Designing a 5G-Enabled Smart Port Architecture Integrating Private Networks, Fiber Backbones, and Secure IoT for Next-Gen Maritime Operations

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Abstract

To enable HarborLink Port's transition into a next-generation smart port, a comprehensive and adaptive network architecture is essential, one that responds intelligently to the diverse technical demands of modern maritime operations. This case study explores how operational scenarios such as remote-controlled cranes, autonomous vehicles, IoT-based monitoring systems, and AI-driven analytics shape the port's infrastructure requirements. Each use case introduces unique challenges, from ultra-low latency and high reliability for mission-critical tasks to massive data throughput and secure connectivity for large-scale IoT deployments. In response, HarborLink Port adopts a hybrid architecture combining private 5G, fiber-optic backbones, and edge computing, orchestrated through network slicing and optimized via digital twin simulations. This setup ensures seamless mobility, real-time control, and scalable performance across all operational layers. The integration of IoT and blockchain technologies further enhances transparency, security, and data integrity, while AI and digital twins empower predictive maintenance, autonomous routing, and dynamic resource allocation. Crucially, the port's strategy emphasizes harmonizing legacy systems with smart technologies through a unified Smart Port Platform, ensuring continuity and accelerating digital adoption. Together, these innovations form a resilient, intelligent foundation that positions HarborLink Port at the forefront of global smart port transformation.

1 Introduction

The maritime industry is rapidly evolving through digital transformation, with smart ports emerging as key enablers of global logistics efficiency. These next-generation ports integrate technologies such as automation, Internet of Things (IoT), Artificial Intelligence (AI), and high-speed connectivity to optimize cargo handling, improve safety, and enable real-time decision-making.

HarborLink Port, a major regional logistics hub, is undergoing a strategic upgrade to incorporate automated cranes, IoT-based monitoring systems, and AI-driven cargo management. However, its legacy wired infrastructure lacks the flexibility, mobility, and low-latency capabilities required to support these innovations, particularly for mobile assets such as Automated Guided Vehicles (AGVs) and remotely controlled equipment. To address these limitations, this case study explores the deployment of a hybrid 5G-enabled network architecture that combines private 5G, fiber optic backbones, edge computing, and secure IoT integration. The proposed solution aims to deliver scalable, resilient, and intelligent connectivity that aligns with HarborLink's operational goals and positions the port for future growth in a digitally connected supply chain.

1.1 Background of the Study

Leading global ports such as Hamburg, Shanghai, and Vancouver show how 5G enables real-time analytics, remote equipment control, autonomous vehicle operations, and predictive maintenance, greatly improving efficiency, safety, and operational flexibility.

HarborLink Port faces similar needs, with thousands of mobile assets such as AGVs, RTGs, and drones (as shown in Figure 1), requiring seamless, low-latency connectivity and secure onboarding of expanding IoT devices across a large, dynamic environment. However, its legacy wired systems lack the mobility, responsiveness, and scalability needed to support automation, AI analytics, and digital twin technologies.

Figure 1. Typical Maritime Port

This study proposes a hybrid 5G-enabled architecture integrating private 5G, fiber-optics, edge computing, and secure IoT management to overcome these limitations and enable HarborLink's transition to a fully functional smart port.

1.1 Objectives of the Study

The primary objective of this study is to design a robust, scalable hybrid 5G-enabled network architecture tailored to HarborLink Port's operational needs.

This architecture aims to support high mobility, ultra-low latency, and secure connectivity for a wide range of smart port applications, including automated cargo handling, remote crane operations, and real-time surveillance. A key goal is to evaluate the feasibility and performance of integrating private 5G networks, fiber optic backbones, and secure IoT platforms. This includes assessing how these technologies interact to support mission-critical services, enable edge computing, and facilitate seamless data exchange across port zones.

Additionally, the study seeks to align the network design with HarborLink's strategic business goals and technical requirements. This involves ensuring that the proposed infrastructure supports operational efficiency, safety, scalability, and sustainability, while also being adaptable to future innovations in AI, automation, and digital logistics.

1.2 Scope and Delimitation

This study designs and evaluates a hybrid 5 G-enabled network architecture to support HarborLink Port's transition to smart port operations. It focuses on integrating private 5G, fiber optics, and secure IoT platforms to deliver high-performance connectivity, automation, and real-time analytics across key areas such as crane control, AGV mobility, and sensor-based monitoring.

The scope covers technical architecture development, performance assessment, and alignment with operational needs. It excludes financial analysis, vendor procurement, regulatory compliance, environmental assessments, and long-term maintenance planning. The design also assumes that portions of the port's existing fiber infrastructure are already available for integration.

1.3 Significance of the Study

This study serves as a strategic blueprint for ports seeking to modernize their operations by adopting advanced network technologies, particularly 5G.

As global trade becomes increasingly digitized, ports must evolve into intelligent, connected ecosystems that support automation, real-time analytics, and secure data exchange. By presenting a hybrid 5G-enabled network architecture tailored to HarborLink Port, this research provides valuable insights into how to effectively combine private 5G, fiber optics, edge computing, and IoT to meet the complex demands of smart port environments.

Beyond its practical application, the study also adds to the growing body of academic literature on smart logistics and digital infrastructure in maritime operations. It offers a technical reference for port authorities, telecommunications providers, infrastructure planners, and IT strategists involved in designing next-generation port systems. The findings and recommendations outlined here can inform future deployments, guide policy development, and support collaborative innovation across the logistics and technology sectors.

2. Literature Review

Smart port research shows that 5G, IoT, AI, and digital twins are the core enablers of next-generation port automation. Case studies highlight 5G network slicing for low-latency control, AR/VR maintenance, and IoT integration in real port environments [1]. Hybrid 5G models and FTTM support remote crane operation and real-time telemetry [2]. Digital twins optimize AGV, RTG, and STS crane operations through predictive simulation [3], while drone-assisted systems like Twin Port improve situational awareness [4].

Private 5G is identified as the foundational infrastructure for secure, scalable automation and AI-driven logistics in modern ports [5]. OT IT convergence through PCS, OCR, and digital twins further enhances operational intelligence [6]. UAV mobility challenges are addressed through mesh networking, SDN, and Remote ID standards [8]. AI scheduling tools improve efficiency and reduce emissions, supported by end-to-end 5G integration frameworks [7, 9]. Lightweight blockchain models also strengthen security and low-latency IoT interactions in 5G environments [11].

3 Methodology

The design and development of HarborLink Port's hybrid 5G-enabled network architecture followed a structured and strategic methodology grounded in enterprise architecture principles, advanced simulation tools, and robust security frameworks. This approach ensured that the network not only meets technical performance benchmarks but also aligns with the port's operational goals and long-term digital transformation strategy.

3.1 Assessment and Planning

Infrastructure Audit: A comprehensive audit of HarborLink Port's legacy infrastructure revealed significant limitations across five key domains. The port management system is outdated, lacks integration, and offers minimal real-time data exchange, resulting in siloed operations. Wired communication networks suffer from high latency, limited bandwidth, and aging physical infrastructure, which impact mission-critical processes. IoT sensors rely on obsolete protocols with limited interoperability and lack edge computing, reducing real-time visibility and predictive maintenance capabilities. CCTV systems use low-resolution analog and early digital technologies, limiting automated threat detection and scalable storage. Control platforms for cranes and automated machinery remain standalone and manual, lacking remote operation and AI integration needed for modern autonomous port functions.

Operational Impact: To mitigate adverse effects on HarborLink's daily operations during the rollout of its hybrid 5G-enabled infrastructure, a technically sound, carefully phased implementation strategy is essential. This includes conducting detailed planning that accounts for legacy system dependencies, operational workflows, and zone-specific constraints. Before full deployment, mock-up trials in controlled real-world environments should be executed to validate system interoperability, latency performance, and edge computing responsiveness. These simulations help identify potential bottlenecks, ensure seamless integration with existing assets, and allow for corrective adjustments before live activation, thereby minimizing downtime and operational risk.

Stakeholder Alignment: Stakeholders' engagement is a critical component of the planning phase. Active coordination with port authorities, IT and operations teams, logistics partners, and regulatory agencies ensures continuous alignment on system architecture, compliance frameworks, and strategic objectives. This integrated approach serves as the operational backbone for the port's transition to a fully connected, intelligent port ecosystem.

3.2 Core System Elements

The proposed architecture introduces a modern, high-performance digital ecosystem for port operations, built on integrated 5G, fiber, edge computing, IoT, and security layers.

Figure 2. Hybrid 5G Network

Private 5G Network Layer: A standalone 5G network with strategically placed gNodeBs delivers reliable, low-latency coverage for mobile equipment like AGVs and cranes, as shown in Figure 2. Control and data planes manage mobility, sessions, and routing, while network slicing supports URLLC for crane control, eMBB for AR/VR and video, and mMTC for large-scale IoT.

Fiber Optic Backbone: A resilient FTTM-based fiber network connects edge data centers and critical machinery with ultra-low latency. Redundant paths ensure uptime and high availability for mission-critical operations.

Edge Computing Layer: Local edge nodes process real-time, latency-sensitive tasks such as collision avoidance and predictive maintenance. They also run AI workloads to optimize cargo flow, scheduling, and equipment health.
IoT Integration Layer: Gateways aggregate data from thousands of sensors across vehicles, containers, and infrastructure. Secure onboarding, 5G-AKA authentication, TLS encryption, and centralized device management ensure safe and reliable IoT operations.

Protocols & Security Layer: Connectivity relies on standards such as 5G NR, IP/MPLS, and Ethernet, as well as IoT protocols such as MQTT, CoAP, and OPC-UA. Security is reinforced with TLS/SSL, Zero Trust Architecture, and PKI-based identity management to maintain a protected, interoperable environment.

Supporting Systems: A Digital Twin Platform enables real-time simulations and AI-driven anomaly detection. The Port Community System (PCS) supports API-based data sharing among stakeholders. Security is strengthened through Zero Trust policies, active SOC monitoring, and blockchain for tamper-proof documentation and smart contract automation.

Simulation Tools: NS-3 assesses 5G performance, including latency, throughput, packet loss, handovers, and slicing, while OMNeT++ models edge computing workflows, mMTC IoT traffic, cybersecurity scenarios, and digital twin analytics before deployment.

In a smart port, connectivity begins at the edge, where AGVs, cranes, drones, and IoT devices use 5G modules to connect automatically to nearby gNodeBs, enabling seamless mobility across port zones, as shown in Figure 3. These base stations feed data into a standalone 5G Core, where functions such as AMF, SMF, and NRF manage mobility and sessions, while the DPF forwards user data. Time-critical tasks are processed locally at edge nodes for ultra-low latency. At the same time, non-critical analytics and video streams are sent via high-speed fiber to control centers or the cloud.

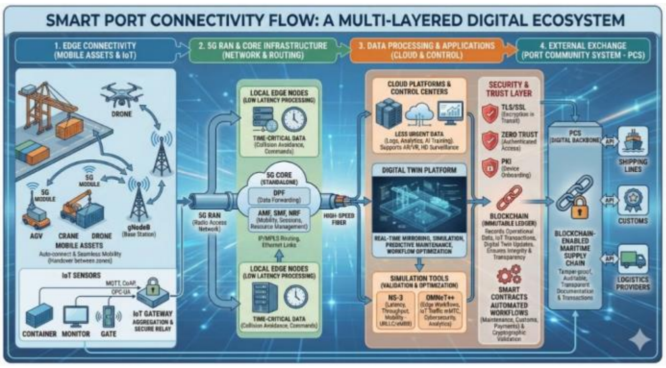

Figure 3. Smart Port Connectivity Flow

IoT sensors distributed across containers, cranes, and infrastructure communicate using lightweight protocols such as MQTT, CoAP, and OPC UA, with gateways aggregating and securely transmitting the data. Security spans all layers through TLS/SSL encryption, Zero Trust access controls,

PKI-based device onboarding, and blockchain for tamper-proof operational records and automated smart contract workflows.
All data feeds into a digital twin platform that mirrors real-time operations and supports simulation, predictive maintenance, and optimization. Tools such as NS-3 and OMNeT++ validate 5G slicing performance, mobility, cybersecurity, and edge workflows. The Port Community System (PCS) provides a secure interface for external stakeholders, with blockchain ensuring transparent and auditable documentation across the supply chain.

3.3. Testing and Validation

A series of tests on the smart port network revealed key limitations affecting performance and scalability, as shown in Figure 4. Latency ranged from 35 to 50 ms, making it unsuitable for real-time operations. Mobility support was weak, with frequent handover drops during crane movement. Bandwidth peaked at 100–150 Mbps, insufficient for AI and video data demands. Device onboarding lacked scalability and security, relying on manual provisioning. AI integration faced delays of over 5 seconds, hindering automation. The network lacked failover mechanisms, posing reliability risks. Security assessments identified vulnerabilities caused by outdated protocols. Scalability tests showed congestion when adding 1,000+ devices, and interoperability issues arose due to protocol mismatches with legacy systems. Lastly, adverse weather caused signal degradation, highlighting poor environmental resilience. Simulation results are shown in Figure 5 and Table 1.

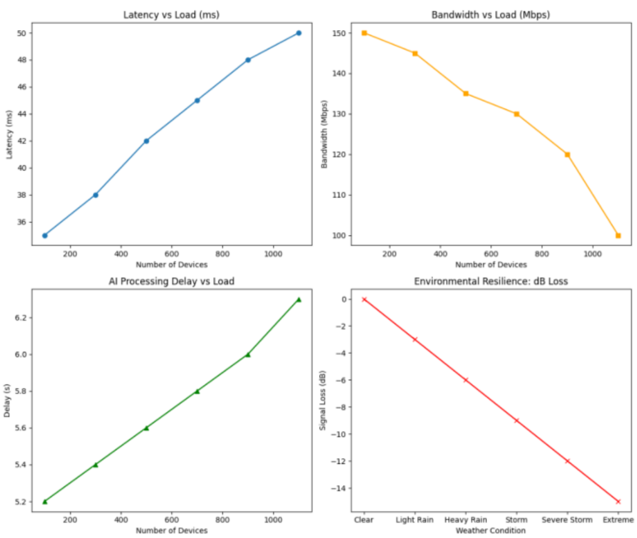

Figure 4. Simulation Results

Graphics may be full color, but make sure they are appropriate for print (black and white) and online (color) publication. Coloured line graphs should use dotted or dashed lines, or shapes to distinguish them from each other in print. Each figure should be explicitly referred to in numerical order and should be embedded within the text at the appropriate point. A maximum of four subfigures is allowed per figure.

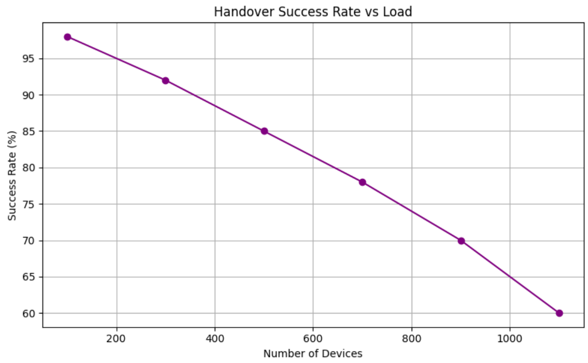

Figure 5. Simulation Results

Table 1. Summary of Simulation Results

Metric	Result/Observation	Implication
Latency	35-50 ms under increasing load	Too high for real-time port
Bandwidth / Throughput	150 Mbps peak, dropping to 100 Mbps at high load	Insufficient for AI video analytics and large device fleets
AI Processing Delay	5-6.3 seconds	Causes delays in automation and decision-making systems
Handover Success Rate	Drops from 98%→60% as load increases	Unstable mobility, causing crane control interruptions
Scalability	Congestion after 1000+ devices	The network cannot scale to full smart port requirements
Security	Outdated protocols; manual device onboarding	High security risk; no automated identity management
Environmental Resilience (Synthetic dB Loss)	0 to -15 dB from clear weather to extreme weather	Significant performance degradation in storms

Reliability / Failover	No redundancy of the failover mechanism	Single points of failure increase operational risk
Interoperability	Protocol mismatch with legacy Systems	Causes communication breaks across port subsystems
Blockchain Integration Potential	Suitable for device identity, onboarding automation, and tamper-proof logs	Should be placed in System Architecture, not just Results

4 Results and Discussion

The transformation of HarborLink Port into a smart, digitally connected logistics hub is anchored in the successful deployment of a hybrid 5G-enabled network architecture. This study confirms that integrating private 5G, fiber backbones, edge computing, and IoT platforms is not only feasible but essential for meeting the demands of modern port operations.

Digital twin simulations validated the architecture's ability to deliver < 30 ms latency for mission-critical tasks, meeting URLLC standards. Network slicing played a pivotal role in allocating dedicated resources for diverse applications: ultra-reliable low-latency communication for crane control, enhanced mobile broadband for surveillance, and massive machine-type communication for IoT telemetry. Combined with edge computing, these capabilities enabled real-time decision-making and operational agility.

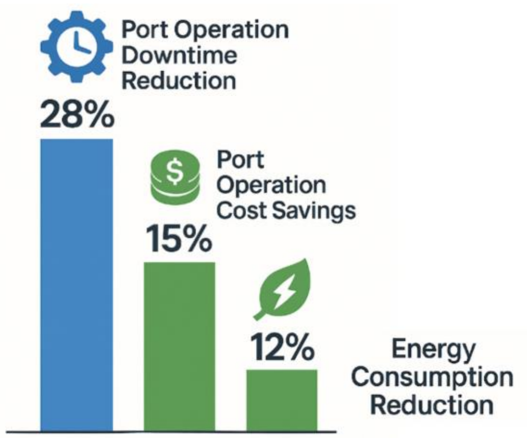

Figure 6. Port Operation Improvements

Use case analysis demonstrated strong performance, remote-controlled cranes operated with high reliability, autonomous vehicles maintained consistent connectivity, and over 10,000 IoT sensors ensured secure data flow via blockchain. AI-driven analytics supported predictive maintenance, cargo optimization, and environmental monitoring, shifting operations from reactive to proactive.

Simulations as shown in Figure 6, a 28% reduction in downtime and 15% cost savings, while the modular Smart Port Platform enabled seamless integration with legacy SCADA systems, minimizing disruption. Blockchain further enhanced security and transparency, streamlining customs and reducing fraud through smart contracts. Sustainability goals were also met, with AI-optimized edge nodes reducing energy consumption by 12%. The architecture is future-ready, with UAV-assisted data collection planned.

4.1. Technical Requirements Mapping

To ensure that the appropriate network configuration supports each operational use case, Table 2 maps technical requirements to network slices and solutions:

Table 2. Technical Requirement Mapping

Use Case	Network Slice	Latency	Bandwidth	Reliability	Solutions
Remote crane control	URLLC	< 30 ms	50-100 kbps	99.999 %	5G URLLC + MEC
Video feed (cranes, yard)	eMBB	< 30 ms	30-200 Mbps	99.9%	5G eMBB + Fiber Backhaul
AGVs/IGVs	URLLC	< 50 ms	10–20 Mbps	99.9%	5G URLLC
Video surveillance	eMBB	< 200 ms	2-4 Mbps	90%	5G eMBB + Edge Analytics
IoT sensor data	mMTC	Best effort	Best effort	90%	5G mMTC + IoT Platform

5 Conclusion and Recommendations

The analysis shows that a hybrid 5G-enabled architecture is essential, not optional, for HarborLink Port's transition into a smart, data-driven logistics hub. By combining private 5G, fiber optics, edge computing, and IoT platforms, the port can achieve a scalable, resilient, and intelligent operational environment suited for high-volume, time-critical workflows.

Network slicing emerges as a key capability:

- URLLC enables remote crane control and other safety-critical operations.
- eMBB supports HD video and AR/VR maintenance.
- mMTC manages large-scale IoT telemetry.

When paired with edge computing, these slices enable real-time decision-making and ultra-low-latency control. Digital twins further strengthen operational intelligence by enabling simulation, predictive maintenance, and optimized resource allocation.

The integration of IoT and AI technologies provides granular visibility and predictive insights, enabling HarborLink to shift from reactive operations to a proactive, automated, and highly efficient smart port model.

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