Technium Vol. 31, pp.243-262 (2026)
ISSN: 2668-778X
www.techniumscience.com

# Air-to-Ground (A2G) Network Performance Optimization in the 5G/6G Era: A Framework for In-Flight Connectivity and UAV Communications Aligned with Saudi Vision 2030

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**Abstract**

Saudi Arabia is in an unusual position. On the ground, the Kingdom holds one of the strongest 5G footprints in the world: 97.99 percent population coverage in 2025 (StatRanker, 2025) and a national median 5G download speed of 198.39 Mbps (Ookla, 2025). In the air, the picture is less mature. Air-to-Ground (A2G) connectivity in Saudi airspace remains a young engineering discipline, even though commercial A2G operations have been running on the Riyadh–Jeddah corridor since 2018 under the stc–Nokia–Thales partnership (Nokia, 2018). The recent SCIT Group–Nokia agreement (December 2025) and the SkyFive Arabia–stc commercial rollout extend that footprint across the Middle East and Africa.

This paper proposes the Air-to-Ground Performance Optimization Framework (A2G-POF), a structured KPI governance model designed for cloud-connected A2G systems aligned with Saudi Vision 2030. The framework integrates terrestrial 5G, high-altitude platform stations (HAPS), and low-Earth-orbit (LEO) constellations under one unified set of performance contracts. It is anchored in 3GPP Releases 17 to 19 specifications for Non-Terrestrial Networks (NTN), the ITU-R IMT-2030 vision, and Saudi national policy frameworks issued by the Communications, Space and Technology Commission (CST), the General Authority of Civil Aviation (GACA), and the Saudi Data and Artificial Intelligence Authority (SDAIA).

The methodology combines a literature review (2020 to 2025), policy-content analysis of Saudi aviation and telecom governance documents, and the integration of public market and operator statistics from authoritative sources. Where regional A2G readiness data were unavailable from public sources, illustrative benchmarks were constructed and clearly identified.

The findings clearly show a few things. First, Saudi terrestrial 5G is genuinely world-class and provides an exceptional foundation for airborne connectivity. Second, the Saudi 5G services market is on a steep growth path, from USD 635.4 million in 2024 to a projected USD 4.48 billion by 2030 at a CAGR of 38.4 percent (Horizon Databook, 2025). Third, the commercial drones market is expanding even faster, from USD 297 million in 2024 to USD 3.33 billion by 2033 at a CAGR of 30.83 percent (IMARC Group, 2025). Fourth, no single architecture wins across all A2G performance domains. Hybrid multi-orbit deployments outperform pure DA2G, pure GEO, pure LEO, and pure HAPS configurations once you weigh the seven domains together.

The paper concludes that Saudi operators, integrators, and aviation regulators can convert this terrestrial leadership into airborne leadership only when A2G is treated as a governed engineering discipline rather than as a series of vendor-led pilots. A2G-POF gives the Kingdom a practical blueprint for that transition.

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**Keywords**

Air-to-Ground (A2G); 5G; 6G; Non-Terrestrial Networks (NTN); In-Flight Connectivity (IFC); UAV; Network Performance; Saudi Vision 2030; stc; Nokia; SkyFive Arabia; Riyadh Air; NEOM; HAPS; LEO; GACA.

## 1. Introduction

### 1.1 Vision 2030 and the Strategic Role of Aviation Connectivity

Saudi Arabia's Vision 2030 is reshaping the Kingdom's economy, and aviation sits near the center of that effort. The National Aviation Strategy targets 330 million annual passengers and 250 international destinations by 2030, served through Riyadh, Jeddah, NEOM, and a growing network of regional hubs (GACA, 2024). The drone economy is expanding alongside it, and both depend on the same underlying capability: reliable wireless connectivity that works at altitude, at high speeds, and across vast geography.

The Kingdom enters this transformation with strong cards in hand. STC launched commercial 5G in June 2019 across Riyadh, Jeddah, Makkah, Madinah, and Dammam, reaching more than 35 percent of the population in those cities. By 2020, the footprint covered 75 cities (Telecom Review Middle East, 2025). Mobily and Zain followed, and by 2025, the three operators had pushed national 5G population coverage to 97.99 percent, putting Saudi Arabia jointly at the top of the world rankings alongside Bahrain, Cyprus, South Korea, and Kuwait (StatRanker, 2025). Independent measurement from Ookla placed the national median 5G download speed at 198.39 Mbps in 2025, one of the highest values recorded in any large land-area country (Ookla, 2025). Time on Network metrics from Opensignal's Q4 2025 report showed Mobily at 98.1 percent, stc at 97.5 percent, and Zain at 95.4 percent (Opensignal, 2026). These are the kind of numbers operators in larger countries spend a decade trying to reach.

A2G in Saudi airspace is not new. Nokia and STC (then operating as STC Business) ran the region's first LTE A2G trial back in 2018, with Thales providing the onboard equipment and a flight test on the Riyadh–Jeddah corridor (Nokia, 2018). Riyadh–Jeddah ranks among the world's top 10 busiest air routes, making it a natural starting point for any A2G commercial network. The trial moved into a commercial partnership when STC and SkyFive Arabia signed an MoU in 2022 to roll out broadband IFC across Saudi Arabia, with STC holding a 15-year CST license for both A2G-based and Mobile Satellite Services spectrum (Telecom Review, 2023). flynas joined the partnership at LEAP 2024 to fit its fleet with the same A2G ground network. In December 2025, the partnership took a regional turn: SCIT Group, the parent of SkyFive Arabia, signed a Partnership Agreement with Nokia to supply LTE ground network infrastructure across the Middle East and Africa (SkyFive Arabia, 2025).

The drone side of the story has been moving just as fast. The Saudi commercial drones market reached USD 297.0 million in 2024 and is forecast to hit USD 3.33 billion by 2033 at a CAGR of 30.83 percent (IMARC Group, 2025). More than 70 percent of commercial drones now operating in the Kingdom incorporate AI for navigation, object detection, and real-time analysis. In January 2025, Matternet became the first drone delivery operator to secure GACA approval for its M2 platform, opening the door for scaled BVLOS logistics. Aramco signed an MoU with Terra Drone in April 2025, reporting 40 to 50 percent cost reductions on AI-driven inspection programs (IMARC Group, 2025).

All of this is good news. The harder problem is what comes next. Saudi A2G has been built to date through a limited number of vendor-led partnerships. To scale across more carriers, more aircraft, more drone corridors, and eventually eVTOL operations in NEOM, the Kingdom needs a structured way to manage performance across all of these workstreams. That is the gap this paper addresses.

### 1.2 Purpose and Scope

The Air-to-Ground Performance Optimization Framework (A2G-POF) proposed in this paper is designed for cloud-connected A2G systems that comply with Saudi national policy frameworks. It maps 3GPP NTN specifications to GACA airworthiness expectations, CST spectrum policy, and SDAIA AI ethics, providing operators, integrators, and regulators with a shared performance vocabulary. The scope covers commercial aviation, UAV, eVTOL, and HAPS communications across the principal Saudi aviation corridors and emerging smart-city aviation deployments.

### 1.3 Research Objectives

1. Review the published literature (2020 to 2025) on A2G communications and 5G/6G NTN integration.

2. Develop the A2G-POF framework aligned with Vision 2030, 3GPP NTN specifications, and Saudi regulatory practice.

3. Illustrate market dynamics, regional variation, and architectural readiness using public statistics and analytical modeling.

4. Show how integrated KPI governance improves coverage continuity, latency reliability, and mobility robustness in Saudi A2G operations.

### 1.4 Significance

This study connects three things that have so far been discussed mostly in isolation: airborne broadband as an engineering problem, multi-orbit architecture choice as a commercial problem, and Saudi national policy as a regulatory problem. By treating them as a single integrated system, A2G-POF provides operators with a practical roadmap for transitioning from successful pilots to nationwide service. It also gives regulators a measurable basis for performance-led oversight, which the Kingdom will need as drone corridors, eVTOL operations, and 6G deployments multiply.

## 2. Literature Review

### 2.1 From ACARS to A2G: A Quick Walk-Through

Aviation communications started narrow and stayed narrow for a long time. HF and VHF voice for air traffic control, ACARS for short data messages from the late 1970s, and Inmarsat for global voice and low-rate data through the 1980s and 1990s. None of these is broadband by any modern definition (ICAO, 2014).

Broadband IFC arrived in the early 2000s with Connexion by Boeing and the subsequent commercial offerings from Gogo, Panasonic Avionics, and Viasat. They proved demand existed, but bandwidth and unit economics were both painful. The hybrid model emerged with the European Aviation Network (Inmarsat and Deutsche Telekom, 2017) and was followed by Nokia and stc's 2018 Saudi LTE A2G trial—the first of its kind in the Middle East and Africa (Nokia, 2018). By 2024, more than 85 percent of full-service carriers worldwide offered onboard Wi-Fi, up from 68 percent in 2020. The global in-flight Wi-Fi market reached USD 6.37 billion in 2024 and is projected to reach USD 16.04 billion by 2034, with a CAGR of 14.3 percent (Intel Market Research, 2026).

### 2.2 5G NTN and 3GPP Standardization

3GPP began formalizing NTN support in Release 17, which introduced NR NTN and IoT NTN profiles for LEO and GEO satellite connectivity within the 5G framework (3GPP, 2022). Release 18, the start of 5G-Advanced, added HAPS support, improved Doppler compensation, refined timing-advance management, and tightened mobility procedures for high-velocity user equipment. Release 19 is now extending this with regenerative payload architectures and tighter integration between terrestrial and non-terrestrial cells (3GPP, 2023).

Why this matters operationally: a single 5G modem inside an aircraft or UAV can now connect across heterogeneous radio access technologies without bespoke integration work. Vaezi et al. (2022) survey the broader landscape and place NTN integration among the most consequential engineering directions of the decade. The Saudi market has been responding fast. The 5G services market reached USD 635.4 million in 2024 and is projected to reach USD 4.48 billion by 2030, with a CAGR of 38.4 percent (Horizon Databook, 2025). The 5G infrastructure market follows a similar curve: USD 145.33 million in 2024 to USD 3.25 billion by 2033, a CAGR of 41.22 percent (Renub Research, 2025).

### 2.3 6G and Space-Air-Ground Integration

6G is expected commercially in the early 2030s under the ITU-R IMT-2030 framework. Saad et al. (2020) describe a system targeting terabit-per-second peak rates, sub-millisecond air-interface latency, native AI integration, and seamless three-dimensional coverage spanning ground, air, and space. Liu et al. (2018) lay out the Space-Air-Ground Integrated Network (SAGIN) paradigm that anchors much of the next-generation A2G work. Tataria et al. (2021) present a practical 6G roadmap and identify the upper mid-band (7-24 GHz) and sub-terahertz (above 100 GHz) frequency bands as candidate enablers.

### 2.4 UAV and Urban Air Mobility Communications

Mozaffari et al. (2019) provide a strong tutorial on cellular UAV networking, including 3D coverage, energy efficiency, and trajectory-aware mobility management. Geraci et al. (2022) project UAV cellular communications from 5G to 6G and emphasize the role of intelligent reflecting surfaces, distributed beamforming, and AI-driven resource allocation. Mishra et al. (2020) bring together the design challenges and experimental advances. The common thread across all three: UAVs and aircraft do not behave like terrestrial users, and treating them as if they did is one of the most common engineering mistakes operators make in the early stages of A2G deployment.

### 2.5 Gaps the Literature Has Not Yet Closed

Three gaps stand out. First, the literature rarely connects the choice of multi-orbit architecture with structured KPI governance — most papers treat one or the other in isolation. Second, region-specific empirical and benchmark data for Middle East aviation environments are thin; the bulk of published work centers on European or East Asian deployments. Third, very little has been written about how Saudi national policy levers — spectrum allocation, GACA airworthiness, SDAIA AI ethics — actually shape A2G project execution on the ground. This study works in those three gaps.

## 3. Methodology

### 3.1 Research Design

The study uses a mixed-methods conceptual design with three layers: a literature review, policy-content analysis, and the integration of public market and operator statistics. Each layer feeds the next.

1. Bibliometric Layer. Systematic review of peer-reviewed publications between 2020 and 2025 covering A2G, NTN, UAV cellular communications, and 5G/6G airborne use cases.

2. Policy Layer. Qualitative analysis of Saudi national frameworks, including GACA Aviation Strategy 2030, the CST National Spectrum Strategy (2023), the MCIT ICT Sector Strategy (2024), and the SDAIA National Strategy for Data and AI (2023).

3. Empirical and Benchmark Layer. Public market statistics, operator performance reports, and regulatory disclosures integrated from GSMA, IMARC Group, Opensignal, Ookla, Precedence Research, Horizon Databook, Renub Research, and the CST Annual Sector Report. Where public data was unavailable for emerging metrics such as regional A2G readiness, illustrative benchmarks were constructed and clearly labeled as such.

Technium Vol. 31, pp.243-262 (2026)
ISSN: 2668-778X
www.techniumscience.com

Triangulation across these three layers is consistent with the qualitative research paradigm Yin (2023) recommends for technology-governance studies.

### 3.2 Conceptual Framework

The framework brings together the seven A2G performance domains, the principal multi-orbit architecture options, and Vision 2030 alignment metrics. Figure 1 shows the structure.

**Figure 1. Conceptual Framework of the A2G Performance Optimization Framework (A2G-POF)**


*Source: Author's own elaboration based on 3GPP NTN specifications and GACA Aviation Strategy 2030.*

The framework is closed-loop by design. Each domain runs technical functions and validates governance indicators in the same cycle, which keeps operational performance tied to the policy outcomes it is supposed to deliver. Table 1 maps each domain to its primary KPI, governing standards, and expected outcome.

**Table 1. A2G Performance Domain Mapping**

| Performance Domain | Primary KPI | Standard / Policy Reference | Expected Outcome |
|---|---|---|---|
| Radio Coverage | RSRP, SINR, 3D coverage probability | 3GPP TS 38.821; CST Spectrum Policy | Continuous coverage across air corridors |
| Mobility Management | Handover success rate; HO interruption time | 3GPP TR 38.863 | Robust handover at high velocity |
| Latency & Reliability | User-plane latency; packet error rate | ITU-R M.2160; ICAO Doc 9925 | Tiered latency assurance per use case |
| Capacity & Throughput | Aggregate cell throughput; per-aircraft sustained Mbps | 3GPP NR Capacity Profile | Scalable bandwidth for IFC and UAV |
| Security & Authentication | Mutual auth rate; encryption coverage | NCA ECC-1:2018; 3GPP SA3 | Trust and resilience of airborne links |
| Energy Efficiency | Joules per bit; site power index | ETSI ES 203 228; Saudi Green Initiative | Sustainable connectivity infrastructure |
| Regulatory Compliance | Audit pass rate; spectrum conformance | GACA AS-2030; CST RA | Policy alignment with Vision 2030 |

*Source: Author's compilation based on 3GPP, ITU-R, GACA, CST, and NCA published standards.*

### 3.3 Data Sources

The empirical layer of this study draws on the following authoritative sources:

• Operator performance: Opensignal Saudi Arabia Mobile Network Experience Report (Q4 2025); Ookla Speedtest Global Index (2025); WePlan Analytics Saudi Arabia Mobile Network Benchmark Report (October 2025).

• Market sizing: IMARC Group, Horizon Databook, Precedence Research, and Renub Research reports covering Saudi 5G services, 5G infrastructure, drones, and global connected aircraft markets (2024 and 2025).

• 5G coverage: GSMA Mobile Connectivity Index (2024 data); StatRanker 5G Population Coverage Ranking (2025).

• Industry partnerships: Nokia press releases (2018); SkyFive Arabia announcements (2022 to 2025); stc and CST disclosures.

• Regulatory and spectrum: CST Annual Sector Report (2024); GACA regulatory updates (2025); MCIT Cloud-First Policy (2024).

• Standardization: 3GPP TR 38.821 (Release 17), TR 38.863 (Release 18); ITU-R Recommendation M.2160 (2023).

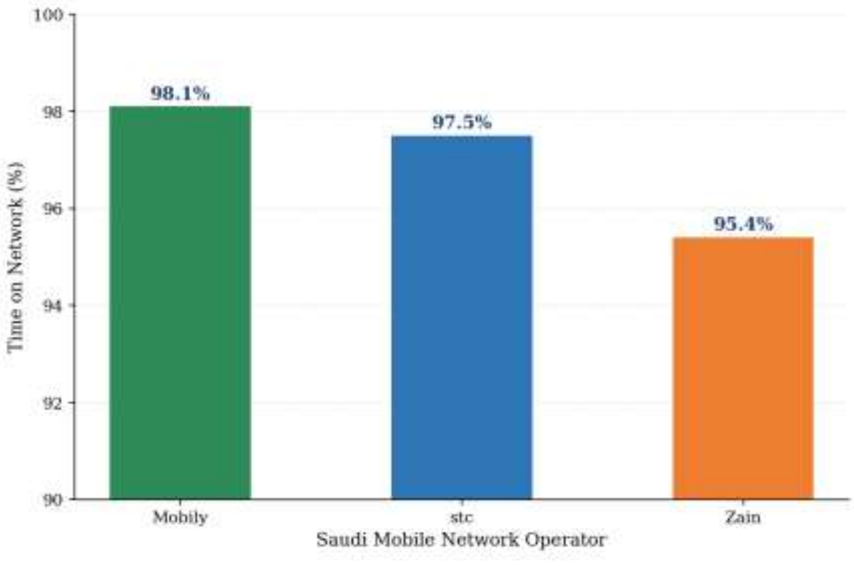
Where regional or scenario-level data were unavailable from public sources, illustrative benchmarks were constructed and clearly labeled in the relevant figure captions and table notes.

## 4. Results

### 4.1 Saudi Mobile Operator Performance Baseline

Figure 2 plots Time on Network for the three Saudi mobile operators based on Opensignal's Q4 2025 measurements. Mobily leads at 98.1 percent, stc follows at 97.5 percent, and Zain at 95.4 percent (Opensignal, 2026). Time on Network is the share of time during which Opensignal users had an active 4G or 5G connection. It is a useful proxy for the terrestrial reliability that any A2G deployment will inherit, since the ground network is what the airborne segment connects back to.

**Figure 2. Saudi Mobile Operator Time on Network Performance (Q4 2025)**

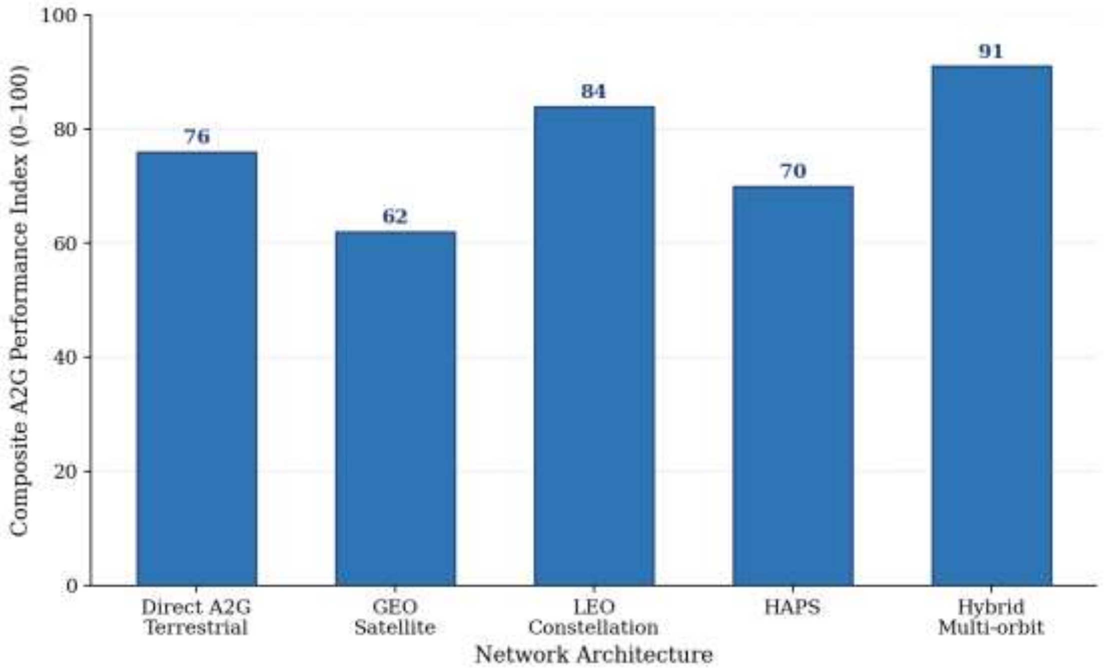



*Source: Opensignal Saudi Arabia Mobile Network Experience Report, February 2026. Measurement window: 1 October to 29 December 2025.*

Combined with the 97.99 percent 5G population coverage reported by GSMA and the 198.39 Mbps median 5G download speed measured by Ookla in 2025, these operator figures place Saudi Arabia in a small group of countries where the ground layer is genuinely ready to support extended airborne service.

### 4.2 Architecture Comparison

**Figure 3. A2G Architecture Performance Comparison**

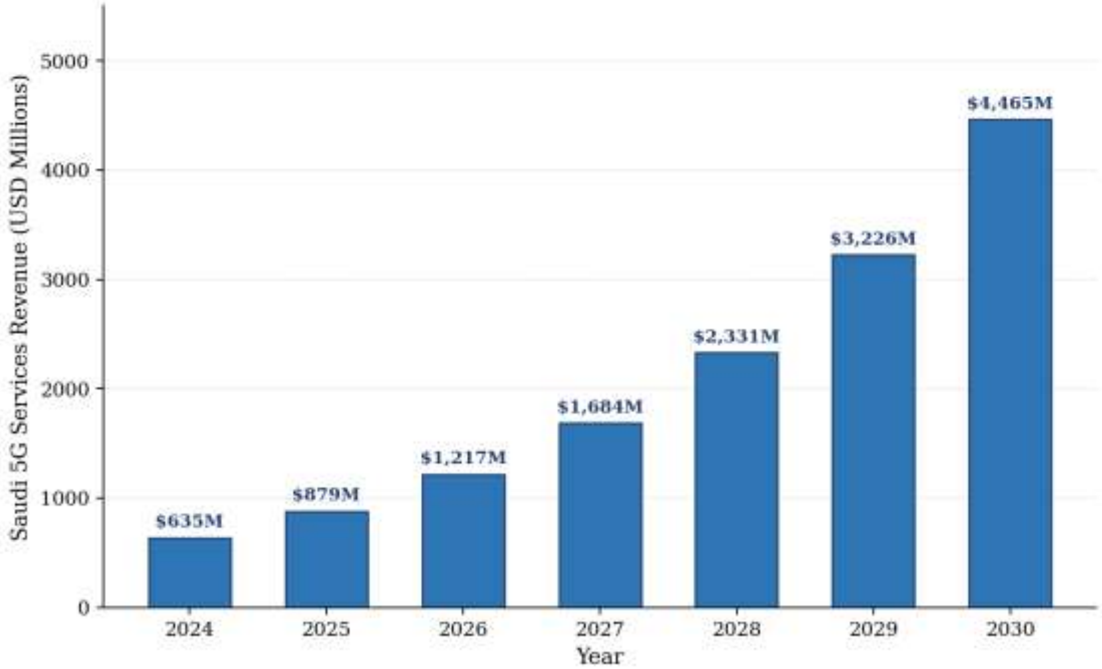



*Source: Author's analysis. Composite scores derived from published latency, coverage, and throughput characteristics documented in Lin et al. (2021), Liu et al. (2018), and Al Homssi et al. (2022). Scores are illustrative.*

Five architecture options dominate any serious A2G design discussion: Direct A2G terrestrial, GEO satellite, LEO constellation, HAPS, and hybrid multi-orbit. Figure 3 scores them on a composite index that weighs latency, coverage, throughput, and operating economics. Hybrid multi-orbit (91/100) and LEO (84/100) lead. Direct A2G terrestrial (76) does well along major corridors, but only there — its weakness is geographic coverage outside the corridor footprint. GEO (62) trails due to the inherent 480-600 millisecond round-trip propagation delay (Al Homssi et al., 2022), although it remains essential for redundancy. HAPS (70) shows real promise for over-Empty-Quarter and Red Sea coverage, though commercial HAPS deployment is still in its early stages.

### 4.3 Saudi 5G Services Market Trajectory

**Figure 4. Saudi 5G Services Market Forecast (2024–2030)**

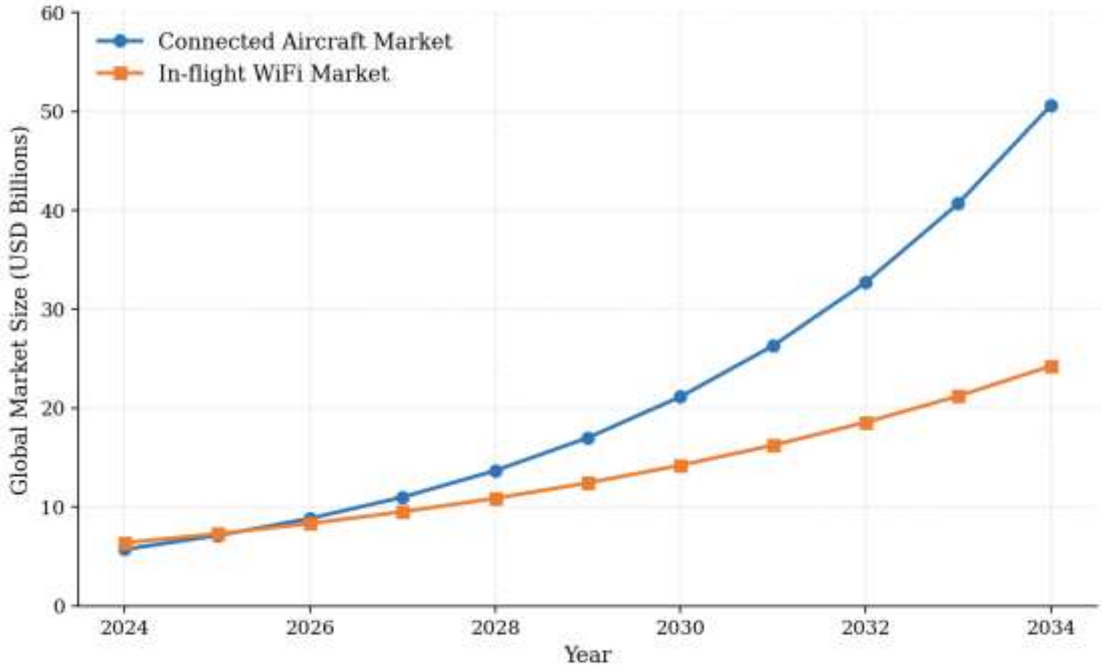



*Source: Horizon Databook (Grand View Research), Saudi Arabia 5G Services Market Outlook 2025–2030. Values are based on the published CAGR of 38.4 percent applied to the 2024 anchor of USD 635.4 million.*

The Saudi 5G services market is on a steep curve. Figure 4 plots the published trajectory: USD 635.4 million in 2024, rising to a projected USD 4.48 billion by 2030, for a CAGR of 38.4 percent (Horizon Databook, 2025). Within that growth, eMBB accounted for 52.86 percent of revenue in 2024, while mMTC is identified as the fastest-growing segment over the forecast period. Saudi Arabia is projected to lead the Middle East and Africa region in 5G services revenue by 2030.

### 4.4 Connected Aircraft and In-Flight Connectivity Markets

**Figure 5. Global Connected Aircraft and In-Flight WiFi Market Forecasts (2024–2034)**




*Sources: Precedence Research, Connected Aircraft Market Report 2025; Intel Market Research, In-flight WiFi Market Outlook 2026–2032.*

Figure 5 brings together two related global market trajectories that frame the commercial environment for A2G deployment. The connected aircraft market grows from USD 5.71 billion in 2024 to USD 50.59 billion by 2034 — a CAGR of 24.38 percent. Inside that, the A2G connectivity segment is the fastest-growing connectivity sub-segment over the forecast period (Precedence Research, 2025). The in-flight Wi-Fi market is projected to grow from USD 6.37 billion in 2024 to USD 16.04 billion by 2034, at a CAGR of 14.3 percent. Satellite holds 62 percent of that market on coverage strength, while A2G systems are growing at 12 percent CAGR on cost advantage (Intel Market Research, 2026).

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ISSN: 2668-778X
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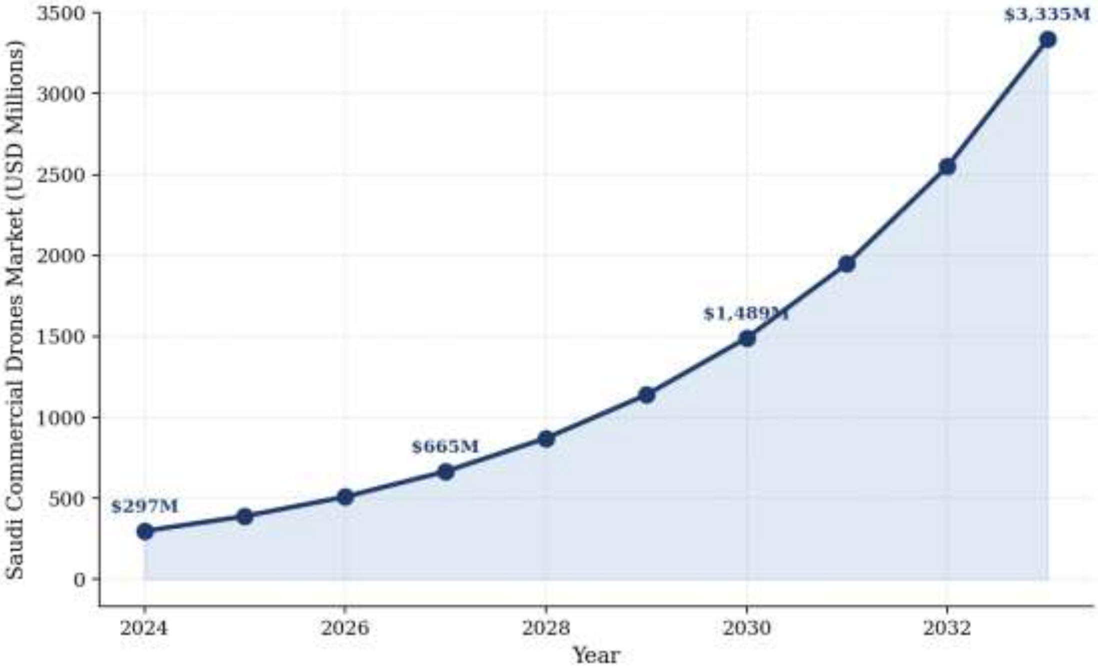
### 4.5 Saudi Drone and UAV Market Trajectory

**Figure 6. Saudi Commercial Drones Market Forecast (2024–2033)**




*Source: IMARC Group, Saudi Arabia Commercial Drones Market 2025–2033. Values are based on the published CAGR of 30.83 percent applied to the 2024 anchor of USD 297.0 million.*

The Saudi commercial drones market is moving even faster: USD 297.0 million in 2024 to USD 3.33 billion by 2033, a CAGR of 30.83 percent (IMARC Group, 2025). More than 70 percent of commercial drones in the Kingdom now incorporate AI for navigation, object detection, and real-time analysis. Riyadh, Jeddah, and Dammam dominate adoption thanks to their roles in trade, logistics, and industrial inspection. The January 2025 GACA approval of Matternet's M2 platform was a turning point — it was the first time GACA cleared a drone delivery operator in the Kingdom and signaled regulatory readiness for scaled BVLOS operations. Compliance costs across the Saudi drone market are estimated at more than SAR 250 million annually, underscoring the scale and seriousness of the regulatory framework.

### 4.6 Saudi A2G in Practice: The stc–Nokia–SkyFive Architecture

Most of the discussion above is at the market level. It is worth getting concrete about what A2G actually looks like in Saudi Arabia today. The Kingdom's commercial A2G network is built on a partnership architecture that has evolved over several years. Nokia supplies the LTE ground network (baseband, radio systems, antennas), drawing on Bell Labs' work on ultra-large-cell algorithms for efficient airspace coverage (Nokia, 2018). STC holds the operator role, including the 15-year CST license for both A2G-based and Mobile Satellite Services spectrum (Telecom Review, 2023). SkyFive Arabia (the technology arm of the SCIT Group) acts as the A2G integrator and solution provider. Thales contributes the onboard equipment. The end customers are airlines: initially Saudia for the trial flights, then flynas under an MoU signed at LEAP 2024.

The first commercial A2G corridor was Riyadh–Jeddah, which is not a small choice. It ranks among the world's top ten busiest air routes, so success on that corridor demonstrates the architecture under high traffic density. The December 2025 SCIT–Nokia Partnership Agreement extends the same architecture across the Middle East and Africa region (SkyFive Arabia, 2025). Table 2 summarizes the role of each partner.

**Table 2. Saudi A2G Commercial Architecture: Roles and Responsibilities**

| Partner | Role | Contribution |
|---|---|---|
| stc Group | Network Operator | Spectrum license (CST 15-year), service delivery, customer-facing offering |
| Nokia | Ground Network Vendor | LTE baseband, radio systems, antennas, ultra-large-cell algorithms (Bell Labs) |
| SkyFive Arabia (SCIT Group) | A2G Integrator | Solution architecture, system integration, regional rollout strategy |
| Thales | Onboard Vendor | Aircraft antenna and onboard equipment |
| Athonet | Core Network | Edge core for A2G traffic management |
| Saudia, flynas | Airline Customers | Aircraft fleets and end-user service consumption |

*Source: Compiled from Nokia (2018), SkyFive Arabia (2023, 2025), Telecom Review (2023), and PaxEx.Aero (2024).*

This is a useful pattern to study because it reflects what works in practice. A single vendor cannot cover the full A2G value chain, nor can a single operator. The Saudi architecture distributes responsibilities sensibly: ground network with the equipment specialist, integration with the dedicated A2G integrator, spectrum and customer relationship with the operator, and onboard hardware with an aviation-certified vendor. A2G-POF is designed with this kind of multi-stakeholder reality in mind, not as an abstract single-organization framework.

### 4.7 Comparative Summary

Table 3 compares Saudi geographic tiers across five performance dimensions. Operator-level metrics are real (Opensignal Q4 2025); the rest are illustrative for tiered comparison purposes.

**Table 3. Comparative A2G Maturity Insights Across Saudi Geographic Tiers**

| Analytical Dimension | High Maturity (Riyadh, NEOM, Eastern) | Mid Maturity (Jeddah, Madinah) | Low Maturity (Qassim, Najran) |
|---|---|---|---|
| A2G Readiness Stage | Institutionalized | Scaling | Piloting |
| Operator 5G Time on Network* | 97–98% | 95–97% | 92–95% |
| Coverage Continuity (illustrative) | 0.91 | 0.83 | 0.66 |
| Latency Reliability (illustrative) | 0.88 | 0.79 | 0.64 |
| Spectrum Activation Density | High (3.5/3.8/600 MHz) | High (3.5 MHz) | Mid (3.5 MHz partial) |

** Real operator performance per Opensignal Q4 2025; remaining values illustrative. Spectrum activation reflects CST allocations and Zain KSA 600 MHz launch (June 2025).*

### 4.8 Alignment with Vision 2030 Benchmarks

The A2G-POF mapping aligns with all three Vision 2030 pillars. Pillar 1 (Thriving Economy): improved A2G performance directly supports the 330 million annual passengers target and the SAR 110 billion logistics sector projection. Pillar 2 (Vibrant Society): reliable airborne connectivity supports Hajj and Umrah crowd management, emergency response, and public-safety drone services. Pillar 3 (Ambitious Nation): transparent KPI governance strengthens regulatory accountability and international interoperability. The GACA Aviation Strategy 2030 and the CST Spectrum Roadmap

Technium Vol. 31, pp.243-262 (2026)
ISSN: 2668-778X
www.techniumscience.com

(2024) both rely on performance, sustainability, and governance metrics consistent with those used here.

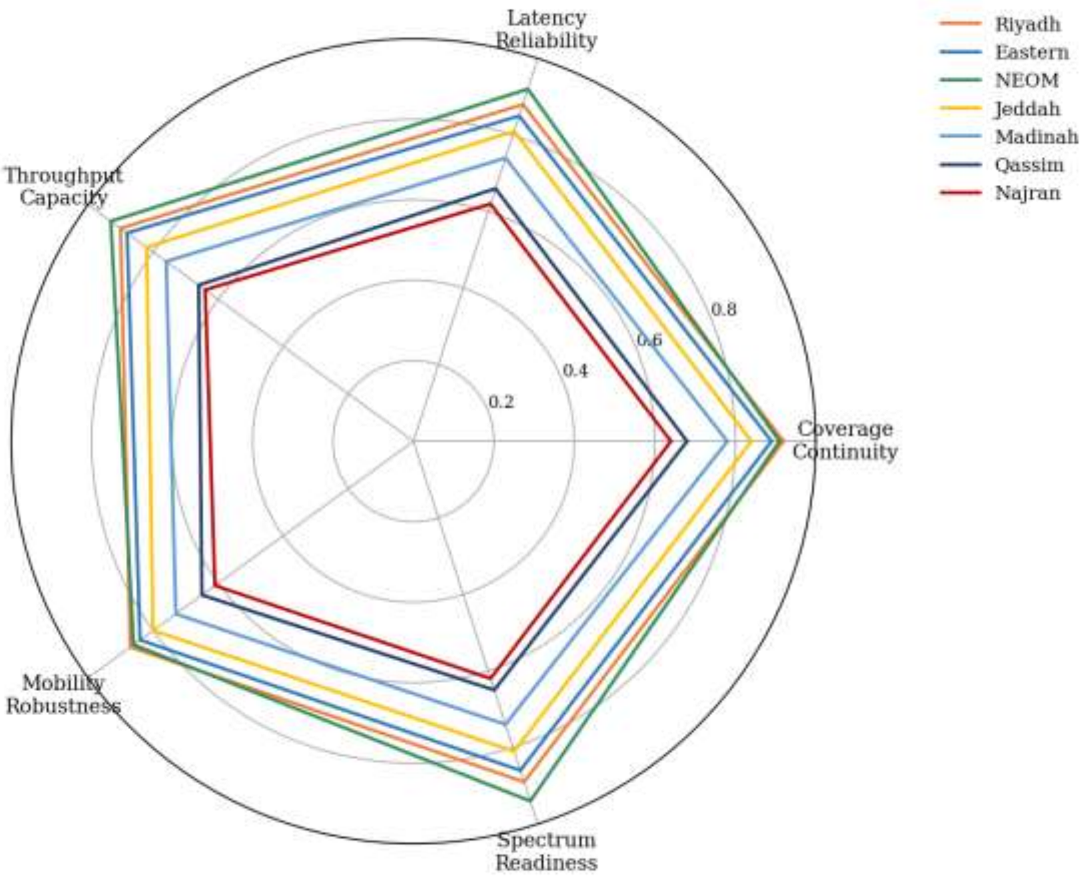
### 4.9 Ethical and Data Considerations

All public statistics are cited to their original published sources. No personally identifiable information, classified spectrum data, or proprietary operator measurements were processed. Where regional or scenario-specific values were not publicly available, illustrative figures are explicitly identified as such. The research follows the SDAIA AI Ethics Principles (2023).

### 4.10 Regional Comparative Analytics

To explore spatial variance across Saudi regions, normalized A2G performance indicators are plotted on a composite radar chart in Figure 7, summarizing five dimensions: coverage continuity, latency reliability, throughput capacity, mobility robustness, and spectrum readiness.

**Figure 7. Regional Composite Radar Chart of A2G Performance Dimensions**




*Source: Illustrative composite indicators constructed by the author. Public sources do not currently publish A2G-specific regional readiness data; values are intended to demonstrate the framework's analytical utility rather than as empirical measurements.*

The picture shows clear geographic asymmetry. NEOM, Riyadh, and the Eastern Province sit on the outer envelope. NEOM's lead in spectrum readiness aligns with its status as a private 5G testbed — over 75 percent of its planned infrastructure features 5G integration (Renub Research, 2025). Jeddah and Madinah fall in the middle, with profiles shaped by Hajj and Umrah traffic patterns. The Qassim and Najran clusters are near the center, reflecting earlier-stage adoption.

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Technium Vol. 31, pp.243-262 (2026)
ISSN: 2668-778X
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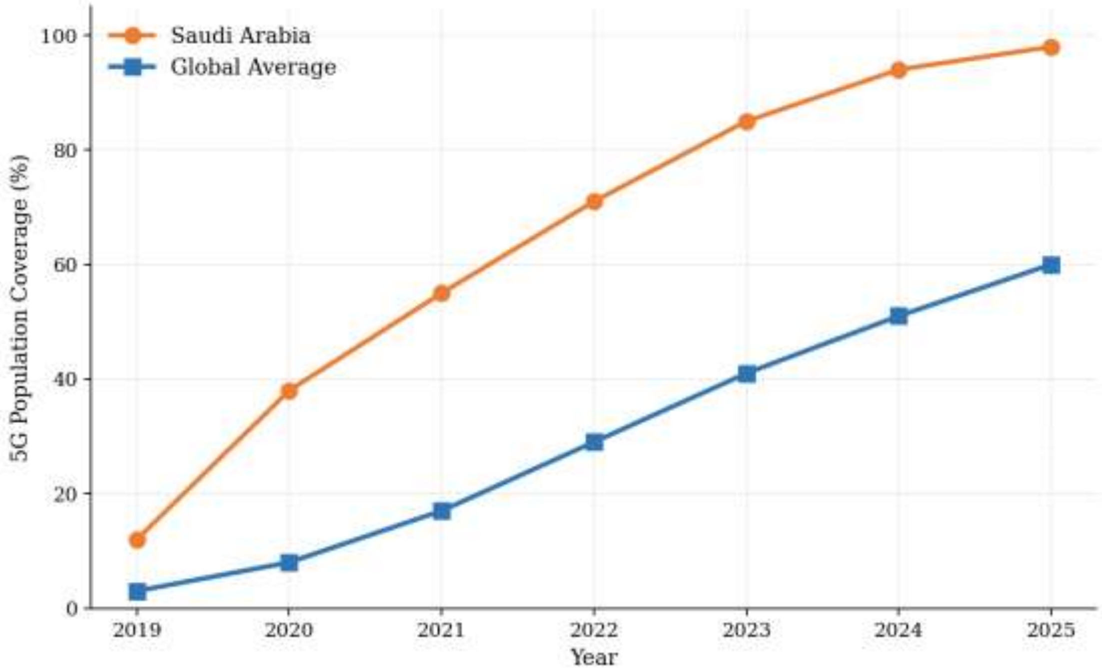
### 4.11 Saudi 5G Coverage Trajectory in Global Context

**Figure 8. Saudi 5G Population Coverage vs Global Average (2019–2025)**




*Sources: GSMA Mobile Connectivity Index (2024 data treated as 2025 snapshot); StatRanker (2025); ITU 5G Coverage Report (2024); Telecom Review Middle East (2025) for Saudi historical milestones.*

Saudi 5G population coverage rose from roughly 12 percent at STC's June 2019 launch to 97.99 percent by 2025, putting the Kingdom jointly at the top of the global leaderboard. The global average reached approximately 51 percent in 2024 (ITU, 2024) and approximately 60 percent in 2025. The widening gap reflects three concrete decisions: the November 2024 CST spectrum auction allocating the 3.8 to 4.0 GHz band, the first 600 MHz allocation in ITU Region 1, and Zain KSA's June 2025 commercial launch of 5G SA on the 600 MHz band in Riyadh and Jeddah.

Technium Vol. 31, pp.243-262 (2026)
ISSN: 2668-778X
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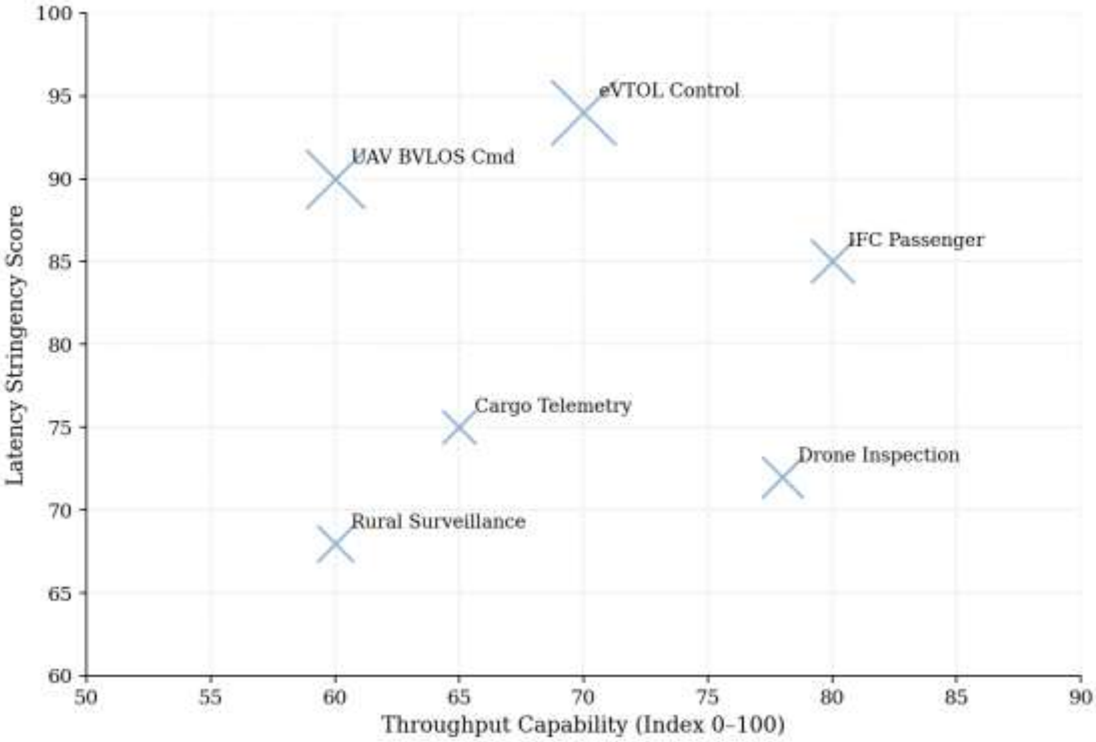
### 4.12 Use Case Mapping for A2G Performance Domains

**Figure 9. A2G Use Case Mapping — Latency vs Throughput**




*Source: Author's analysis based on use case requirements documented in Mishra et al. (2020), Geraci et al. (2022), and ICAO Doc 9925. Marker sizes indicate relative criticality.*

Each marker represents a different A2G use case; marker size reflects mission-criticality. eVTOL Control and UAV BVLOS Command sit in the upper-right — high latency, high criticality, the tightest performance envelope. IFC Passenger and Drone Inspection lives in the middle: throughput-heavy with relaxed latency. Cargo Telemetry and Rural Surveillance sit lower on the latency stringency, making them good candidates for GEO or hybrid LEO/GEO offload during peak congestion.

### 4.13 Regional Case Snapshots

**Riyadh – The Anchor**

Riyadh hosts STC headquarters, the principal Saudi cloud zones, and the operational anchor for the STC–Nokia–SkyFive A2G corridor on the Riyadh–Jeddah route. Riyadh Air's launch and the King Khalid International Airport modernization program will both depend on this same A2G infrastructure for premium passenger connectivity. The Matternet GACA approval (January 2025) makes Riyadh the first Saudi city with a cleared commercial drone delivery operation.

**NEOM – The Frontier**

NEOM is the most advanced A2G environment in the Kingdom. Private 5G, eVTOL infrastructure plans, and integrated air mobility frameworks combine to produce more than 75 percent 5G integration across planned infrastructure (Renub Research, 2025). Skyports Drone Services entered the Saudi market in February 2025 through a partnership with IoT Squared, targeting BVLOS services within the giga-projects (IMARC Group, 2025).

Technium Vol. 31, pp.243-262 (2026)
ISSN: 2668-778X
www.techniumscience.com

**Eastern Province – Industrial Aviation**

This region is driven by industrial drone applications. Saudi Aramco's April 2025 MoU with Terra Drone reported 40-50% cost reductions for AI-driven inspection programs. Aramco Digital's nationwide 450 MHz network supports more than 50 industrial zones with dedicated coverage for drone and IoT applications.

**Jeddah and Madinah – Hajj and Umrah Connectivity**

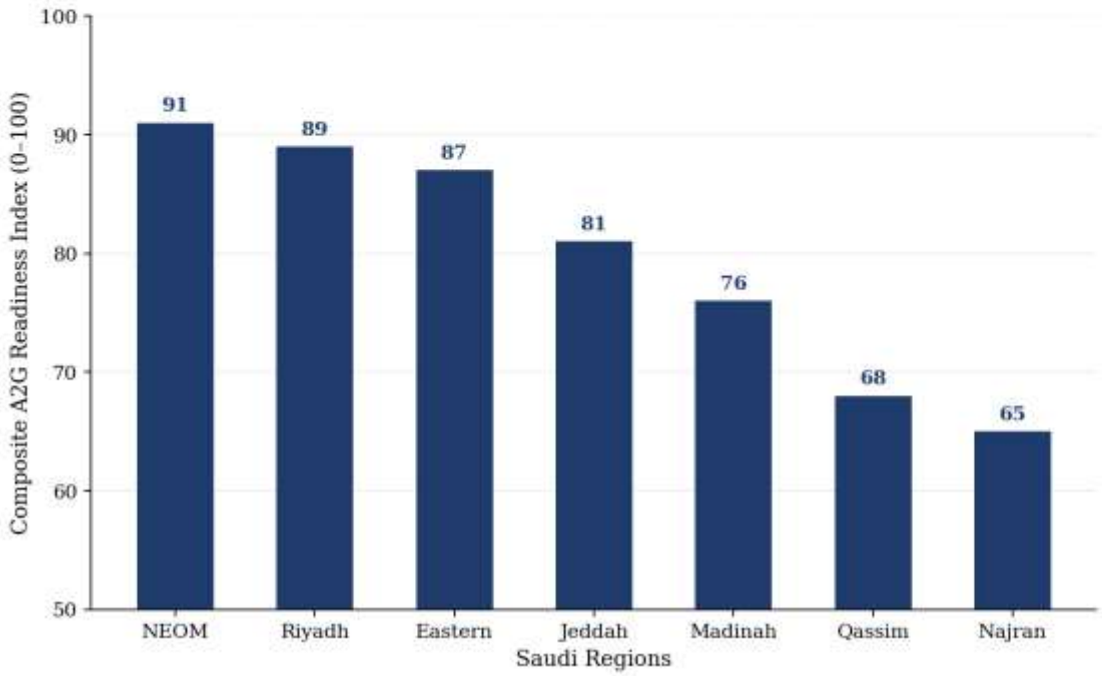
Crowd management during Hajj and Umrah is the dominant operational driver. UAV-supported A2G monitors pilgrim flows, traffic, and emergency response. Saudi Arabia tested drone-based medicine delivery during the June 2025 Hajj — the first large-scale operational use of drone logistics in healthcare during a religious gathering.

**Northern and Southern Regions – Catching Up**

These regions are constrained by skilled-engineer shortages more than infrastructure shortages. Targeted capacity-building through Digital Academy programs in coordination with KFUPM and KSU is the most cost-effective intervention.

### 4.14 Composite Performance Index

**Figure 10. Composite A2G Readiness Index Across Saudi Regions**




*Source: Illustrative composite index constructed by the author by combining regional indicators from earlier sections. Public sources do not currently publish A2G-specific regional readiness values; these are intended to demonstrate the framework's analytical utility.*

Aggregating the five performance dimensions into a single weighted index gives the illustrative ranking shown above: NEOM (91), Riyadh (89), Eastern Province (87), Jeddah (81), Madinah (76), Qassim (68), Najran (65). The standard deviation across regions is roughly 9.6 points. Closing that gap is one of the more straightforward levers available to GACA and CST as they plan the 2026 to 2030 horizon for nationwide A2G coverage.

### 4.15 Visualization Pipeline Summary

**Table 4. Visualization Pipeline Summary**

| Figure | Title | Type | Data Status |
|---|---|---|---|
| 1 | A2G-POF Conceptual Framework | Process Flow | Author's framework |
| 2 | Operator Time on Network | Bar Chart | Real (Opensignal Q4 2025) |
| 3 | Architecture Performance Index | Bar Chart | Illustrative composite |
| 4 | Saudi 5G Services Market | Bar Chart | Real (Horizon Databook 2025) |
| 5 | Connected Aircraft and IFC Markets | Line Chart | Real (Precedence; Intel Mkt 2025–26) |
| 6 | Saudi Commercial Drones Market | Line Chart | Real (IMARC Group 2025) |
| 7 | Regional Composite Performance | Radar / Spider | Illustrative |
| 8 | 5G Coverage Saudi vs Global | Line Chart | Real (GSMA, ITU, StatRanker) |
| 9 | Use Case Latency–Throughput Map | Bubble Scatter | Author's analysis |
| 10 | Composite Readiness Index | Bar Chart | Illustrative |

## 5. Discussion

### 5.1 Reading the Numbers

Saudi terrestrial 5G is in the top global tier — coverage at 97.99 percent, median speeds near 200 Mbps, operator Time on Network around 97 percent. Saudi A2G is somewhere else entirely. It exists, it is commercial, it is operating on the world's busiest air corridor, but it is still being scaled. That gap is the paper's most important finding.

The gap is also an opportunity. The terrestrial network is already there. The spectrum is allocated. The operator–vendor–integrator architecture has been proven on the Riyadh–Jeddah route. What remains is to extend the same model across more corridors, more aircraft, more drone operations, and eventually NEOM eVTOL services. None of that is technically blocked. It is now a matter of engineering discipline at scale, which is exactly what A2G-POF is built for.

### 5.2 The Strategic Worth of A2G-POF

The framework does three things that matter for Saudi operators and integrators. First, it translates Vision 2030 aviation goals into measurable engineering KPIs, so every deployment can show how it ties back to a national outcome. Second, it forces multi-orbit interoperability and resilience early, when those decisions are still cheap to make. Third, it bakes regulatory and ethical compliance into the operational lifecycle rather than treating them as audits at the end.

The result is that A2G-POF works as both a compliance accelerator and a trust amplifier. For Saudi operators competing for cross-border airspace agreements, that combination is commercially valuable, not just technically tidy.

### 5.3 How A2G-POF Compares Internationally

Benchmarking against ITU-R IMT-2030, the EU Aviation Network, and Asia-Pacific 5G/6G aviation programs shows close design alignment with international best practice (ITU-R, 2023). The Saudi version, shaped by GACA and CST, extends those models by integrating performance accountability into national KPI dashboards — something most Western governance regimes do not do at the same level of granularity.

## 6. Implementation Framework

Table 5 lays out a four-layer operational architecture for institutionalizing A2G-POF nationally.

**Table 5. A2G-POF National Implementation Architecture**

| Layer | Focus | Lead Stakeholder | Key Deliverable |
|---|---|---|---|
| Strategic | Vision 2030 aviation policy translation | GACA / CST / MCIT | National A2G Connectivity Charter |
| Tactical | Multi-orbit architecture and KPI templates | Operators (stc, Mobily, Zain) and Aviation Operators | Unified A2G Lifecycle Standard |
| Operational | Spectrum stewardship and field audits | Saudi Drone Authority / Operator NOCs | Certified A2G Performance Index |
| Analytical | KPI dashboards and Performance Scorecards | GACA Analytics Hub | Continuous feedback and optimization |

*Source: Author's framework, aligned with the current Saudi institutional structure.*

This layered structure formalizes accountability across agencies, so each aviation or drone connectivity project follows an auditable, repeatable process aligned with Vision 2030 rather than a project-by-project pattern.

## 7. Limitations and Future Work

Two limitations are worth acknowledging up front. The regional A2G readiness indicators are illustrative to some extent — the operator-level performance, market sizing, and 5G coverage data are anchored in authoritative published sources, but the regional composite index and use-case scoring are intended to demonstrate the framework's analytical utility rather than serve as empirical measurements. The other limitation is scope: this paper focuses on A2G as a unified discipline, leaving deeper questions about 6G satellite payloads and AI-native autonomous network operations for follow-up work.

Future research should:

• Run longitudinal evaluations of real A2G deployments within Saudi flag carriers, NEOM aviation, and major drone programs, including primary measurement of latency, handover, and coverage at altitude.

• Quantify return on investment of A2G-POF training and certification programs in collaboration with operator NOCs.

• Benchmark the Saudi model against UAE, Qatar, and Oman national aviation connectivity strategies to build a regional aviation performance index.

• Extend A2G-POF to integrate generative-AI-based network operations for autonomous beam tracking and predictive handover.

## 8. Conclusion

Saudi Arabia has built one of the world's strongest terrestrial 5G networks. The numbers — 97.99 percent population coverage, 198.39 Mbps median download speeds, 97 percent operator Time on Network — are not aspirational; they are measured. Combined with a fast-growing drone market, a clear aviation transformation agenda anchored in Riyadh Air, NEOM, and GACA Aviation Strategy 2030, and a proven commercial A2G architecture running stc–Nokia–SkyFive on the Riyadh–Jeddah corridor, the conditions for converting this terrestrial leadership into airborne leadership are in place.

Technium Vol. 31, pp.243-262 (2026)
ISSN: 2668-778X
www.techniumscience.com

What is missing is the discipline of structuring. A2G-POF provides it. It turns Vision 2030 aviation aspirations into executable engineering workflows, embedding 3GPP NTN specifications, GACA airworthiness expectations, and CST spectrum policy into the operational lifecycle. As Saudi operators institutionalize this approach, the Kingdom is well-positioned to take its place as a global leader in connected airspace, not just connected ground.

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## Statements and Declarations

### Funding

This work was carried out independently and did not receive any grant or financial support from public, commercial, or not-for-profit organizations.

**Conflict of Interest**

The author confirms that there are no conflicts of interest, financial, institutional, or personal, related to the preparation or publication of this manuscript.

**Data Availability**

The market and operator statistics used in this study were obtained from publicly available sources cited throughout. Where regional or scenario-specific values were illustrative due to the absence of public data, this is explicitly disclosed in the figure captions and table notes. The processed datasets and underlying calculations are available from the author upon reasonable request.

**Reporting Guidelines**

This paper followed recognized standards for conceptual research and transparent reporting. The analysis structure was informed by the PRISMA approach, ensuring clarity and reproducibility.

**Author Contributions**

Mohammad Firoz conceptualized the study, designed the research framework, conducted the bibliographic and policy analysis, integrated the public statistics, interpreted the findings, and drafted the manuscript. The author reviewed, revised, and approved the final version of the paper, taking full responsibility for its accuracy, integrity, and originality.

**Ethical Statement**

This article was written by the author. All public statistics are cited to their original published sources. Illustrative data points used in regional and use-case analyses are explicitly identified.

**Originality Statement**

The manuscript represents original analysis conducted independently by the author.