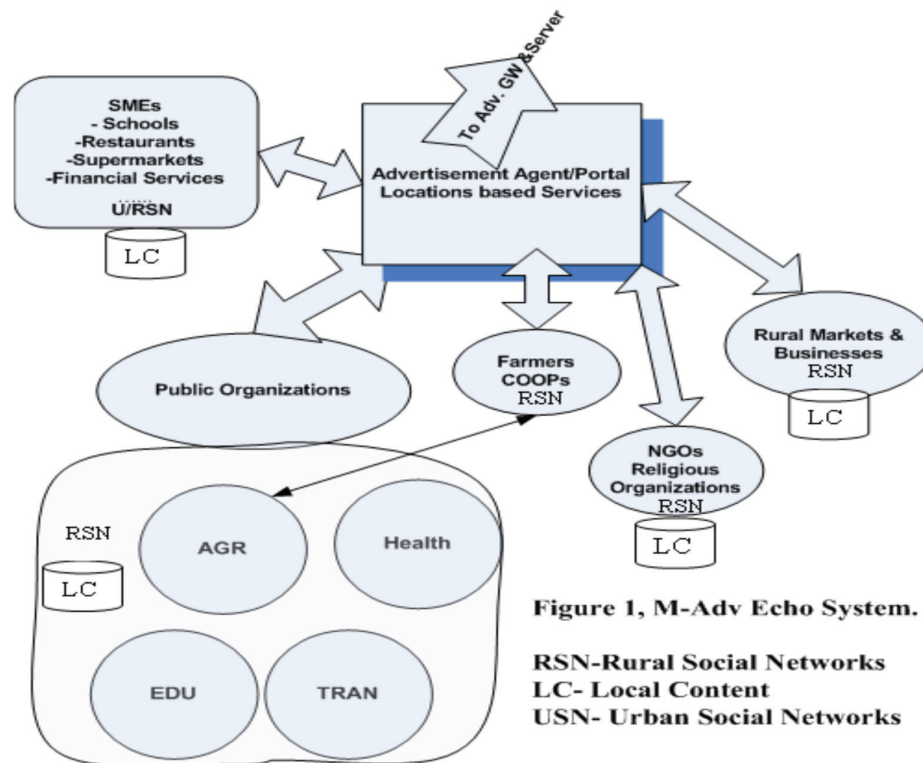


Figure 1.

A picture of rural/urban sustainable social network & ecosystem.

(ITU) study has shown that a 10% increase in broadband penetration can raise economic growth by up to 1.4% and that doubling broadband speed can increase Gross Domestic Product (GDP).

The paper subsequently discusses ecosystems for rural/urban social networks (RUSN), and the development of a locally relevant data base, to enable locally relevant innovative mobile cloud services, based on an indigenous social network data base. Subsequent sections discuss the use of the RUSN to enable local digital entrepreneurs and local network operators for sustainable digital transformation. Sustainable digitalization with respect to 5G deployment and business value creation is also discussed. Finally enabling telecom regulation and policy is presented as a tool to achieve infrastructure sharing, inclusive and sustainable digitalization.

Sustainable Social Networks & Ecosystems

One way to promote sustainable digitalization and entrepreneurial ecosystems is the concept of Rural/Urban social networks (RUSN) and associated local databases, as shown in Figure 1 below. These can provide a way to solve some of the affordability problems associated with mobile web services. Some of the issues that must be addressed to solve the affordability of innovative mobile data services in developing countries are; (1) The placement of a regulatory and policy mechanism to promote a collaborative working relationship between network operators and 3rd party local mobile service & content creators. (2) Regional research

initiatives and innovation-hubs in the area of rural/urban social networks (RUSN) to promote indigenous local mobile content creation. The formal creation of indigenous databases and validation for a general ICT for development (ICT4D) intervention in rural communities is well studied in reference [6]. However, in this paper a simple model of an ecosystem of RUSN based on a mobile local content and mobile advertisement service for improved affordability is presented. The model uses a local rural market scenario to describe the usage of the model by social networks that are created as a natural consequence of the interaction in the RUSN members. Figure 1 shows a RUSN ecosystem based on mobile services, involving both rural and urban social networks, with a further public and private organizations contributing to the ecosystem. Social networks can be public or private organizations, cooperatives (COOPs), associations dealing with services such as health, agriculture (AGR), business, transport (TRAN) or education (EDU). These social network groups can build their own local content database, share and sell content to services providers, public and private organizations and other RSN groups. These local content databases (LC) contain a wealth of information for timely, relevant and location based M-Adv services.

The aggregate of these databases also provide a platform which can be used by the network and service providers to perform customer behavior studies to build next generation intelligent mobile advertising systems. Furthermore, the model promotes a negotiation platform between mobile network & service providers and the social networking groups. The negotiation can result in

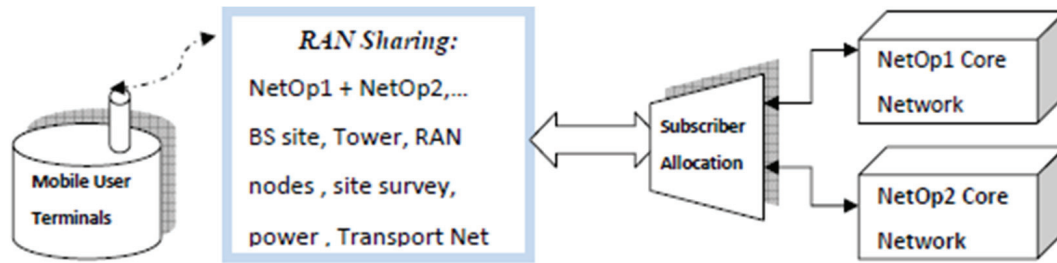


Figure 2.

Infrastructure sharing for affordable digitalization.

discounted prices for the RUSN members on basic and mobile value added services. However, this depends on how much the RUSNs invest on developing their local mobile content and the mobile advertising income through the M-adv advertising system.

Network Sharing for Affordable Digitalization

The traditional universal access funds (USF) used to address the digital divide between rural and urban areas of developing countries is becoming insufficient to bridge the gap between the information haves and those who cannot afford to buy the services [6,9]. This is clearly seen by the fact that mobile cloud service costs become unaffordable for a significant percentage of subscribers, and despite available mobile coverage the number of *active* users of both basic and value added services and mobile cloud services is limited in developing countries [1,4,10]. This is more profound in rural and marginalized communities, and a crucial parameter to be addressed to guarantee the success of future content based mobile cloud services. Furthermore, if this trend continues new mobile intelligent cloud services will have limited footprint and at the same time result in significant number of people being left outside of access to public and relevant digital information. Therefore, to reduce the cost of mobile broadband infrastructure and service provision a new techno-economic model with long term planning is necessary.

Radio access network (RAN) sharing by competing operators, is one of the effective tools and long term solutions to reduce both cost of infrastructure deployment and power consumption of 3–5G broadband mobile networks [4,5]. As shown in Figure 2, the main CAPEX load of broadband wireless infrastructure is the cost of the RAN and associated deployment cost [4,12]. The two network operators, NetOp1 & NetOp2 can use the network sharing opportunity to reduce the cost of mobile broadband infrastructure. The CAPEX savings can be in sharing base station (BS) cell site, BS tower, BS Power supply and site survey. A number of European mobile operators are opting to this scheme, to reduce the cost of mobile cloud services, made possible by network sharing agreements [4,10]. This is motivated by the reduction in deployment, operational and power consumption costs, that is achievable with network sharing. It is for example estimated that the deal by network operators T-Mobile and 3-mobile, recently reported could achieve a cost savings of 2 Billion UK Pounds, a 30% reduction of base station sites and a 70% reduction of the power consumption by the network nodes [2,3,6].

Mobile Innovation & Sustainable Digitalization

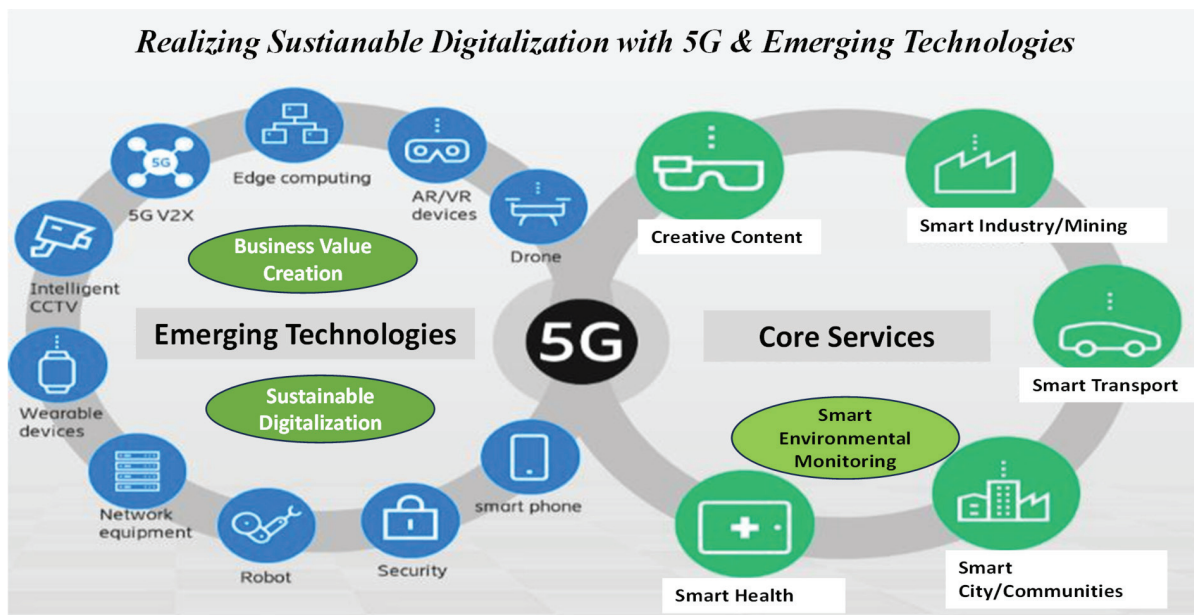
The main purpose of mobile innovations and standards is to achieve a sustainable digitalization of society and provide advanced digital services wirelessly anywhere and anytime. Furthermore, mobile technology standards will not only address anytime and anywhere wireless connectivity, but also personalized service experiences, societal services, drive business and industrial growth, contributing to an inclusive, sustainable and networked digital society. In this respect mobile operators and rural internet service providers (ISPs) are crucial players and need to develop innovative frameworks and embrace sustainable digitalization while deploying emerging digital technologies (EDTs) in connection with emerging mobile technology standards.

This will help to improve the efficiency of resource utilization, relevance and sustainability of societal digital services. Innovation and sustainable digitalization are expected to play a crucial role in the formulation of the digital transformation agenda of global communities and hence mobile technology ecosystem players have a crucial role to play in this transformation agenda. The principal definition of Innovation and sustainable digitalization for mobile systems includes the three pillars shown in Figure 3: Standards & Regulatory Innovation, Technology & Service Innovation, and Innovation for Sustainability. Mobile industry stakeholders dealing with digital transformation and service provision will need to address these factors for successful operational efficiency, business development, and innovative service creation.

Furthermore, mobile industry is required to develop frameworks to continuously engage in innovative mobile services creation and sustainable business model development in order to be able to compete and survive in a global digital world shaken by the emergence of 5G-advanced technologies and Generative AI techniques. At the same time digital innovation should result in intellectual assets and become a requirement for additional function by mobile operators to manage and translate these intellectual properties into commercial products. Figure 4, shows a few of the connections between emerging mobile digital technologies, and the core services and use cases the standards indicate. However, the figure also shows further use cases such as smart environmental monitoring could be supported with 5G EDTs. The International telecom union (ITU), IEEE, GSMA, ETSI and other regulatory and policy forming organizations are all working to enable innovation and sustainable digitalization through mobile technology standards and the creation of global consensus for their seamless integration with emerging digital technologies [3,6,10].

**Figure 3.**

Innovation & sustainable digitalization in mobile development.

**Figure 4.**

5G & emerging digital technologies for sustainable digitalization.

Role of Policy and Telecom Regulation

Apart from incentivizing mobile operators to share infrastructure which reduces cost and wastage of resources, important mechanisms by telecom regulators and policy makers need to encourage operators to invest in sustainable frameworks in their technology deployment. This will help operators to reduce CAPEX and OPEX, operational and service provision costs while at the same time develop environmentally sound and life cycle aware mobile networks. Governments and regulators can support and influence operators' choice of sustainable business models through: enabling spectrum policy and licensing conditions, energy efficiency standards, carbon reporting and taxation mechanisms, and incentives for use of renewable energy and infrastructure sharing [2–4]. Effective regulatory frameworks align

market incentives with sustainability objectives, enabling mobile operators to invest in green network technologies, electronic device design techniques and life cycle analysis, while maintaining competitiveness [3].

Factors for Rural Sustainable Digitalization

Sustainable rural digital businesses require interfaces to a number of sectoral, industry and community organizations to be able to design sustainable business models to maintain and grow their business. Rural digital entrepreneurs need these healthy interfaces and consider the factors affecting their business. This will provide them with the necessary skills to develop their digital business in a more difficult environment with low income population and low basic infrastructure availability. However, as society is becoming

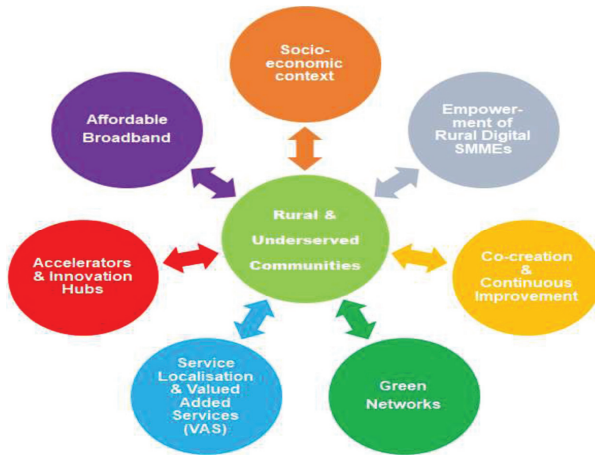


Figure 5.

Factors to consider for sustainable digitalization in a rural community [2].

increasingly dependent on fast reliable broadband connectivity for running government institutions, private businesses and social services, the digital entrepreneurial rural ecosystem (DERE) requires these societal and skill factor interfaces [2–4], to succeed and maintain its business as shown in Figure 5. The connections and interfaces will enable the digital entrepreneurs to design a more relevant and reliable digital services which are necessary with low-cost broadband Internet access, development of innovative mobile services and the building a sustainable rural digital society.

Some of the factors such as service localization, co-creation and green networks go beyond the traditional connectivity infrastructure and provide the rural digital entrepreneurs (RDEs) the necessary tools to grow their sustainable digital businesses. The connection to innovation accelerators and local innovation hubs will improve the growth of innovative and locally relevant ICT services benefitting health, agriculture and transportation sectors, and creating necessary youth employment. The rural entrepreneurship project created by the CSIR-UNDP is a good example in this respect [2].

Conclusion

The paper presented an ecosystem based rural/urban social network (RUSN) framework for sustainable digitalization in developing economies. The framework was developed based on a locally relevant data base, which made the emergence of locally relevant innovative mobile cloud services based on an indigenous social network data base, involving most of the stakeholders in the local community and sectors of the economy. Subsequently the paper discussed the use of emerging mobile digital technologies (5G+) in support of the RUSN and enabling

local digital entrepreneurs transform to local network operators for sustainable connectivity and digital transformation. Furthermore, the paper presented a framework for the creation a digital entrepreneurial rural ecosystem (DERE) to increase and revitalize rural entrepreneurship and benefit the local economy, including employment creation. Sustainable digitalization with respect to 5G deployment and business value creation is also discussed. Finally enabling telecom regulation and policy is presented as a tool to achieve infrastructure sharing, reducing service and deployment cost to support inclusive and sustainable digitalization.

References

- [1] International Network Generation Roadmap INGR-IEEE-CTU report-2025. The link is https://futurenetworks.ieee.org/images/files/pdf/INGR_2024_Edition/IEEE_INGR_CTU_2024-Edition-FINAL.pdf.
- [2] F. Mekuria, M. Mzyece, L. Mfupe and A. Odusola, “Affordable Connectivity and Digital Entrepreneurial Ecosystem for Rural Africa,” *2021 IEEE AFRICON*, Arusha, Tanzania, United Republic of, 2021, pp. 1–6, doi:10.1109/AFRICON51333.2021.9570984.
- [3] L. Banda, F. Mekuria and M. Mzyece, “5G Regulatory and Policy Framework in Emerging Economies,” *2025 IEEE Future Networks World Forum (FNWF)*, Bangalore, India, 2025, pp. 1–6, doi:10.1109/FNWF66845.2025.11317188.
- [4] F. Mekuria “Technology Choice for Mobile Broadband Services in Developing Regions.” *Proceedings of Wireless for development conference*, W4D-08, Karlstad, Sweden, Dec. 10–12, 2018.
- [5] S. Boyera, “Mobile Web for Social development,” White Paper. Available: www.W3C.org, January, 2008.
- [6] “A guide to Network Operators 3UK and T-mobile network sharing agreement.” *Mobile Today Magazine*, Available [online]: www.mobiletoday.co.uk/22/10/2008.
- [7] L. Lin, L. Ping, “A Business Model for Dynamic Composition of Telecommunication Web Services.” *IEEE Communications Magazine*, Vol. 45, No. 7, July 2007.
- [8] D. Griffin, et.al., “A Survey of Web Services in Telecommunications.” *IEEE communications Magazine*, Vol. 45, No. 7, July 2007.
- [9] M. P. Thinyane, *A Knowledge-Oriented, Context-Sensitive Architectural Framework for Service Deployment in Marginalized Rural Communities*, Ph.D. dissertation, Rhodes University, Grahamstown, South Africa, 2009.
- [10] F. Mekuria, “Educating the Architectures of the Mobile Economy,” *Proc. of W3C Workshop, on the Role of Mobile Technologies for Social Development*, Sao Paulo, Brazil, June 2–3, 2018.
- [11] P. Agrawal, J.-H. Yeh, J.-C. Chen and T. Zhang, “IP multimedia subsystems in 3GPP and 3GPP2: overview and scalability issues,” in *IEEE Communications Magazine*, vol. 46, no. 1, pp. 138–145, January 2008, doi:10.1109/MCOM.2008.4427242.
- [12] “Affordability Key in bringing Digital Inclusion,” *Expanding horizons* 1/2008, pp. 12–14. Available [online]: www.nokia.com/expandinghorizons
- [13] “Mobile Broadband: Ensuring sustainable Profitability.” White Paper, Omnitele, May 2008.
- [14] F. Mekuria and E. Sutherland, “Future Communication Networks & Services for Emerging Markets”, *Proc. of IEEE international conference on Innovations in IT, IIT-2016*, Nov. 19–21, Dubai, UAE.

Biographies



Fisseha Mekuria, Malmö University. <https://orcid.org/0009-0006-6443-4483>; Fisseha has a PhD Degree from Linköpings University, Sweden, he worked as Senior Research Engineer, at Ericsson Mobile Communications research lab in Lund, Sweden. He is author of over 85 peer reviewed conference and Journal papers, and several book chapters, including over 15 Patents in wireless communications and signal processing. Dr. Mekuria lead a number of research and development projects with Ericsson, SIDA and mobile operators on skills development and sustainable deployment of Mobile Technology systems in Africa. He also joined the Council for Science & Industrial Research (CSIR), as Chief Scientist leading several projects on sustainable digitalization and emerging digital technology applications for environmental protection in collaboration with Industry, UNDP and ITU. He supported research and postgraduate education as adjunct professor at University of Johannesburg and the university of the Witwatersrand, South Africa. He is recipient of the global Google Research Award for Mobile Computing and the National Research & Innovation Award NTSA, South Africa. At present he is researcher & educator at the research Centre for sustainable digitalization at Malmö University, in emerging

digital technologies 5G, IoT and AI for applications in advanced environmental monitoring and Sustainable digitalization of societal services and industrial processes.



Laurence Banda received the B.Eng. degree in Electrical and Electronic Engineering from the University of Zambia, Zambia, in 2006, the M.Sc. degree in Electronic and Communications Engineering from ESIEE Paris, France, in 2012, the M.Eng. degree in Electrical Engineering from the Tshwane University of Technology, South Africa, in 2013, and the Ph.D. degree in Technology and Operations Management from the University of the Witwatersrand, South Africa, in 2024.

He has over 15 years of experience in telecommunications, digital transformation, and technology management. He began his career with Celtel Zambia Ltd. as a Radio Network Planning and Optimization Engineer and later spent more than a decade with Huawei Technologies South Africa in various technical and leadership roles.

Dr. Banda's research interests include telecommunications regulation, 5G/6G networks, digital transformation, business models, AI, IoT, and intelligent connectivity. He is currently a Postdoctoral Research Fellow at the University of South Africa.

Engineering Broadband Connectivity: Wireless Solutions for All

Shruthi Koratagere Anantha Kumar, H. Sama Nwana, Robert W. Stewart and David H. Crawford*

Abstract: Digital connectivity has become essential for enabling access to education, healthcare, career and business opportunities, and economic well-being worldwide. However, the digital divide continues to hinder inclusive access for all. This article presents a concise study on meaningful connectivity, infrastructure gap, usage gap, demand gap, and the integration of space-air-ground integrated networks (SAGIN). Furthermore, there is a need to understand the market drivers in terms of supply, demand, macro-economy, technology, and policy and regulation. This article highlights how these market drivers play a crucial role in widening the global digital divide. We examine the interdependencies among various stakeholders to address the digital divide. This article uniquely integrates technical solutions with socioeconomic perspectives, outlines pathways towards engineering wireless broadband connectivity, and promotes equitable access for all.

Keywords: Digital divide, demand gap, infrastructure gap, meaningful connectivity, SAGIN, stakeholder collaboration, usage gap.

1. Introduction to Digital Connectivity and the Divide

Digital connectivity has become a cornerstone of modern life, permeating every sector and contributing significantly to economic growth and individual opportunities. Yet despite this progress, over 2 billion people worldwide remain unconnected as of 2026, and the digital divide remains a pressing challenge [1]. The issue doesn't end by offering the network coverage to those who are unconnected; it is about quality, affordability, reliability, security, and the meaningfulness of that connectivity [2].

Tackling the digital divide requires a multi-dimensional approach that needs to focus on the infrastructure gap, the usage gap, and the demand gap. This is a complex challenge, where no single solution fits all the underserved regions, as each area has its own unique challenges [3]. Key focuses of the United Nations Sustainable Development Goal (SDG) 9 are: building resilient

infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation [4]. The studies have shown that there is a vast disparity in 5G coverage in high-income countries (84%) and low-income (4%) countries [1]. Addressing this disparity is dependent on bridging the digital divide and empowering individuals to reap the benefits of the technology. In recent years, billions of dollars in funding through pilot trials, projects, and financial investments have been directed towards a myriad of potential solutions (hybrid architectures and innovative business models) with the aim of achieving an inclusive digital ecosystem for all [5].

Yet technology alone will not build a 100% inclusive digital ecosystem, as this is dependent on the market drivers that determine whether the solution is scalable, affordable, suitable, and economically viable [6]. The telecommunication sector is evolving at a faster rate, and is capital-intensive, highly regulated, and dependent on multiple sectors. Therefore, collaboration among the telecommunication stakeholders, both from the public and the private sectors, is necessary and crucial to avoid resource and effort duplication that slows the process via fragmented initiatives. There is a need to translate the learnings across the stakeholders to ensure faster rollout, which is resilient in nature [7, 8].

Building on the comprehensive analysis presented in the monograph [5], the unique contribution of this paper is to propose a holistic framework, integrating technology, economics, and policy, focused on bridging the digital divide. The pathways toward inclusive broadband futures include: focus on bridging the gaps, invest in hybrid architectures, align with market drivers, and foster stakeholder collaborations. Policymakers need to create an enabling regulatory environment to drive innovation in solutions aimed at building an inclusive ecosystem and lowering the entry barriers for solutions aimed at closing the digital divide while ensuring end-users' well-being.

This paper proceeds as follows: Section 2 reviews the gaps that need to be addressed in bridging the digital divide. Section 3 highlights the different technologies that could be integrated to address the digital divide while also considering the network economics. Section 4 focuses on the five key market drivers to support a thriving ecosystem for the technological solutions, and stresses the need for collaboration among the stakeholders to achieve the desired results. Section 5 concludes.

2. Understanding the Gaps

Why is there a digital divide? Though technology has progressed over the years, the cost of network infrastructure rollout has

StrathSDR lab, Department of Electrical Engineering, University of Strathclyde, Glasgow, G1 1XQ, United Kingdom
E-mail: k.a.shruthi@strath.ac.uk; h.nwana@strath.ac.uk; r.stewart@strath.ac.uk; david.crawford@strath.ac.uk

*Corresponding Author

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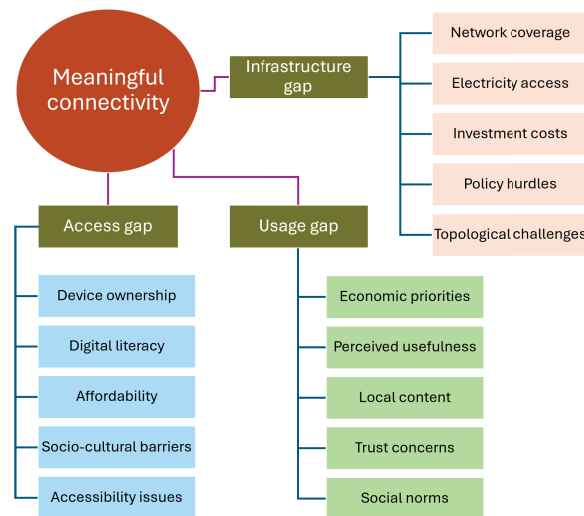


Figure 1.

Conceptual framework of meaningful connectivity showing infrastructure, usage, and demand gaps.

increased exponentially. There are several reasons for the existence of the digital divide, and they can be distilled into three broad categories: infrastructure gap, usage gap and demand gap. Addressing these requires the stakeholder to focus on meaningful connectivity, which helps them understand why the digital divide exists, though technology is progressing [5].

2.1. Meaningful Connectivity

The ITU definition for “Universal Connectivity” ensures that everyone has access to internet connectivity, and focuses on the availability of the infrastructure, but not any other factor [9]. As per ITU, billions of people are yet to be connected to the Internet, and several million people living within the coverage regions don’t have ‘meaningful connectivity’ (which measures not just the availability of the digital infrastructure, but also its affordability, availability, accessibility, reliability, and quality of service (QoS) to enable full participation in digital life). Meaningful connectivity “implies regular, dependable, and effective access to the Internet – one that enables users to benefit from online resources and services anytime, and anywhere” [10]. Today, there is an urgent priority to build a digitally inclusive society for all, yet significant barriers exist in the form of infrastructure gaps, usage gaps, and demand gaps, as shown in Figure 1.

2.2. Infrastructure Gap

One of the main reasons that leads to the digital divide is the infrastructure gap. In many regions, the absence of adequate telecommunication infrastructure stems from a lack of network coverage and higher deployment costs, often resulting in poor or no return on investment (ROI) [5]. Beyond connectivity, these regions struggle with supporting infrastructure, such as unreliable electricity, inadequate road access, and logistical barriers. They also

face policy and regulatory hurdles that hinder network rollout; for example, complex permission processes, right-of-way (ROW) issues, a lengthy spectrum allocation process, high market entry barriers, and unclear coordination among ministries, departments, and agencies (MDAs) [10].

- *Network coverage:* Many rural and remote areas are outside the reach of the current telecommunication infrastructure coverage region. The network coverage gap also exists in urban and suburban regions, when there is a blind spot where terrain, vegetation, distance, or clutter disrupts the signal availability.
- *Electricity access:* Electricity is fundamental in the functioning of the telecommunication infrastructure. End-user devices, equipment, and supporting telecommunication infrastructure would not function consistently without a reliable and accessible power supply. In regions with intermittent or no access to electricity, service interruptions often limit end-users from participating in the digital ecosystem.
- *Investment costs:* The cost of rolling out broadband infrastructure is exorbitant in regions with infrastructure gaps, and limited demand driven by low income levels further constrain ROI for operators, making it financially challenging. This discourages operators from extending the infrastructure in underserved regions without external financial incentives and subsidies.
- *Policy hurdles:* Several approaches and efforts aim to bridge the infrastructure gaps, but often encounter regulatory and administrative challenges. Inconsistent policy implementations, for example, ROW permissions, spectrum allocation for new entrants, and slow disbursement of funds aimed to encourage infrastructure deployment. Coordination among the MDAs is fragmented, while the absence of a streamlined process, such as a single window for clearance and permissions, adds further delay.
- *Topographical challenges:* Terrain, such as mountains, deserts, islands, forests, and inaccessible regions, poses a significant barrier to expanding network infrastructure, driving network costs significantly higher. This also hampers the rollout of the electricity network, network operations, and maintenance.

2.3. Usage Gap

The usage gap arises when the infrastructure exists; however, adoption is limited due to social, economic, and cultural factors, such as [5,10]:

- *Economic priorities:* Households often prioritise essential human needs, such as food, water, clean sanitation, healthcare, and education, over access to digital services and the Internet.
- *Perceived usefulness:* If the broadband access adds limited relevance to their daily life, then the end-users are not keen on opting for digital services.
- *Local content:* A vast majority of the content available on the Internet is in English, while only 1.5 billion of the 8 billion people speak English. The lack of content in the local language is a significant barrier in many countries.
- *Trust concerns:* End-users fear that using digital services would harm them through activities such as financial scams, identity threats, digital arrests, privacy breaches, and misinformation.
- *Social norms:* Prevailing social expectations and cultural traditions can reinforce reliance on non-digital communication and constrain digital access, especially among women and children.

2.4. Demand Gap

The demand gap highlights another scenario, where infrastructure exists, but individual capability and affordability are a challenge [5].

- *Device ownership*: Broadband access is dependent on the access of the end-user devices. For many, digital devices, such as smartphones, laptops, or computers, remain out of reach.
- *Digital literacy*: End-users may lack knowledge of how to use the devices, navigate in the digital ecosystem, use e-services, and access digital governance confidently, which restricts the meaningful usage of the services.
- *Affordability*: For individuals with low-income levels, affordability of the end-user devices and financially sustainable broadband service plans are essential requirements for sustained adoption.
- *Socio-cultural barriers*: Traditions and cultural norms restrict certain groups of people from accessing and using digital services and technologies. The barrier goes beyond individual choice, making it harder for them to overcome it without targeted interventions respecting the local culture and inclusivity.
- *Accessibility issues*: The design phase of the digital ecosystem should also consider people with disabilities. The design should be inclusive and support adaptive technologies.

2.5. Learnings

Connecting the majority of the population is relatively straightforward, but the remaining fraction requires disproportionately greater efforts and resources [10]. The approaches for connecting 68% of the population are insufficient for connecting the rest. Bridging this gap requires the development of light-weight solutions that are scalable, affordable, accessible, and reliable.

3. Hybrid Architecture: Integrated Solutions

Bridging connectivity gaps requires more than a single technology; it requires integrated solutions that are a combination of technologies, suitable for a particular region, balancing cost, economic feasibility, supporting infrastructure, and long-term sustainability. A hybrid architecture approach understands the need for the integration of several technologies to deploy a network that uniquely addresses the digital divide challenges due to the infrastructure gap, usage gap, and demand gaps; refer [3, 5] for details. By adopting a hybrid architecture, the solution would be technologically feasible, socially inclusive, and financially viable as well as sustainable.

3.1. Ground Layer

Ground layer technologies consist of terrestrial networks and include both wired and wireless networks. The ground layer handles the majority of the global Internet traffic through fibre optics and other terrestrial networks. It offers shorter latency, higher throughput, and greater reliability at a lower cost compared to the air layer and space layer. The wired broadband technologies that form the backhaul network include fibre, subsea cables, copper cables, Ethernet, wired telephone networks, wired

television networks, wired relay networks, and coaxial cables. It also consists of wireless broadband technologies such as cellular communication systems (2G, 3G, 4G, 5G, and 6G), Wi-Fi, Li-Fi, worldwide interoperability for microwave access (WiMAX), wireless relay networks, long-range wide area network (LoRaWAN), and microwave. Hybrid solutions combine elements of wired and wireless infrastructure, such as satellite integration with terrestrial networks, TV White Space (TVWS), distributed antenna systems (DAS), fixed wireless access (FWA), and community networks.

Wired networks are well-known for their reliability, performance, consistent QoS, and resilience; however, they are not feasible to be deployed everywhere due to high installation costs, complex cabling requirements, skilled personnel, and expensive ongoing maintenance challenges. Hence, wireless networks are gaining popularity as a low-cost solution to bridge the digital divide. Wireless broadband solutions deliver faster data rates, greater energy efficiency, and lower latency, while reducing the need for cabling and enabling flexible deployment with remote diagnostics. These technologies are versatile and are compatible with a wide range of end-user devices.

3.2. Space Layer

The space layer consists of the geostationary orbit (GEO), medium earth orbit (MEO), and low earth orbit (LEO) satellites. A communication satellite is an artificial satellite that creates a communication channel from a source transmitter to relay and amplify telecommunication signals via a transponder to a different receiver on Earth. The footprint of the satellite coverage region is large, as it is located far above the stratosphere (160 km to 35,786 km). Some of the benefits offered by satellite include two-way communication, broadcasting, remote sensing, disaster survey and response, backhaul networks, and maritime and airtime applications. Some of the satellites have fixed coverage, while others have electronically steered antennas to support service on demand.

With the commercial scalable deployment of LEO satellites, the network latency is comparable to the 4G networks, and it can deliver connectivity to any region where the ground network is unavailable. Once the satellite terminals are deployed, the network can be operational almost immediately, unlike terrestrial wired networks. While satellites offer broad coverage and the potential to reduce the digital divide, their construction, deployment, and operational costs in 2026 remain prohibitively high, limiting their economic viability for large-scale solutions. Some other challenges that exist are limited spectrum resources, orbital debris and space traffic management, propagation delays, standardisation, launch cost and access to space, affordable handsets, and position, navigation, and timing issues.

3.3. Air Layer

In recent years, air layer technologies have been widely explored by stakeholders globally to provide telecommunication services. The air layer consists of high altitude platforms (HAPS), unmanned aerial vehicles (UAVs), and network tethered flying platforms (NTFPs). These technologies are gaining popularity in regions where it is challenging to deploy terrestrial networks, and it is expensive to set up a satellite communication network. The air

layer offers the benefits of the ground layer, such as lower latency, lower deployment cost, and reliable QoS, as well as the benefits of the space layer, such as wider coverage area and easier network rollout. Another key benefit of air layer technologies is the ease of interoperability with the end-user devices.

The ongoing research in these technologies explores the design where the network would support International Mobile Telecommunication (IMT) spectrum bands to provide cellular coverage in a larger area, but the size would be much smaller than a satellite, as air layer technologies operate at an altitude between 2 and 50 km. These technologies face multiple obstacles to commercial viability. Examples include power reliability, high cost of maintaining the network in the air, cost-effectiveness, scalability, interference from the terrestrial network, and frequent take-offs and landings.

3.4. SAGIN

Advancements in the telecommunications industry have spurred the development of a solution that can vertically integrate across all three layers; this architecture is known as the space-air-ground integrated network (SAGIN), as shown in Figure 2 [5, 11, 12].

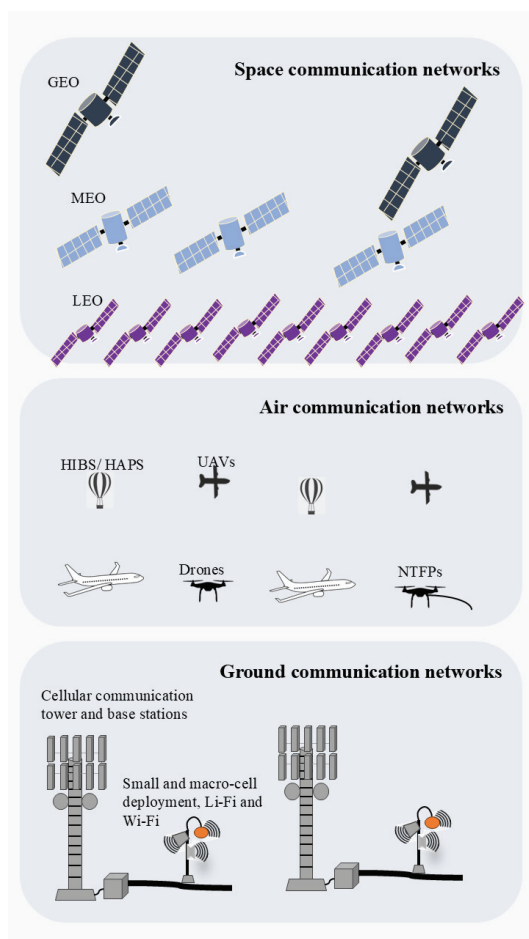


Figure 2.

SAGIN architecture – integration of space, air, and ground layers.

The architecture aims to provide ubiquitous connectivity and seamless broadband access across the globe. This architecture aims to focus on both urban and rural communities by leveraging a unified, hybrid, resilient communication network to offer an inclusive digital ecosystem for all.

SAGIN is gaining popularity as, individually, no layer is able to provide ubiquitous, reliable broadband access everywhere on the Earth. This integrated architecture offers the benefits of each layer and overcomes the challenges of each layer. This emerging architecture needs to focus on interoperability across the layers, efficient resource planning and management, scalability, and reliability. Additionally, there is a need to understand how user data is shared among layers, ensure data security, coordinate across layers, manage interference, synchronise timing, optimise energy efficiency, and manage device mobility.

4. Market Drivers and Stakeholder Interdependencies

Beyond technology, market drivers and stakeholder interdependencies play a crucial role in addressing the global digital divide.

4.1. Market Drivers

There is a need to understand the key market drivers that impact the digital ecosystem in any country; these factors determine whether a technology or solution scales successfully or declines [5]. The market drivers determine the solution's economic feasibility, while societal returns that improve the overall well-being of people facing the digital divide are to be considered. The key market drivers include [10]:

- **Demand:** Demand assessment helps in understanding affordability, priorities, and usage patterns. Without a clear demand, any proposed solution would not scale. To motivate operators to deploy the network, there must be commercially viable demand or support for the business in the form of subsidies and interventions.
- **Supply:** The technology deployments and operations require supportive infrastructure in terms of spectrum availability, electricity access, infrastructure providers who would deploy the networks, distribution channels, logistics and supply chain, equipment manufacturers, interoperability among the devices, and a strong distribution channel. Additionally, affordable end-user devices would support scaling of the infrastructure deployment.
- **Technology:** For a technology uptake to become widespread, it should be readily available, scalable, interoperable, and standardised, and should support innovation. A solution should be technologically feasible in the region of interest, considering the infrastructure gap, usage gap, and demand gap. In addition, the design must accommodate future upgrades at reduced cost, thereby ensuring that the overall total cost of ownership (TCO) remains sustainable. The technology determines the penetration of digital tools, artificial intelligence (AI) usage, and automation.
- **Macroeconomy:** Economic factors, such as gross domestic product (GDP), consumer spending trends, inflation, interest rates, tax, customs, average revenue per user (ARPU), and equipment cost, determine the network uptake. Even if demand

and supply exist, and technology is ready, high inflation, weak consumer spending, or prohibitive equipment costs can stall adoption. Economic parameters must be optimized to attract investment in solutions and technologies.

- **Policies and regulations:** How well a business thrives in a market ecosystem is determined by the policies and regulations laid out for the market. The policies and regulations should offer a supportive ecosystem for businesses to grow, as well as protect consumers and their well-being. The adoption of a technology or a solution focusing on the digital divide is determined by the spectrum cost, RoW, import taxes, new entrant market barriers, ease of licensing, ease of obtaining approvals and permissions, digital inclusion policies, roadmaps for achieving meaningful connectivity, and coordination among the MDAs [8,13]. Therefore, policies and regulations act as a key enabler or barrier for scaling the digital ecosystem and bridging the digital divide.

Hence, these aforementioned five drivers need to align, ensuring that economic feasibility is achieved along with social returns for tackling the digital divide and enhancing meaningful connectivity.

4.2. Stakeholder Interdependencies

The telecommunications market is driven by collaboration among the key stakeholders, which includes telecom service providers (TSPs), telecom regulatory bodies, international organisations, standardization bodies, equipment manufacturers, and end users. The telecommunication sector relies on several supporting MDAs, and efficient collaboration among them is essential to ensure seamless performance, coordinated policy implementation, and efficient delivery of services [14, 15]. Some of the key ministries include:

- **Power/energy ministry:** For reliable electricity for the network operations, and powering end-user devices.
- **Transport and roadway ministry:** The network rollout and its maintenance are highly dependent on access to the location of interest. Well-connected roadways would ensure an efficient supply of the components required for deploying and maintaining the network.
- **Education ministry:** For enhancing the digital literacy skills and increasing the service adoption of the end-users.
- **Information and communication technology (ICT) ministry:** They provide the overarching digital strategy for the country, set targets for digital inclusion, and coordinate the national broadband targets. They are helping with the technology rollout.
- **Finance ministry:** They influence the rollout of the network through import taxes, customs duties, subsidies, tax incentives, and investments. They design financial policies that would enable or act as a barrier to digital connectivity.
- **Commerce and manufacturing industry:** They encourage the local manufacturing of the products to lower the equipment and end-user device cost, which in turn would improve the ROI and affordability.

The telecommunication sector also coordinates with ministries, such as the urban development and housing ministry, the rural development ministry, the healthcare ministry, the defence and home affairs ministry, and the environment ministry.

When several stakeholders and MDAs are involved, there is a need to ensure that the coordination efforts are in the right direction and minimise resource duplication to ensure that the right solutions reach the underserved communities sooner.

5. Conclusion - Pathways Towards Inclusive Broadband Futures

Digital connectivity is becoming fundamental for social and economic participation for an individual; however, the digital divide continues to exclude billions from tapping into their potential. This paper proposes a holistic framework integrating technology, economics, and policy to address this challenge. Predominantly, a combination of infrastructure gap, demand gap, and a usage gap coexists for underserved communities, and wireless approaches are generally more cost-effective than extending wired networks, offering a pragmatic path to connectivity. There is a need for exploring hybrid network (space, air, ground, SAGIN) architectures that help in rolling out a technologically feasible solution that offers adequate coverage, QoS, throughput, latency, and reliability, along with being economically viable for operators and affordable for end-users.

The work also focuses on the need for technological innovation to align with market drivers and stakeholder interdependencies. The pathway for engineering broadband connectivity is dependent on bridging the existing gaps, investing in hybrid architectures, aligning with market drivers, and fostering collaboration among stakeholders. The innovation at scale is driven by the enabling regulatory environments that support businesses and protect end-users. Together, these actions would ensure that the digital ecosystem is inclusive for all and that SDG 9 is achievable.

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References

- [1] International Telecommunication Union, "Measuring Digital Development: Facts and Figures 2025," 2025, accessed: 2026-04-22.
- [2] World Bank, *World Development Report 2021: Data for Better Lives*, World Bank, Washington, DC, 2021.
- [3] S. Dixit and et al, "IEEE FNTC CTU Newsletter," *IEEE Network*, vol. 40, no. 2, pp. 16–25, 2026.
- [4] United Nations, "Sustainable Development Goal 9: Industry, Innovation and Infrastructure," 2015, accessed: 2026-04-22.
- [5] S. K. A. Kumar, *Wireless Broadband Access to Bridge the Digital Divide*, Springer Nature Switzerland, 1 edn., 5 2026.
- [6] OECD, "Bridging the Digital Divide: Policy Considerations," OECD Digital Economy Papers, OECD, 2020.
- [7] S. Lee, *Stakeholder Engagement in Telecom Policy: A Comprehensive Guide*, Wiley, 2025.
- [8] Ericsson and ITU, "Bridging the Digital Divide: A Data-Driven Approach to Transformational Connectivity," 2025, accessed: 2026-04-22.
- [9] ITU, "Universal and Meaningful Connectivity," 2024, accessed: April 17, 2026.
- [10] H. Nwana, *The Connectivity Crisis: Half the World Left Behind*, Strathclyde Academic Media, 2025.

- [11] S. Zhang et al., "Space–Air–Ground Integrated Wireless Networks for 6G: Basics, Key Technologies, and Applications," *IEEE Access*, vol. 13, pp. 12345–12367, 2025.
- [12] J. Chen et al., "Space–Air–Ground Integrated Network (SAGIN): A Survey," *IEEE Communications Surveys & Tutorials*, vol. 26, no. 1, pp. 1–35, 2024.
- [13] Fiber Broadband Association, "The Impact of Fiber Broadband on Rural and Underserved Communities," 2025, accessed: 2026-04-22.
- [14] World Economic Forum, "Here's how we can work together to bridge the digital divide," January 2023, accessed: 2026-04-22.
- [15] V. M. Gallegos-Rejas and et al, "A multi-stakeholder approach is needed to reduce the digital divide and encourage equitable access to telehealth," *Journal of Telemedicine and Telecare*, vol. 29, no. 1, pp. 73–78, 2023.

Biographies



Shruthi Koratagere Anantha Kumar is a Research and Innovation Associate with the StrathSDR lab at the University of Strathclyde and serves as an Associate Consultant with Real Wireless and a Technical Consultant with Cenerva. She also works as an independent consultant, specializing in rural telecommunication, techno-economic feasibility assessment, sustainability frameworks, resilient infrastructure, disaster resilience, and educational outreach programs. She was a Visiting Faculty member with George Mason University, Fairfax, USA. She earned her Ph.D. degree from the University of Strathclyde, Glasgow, UK, in 2023.



H. Sama Nwana, CITP, FBCS, FIET, CEng, BSc (Hons), MSc, PhD, MA (Cambridge), MBA (Dist.) (London Business School) is Managing Partner, Cenerva Ltd UK (www.cenerva.com) – a

boutique training-led consultancy on all TMT regulatory across emerging markets based in London. He is a Full Visiting Professor at the University of Strathclyde (UK) and other higher institutes. His most recent (2025) book relevant to this paper is titled *The Connectivity Crisis: Half the World Left Behind*, published by Strathclyde Academic Media.



Robert W. Stewart is the Director of the Strathclyde Software Defined Radio (StrathSDR) team. Currently, the team is working on several DSIT-funded 5G projects, including the lead partner with Cisco Systems on the Open Networks Shared Spectrum Innovation Environment project, which includes other industry partners, AMD, BBC R&D, Neutral Wireless, and University of Glasgow. Bob is also the Director of the University of Strathclyde startup company, Neutral Wireless Ltd, which has developed its own private 5G radio for deployment in private networks and has worked for some high-profile events.



David H Crawford received BSc, MSc, PhD, and MBA degrees from the University of Strathclyde, Glasgow, UK. After spending several years in industry in various roles related to telecommunications and digital signal processing, he returned to the University of Strathclyde in 2011 to run the then newly-formed Centre for White Space Communication. David manages a programme of industry/academic collaborative projects at the University of Strathclyde, focusing on shared spectrum, private 5G networks, and future advanced communications. He has championed the sharing of spectrum for over a decade and continues to pursue increased spectrum sharing as an overarching strategy for the future management of spectrum.

Predictive Energy-Aware Uplink Antenna and Link Selection for Multi-Network Cellular User Equipment

Mahesh Devdatta Telang

Abstract: Modern cellular user equipment (UE) increasingly supports multiple switchable antenna panels and concurrent connectivity to both terrestrial networks (TN) and non-terrestrial networks (NTN), including low-earth-orbit (LEO) satellite links. Existing uplink antenna and link selection schemes suffer from three fundamental limitations: they rely on downlink reference signal measurements as proxies for uplink path quality; they delegate selection to the network via capability reporting and scheduling commands; or they minimize only transmit power without accounting for the transient energy costs of antenna switching, retuning, and baseband chain activation. These limitations render existing approaches suboptimal for emerging multi-panel, multi-link UE architectures – particularly wearables and augmented reality (AR) devices with tight thermal budgets and rapidly varying propagation environments. This paper proposes a fully autonomous, UE-side uplink selection framework based on a five-component total energy cost function: $E_{\text{total}} = E_{\text{tx}} + E_{\text{baseband}} + E_{\text{switching}} + E_{\text{tuning}} + E_{\text{margin}}$, where E_{tx} is the transmit energy, E_{baseband} is the baseband and RF chain activation energy, $E_{\text{switching}}$ is the antenna panel and link switching transient energy, E_{tuning} is the antenna retuning and settling energy, and E_{margin} is an uncertainty margin penalty. The selection is performed entirely on-device using internal UE measurements, impedance/VSWR sensing, power amplifier (PA) telemetry, and inertial measurement unit (IMU)/grip sensing – without network assistance. A forward-looking extension over a prediction horizon T uses satellite ephemeris and Doppler trajectory data to minimize cumulative energy expenditure for NTN links. Joint carrier aggregation (CA) and simultaneous TN+NTN multi-link selection are addressed within the same framework. Hysteresis is enforced by conditioning switching events on the criterion that the reduction in E_{tx} and E_{baseband} exceeds the sum of $E_{\text{switching}}$ and E_{tuning} by a programmable margin. Analytical results demonstrate the validity of the proposed framework across a range of multi-panel and multi-link UE scenarios.

Keywords: Antenna selection, carrier aggregation, energy efficiency, non-terrestrial networks, power amplifier telemetry,

predictive link selection, satellite communications, uplink transmission, user equipment, VSWR.

1. Introduction

The rapid evolution of cellular user equipment toward multi-panel antenna architectures, carrier aggregation across multiple component carriers, and concurrent terrestrial and non-terrestrial network connectivity has introduced a new class of energy management challenges that existing uplink resource selection frameworks are ill-equipped to address. Smartphones, wearables, and augmented reality (AR) devices now routinely incorporate four or more antenna panels, multiple independent transmission chains, and modems capable of simultaneous operation on 5G New Radio (NR) terrestrial links and low-earth-orbit (LEO) satellite NTN links as standardized in 3GPP Release 17 and beyond. Wearables and AR devices are particularly susceptible to uplink energy inefficiency owing to their significantly reduced battery capacities, constrained antenna apertures, and heightened sensitivity to grip-induced impedance variation resulting from their worn or hand-held usage patterns.

Existing approaches to uplink antenna and link selection fail to account for the multi-component energy costs arising from antenna switching, retuning, baseband chain activation, and propagation uncertainty. A first class of approaches uses downlink reference signal measurements (such as RSRP or CQI) as proxies for uplink path quality. This approach is fundamentally indirect: downlink and uplink propagation conditions can differ substantially, particularly in frequency-division duplex (FDD) systems and in multi-panel UEs where the active panel for reception may differ from the optimal panel for transmission. A second class delegates antenna selection to the network, which introduces signaling overhead, is inapplicable in high-latency NTN scenarios, and is unavailable in networks lacking advanced uplink antenna selection signaling. A third class, represented by sounding reference signal (SRS)-based antenna switching, reconfigures SRS resources but is oriented toward channel sounding rather than data transmission energy minimization.

The contributions of this paper are as follows:

1. A five-component total energy cost function is proposed for UE-side uplink antenna panel and network link selection, providing the first unified formulation that explicitly and simultaneously accounts for all material energy costs in multipanel, multi-link UE architectures.

San Ramon, California, United States

E-mail: maheshdevdatta.telang@gmail.com

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2. A fully autonomous on-device selection algorithm is presented that populates the five-component cost function using internal UE measurements without requiring network assistance.
3. The cost function is extended to a forward-looking prediction horizon using satellite ephemeris and Doppler trajectory data for NTN links.
4. Joint carrier aggregation and simultaneous TN+NTN multi-link selection are addressed within the same framework, deriving a hysteresis condition that prevents energetically unjustified switching events.
5. An analytical characterization of the energy terms and a demonstration of the framework's energy-saving properties are presented.

2. Related Work

2.1. Uplink Antenna Selection in Multi-Antenna UE

Transmit antenna selection (TAS) for uplink communications has been studied extensively in the context of MIMO systems. In 3GPP LTE and NR, uplink TAS is specified as a closed-loop procedure. Extensions to carrier aggregation environments have been proposed, but these are fundamentally network-driven and do not optimize UE-side energy consumption. Work on UE-side power minimization for multi-antenna uplink transmission has considered the selection of the number of active transmit chains, but this formulation does not model switching transient energy, retuning energy, or baseband activation energy. The impact of user hand grip on antenna performance in multi-panel UE has been studied, demonstrating that grip-induced antenna efficiency degradation can exceed 10 dB. Grip-aware beam codebook adaptation has been proposed, but without integration into an energy cost optimization framework.

2.2. Energy-Efficient Carrier Aggregation

Carrier aggregation in 5G NR enables UEs to aggregate multiple component carriers, increasing throughput at the cost of activating additional baseband chains and RF front-end components. The energy cost of CA has been studied to jointly optimize component carrier selection and resource block allocation. AI-enabled approaches have also been proposed for energy-aware CA, but these works address only the baseband component of the total energy cost and do not model switching/tuning energy.

2.3. Non-Terrestrial Network Integration and Energy Efficiency

The integration of LEO satellite NTN links into 5G NR introduces new challenges due to high path loss, large Doppler shifts, and long propagation delays. Satellite ephemeris data enables UE-side prediction of satellite geometry and Doppler trajectory. Energy-efficient multi-connectivity scheduling for uplink NTN has been studied, but these works focus on network-side schedulers rather than UE-side autonomous selection based on a comprehensive energy cost function.

2.4. Internal UE Measurement for Uplink Path Quality Estimation

Prior works have explored individual sensor modalities such as impedance sensing and PA telemetry in isolation, but combining all three – VSWR/impedance sensing, PA telemetry, and IMU/grip sensing – as inputs to a unified uplink energy optimization framework has not been previously proposed.

3. System Model

3.1. UE Architecture

A UE device equipped with $N_p \geq 2$ switchable antenna panels is considered. The UE supports N_C transmission chains, which can be connected to different antenna panels through an RF switching fabric. The UE can connect to N_I network links, comprising TN and NTN links. It supports carrier aggregation across up to N_{CA} component carriers. At each uplink transmission opportunity t , the UE must select a configuration tuple $(i, j, k) \in S$, where S denotes the set of feasible configurations.

3.2. Channel and Propagation Model

For TN link k , the uplink path loss at time t is modeled as:

$$PL_TN(k, t) = PL_0(k) + 10\eta \log_{10}(d(t)/d_0) + X_{\sigma} \quad (1)$$

PL_0 is the reference path loss at d_0 , η is the path loss exponent, X_{σ} is log-normal shadow fading (zero-mean Gaussian in dB with std σ)

For NTN link k , the uplink path loss at time t is modeled as:

$$PL_NTN(k, t) = 20 \log_{10}(4\pi d_s(t)f_c/c) + L_{atm}(\theta(t)) + L_{rain} + L_{point}(t) + X_{\sigma, NTN} \quad (2)$$

$\theta(t)$ is elevation angle; $d_s(t)$ is the slant range between UE and satellite; $L_{point}(t)$ is pointing/misalignment loss; $X_{\sigma, NTN}$ is NTN shadow fading term per 3GPP TR 38.811.

3.3. Antenna Efficiency and VSWR Model

The total radiation efficiency of antenna panel i at time t is:

$$\eta_{rad}(i, t) = (1 - |\Gamma(i, t)|^2) * \eta_0(i, t) \quad (3)$$

The VSWR is measured directly by the UE's internal impedance measurement circuit:

$$VSWR(i, t) = (1 + |\Gamma(i, t)|)/(1 - |\Gamma(i, t)|) \quad (4)$$

The required PA output power to achieve a target EIRP is calculated accordingly:

$$P_{PA}(i, j, k, t) = P_{EIRP_target}(k, t) * L_{feed}(i) / (G_{ant}(i) * \eta_{rad}(i, t)) \quad (5)$$

where $G_{ant}(i)$ is the antenna gain of panel (i) in linear scale and $L_{feed}(i) \geq 1$ is the feed and connector loss factor between the PA output port and the antenna feed point.

The intrinsic radiation efficiency $\eta_0(i, t)$ in (3) is affected by grip-induced body loading, which varies with grip state and device orientation as estimated from IMU and grip sensor measurements. Misclassification of grip state introduces uncertainty in $\eta_{\text{rad}}(i, t)$ via (3) and consequently in $P_{\text{PA}}(i, j, k, t)$ via (5), degrading the accuracy of the uplink path quality estimate for body-loaded panel configurations.

4. Five-Component Total Energy Cost Function

The total energy consumed by the UE for an uplink transmission using configuration (i, j, k) is modeled as the sum of five components:

$$\begin{aligned} E_{\text{total}}(i, j, k) = & E_{\text{tx}}(i, j, k) + E_{\text{baseband}}(i, j, k) \\ & + E_{\text{switching}}(i, j, k) + E_{\text{tuning}}(i, j, k) \\ & + E_{\text{margin}}(i, j, k) \end{aligned} \quad (6)$$

A weighted form with dynamically configurable coefficients (shadow pricing) is:

$$\begin{aligned} E_{\text{select}}(i, j, k) = & \alpha * E_{\text{tx}}(i, j, k) + \beta * E_{\text{baseband}}(i, j, k) \\ & + \gamma * E_{\text{switching}}(i, j, k) + \delta * E_{\text{tuning}}(i, j, k) \\ & + \varepsilon * E_{\text{margin}}(i, j, k) \end{aligned} \quad (7)$$

The coefficients $\alpha, \beta, \gamma, \delta, \varepsilon \geq 0$ in (7), with at least one strictly positive, represent the relative priority assigned to each energy component in the selection objective. A negative coefficient would reward increased expenditure on that component, contradicting the minimization objective.

The weights are adapted dynamically as a function of UE operating state: α and β are elevated under battery-critical conditions to penalize sustained energy consumption; β is elevated under thermal throttling to suppress baseband chain activation; γ, δ , and ε are elevated under high mobility to penalize switching transients and uncertain estimates; and ε is elevated when NTN satellite elevation is low, biasing selection toward the TN link until geometry improves.

4.1. Transmit Energy Term (E_{tx})

The estimated RF output energy required to deliver an uplink payload of B bits over configuration (i, j, k) during a transmission interval of duration T_{tx} :

$$E_{\text{tx}}(i, j, k) = P_{\text{PA}}(i, j, k, t) * T_{\text{tx}} / \eta_{\text{PA}}(i, j, k). \quad (8)$$

4.2. Baseband Activation Energy (E_{baseband})

The state-dependent energy cost of activating or maintaining the baseband processing chain and RF front-end:

$$E_{\text{baseband}}(i, j, k) = P_{\text{BB}}(j, k) * T_{\text{tx}} + \Delta E_{\text{act}}(j, k, j_0, k_0). \quad (9)$$

Where $P_{\text{BB}}(j, k)$ is the steady-state baseband chain power draw and $\Delta E_{\text{act}}(j, k, j_0, k_0)$ is the one-time activation energy when transitioning from chain-link pair (j_0, k_0) to (j, k) .

4.3. Switching Transient Energy ($E_{\text{switching}}$)

The energy consumed during the physical transition from the currently active configuration to the candidate configuration (including RF switch actuation and modem state transitions):

$$E_{\text{switching}}(i, j, k) = E_{\text{sw_RF}}(i, i_0) + E_{\text{sw_modem}}(j, k, j_0, k_0) \quad (10)$$

where $E_{\text{sw_RF}}(i, i_0)$ is the RF switch actuation energy transitioning from panel i_0 to i , and $E_{\text{sw_modem}}(j, k, j_0, k_0)$ is the modem state-transition energy.

4.4. Antenna Retuning Energy (E_{tuning})

The energy consumed by the antenna impedance matching network reconfiguration process and settling time:

$$\begin{aligned} E_{\text{tuning}}(i, j, k) = & E_{\text{tune_ctrl}}(i, k, i_0, k_0) \\ & + P_{\text{PA_settle}}(i, k) * T_{\text{settle}}(i, k). \end{aligned} \quad (11)$$

where $E_{\text{tune_ctrl}}(i, k, i_0, k_0)$ is the control energy of the tunable matching network and $P_{\text{PA_settle}}(i, k)$ is the PA power during the settling transient, with $T_{\text{settle}}(i, k)$ being the impedance settling time.

4.5. Uncertainty Margin Energy Penalty (E_{margin})

An optional uncertainty penalty derived from the confidence level of the uplink path quality estimate:

$$E_{\text{margin}}(i, j, k) = \lambda * (1 - \rho(i, j, k)) * E_{\text{tx}}(i, j, k). \quad (12)$$

where $\rho(i, j, k) \in [0, 1]$ is the confidence in the path quality estimate for configuration (i, j, k) and $\lambda \geq 0$ is a tunable penalty weight.

4.6. Optimization Problem

The UE selects the configuration (i^*, j^*, k^*) that minimizes the weighted total energy cost subject to QoS and regulatory constraints:

$$(i^*, j^*, k^*) = \text{argmin}(i, j, k) \in S_{\text{select}}(i, j, k) \quad (13)$$

5. Autonomous On-Device Selection Using Internal UE Measurements

The cost function in (7) is populated using internal UE measurements rather than network-provided measurements or downlink reference signals. This avoids signaling overhead and mitigates the downlink-proxy inaccuracies inherent in FDD systems. Three measurement modalities are employed.

5.1. Impedance and VSWR Sensing

The UE's internal impedance measurement circuit monitors $|\Gamma(i, t)|$ at each antenna panel, from which $\eta_{\text{rad}}(i, t)$ is computed

via (3) and $VSWR(i, t)$ via (4). The required PA output power $P_{PA}(i, j, k, t)$ is then obtained via (5), directly populating E_{tx} in (8). The confidence of this measurement is reflected in $\rho(i, j, k)$ in (12), such that panels with elevated mismatch uncertainty incur a higher E_{margin} penalty in (7), discouraging their selection under uncertain impedance conditions.

5.2. Power Amplifier Telemetry

PA telemetry provides real-time measurement of PA efficiency $\eta_{PA}(i, j, k)$ and actual RF output power, which are substituted directly into E_{tx} in (8).

5.3. IMU and Grip Sensing

IMU and grip sensor measurements estimate device orientation and grip state, identifying body-loaded panels with degraded $\eta_{0}(i, t)$ in (3). As established in Section III-C, grip state misclassification introduces uncertainty in $\eta_{rad}(i, t)$ via (3) and $P_{PA}(i, j, k, t)$ via (5), which propagates into $\rho(i, j, k)$ in (12) and increases E_{margin} in (7) for affected panel configurations, penalizing their selection in (13).

6. Hysteresis Framework

To prevent energetically unjustified switching in volatile propagation environments, a transition from the current configuration to a candidate configuration is executed only if:

$$\begin{aligned} & E_{select}(i_{curr}, j_{curr}, k_{curr}) \\ & - E_{select}(i_{cand}, j_{cand}, k_{cand}) \\ & > E_{switching}(i_{cand}, j_{cand}, k_{cand}) \\ & + E_{tuning}(i_{cand}, j_{cand}, k_{cand}) + \Delta_{margin}. \end{aligned} \quad (14)$$

7. Forward-Looking Prediction for NTN Links and Future Work

For NTN satellite links, the UE uses satellite ephemeris data (orbital parameters, position, velocity) to predict the satellite elevation angle and slant range over a forward-looking horizon T . This allows the UE to proactively switch panels or links based on predicted path loss evolution and Doppler shift rather than reacting post-degradation.

The proposed framework establishes the analytical foundation for autonomous UE-side uplink energy optimization. Numerical evaluation of the 5C-EAF against transmit-power-only and network-assisted baselines, including per-component energy savings quantification and sensitivity analysis of the weight coefficients $\alpha, \beta, \gamma, \delta$, and ε across varying UE operating states, TN channel conditions, and NTN satellite geometries, are left for future work. Hardware-in-the-loop validation on commercial UE platforms equipped with PA telemetry and impedance sensing capability will further confirm the practical realizability of the on-device selection algorithm under realworld grip, mobility, and multi-link conditions.

8. Conclusion

This paper has presented a five-component total energy cost function for autonomous UE-side uplink antenna and link selection, establishing an analytical foundation for energy-aware uplink selection that addresses the limitations of legacy single-metric systems.

References

- [1] A. Karimi and K. I. Pedersen, "5G system-level performance analysis of uplink multi-panel transmission in mm-wave frequencies," in Proc. IEEE Veh. Technol. Conf. (VTC-Fall), Sep.
- [2] F. Abinader, C. Rom, K. Pedersen, and S. Hailu, "System-level analysis of mmWave 5G systems with different multi-panel antenna device models," in Proc. IEEE Veh. Technol. Conf. (VTC-Spring), Apr.
- [3] A. Sattarzadeh, M. Mozaffari, and P. Popovski, "Satellite-based non-terrestrial networks in 5G: Lessons learned and opportunities," IEEE Access.
- [4] T. Fukui and K. Yokomakura, "Investigation of performance of uplink multi-panel transmission for multi-TRP operation in 5 G - advanced system," IEICE Trans. Commun., vol. E-B.
- [5] B. Shang, L. Liu, R. Q. Hu, and P. Zhu, "Multi-connectivity between terrestrial and non-terrestrial networks," IEEE Wireless Commun.
- [6] M. Tayyab, X. Gelabert, and R. Jäntti, "Uplink reference signals for energy-efficient handover," IEEE Access.
- [7] 3GPP, "NR; Physical layer procedures for control," 3rd Generation Partnership Project, Tech. Spec. TS.
- [8] H. Hojatian, J. Nadal, J.-F. Frigon, and F. Leduc-Primeau, "Learning energy-efficient transmitter configurations for massive MIMO," IEEE Trans. Wireless Commun.
- [9] K. Muralidhar, A. Papadogiannis, and S. Parkvall, "SRS interference management in TDD CJT for 5G," IEEE Access.
- [10] 3GPP, "NR; Physical layer procedures for data," 3rd Generation Partnership Project, Tech. Spec. TS. (UE-side transmit chain selection for uplink beamforming.)
- [11] R. Joda, M. Elsayed, H. Abou-Zeid, R. Atawia, A. Bin Sediq, and G. Boudreau, "Carrier aggregation with optimized UE power consumption in 5G," IEEE Netw. Lett.
- [12] F. Khoramnejad, M. Erol-Kantarci, and B. Kantarci, "AI-enabled energy-aware carrier aggregation in 5G new radio," IEEE Access.
- [13] M. N. Dazhi, H. Al-Hraishawi, M. R. Bhavani Shankar, S. Chatzinotas, and B. Ottersten, "Energy-efficient service-aware multi-connectivity scheduler for uplink multi-layer non-terrestrial networks," IEEE Trans. Green Commun. Netw.
- [14] A. F. Molisch and M. Z. Win, "MIMO systems with antenna selection," IEEE Microw. Mag.
- [15] A. Al Ayidh, A. Celik, and A. M. Eltawil, "Antenna selection based on matching theory for uplink cell-free massive MIMO," Telecom.
- [16] 3GPP, "NR; Physical channels and modulation," 3rd Generation Partnership Project, Tech. Spec. TS. (Uplink transmit antenna selection in carrier aggregation.)
- [17] S. Ahlbom, C. Gustafson, and B. K. Lau, "Hand grip impact on 5G mmWave mobile devices," IEEE Access.
- [18] A. Karimzadeh Bae, L. Akhoondzadeh-Asl, and P. S. Hall, "User effect on the MIMO performance of a dual antenna LTE handset," in Proc. Eur. Conf. Antennas Propag. (EuCAP).
- [19] A. AlAmmouri, J. Mo, B. L. Ng, J. C. Zhang, and J. G. Andrews, "Grip-aware analog mmWave beam codebook adaptation for 5 G mobile handsets," arXiv.
- [20] M. Caus, J. Bas, A. I. Pérez-Neira, and M. Á. Vázquez, "Non-terrestrial networks in 5G and beyond: A survey," IEEE Access.

- [21] R. Shrestha and H. Al-Hraishawi, "Elevation-aware supplementary uplink for direct satellite-to-device communications," arXiv.
- [22] M. Alibakhshikenari, B. S. Virdee, L. Azpilicueta, M. N. Moghadasi, and E. Limiti, "Optimum power transfer in RF front end systems using impedance matching technique," Sci. Rep.
- [23] N. Ye, X. Cao, X. Ding, J. Li, and D. Zhao, "Multi-connection to the sky: Energy-efficient beamforming for multi-satellite uplink transmission with lens antenna array," IEEE Trans. Veh. Technol.
- [24] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," 3rd Generation Partnership Project, Tech. Rep. TR.

Biographies



Mahesh Devdatta Telang received his B.E. in Electronics and Communication Engineering from Visvesvaraya Technological

University in 2011 and M.S. in Computer Engineering from the University of Texas at Dallas in 2013. From 2012 to 2019, he was a Senior Engineer at Qualcomm Technologies Inc., contributing to the research and development of 4G and 5G wireless communication technologies. Subsequently, he worked at Google from 2019 to 2022, where his focus was on baseband and connectivity for Android and Pixel devices. Mr. Telang currently works at Meta Platforms Inc., where he is involved in designing and developing innovative connectivity solutions for AR/VR/XR devices. His research interests include Control and Data plane for Wireless technologies like 4G, 5G, NTN. Power, Thermal and SAR Mitigation techniques for wearables and prototyping of new innovations on AR/XR and wireless devices.

High-Frequency Dual-Band Super-Compact MIMO Antenna for Resilient 5G Vehicular Communications

Moustafa M. Nasralla, Mehr E Munir and Haleem Farman*

Abstract: In 5G vehicular services, advanced antenna systems are essential to deliver robust, reliable, and efficient wireless links under real driving conditions. Vehicles operate in highly dynamic and interference-prone radio environments, where signals are frequently obstructed by surrounding objects and rapidly changing mobility patterns. Moreover, the limited physical space available for on-board electronics further constrains antenna design. These factors collectively hinder the deployment of reliable high-capacity links, highlighting the need for advanced, compact, and resilient antenna systems tailored for vehicular communications. To meet these constraints, this paper presents a high-frequency, dual-band, super-compact MIMO antenna designed for resilient 5G vehicular communications. The proposed antenna is designed on 0.51 mm RO4350B substrate and operates in two widely separated bands 8–11 GHz (microwave band) and 24–34 GHz (mmWave band) so that a single element can support both dependable coverage and high-capacity services. The design incorporates five vertical slots integrated with three horizontal slots on patch while a partial ground plane with a square slot is incorporated on ground plane. In the 8–11 GHz range, the antenna achieves a peak gain of 4.64–5.99 dBi while in the 24–34 GHz, it provides a peak gain of 4.7–6.4 dBi, enabling high data rates and low latency for demanding applications. Across both ranges, the antenna maintains >90% radiation efficiency, while isolation between radiating elements exceeds –19 dB, ensuring reliable and energy-efficient operation. The design features a $25 \times 10 \times 0.51$ mm³ footprint on an RO4350B substrate, making it well-suited to space-constrained vehicular platforms. Furthermore, experimental validation and link-budget analysis on a vehicular model confirm the antenna's promising performance. By combining dual-band functionality, high efficiency, compact dimensions, and validated performance, the proposed antenna addresses user needs, service requirements, and high-frequency technology demands essential for next-generation, resilient 5G vehicular communication systems. Its dual-band capability enhances spectrum flexibility and supports diverse vehicular communication scenarios, including advanced driver-assistance systems (ADAS),

vehicle-to-everything (V2X) connectivity, and high-data-rate services.

Keywords: Dual band, MIMO Antenna, mmWave antenna, X-band, 5G.

1. Introduction and Related Work

Modern in-vehicle radios are being designed to work across X-band (8–12 GHz) and mmWave (24–300 GHz) so a single platform can deliver two complementary functions: dependable mid-band coverage for control and V2X safety, and very high-capacity, low-latency links for ADAS telemetry, cooperative perception, and infotainment. This dual role forces the antenna to meet three tough requirements at once: it must be ultra-compact to fit inside tight housings (e.g., shark-fin or mirror pods), highly efficient despite the small electrical size and nearby lossy materials, and well matched with stable radiation patterns across two widely separated bands. Consequently, even with recent advances in compact dual-band and miniaturized mmWave arrays (e.g., around 28/38 GHz), achieving high efficiency in a very small form factor while simultaneously supporting a separated lower band remains a primary integration challenge [1].

The authors in [2] designed a mmWave antenna for wearable devices operating at 28 and 38 GHz, with overall dimensions of $30 \times 30 \times 1.575$ mm³. It supports only two bands and provides a narrow impedance bandwidth of 1 GHz at each frequency. Moreover, the footprint is relatively large, making it unsuitable for many practical 5G wearable applications. The authors in [3] presented an antenna for vehicular applications operating in three bands 1.565–1.578 GHz, 2.2–3.8 GHz, and 5.8–6 GHz with overall dimension of $50 \times 50.5 \times 1$ mm³. Despite covering multiple bands, the design exhibits a very narrow impedance bandwidth, and its large footprint makes it unsuitable for practical 5G vehicular deployments. The authors in [4] designed a 5G mmWave antenna for vehicular applications targeting the n258 band (24.25–27.5 GHz) on a Rogers RO4003C substrate. The design achieved peak gains of 4.6 and 5.15 dBi, but it operates in only a single band. For modern vehicular 5G platforms, dual-band or multi-band operation is typically required to ensure efficient, versatile performance. The authors in [5] designed a mmWave MIMO antenna operating at the 28 and 38 GHz bands, using a defected patch structure with overall dimensions of 30×30 mm². The antenna exhibits good impedance bandwidth and solid MIMO performance; however, its large footprint makes it unsuitable for many practical 5G devices.

Smart Systems Engineering Laboratory, Department of Communications and Networks Engineering, College of Engineering, Prince Sultan University, PO BOX 66833, Riyadh, 11586, Saudi Arabia

E-mail: mnasralla@psu.edu.sa; mmunir@psu.edu.sa; hfarman@psu.edu.sa

*Corresponding Author

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The authors in [7] present a two-element dual-band MIMO antenna using an inset-fed primary patch and an overlaid arc-shaped parasitic to realize operation at 28 GHz and 38 GHz with strong isolation (≈ 20 dB) while maintaining a compact footprint illustrating a clean pathway to dual-band miniaturization via parasitic loading and ground tailoring. A noted trade-off is the modest realized gain (≈ 1 –2 dB in cited comparisons), which may be insufficient for harsher outdoor/vehicular links without arraying or additional aperture engineering. A 2×2 dual-band array targeting 28/38 GHz with higher realized gain and wider impedance bandwidth is reported in [8], and is useful for terminals requiring both diversity and directional performance. The studies document multi-port arrangements with isolation control and report high-gain variants suitable for mmWave links. A limitation is that increasing port count and gain often demands tighter layout tolerances and can introduce pattern distortion in constrained housings practical concerns for vehicular body-integrated installations. In [9], the authors propose an arc-shaped, very small 28 GHz radiator (monopole radius ≈ 1.3 mm) with an elliptical slot to enhance bandwidth ssssan appealing seed element for dense MIMO tiling where board area is scarce. The main drawback is that extreme miniaturization can constrain efficiency and gain, so multiple elements or superstrates may be required to meet link budgets in dynamic vehicular channels. In [10], surveys how GNSS/IMU/side-information can prune mmWave beam search, reduce training overhead, and stabilize links directly relevant to “resilience” when antennas are mounted on fast-moving vehicles and frequent blockages occur. The limitation is that this is a protocol/algorithmic perspective rather than a hardware design; it improves link continuity but does not by itself solve RF constraints such as mutual coupling or element efficiency. In [11], the authors compile vehicular-centric measurements and models, highlighting blockage, Doppler, and fast fading in V2V/mmWave scenarios, and outlining the array requirements imposed by these channel dynamics. The main limitation for immediate design guidance is that, as a broad survey, it does not prescribe exact antenna geometries or isolation techniques; translating channel insights into PCB-level MIMO layouts remains the designer’s task. Similarly, in [12], the authors introduce a circular, double-sided EBG texture to suppress surface waves and improve isolation in a compact dual-band MIMO design (with single-element $\approx 10 \times 8.5$ mm² and MIMO $\approx 15.8 \times 8$ mm²). This is a proven, fabrication-friendly approach to reducing ECC without requiring large spacing’s. The caveat is added stack-up complexity: EBG/DGS patterns increase design and fabrication effort and can complicate multi-board integration or conformal vehicle mounting.

The proposed design is a high-frequency, dual-band, super-compact MIMO antenna for resilient 5G vehicular communications. It covers 8–11 GHz and 24–34 GHz, achieving peak gains of 4.64–5.99 dBi (microwave band) and 4.64–5.99 dBi (mmWave band), while maintaining $>90\%$ radiation efficiency in both bands. The antenna was also tested on a vehicular model, where it demonstrated strong performance, confirming its suitability for practical 5G vehicular applications.

2. MIMO Antenna Design

The proposed MIMO antenna is lightweight, compact, simple to fabricate, and easy to integrate with X-band and mmWave devices.

It is designed and optimized using CST Studio Suite 2022 and a low-loss microwave laminate such as RO4350B is employed to support high radiation efficiency in both bands while remaining PCB-process friendly. This material choice helps achieve $>90\%$ efficiency while keeping the stack-up simple for automotive modules. The present work reports results only in the mmWave band [6], while an extended version of the same design enables operation over 8–11 GHz (microwave band) and 24–34 GHz (mmWave band), with a total size of $25 \times 10 \times 0.51$ mm³, and has been experimentally tested on a vehicle CAD model. The design leverages three techniques:

2.1. DPST Technique

A defected patch structure technique (DPST) means that the normal metal patch of the antenna is intentionally modified by introducing slots or cuts. These slots alter the surface current paths, allowing the patch to support more than one natural resonant frequency instead of a single band. As a result, the same compact patch can generate multiple resonances, enabling multiband or wider-band operation without increasing the overall antenna size (see Figure 1).

2.2. Partial Ground Plane Technique

A partial ground plane means the ground metal is intentionally shortened rather than covering the full substrate, which helps improve impedance matching and bandwidth. In this design, a square slot is etched in the ground to further tune the resonance and extend the usable frequency range, as shown in Figure 2.

2.3. Connected Ground Plane Technique

The connected ground plane approach means that all four antenna elements are tied to the same continuous ground instead of having separate grounds. Arranged in a linear array, these four elements sharing a common ground help achieve compact integration and better MIMO performance, as illustrated in Figure 2.

3. Results and Discussions

The proposed MIMO antenna operates over two bands, 8–11 GHz in the microwave range and 24–34 GHz in the mmWave range, as illustrated in Figure 3, making it well suited for practical 5G vehicular applications. In the lower band, the antenna achieves a

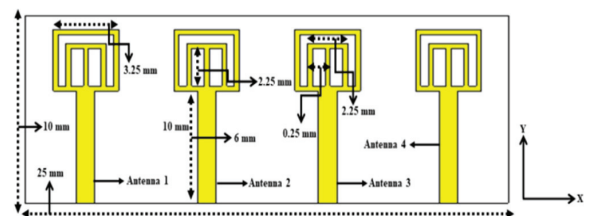


Figure 1.
Front view of MIMO antenna [6].

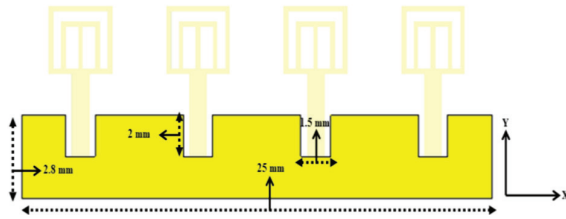


Figure 2.
Back view of MIMO antenna [6].

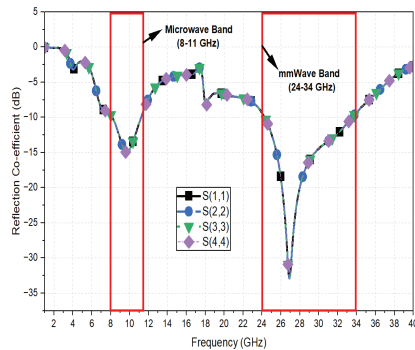


Figure 3.
S-parameter of MIMO antenna.

3 GHz impedance bandwidth, providing robust coverage across the entire X-band allocation of interest. In the upper band, it offers a much wider 10 GHz bandwidth, which is beneficial for high-data-rate mmWave links and multi-service integration. Together, these dual bands enable flexible support for long-range sensing/communications and high-capacity 5G links on vehicles. In this design, the port isolation is < -19 dB in both the lower and upper operating bands (see Figure 4), meaning that only a small amount of power from one element couples into the others across the full spectrum. Maintaining this low coupling over 8–11 GHz and 24–34 GHz helps preserve the independence of the MIMO channels and reduces inter-port interference. As a result, the antenna can deliver more reliable diversity and capacity performance for wideband vehicular 5G links.

The proposed MIMO antenna demonstrates strong performance in terms of gain, radiated efficiency, and total efficiency, as shown in Figure 3. At 11 GHz, it achieves a gain of 5.89 dBi with a radiated efficiency of 92% and a total efficiency of 88%. At 28 GHz, the gain increases to 6.4 dBi, with a radiated efficiency of 95.85% and a total efficiency of 92.5%, confirming its suitability for NR 5G bands. Figure 4 presents the fabricated four-element MIMO antenna prototype, validating the practicality of the design.

Figure 6 compares the simulated and measured reflection coefficient of the proposed four-element MIMO antenna. The measured curves closely follow the simulated ones, with only minor deviations mainly attributed to connector and fabrication losses. This close agreement confirms that the antenna maintains its intended impedance matching and bandwidth in practice. The strong correlation between simulation and measurements verifies the design's suitability for sustainable 5G vehicular networks. The antenna under test is presented in Figure 7, where its physical

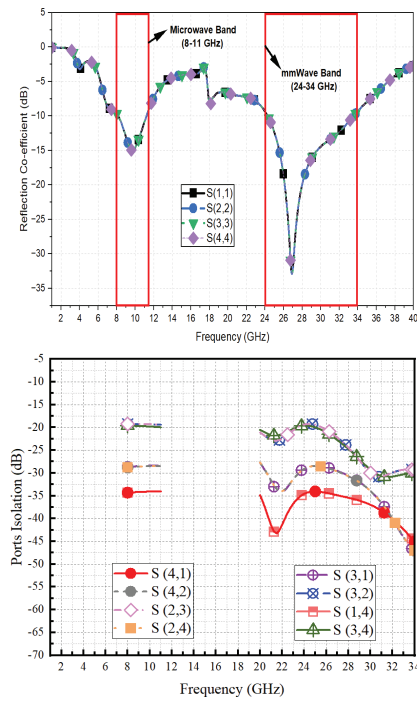


Figure 4.
Port isolation of MIMO.

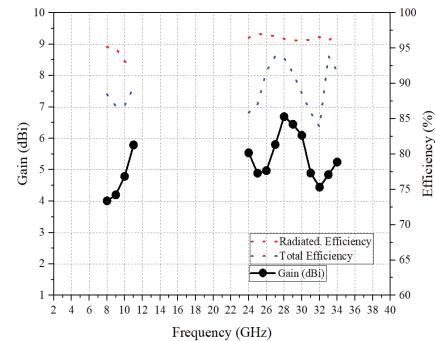


Figure 5.
Gain, radiated and total efficiency.

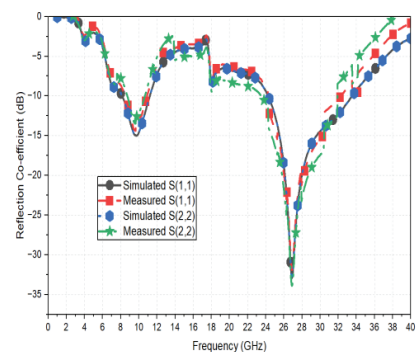


Figure 6.
Simulated and measured reflection co-efficient.

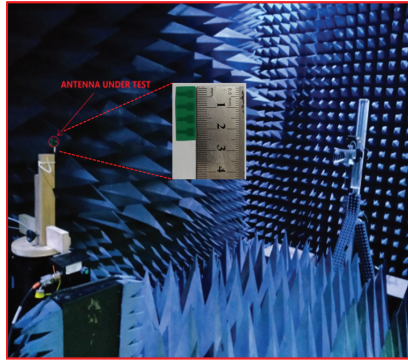


Figure 7.
MIMO antenna under test.

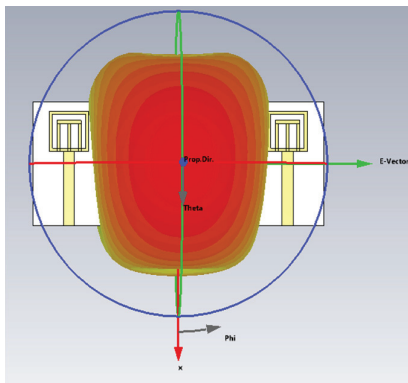


Figure 8.
3D gain at 11 GHz.

layout and feeding configuration can be clearly observed. The corresponding 3D gain pattern at 11 GHz is illustrated in Figure 8, highlighting the main radiation lobes and overall directivity.

4. MIMO Performance Evaluation

The proposed four-element MIMO array is further assessed through key performance metrics to verify its effectiveness and overall performance capability.

The diversity gain (DG) presents the performance of four antenna ports, labeled DG1 to DG4, across the frequency range of 2 to 40 GHz, as shown in Figure 9.

DG quantifies the effectiveness of a MIMO antenna in mitigating multipath fading. A value near 10 dB is generally regarded as optimal for MIMO diversity performance [19]. In the presented results, all four DG curves remain close to 10 dB within both operating bands:

- 8 to 11 GHz: DG is approximately 9.99 dB to 10 dB
- 24 to 34 GHz: DG is approximately 9.99 dB to 10 dB

These results indicate that the four ports are sufficiently decorrelated and are capable of providing strong diversity performance. Minor variations among DG1, DG2, DG3, and DG4 are expected, as each antenna port may exhibit slightly different coupling and radiation characteristics. The results demonstrates

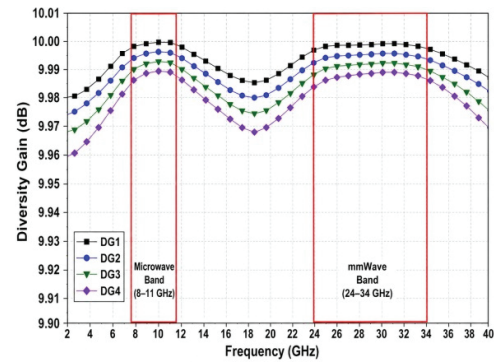


Figure 9.
DG of the proposed 4-port MIMO.

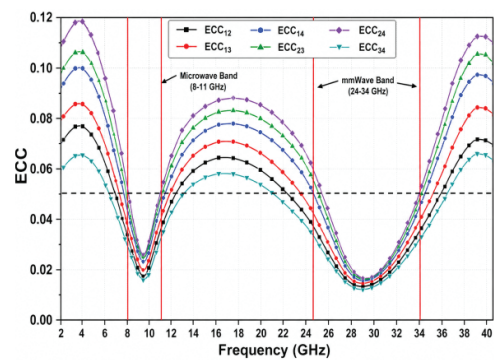


Figure 10.
ECC of the proposed 4-port MIMO antenna.

that the antenna achieves excellent diversity performance in both the microwave and mmWave bands. A DG value exceeding approximately 9.95 dB is commonly used as a benchmark for strong MIMO diversity behavior.

Figure 10 shows the envelope correlation coefficient (ECC) of the proposed 4-port MIMO antenna across 2–40 GHz, with the two intended operating bands highlighted in red: 8–11 GHz and 24–34 GHz.

ECC is an important MIMO performance parameter because it measures the correlation between antenna elements. Lower ECC means the antenna ports are more independent, which improves diversity performance and helps the MIMO system transmit/receive multiple data streams more efficiently. ECC is directly related to diversity behavior; when ECC is low, the diversity gain approaches the ideal value of 10 dB [18].

In Figure 10, the ECC curves are plotted for different port combinations, such as ECC₁₂, ECC₁₃, ECC₁₄, ECC₂₃, ECC₂₄, and ECC₃₄. These curves represent the correlation between each pair of antenna ports in the 4-port structure. Within the first operating band, 8–11 GHz, all ECC values drop significantly and remain low, mostly around 0.015–0.05. This means the antenna elements have weak correlation in the microwave band, confirming good isolation and diversity behavior. Within the second operating band, 24–34 GHz, the ECC values are also low, especially near the center of the band, 27–30 GHz, where several curves approach

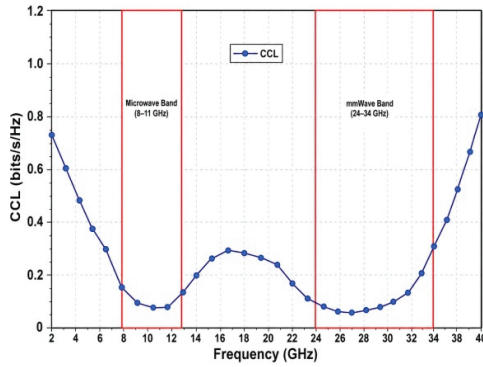


Figure 11.

CCL of the proposed 4-port MIMO antenna.

0.01–0.02. Toward the upper edge near 33–34 GHz, the ECC increases slightly but remains in the acceptable low-correlation region.

Figure 11 presents the Channel Capacity Loss (CCL) as the expected reduction in MIMO channel capacity resulting from correlation and mutual coupling between antenna elements.

For practical MIMO antennas, the stocktickerCCL should typically remain below 0.4 bits/s/Hz [17]. In the presented results, the stocktickerCCL remains well below this threshold across both operating bands:

- 8–11 GHz: The CCL is approximately 0.05 to 0.15 bits/s/Hz.
- 24–34 GHz: The CCL is approximately 0.05 to 0.15 bits/s/Hz.

These results indicate that the proposed four-port antenna exhibits low inter-port correlation and minimal capacity degradation. Consequently, the antenna can support efficient MIMO data transmission without significant loss in channel capacity. This characteristic is critical for practical 5G and millimeter-wave (mmWave) systems, as elevated CCL values would reduce spectral efficiency and data throughput. Several MIMO antenna studies consider CCL values below 0.4 bits/s/Hz as an acceptable practical limit.

The total active reflection coefficient (TARC) behavior of the 4-port MIMO antenna when all ports are excited simultaneously. This is more realistic than evaluating only the individual S_{11} , S_{22} , S_{33} , or S_{44} values because, in a MIMO system, multiple ports operate simultaneously. Figure 12 shows three cases:

- TARC, in-phase: all ports excited with the same phase.
- TARC, average phase: average response for different excitation phases.
- TARC, worst phase: worst-case reflection under phase variation.

The dashed horizontal line at -10 dB is the practical matching reference. In both highlighted operating bands, the TARC curves remain below -10 dB, which means the antenna maintains acceptable active impedance matching when all four ports are excited [16].

The graph shows strong TARC dips at approximately 9 GHz and 28 GHz, where TARC values are very low. These deep minima indicate strong resonance and low reflected power. In the 8–11 GHz band, the curves fall well below -10 dB, confirming good active matching. In the 24–34 GHz band, the TARC also

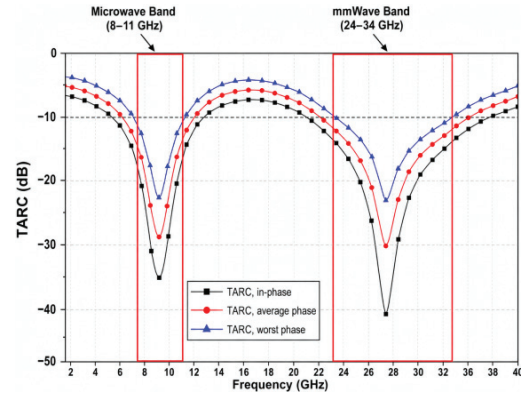


Figure 12.

TARC of the proposed 4-port MIMO antenna.

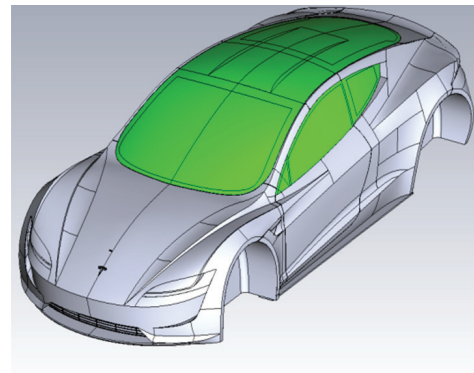


Figure 13.

EV Tesla car CAD model.

stays below -10 dB over the operating region, confirming stable mmWave MIMO operation.

5. Car Model Analysis

To assess the real-world performance of the proposed antenna, it is placed on an EV Tesla car CAD model, representing a practical vehicular installation scenario, as shown in Figure 13. The electromagnetic simulation is then carried out on this full vehicle model using a high meshing density of 17 cells per wavelength to accurately capture all coupling and scattering effects. This fine mesh ensures that subtle interactions between the antenna and the car body are properly resolved. Remarkably, the simulated S -parameters remain essentially unchanged compared to the standalone case, as shown in Figure 14, while the antenna continues to operate effectively in both the X-band (8–11 GHz) and the mmWave band (24–34 GHz). This confirms that the antenna preserves its matching and isolation characteristics on the vehicle, demonstrating reliable and consistent performance in a realistic automotive environment.

The gain in the lower band (8–11 GHz) ranges from 8.02 dBi to 9.06 dBi, while in the upper band (24–34 GHz) it varies from 7.23 dBi to 9.22 dBi, highlighting the effectiveness of the proposed design. Specifically, the 3D gain at 9 GHz reaches 9.06 dBi,

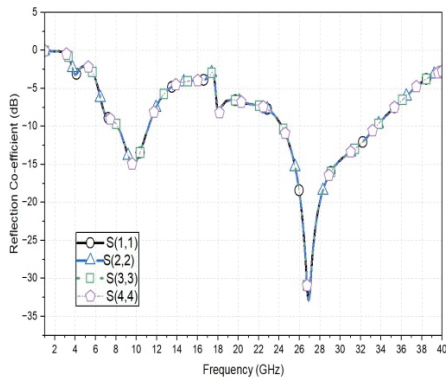


Figure 14.
EV Tesla car CAD model.

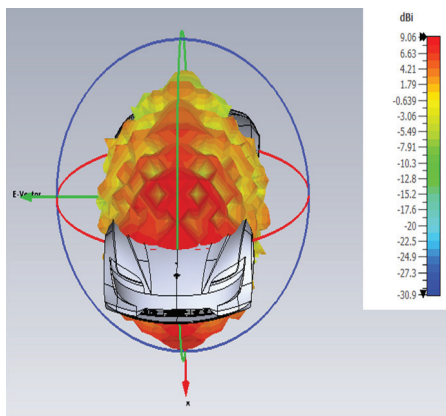


Figure 15(a).
3D gain at 9 GHz for the antenna integrated with the car CAD model.

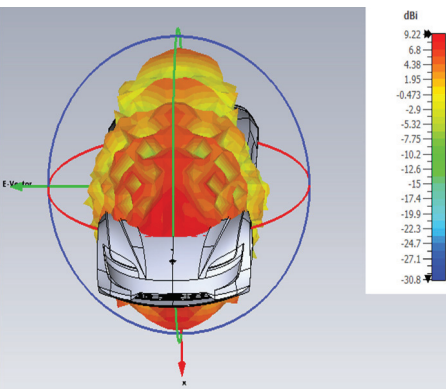


Figure 15(b).
3D gain at 28 GHz for the antenna integrated with the car CAD model.

demonstrating strong radiation performance in the X-band. Similarly, at 28 GHz, the 3D gain increases to 9.22 dBi, as illustrated in Figures 15(a) and 15(b), confirming robust operation in the mmWave band.

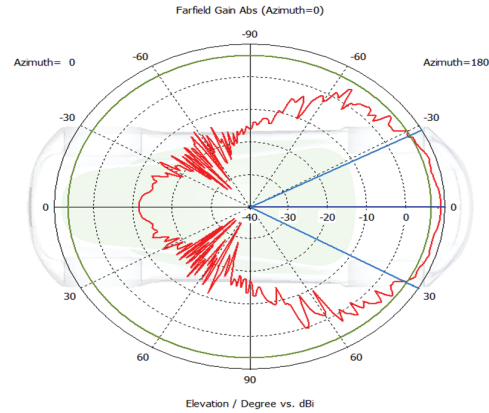


Figure 16(a).
Radiation Pattern at 9 GHz for the antenna integrated with the car CAD model.

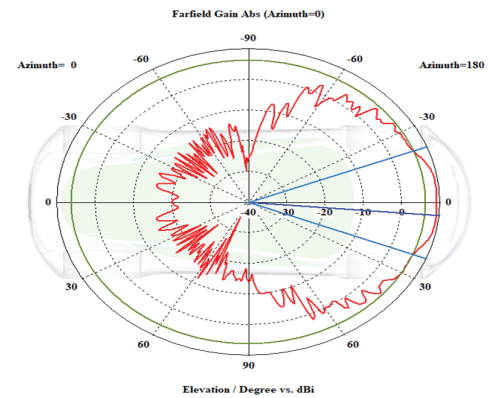


Figure 16(b).
Radiation Pattern at 12 GHz for the antenna integrated with the car CAD model.

The radiation patterns in both the lower band (8–11 GHz) and the upper band (24–34 GHz) are directive, meaning the radiated energy is concentrated into a main lobe with higher gain and reduced side and back lobes, which is beneficial for focused links and improved link budgets. At 11 GHz, the main lobe magnitude is 8.91 dBi, the main lobe direction is 0°, the 3 dB angular-width is 58.4°, and the side lobe level is -2.4 dB, as shown in Figure 16(a). At 28 GHz, the main lobe magnitude increases to 9.19 dBi, the main lobe direction shifts slightly to 5°, the 3 dB angular width narrows to 43°, and the side lobe level is -2.9 dB, as also illustrated in Figure 16(a). These results confirm that the antenna maintains a stable, directive beam over both operating bands.

The E-field distribution is also evaluated at 28 GHz, where the maximum E-field is observed to be 200 V/m. The results show that the antenna's radiation is largely confined to the region where the antenna is mounted on the car. The fields do not significantly propagate into other parts of the vehicle body, indicating minimal unwanted coupling or scattering. This localization of radiation confirms that the antenna operates efficiently on the designated mounting area without adversely affecting the rest of the car structure, as shown in Figure 17.

Table 1.

Link budget analysis of the proposed MIMO antenna for car communication			
Parameter	Equation/Value	Case A: 9 GHz, 100 m	Case B: 28 GHz, 100 m
Frequency	f	9000 MHz	28000 MHz
Distance	d	0.1 km	0.1 km
Transmit power	P_{TX}	20 dBm	20 dBm
Tx antenna gain	G_{TX}	9.06 dBi	9.22 dBi
Rx antenna gain	G_{RX}	9.06 dBi	9.22 dBi
System losses	L_{sys}	3 dB	3 dB
FSPL	$32.44 + 20 \log_{10}(f_{MHz}) + 20 \log_{10}(d_{km})$	91.52 dB	101.38 dB
Received power	$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{FS} - L_{sys}$	-56.40 dBm	-65.94 dBm
Bandwidth	B	100 MHz	100 MHz
Thermal noise	$-174 + 10 \log_{10}(B)$	-94 dBm	-94 dBm
Noise figure	NF	5 dB	5 dB
Total noise power	$N_{tot} = N_{th} + NF$	-89 dBm	-89 dBm
SNR	$SNR = P_{\hat{f}} \downarrow N_{tot}$	32.60 dB	23.06 dB

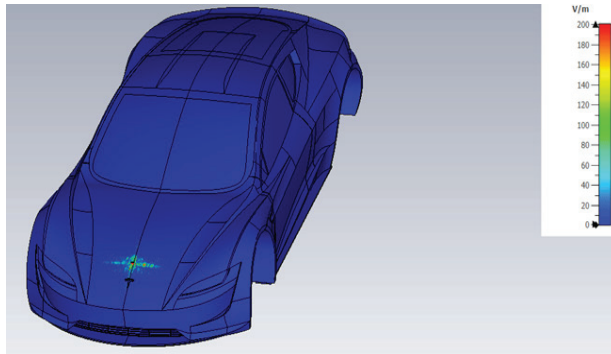


Figure 17.
E-Field analysis 28 GHz.

6. Car Link Budget Analysis

The mathematical analysis of the car link budget is based on the Friis transmission equation expressed in dB, where the received power is calculated by adding the transmit power and antenna gains and subtracting the free-space path loss and other system losses. The free-space path loss is computed using [13–15], which demonstrates how both distance and frequency significantly affect signal attenuation. The received power is then compared with the total noise power, derived from the thermal noise floor, system bandwidth, and receiver noise figure, to calculate the signal-to-noise ratio (SNR). The link budget calculation is presented in Table 1.

The calculated SNR for the proposed car link shows strong performance in both operating bands. In the lower band around 9 GHz, using a transmit power of 20 dBm, antenna gains of about 9.06 dBi at both ends, a 100 m link distance, and 3 dB system loss, the received power is approximately -56.4 dBm. With a 100 MHz bandwidth and a receiver noise figure of 5 dB, this corresponds to an SNR of about 32.6 dB, which is suitable for high-order modulation and robust 5G links. In the upper band around 28 GHz, the higher path loss reduces the received power to

roughly -65.54 dBm, giving an SNR of about 23.46 dB, which is still comfortably above the threshold for reliable NR 5G operation and high data rates in vehicular scenarios.

7. Conclusion

The proposed design is a high-frequency, dual-band, super-compact MIMO antenna developed for resilient 5G vehicular services. It covers 8–11 GHz (microwave band) and 24–34 GHz (mmWave band), delivering peak gains of 4.64–5.99 dBi in the lower band and 4.7–6.4 dBi in the upper band, while maintaining radiation efficiency greater than 90% across both bands. The inter-element isolation is <19 dB supports stable MIMO operation and facilitates RF coexistence on space-constrained automotive platforms. The antenna is fabricated on an RO4350B substrate with a compact size of $25 \times 10 \times 0.51 \text{ mm}^3$, and when mounted on a vehicular CAD model it preserves its reflection characteristics and achieves a realized gain of 9.06 dBi at 9 GHz and 9.22 dBi at 28 GHz, indicating robust performance under realistic installation conditions. The link-budget analysis confirms strong performance in both the 8–11 GHz and 24–34 GHz bands, with SNR values of approximately 32.6 dB at 9 GHz and 23.46 dB at 28 GHz, providing ample margin for high-order modulation, reliable connectivity, and high data rates. Furthermore, the antenna addresses key requirements for next-generation vehicular links resilience, spectrum flexibility, energy-aware operation, and ease of integration and is well suited for V2X safety messaging, ADAS telemetry, and high-data-rate services that demand both dependable coverage and mmWave capacity.

Acknowledgment

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References

- [1] Munir, M. E., Nasralla, M. M., and Esmail, M. A. (2025, June). Design and Analysis of 8×1 Wideband Mmwave MIMO Antenna Array for High-Performance 5G UAV Communications. In 2025 IEEE 101st Vehicular Technology Conference (VTC2025-Spring) (pp. 1–7). IEEE.
- [2] Tiwari, R. N., Sharma, D., Singh, P., and Kumar, P. (2024). A flexible dual-band 4×4 MIMO antenna for 5G mm-wave 28/38 GHz wearable applications. *Scientific reports*, 14(1), 14324.
- [3] Li, M., Su, Y., Zhang, W., and Lin, X. (2024). A versatile shared-aperture antenna for vehicle communications. *Electronics*, 13(20), 4009.
- [4] Saleh, S., Saeidi, T., Timmons, N., Althwayb, A. A., and Razzaz, F. (2025). Compact 5 G mmWave vivaldi antenna for vehicular communication. *Vehicular Communications*, 53, 100893.
- [5] Awan, W. A., Abbas, A., Choi, D., Hussain, N., Lee, H., Sim, D., and Kim, N. (2025). Compact and Directional Dual Band Antenna with Low Mutual Coupling MIMO Configuration for mm-Wave Communication. *Results in Engineering*, 105457.
- [6] Nasralla, M. M., Munir, M. E., Farman, H., and Choudhury, N. (2025). Design and Analysis of Millimeter-wave Antenna for New Radio (NR) 5G Bands Supporting a Green Wireless Future. *Wireless World Research and Trends Magazine*, 9–14.
- [7] Esmail, B. A. F., et al. "Dual-band millimetre wave MIMO antenna with reduced mutual coupling," *Scientific Reports*, 2024.
- [8] Aghoutane, B., et al. "A novel dual band high gain 4-port millimeter wave MIMO antenna array for 28/38 GHz 5G applications," *AEU – International Journal of Electronics and Communications*, 2022/2023.
- [9] Kumar, P., et al. "An Ultra-Compact 28 GHz Arc-Shaped Millimeter-Wave Antenna," *Micromachines*, 2022.
- [10] Nor, A. M., et al. "Survey on positioning-information assisted mmWave beam training," *Computer Networks*, 2022.
- [11] Eldowek, B. M., et al. "A survey of 5G millimeter wave, massive multiple-input multiple-output, and vehicle-to-vehicle channel measurements and models," *International Journal of Communication Systems*, 2021.
- [12] Tu, D. T. T., et al. "Improving Characteristics of 28/38 GHz MIMO Antenna for 5G Applications by Using Double-Side EBG Structure," *Journal of Communications*, 2019.
- [13] Kashif, H., Shabbir, N., and Ojaide, U. S. C. *Matlab Toolbox for Link Budget Analysis in Wireless Networks*.
- [14] Kim, H. (2015). *Wireless communications systems design*. John Wiley & Sons.
- [15] Pedraza, L. F., Hernández, C. A., and López, D. A. (2017). A Model to Determine the Propagation Losses Based on the Integration of Hata-Okumura and Wavelet Neural Models. *International Journal of Antennas and Propagation*, 2017(1), 1034673.
- [16] Munir, M. E., Nasralla, M. M., and Esmail, M. A. (2024). Four port tri-circular ring MIMO antenna with wide-band characteristics for future 5G and mmWave applications. *Heliyon*, 10 (8), e28714.
- [17] Ali, A., Munir, M. E., Nasralla, M. M., Esmail, M. A., Al-Gburi, A. J. A., and Bhatti, F. A. (2024). Design process of a compact tri-band MIMO antenna with wideband characteristics for sub-6 GHz, Ku-band, and millimeter-wave applications. *Ain Shams Engineering Journal*, 15(3), 102579.
- [18] Sehrai, D. A., Munir, M. E., Kiani, S. H., Shoaib, N., Algarni, A. D., Elmannai, H., ... and Ali, T. (2024). A high gain array based millimeter wave MIMO antenna with improved isolation and decor-related fields. *IEEe Access*, 12, 89794–89803.
- [19] Sethi, W. T., Kiani, S. H., Munir, M. E., Sehrai, D. A., Savci, H. S., and Awan, D. (2024). Pattern diversity based four-element dual-band MIMO patch antenna for 5G mmWave communication networks. *J. Infrared Milli Terahz Waves*. 45, 521–537 (2024).

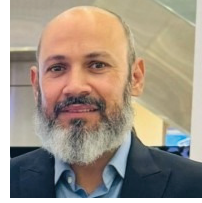
Biographies



Moustafa M. Nasralla (SM'21) received the B.Sc. degree (Hons.) in electrical engineering from Hashemite University, Jordan, in 2010, the M.Sc. degree in networking and data communications from Kingston University, London, U.K., in 2011, and the Ph.D. degree from the Faculty of Science, Engineering and Computing (SEC), Kingston University, London, U.K., in 2015. He is currently an Associate Professor and Chairman of the Department of Communications and Networks Engineering, Prince Sultan University (PSU), Riyadh, Saudi Arabia. He is currently the leader of the Smart Systems Engineering Laboratory (SSEL) at PSU. He was a member of the Wireless Multimedia and Networking (WMN) Research Group at Kingston University. He served as an active reviewer and received several distinguished reviewer awards from reputable journals, such as *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Multimedia*, *IEEE Transactions on Vehicular Technology*, *Wireless Communications (Elsevier)*, and *Computer Network (Elsevier)*. He has solid research contributions in the area of networks and data communications, which are proven with publications in reputable journals with ISI Thomson JCR. He has won several national and internationally funded projects, such as Intelli-Student for the British Council, 5G-enabled Smart City Development for RDIA in Saudi Arabia, U.K. Home Office, and EU FP7 CONCERTO. Currently, he is serving as a Guest Editor for *Alexandria Engineering Journal (Elsevier)*, *International Journal of Distributed Sensor Networks (SAGE)*, *Journal of Communications and Networks (Frontiers)*, and an Organizer of the International Conference on Sustainability: Development and Innovations, and the 5G-Enabled Smart Cities workshop in the IEEE International Conference on Smart Cities. Moreover, he is a Senior Member of IEEE, a member of IEEE ComSoc, and the Association of Computing Machinery (ACM). He has published over 100 articles in high-impact factor journals and reputable conferences. He is a fellow of the Higher Education Academy (FHEA). His research interests include the latest generation of wireless communication systems (e.g., 6G, 5G, LTE A, and LTE wireless networks), wireless sensor networks, network security, the Internet of Things (IoT), machine learning, radio resource allocation, telemedicine and video compression, and multimedia communications.



Mehr E. Munir received the B.Sc. degree (Hons.) in electrical engineering (telecommunication engineering) from the City University of Science and Information Technology (CUSIT), Peshawar, Pakistan, in 2014, and the M.Sc. and Ph.D. degrees in electrical engineering (communication and electronics) from Iqra National University (INU), Peshawar, in 2017 and 2023, respectively. He started his career in February 2015 as a Visiting Lecturer with the Electrical Engineering Department, CUSIT; after that, he joined INU in September 2015 as a Laboratory Engineer with the Electrical Engineering Department. In November 2018, due to his best performance and excellent research profile, he was promoted to the position of Lecturer with the Electrical Engineering Department, INU. In January 2019, he was appointed as a Post Graduate Program Coordinator/Lecturer with the Electrical Engineering Department, INU, and in May 2019, he was appointed as the Senior Design Officer of the Aircraft Rebuilt Factory (ARF), Aviation Design Institute (AvDI), Pakistan Aeronautical Complex (PAC), Kamra, Pakistan. He is currently a Research Fellow with the Smart System Engineering Laboratory, College of Engineering, Prince Sultan University (PSU), Riyadh, Saudi Arabia. He is a young professional member of IEEE Vehicular Technology Society (VTS) and he served his duty as a session chair in 99th and 100th IEEE Vehicular Technology Conference. His research interests include wireless communication, RF and microwave, and advanced antenna design. He has published more than 40 research articles in Clarivate Analytics (ESCI and SCI) internationally reputed journals, HEC approved journals, and several IEEE conference papers in and outside the country.



Haleem Farman (Senior Member, IEEE) is currently an accomplished Researcher and an academic with 15 years of experience at the intersection of academia and industry. As a Researcher at Prince Sultan University and an Adjunct Professor with Whitecliffe, New Zealand, he is driving innovation in smart systems, the IoT, and AI, while actively contributing to major research initiatives and academic leadership. With around 15 years of experience in academia and research, his expertise spans the Internet of Things, privacy preservation, intrusion detection systems, ad hoc networks, smart cities, and artificial intelligence. He has led and contributed to multiple funded research projects supported by prestigious organizations, including British Council, Research Development and Innovation Authority (RDIA), Saudi Arabia, Prince Sultan University, and the Government of Pakistan. He has published over 60 research papers in high-impact journals, conferences, and book chapters, and has actively supervised undergraduate and postgraduate students. He is an IEEE VTS Young Professional Ambassador. He is also serving as the Vice-Chair for the IEEE Smart Cities Awards and Recognition Committee, highlighting his leadership and dedication to advancing smart city technologies and academic excellence. He is serving as an Academic Editor for PLOS One. He has also organized workshops in international conferences, such as the 101 IEEE Vehicular Technology Conference (VTC-Spring2025), the 9th IEEE International Smart Cities Conference 2023, and the 2nd International Conference on Sustainability Development.

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October 28–30, 2026	WWRF 55	Strathclyde University, Glasgow, UK	6G – A New Private Network Universe	Nigel Jefferies/ Hendrik Berndt/ James Irving	Confirmed
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21 September 2026	C-ITS	Online	Collaboration on Intelligent Transport Systems communication standards	Seshadri Mohan	Confirmed (WWRF contri- bution from Sesh)
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Date	Meeting	Location	Theme	WWRF Contact(s)	Status
November 9–27, 2026	PP-26	Doha, Qatar		Nigel Jefferies/ Bharat Bhatia	Confirmed
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May 5–12,	WP5A	Geneva		Bharat Bhatia	Confirmed
Oct 11–18, 2027	Radiocommunication Assembly	Shanghai, China		Nigel Jefferies/ Bharat Bhatia	Confirmed
October 18–November 12, 2027	WRC 2027	Shanghai, China		Nigel Jefferies/ Bharat Bhatia	Confirmed
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- Full papers are optional, and should be submitted according to the instructions on the meeting website: www.wwrf.ch
- A selection of the best-reviewed full papers will be invited for submission to the WWRF Journal: Wireless World Research and Trends (WWRT)
- Full paper submission is a requirement for consideration in the Best Paper Award and for potential publication in WWRT.

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