Digital Engineering for Quantum Communication Networks: A Systematic Review of Models, Simulators, and Testbeds

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***Abstract*—Research on quantum communication networks has grown rapidly in recent years, driven by progress in quantum devices, simulators, and experimental testbeds. As these systems become more complex, there is increasing interest in digital methods that can support analysis, prediction, and performance assessment without relying exclusively on physical experimentation. Surveying articles from 1984 to 2025, this systematic literature review examines the current state of digitalisation in quantum communication networks. It evaluates how existing tools and studies contribute to the longer-term goal of creating digital twin technologies for quantum systems. Using PRISMA, a structured and transparent review process, the literature is grouped into three categories that reflect different levels of digital representation: digital models, digital shadows, and initial attempts that resemble early digital twin practices. The findings show that the community has developed sophisticated simulation platforms and a wide range of modelling approaches, and that several experimental testbeds already support partial data-driven integration. However, the review also shows that continuous synchronisation between physical quantum networks and their digital counterparts remains largely undeveloped. The study identifies the main technical gaps that prevent deeper cyber-physical integration and outlines research directions that could guide the development of future digital frameworks capable of supporting prediction, optimisation, and system-level evaluation across the full lifecycle of quantum communication networks.**

***Index Terms*—quantum communication network, QKD, metropolitan quantum networks, quantum communication protocols, quantum network simulators, testbeds, digital twin, digital engineering, hardware-in-the-loop.**

ABBREVIATIONS

BB84	Bennett–Brassard 1984 Protocol
DES	Discrete Event Simulation
DT	Digital Twin
E91	Ekert's 1991 entanglement-based protocol
ETSI	European Telecommunications Standards Institute
HiL	Hardware-in-the-Loop
KPI	Key Performance Indicator
LLMs	Large Language Models
NetSquid	Network Simulator for Quantum Information using Discrete events
NFV	Network Functions Virtualisation
PICOC	Population, Intervention, Comparison, Outcome, and Context
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QBER	Quantum Bit Error Rate
QCN	Quantum Communication Network
QKD	Quantum Key Distribution
QR	Quantum Repeater
QoS	Quality of Service
RSA	Rivest, Shamir, and Adleman
SDN	Software-Defined Networking
SeQUeNCe	Simulator of Quantum Network Communication
SKR	Secret Key Rate
SLR	Systematic Literature Review

I. INTRODUCTION

The evolution of quantum technology spans nearly a century of scientific progress, moving from foundational physics to operational global infrastructures. For decades, progress was slow and largely confined to theory and laboratory experiments. But in the early 21st century, rapid advances in quantum computing, entanglement distribution, and photonic engineering pushed the field forward, marking a clear shift from laboratory demonstrations to practical and real-world systems, as shown in Figure 1.

The story begins in the 1920s, when the principles of quantum mechanics were established by pioneers such as Einstein, Schrödinger, and Heisenberg. Their work laid the theoretical foundation for phenomena such as superposition, uncertainty, and entanglement principles that would not find technological applications until many decades later [1]. Meanwhile, one of the biggest classical breakthroughs arrived in 1978 with the classical public key cryptosystem, developed by Rivest, Shamir, and Adleman (RSA). By relying on the difficulty of factoring large integers, RSA made secure online communication possible and became the foundation of digital security for many years [2]. At that time, no realistic computational threat seemed capable of breaking it.

This sense of security began to shift in the early 1980s, when Richard Feynman introduced the idea of quantum computers that could harness quantum mechanics to perform certain tasks far faster than classical computers [3]. Around this period, researchers also began exploring how quantum

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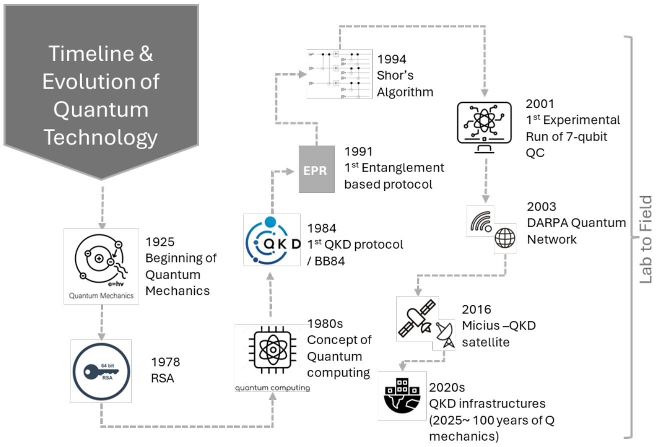

Fig. 1. Key milestones in the development of quantum technologies

mechanics could enable new forms of secure communication. The Bennett–Brassard 1984 Protocol (BB84) introduced a prepare-and-measure approach, where Alice sends single photons in randomly chosen bases and any eavesdropping causes detectable disturbances [4]. A few years later, the Ekert's 1991 entanglement-based protocol (E91) protocol demonstrated an entanglement-based method: instead of sending prepared states, both users receive entangled photon pairs whose correlations are verified through Bell-inequality tests, introduced by physicist John Bell [5]. This shift to entanglement provided stronger security guarantees. However, practical adoption remained limited at the time due to technological constraints and the continued reliability of classical encryption.

Everything changed in 1994, when Peter Shor discovered a quantum algorithm capable of efficiently factoring large numbers [6]. This was the first clear mathematical proof that a future quantum computer could break RSA. The threat became even more real in 2001, when the first experimental demonstration of Shor's algorithm was performed using a 7-qubit Nuclear Magnetic Resonance (NMR) quantum computer [7]. This event sparked the beginning of a new era, the moment the world recognised that classical cryptography would eventually need a quantum-safe alternative.

This growing awareness accelerated interest in practical quantum communication. In 2003, the DARPA Quantum Network became the world's first metropolitan quantum network, continuously operating in Boston and Cambridge and proving that Quantum Key Distribution (QKD) could operate outside the laboratory for the first time [8]. This marked a turning point: quantum communication was no longer just a theoretical or experimental concept; it was becoming a real system.

A decade later, the field took an even bigger leap when China launched the Micius satellite in 2016. Micius demonstrated satellite-to-ground QKD over distances greater than 1,200 km and later enabled the first intercontinental quantum-secured communication [9], [10]. These achievements showed that global-scale quantum networks were possible.

Today, a century after the birth of quantum mechanics, the field continues to advance at an exceptional pace. Progress in quantum processors, integrated photonics, and large-scale QKD deployments is steadily pushing the world toward interconnected quantum communication networks capable of supporting secure communication in the era of quantum computing [11], [12].

A. Motivation and Contribution

As these networks mature, industry efforts have increasingly focused on advancing the hardware that underpins them, including single-photon sources, single-photon detectors, quantum repeaters, and other core photonic components [13]. While many of these devices have been demonstrated through controlled, lower-layer physical experiments, integrating them into a scalable quantum communication network introduces far more complex challenges. Their combined behaviour across multiple nodes, varying configurations, and synchronised operations cannot be characterised through isolated laboratory tests.

Moreover, evaluating the performance of different design configurations, updating device parameters, or comparing traditional and emerging QKD protocols through full physical trials is costly, time-consuming, and often infeasible [14], [15]. For these reasons, there is a growing need for a virtual framework that is integrated with the physical layer to enable controlled, repeatable, and cost-efficient evaluation of component interactions, network-level behaviour, and protocol performance under realistic operating conditions. Such a framework supports systematic examination of alternative design configurations, identification of integration and synchronisation constraints, and assessment of system behaviour under non-ideal or dynamically varying environments that are difficult to reproduce experimentally [16], [17].

Accordingly, this paper presents an Systematic Literature Review (SLR) that evaluates the current readiness for developing a Digital Twin (DT) for quantum communication networks. To date, no prior reviews have examined this area or captured the breadth of relevant studies, making it unique in the existing literature. Addressing DT-related research questions requires a comprehensive and structured assessment of the literature, as no single study is able to cover the full breadth of digital developments required to inform DT research.

To achieve this, we survey and analyse the digital contributions reported to date and organise them into thematic pillars that reflect different levels of digitalisation from static modelling and numerical simulations of isolated or multi-layer components to co-simulation environments and testbed-validated platforms. This structured synthesis enables readers to understand how quantum communication networks are currently modelled and simulated without having to navigate a large number of fragmented or less relevant papers. Furthermore, the review assesses the extent to which existing digital approaches support DT-enabling capabilities, including system integration, configuration, verification, and performance evaluation, thereby providing a consolidated foundation for understanding the present state of digitalisation and the readiness of quantum communication systems for future DT development.

B. Paper Structure

This article is organised as illustrated in Figure 2. Section I defines the scope of the review and introduces the substantial technological developments that have emerged since the foundational principles of quantum mechanics were established. Section II introduces the cryptographic and non-cryptographic contexts in which Quantum Communication Network (QCN) are developed, positioning the study against existing review literature, and formulating the research questions that define its scope. Section III describes the review protocol, including the search design, selection procedure, and analytical strategy used to capture and assess the relevant body of literature. Section IV reports the screening outcomes and presents how the final set of studies was categorised for subsequent analysis. Section V develops the taxonomy-driven synthesis by structuring the literature into pillars, themes, and strands that reflect the different forms of digital representation found across the field. Section VI complements this taxonomy with an evidence-based synthesis that concentrates on studies demonstrating stronger operational characteristics relevant to DT development. Section VII consolidates the synthesised insights to address the research questions of the review and outlines future research directions for the development of digital twins in quantum communication networks. Finally, Section VIII closes the paper by summarising the overall findings and their implications for the future engineering of digital twins in quantum communication networks.

II. BACKGROUND

Quantum mechanics introduces several foundational principles that leverage quantum computers and quantum communication systems [18]. These principles inherently support secure information exchange, and they are described below as shown in Figure 3.

Quantum Bits (Qubits): Qubits are the basic units of quantum information. Unlike classical bits, which take values of 0 or 1, qubits are represented by two-level quantum systems that can encode richer information through complex amplitudes and phase [19].

Superposition: A qubit can exist in a coherent combination of both 0 and 1 states simultaneously. This enables quantum systems to process multiple possibilities at once, giving rise to quantum parallelism and more expressive information encoding [20].

Entanglement: Entanglement creates strong non-classical correlations between two or more quantum particles. Measuring one particle instantly determines the state of its entangled partner, regardless of distance, which is referred to *'spooky action at a distance'* by Einstein [21]. This principle is a fundamental resource for quantum communication and networking.

No-Cloning Theorem: This principle states that it is impossible to create an exact copy of an unknown quantum state [22]. Because attempting to measure or duplicate a quantum state disturbs it, the no-cloning theorem provides natural security against eavesdropping in quantum communication.

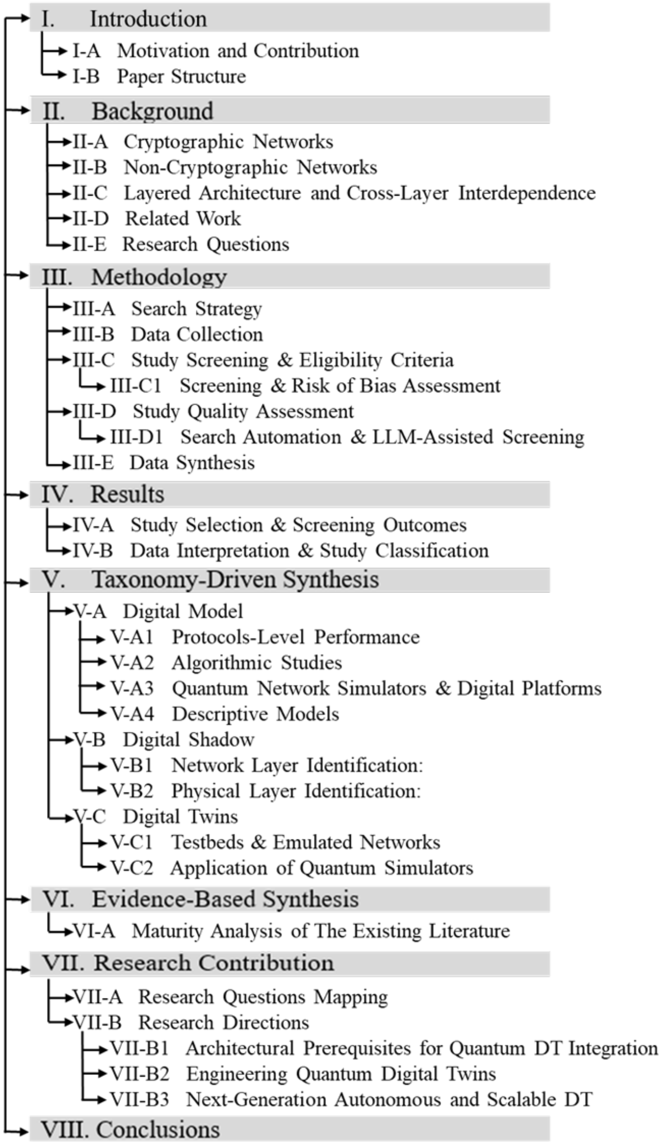

Fig. 2. Structure of the paper

A. Cryptographic Networks

Building on these features, quantum cryptography emerged as a field dedicated to exploiting quantum information to provide confidentiality, authentication, and integrity for communication systems. For many years, QKD dominated this field, as it was the first quantum-cryptographic primitive to be realised experimentally and deployed in real networks. QKD enables two distant nodes to generate shared secret keys with security grounded in physical laws rather than computational hardness, where any eavesdropping attempt inevitably disturbs the transmitted quantum states and is therefore detectable. Its foundational principles were established through the prepare-and-measure BB84 protocol [4] and later expanded through entanglement-based approaches such as the E91 protocol [5]. Over time, another QKD scheme was developed besides those prepare-and-measure and entanglement-based protocols, which is Measurement-Device-Independent (MDI-QKD) [23], and this scheme addresses detector vulnerabilities through an

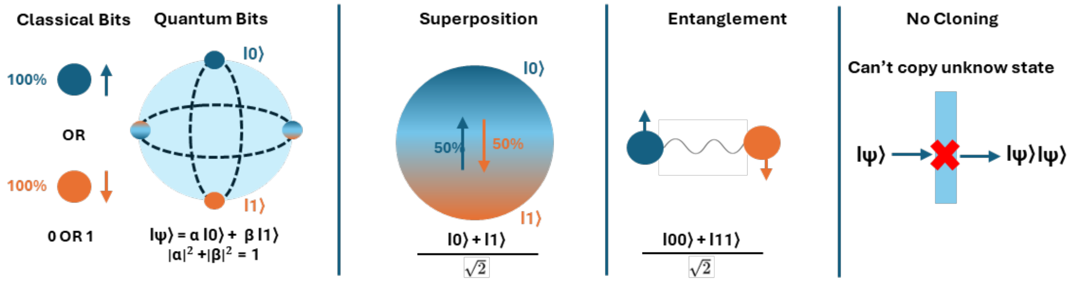

Fig. 3. Quantum mechanics principles

untrusted intermediary.

Although QKD has taken the spotlight and remains the most mature and widely implemented quantum-cryptographic primitive, the broader field also includes other protocols that aim to provide additional security services. Among these, Quantum Digital Signatures (QDS) have emerged as a quantum analogue of classical digital signatures, enabling message authentication and non-repudiation through quantum states [24]. However, despite growing interest in quantum-cryptographic primitives beyond QKD, protocols such as QDS, quantum money, and secure multi-party computation remain largely theoretical. As noted by Broadbent et al. [25], these schemes face significant limitations and challenges, including demanding physical requirements, limited scalability, and unresolved security assumptions. Consequently, this work focuses on QKD-based quantum communication networks, where practical development and standardisation efforts have progressed most significantly.

In real-world network deployments, however, implementing QKD over long distances is non-trivial. Qubits suffer from loss, decoherence, and noise, which limit achievable distances in optical fibre and free-space channels. These limitations motivate the development of quantum repeaters, which generate and swap entanglement across intermediate nodes to extend the communication range. Therefore, understanding the behaviour of repeater-assisted networks becomes essential when characterising next-generation QKD infrastructures and their performance.

B. Non-Cryptographic Networks

Beyond cryptographic applications, quantum networks support a broader family of non-cryptographic communication tasks whose primary objectives are not to guarantee secure message exchange but to enable the manipulation, distribution, and processing of quantum information. These include entanglement distribution, quantum teleportation, blind quantum computation, distributed quantum processing, and high-precision clock synchronisation [26]. Among these protocols, quantum teleportation exemplifies the unique capabilities of quantum mechanics; it transfers an unknown qubit state across space using shared entanglement and classical Bell-measurement outcomes, without physically transmitting the particle [27]. Although not designed as a cryptographic protocol, an adversary cannot reconstruct the state without access to both resources, meaning any security it offers arises from physical principles rather than explicit cryptographic guarantees. Therefore, teleportation has become a critical component in the development of quantum networks [28].

C. Layered Architecture and Cross-Layer Interdependence

Scaling current quantum communication demonstrations into large-scale quantum communication networks requires progress not only in physical hardware, but also in the architectural organisation of the network across multiple layers. As in classical networking, quantum network research increasingly adopts a layered architectural view based on separation of concerns. However, unlike the mature OSI and TCP/IP models, quantum networks do not yet have a universally established standard stack [29]. Instead, the literature and emerging standards propose reference architectures in which physical, link, network, and service-layer functions are separated to manage the unique constraints of quantum information [30]–[33].

In parallel, more application-specific architectural frameworks have been formalised for quantum key distribution networks (QKDNs), where standardisation bodies such as International Telecommunication Union (ITU-T) and European Telecommunications Standards Institute (ETSI) define functional architectures, interfaces, and management entities for key delivery, control, and network interworking [34], [35]. Nevertheless, these frameworks are primarily tailored to QKD services. Since this work aims beyond QKD toward wider quantum networking capabilities such as entanglement distribution, teleportation, and other distributed quantum services, the broader layered architectures proposed in the research literature are adopted here, as illustrated in Table I, to capture the cross-layer dependencies required for future quantum communication networks.

In this layered quantum network architecture, the **physical layer** comprises the underlying quantum channels, such as optical fibres or free-space links, and is responsible for transmitting qubits between interacting quantum devices without performing error correction or entanglement distillation. Above this, the **connectivity layer** addresses imperfections and noise in the physical channels by supporting techniques for long-distance quantum communication, including quantum repeaters, bi- or multipartite entanglement distribution, encoded-state transmission, and percolation-based approaches. Its main role is to establish point-to-point or point-to-multipoint quantum connectivity, but without yet incorporating any notion of service requests.

TABLE I
LAYERED VIEW OF QUANTUM NETWORK STACK

Network Stack	Network Device	Protocols	Functionality
Network Layer	Routers	Routing protocols / path selection	Entanglement manipulation; routing via quantum nodes
Link Layer	Switches	Swapping / purification	Network-state creation; entanglement distillation
Connectivity Layer	Repeaters	QRs protocols / entanglement distribution	Long-distance connectivity; entanglement distribution
Physical Layer	Channels	Entanglement generation and measurement	Qubit transmission; signal conversion

Building on this, the **link layer** defines the boundaries of a quantum network through the establishment of a distributed entangled network state shared among network devices. By utilising the connectivity layer during the dynamic phase, it enables the creation of long-distance entangled states, after which link-layer devices, such as quantum switches, share multipartite entanglement that forms the basis of the network state. Finally, the **network layer** is responsible for generating and manipulating inter-network entanglement to support requests that span multiple quantum networks. At this layer, quantum routers interconnect different entangled regions and coordinate the network-level states required to realise broader graph-state communication across networks.

D. Related Work

Existing review and survey studies have substantially advanced the development of quantum communication networks from several complementary research perspectives. It is evident that efforts provided through these surveys have laid a good foundation for understanding the theoretical and architectural foundations of quantum networking, introducing analytical and performance-evaluation tools for studying entanglement distribution, communication limits, and protocol feasibility across abstract network models [36]. In parallel, research surveys focusing on Quantum Key Distribution (QKD) networks investigated challenges related to secure communication provisioning and operational management, particularly emphasising key generation, distribution, and lifecycle management mechanisms required for scalable quantum-secure infrastructures [37].

Complementing these studies, simulator-oriented reviews examined quantum network modelling platforms and toolkits that enable protocol validation, topology experimentation, and virtual performance assessment. Such works highlighted the importance of simulation environments in exploring quantum network behaviour, while also identifying limitations related to verification and translation towards real-world deployments [38], [39].

More recent software-centric reviews expanded this perspective by analysing quantum network design and operational platforms across infrastructure, logical, and control planes, revealing persistent gaps between theoretical architectural proposals and their realisation within dynamically managed and scalable network environments [40]. Additionally, communication-oriented surveys examining emerging paradigms such as Quantum Secure Direct Communication have explored the evolution of quantum networking protocols and applications towards the broader vision of the quantum internet [41].

Collectively, these studies contribute significantly to the modelling, design, simulation, and secure operation of quantum communication networks. However, existing reviews predominantly examine these developments in isolation, with limited consideration of how they collectively support progression toward digital twin realisation.

Addressing this gap, this SLR provides a structured synthesis of quantum network research from a digital engineering perspective. By integrating advances in modelling, design, and simulation, the review evaluates their combined contribution to digital twin maturity through cross-layer analysis of protocol modelling, optimisation methods, simulation environments, and experimental testbeds. The study further introduces levels of physical–digital coupling, demonstrating that most existing platforms remain at a pre–digital twin stage despite advanced simulation capabilities. Based on this synthesis, the SLR outlines research directions toward digital twins capable of real-time synchronisation and adaptive interaction with dynamic and heterogeneous quantum network behaviours, establishing a conceptual foundation that bridges quantum network engineering and digital engineering paradigms.

E. Research Questions

Building on the related work and the identified gaps, this study defines the following research questions to guide the review:

Q1. *How can a digital framework be designed to enhance and predict the performance of quantum communication networks?*

This question focuses on identifying what a digital framework for quantum communication networks should look like, its structure, components, modelling requirements, and interaction mechanisms. To answer it, the review must determine which architectural features, modelling layers, and functional capabilities are necessary for a digital replica to support performance enhancement and prediction in a quantum context.

Q2. *To what extent do existing experimental setups and testbeds enable cyber-physical coupling to optimise and predict quantum communication network behaviour?*

This question investigates whether experimental setups support any form of interaction or coupling between physical quantum systems and digital models. To answer it, the review must determine if current testbeds demonstrate cyber-physical behaviour, such as feedback, monitoring, synchronisation, or partial mirroring of physical processes in a virtual environment.

Q3. *What performance metrics are most commonly employed in hybrid experiments and emulated quantum communication networks, and how can they inform the requirements of simulation and digital-twin frameworks?*

This question focuses on how performance is assessed in hybrid and experimental quantum network settings in order to inform the requirements of future simulation and digital-twin frameworks. To answer it, the review must identify the metrics most frequently used to evaluate system behaviour and determine how these indicators can be translated into framework requirements for monitoring, validation, optimisation, and prediction.

Q4. *What technical, architectural, and operational limitations currently restrict the digital twinning of quantum communication networks and hinder the integration between virtual and physical components?*

This question seeks to clarify what makes digital twinning difficult in the quantum domain. To answer it, the review must identify whether limitations arise from the physics of quantum systems, from constraints in simulation and modelling tools, or from interoperability challenges that prevent bidirectional data flow and real-time coupling.

These research questions were structured in alignment with the PICOC framework, adapted from the medical research domain, to support the development of precise and comprehensive search strings capable of capturing relevant studies without narrowing the scope excessively. The framework ensures that the research questions can be translated into well-defined, searchable elements suitable for database querying [42].

Several studies have shown that not all systematic literature reviews are truly systematic [43], [44]. A systematic review requires a well-defined sequence of steps and a structured protocol to ensure the quality and reliability of the review, as outlined in the following section, Methodology.

III. METHODOLOGY

This SLR was conducted in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [45]. An overview of the methodology and its sequential stages, aligned with the PRISMA checklist, is presented in Figure 4. The research questions were first structured using the Population, Intervention, Comparison, Outcome, and Context (PICOC) framework [42]. Guided by established query-design principles [46], core concepts were identified and combined into Boolean search strings to maximise sensitivity while reducing irrelevant retrieval.

A. Search Strategy

To apply these strings and capture relevant studies, the search strategy was developed iteratively to address the interdisciplinary nature of quantum communication, where the terminology overlapping with neural networks, quantum computing, and transport networks often leads to ambiguous or noisy results. To avoid both excessive recall and overly restrictive filtering, the search process followed established SLR guidelines [47]–[49].

TABLE II
DATABASES SELECTED FOR THE SYSTEMATIC SEARCH

Database	**Reference**
IEEE Xplore	[50]
Scopus	[51]
ACM Digital Library	[52]

Database Selection: Three major academic databases were selected for their coverage of engineering, computer science, and emerging quantum technologies. These sources are summarised in Table II, and together they provide a broad and complementary coverage suitable for this review.

Formulation & Standardisation: Across these databases, this refinement relied on three main strategies: First, restricting queries to titles, abstracts, and keywords to avoid irrelevant full-text matches; Then, iteratively expanding search terms by examining how early retrieved papers described core concepts; Finally, consistently applying Boolean operators (AND, OR, NOT) while adapting syntax to the requirements of each database.

Scopus allowed direct use of TITLE-ABS-KEY fields, whereas IEEE Xplore and ACM Digital Library required separate searches across titles, abstracts, and keywords that were later combined using OR operators to maintain consistency [52]–[54]. Exact-phrase matching and quotation marks were applied to reduce random broad retrievals. Together, these adaptations ensured a reproducible search that captured the full spectrum of relevant work while remaining robust against interdisciplinary ambiguity, in line with PRISMA-aligned recommendations [55].

Data Filters: The search was conducted sequentially in IEEE Xplore, Scopus, and ACM Digital Library, covering publications from 1984, the year the BB84 quantum key distribution protocol was introduced, through 2025. This timeframe was chosen to capture the full evolution of research in quantum communication and networking. To maintain methodological rigour, only peer-reviewed journals, conference papers, and early access articles were included. Books and course materials were excluded, as they typically lack experimental details.

The final set of search strings and outcomes is summarised in Table III. The number of studies retrieved was recorded, and the year ranges were automatically adjusted by search engines depending on the earliest relevant publication identified.

B. Data Collection

Search results from databases were imported into Rayyan, a well-established tool for systematic reviews that supports PRISMA-aligned screening workflows [56]. Rayyan was selected due to its ability to streamline title–abstract screening, enable one-click duplicate detection, and manage inclusion and exclusion criteria. Its collaborative features allow multiple reviewers to screen independently, label decisions, and resolve conflicts transparently. Using Rayyan reduced manual workload, supported bias minimisation, and ensured a reproducible and efficient screening process for this SLR.

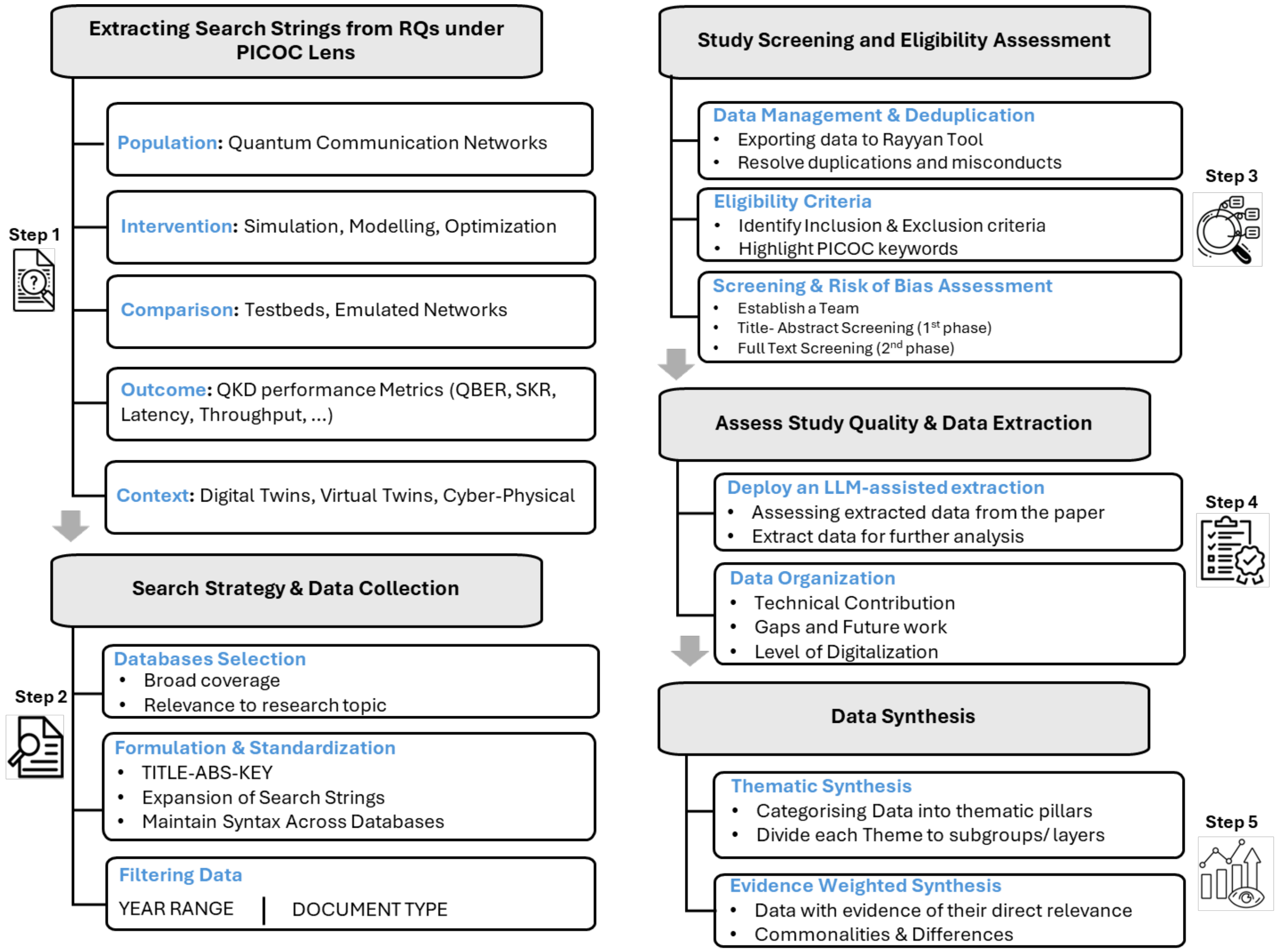

Fig. 4. An Overview of the Research Methodology

C. Study Screening & Eligibility Criteria

Before initiating the screening process, duplicate records were removed. Exact duplicates were automatically detected, while potential overlaps (e.g., identical titles with different author lists, or studies appearing in both conference and journal formats) were examined manually to determine whether they represented true duplicates or distinct contributions.

Following deduplication, inclusion and exclusion criteria were configured in Rayyan to support a consistent and transparent title–abstract screening process, following best-practice guidance [57]. Studies were included if they demonstrated clear relevance to quantum communication networks and provided practical modelling, simulation, architectural, or control-framework contribution, such as DT mechanisms, testbed or hardware–software integration, or simulator-based evaluation using tools like NetSquid, QuNetSim, SeQUeNCe, or QNE-ADK. Papers were excluded if they were outside the scope, such as those focused solely on quantum computing, neural networks, or vehicular networks, or if they lacked implementable models, simulations, or system-level contributions.

Rayyan's keyword highlighting and text-mining features streamlined decision-making, enabling rapid identification of relevant concepts and supporting transparent eligibility decisions. This structured approach reduced screening time, improved consistency across reviewers, and ensured that only studies offering practical, model-driven, or simulation-based insights into quantum communication networks were retained [58].

Screening & Risk of Bias Assessment

Screening proceeded in two phases: an initial title–abstract review, followed by full-text screening for studies meeting the inclusion criteria. To minimise selection bias, the review team and roles were predefined in Rayyan. Two independent reviewers conducted blinded screening, with disagreements resolved by a third reviewer to ensure consistent application of criteria, as recommended by [59]–[61].

D. Study Quality Assessment & Data Extraction

In this SLR, full-text screening, study quality assessment, and data extraction were conducted within a unified workflow to ensure consistency and methodological rigour across the included studies. Study quality assessment placed particular emphasis on the presence of reproducible methods, clearly

TABLE III
KEY STRINGS, NUMBER OF STUDIES, AND YEARS FOR IEEE XPLORE VS. SCOPUS VS. ACM

Key strings	**IEEE Xplore**		**Scopus**		**ACM**	
	No. of Studies	**Years**	**No. of Studies**	**Years**	**No. of Studies**	**Years**
Digital twin AND Quantum communication Network	23	2022–2025	8	2024–2025	2	2022–2025
Digital twin AND QKD Network	9	2023–2025	11	2022–2025	1	2023–2025
Virtual Twin AND Quantum communication Network	4	2022–2025	12	2023–2025	1	2022–2025
Virtual Twin AND QKD Network	1	2025	3	2023–2025	0	–
Framework AND QKD Network	94	2007–2025	232	2006–2025	9	2020–2025
Framework AND "Quantum communication Network"	65	2006–2025	36	2010–2024	26	2004–2025
simulation* AND QKD Network	170	2007–2025	529	2003–2025	10	2020–2025
emulation* AND QKD Network	4	2023–2025	8	2018–2025	0	–
emulation* AND quantum communication network	6	2013–2025	23	1998–2025	1	2020–2025
simulation* AND "quantum communication network"	4	2013–2025	95	2011–2025	4	2020–2025
quantum simulator AND "quantum network"	39	2017–2025	113	2004–2025	22	2004–2025
quantum simulator AND QKD network	13	2016–2025	38	2016–2025	13	2020–2025
testbed AND QKD network	22	2019–2025	53	2003–2025	2	2023–2025
testbed AND "quantum network"	15	2021–2025	54	2003–2025	4	2022–2025
hardware AND "quantum network"	38	2013–2025	197	1997–2025	9	2019–2025
hardware AND QKD network	36	2010–2025	139	2005–2025	2	2020–2025
"SQUANCH" OR "Simulator of Quantum Network Communication" OR "QuNetSim" OR "NetSquid" OR "QDNS" OR "QuISP" OR "SimQN" OR "Cisco Qnetlab" OR "NetQJUL" OR "QuNet" OR "SquidASM" OR "QNE-ADK" OR "ComNetsEmu"	50	2019–2025	95	1984–2025	6	2022–2025

articulated technical contributions, and accessible implementation details, such as simulators, frameworks, or experimental platforms, as these characteristics provide stronger evidence and clearer pathways for future development and system integration. Given the scale of the review and the technical heterogeneity of the literature, Large Language Models (LLMs) were employed to support this process in a manner that enhances efficiency while preserving transparency and reducing the risk of selection bias. The integration of LLMs was motivated by the need to assess studies based on explicit evidence reported in the full text rather than relying solely on abstract-level screening.

Search Automation and LLM-Assisted Screening

Initial full-text screening was performed manually by the first author to establish a reliable baseline for inclusion decisions. Subsequently, LLM-assisted automation was introduced to support large-scale screening and structured data extraction. The LLM-driven workflow was first evaluated using a manually screened subset of studies to verify consistency and reliability, after which the extraction prompts and decision rules were iteratively refined until a stable and repeatable decision-support checklist was achieved. This checklist captured each study's scope, methodological approach, tools or platforms used, reported results, and the nature of the technical contribution, whether simulation, modelling, control-framework development, numerical analysis, or algorithmic optimisation. The incorporation of LLMs substantially reduced screening time while supporting systematic and balanced inclusion across different network layers and digitalisation maturity levels in quantum communication networks. Throughout this process, LLM outputs were used to assist rather than replace author judgment, ensuring that all inclusion and extraction decisions remained evidence-based and aligned with the review protocol.

E. Data Synthesis

In accordance with PRISMA guidelines [62], the data synthesis stage was designed not only to document the current status of the literature but also to organise the extracted evidence in a way that supports structured interpretation and critical analysis. Owing to the diversity of study designs, modelling approaches, tools, and evaluation metrics, a quantitative meta-analysis was not appropriate. Instead, a qualitative synthesis strategy was adopted from narrative synthesis guidance [63], combining thematic synthesis with evidence-weighted synthesis.

Thematic synthesis, referred to here as taxonomy-driven synthesis, was applied to cluster included studies into thematic pillars based on shared concepts, tool usage, and types of technical contribution. At this stage, studies were analysed collectively rather than individually, allowing recurring contribution patterns to be identified and compared in terms of the aspects of quantum networks they address, the methodological approaches they employ, and the key differences in modelling assumptions or optimisation strategies. This pattern-based approach enables comprehensive coverage of a large body of literature while avoiding fragmented, paper-by-paper discussion.

Following thematic synthesis, an evidence-weighted synthesis was conducted to enable a more detailed examination of DT maturity and readiness. While all included studies contribute to quantum network virtualisation to varying extents, detailed critical analysis was concentrated on studies that provide evidence of operational relevance. This combined synthesis approach supports the interpretation of the current state of the field, the identification of key gaps and limitations, and the systematic addressing of the research questions related to the feasibility, constraints, and future development of digital twins for quantum communication networks.

IV. RESULTS

Based on the applied search strategy and review protocol, this section reports the key findings of the SLR, highlighting the identified thematic pillars, their respective contributions, and their level of readiness for integration within a digital twin framework for quantum communication networks.

A. Study Selection and Screening Outcomes

Figure 5a shows the progressive reduction of the literature corpus across successive review stages, highlighting a key outcome of this SLR. Despite a broad initial body of quantum communication and QKD literature, only a small subset satisfies the relevance, quality, and digitalisation requirements needed for DT-oriented analysis.

Figure 5b,c synthesises two key outcomes of this SLR: the dominant reasons for study exclusion and the digital-maturity profile of the retained literature. Together, these distributions provide insight into both the limitations of the existing body of work and the extent to which current studies support DT-oriented modelling of quantum communication networks.

B. Data Interpretation and Study Classification

The exclusion distribution reveals structural characteristics of the literature rather than artefacts of the screening process. The most frequent exclusion reason, insufficient methodological detail (25%), indicates that many studies remain conceptual or descriptive, often lacking reproducible workflows, explicit algorithms, or clearly defined simulation pipelines. A further 19.5% of excluded studies did not employ any software or digital environment, relying instead on analytical or numerical evaluations that cannot support system-level digital representation or extensibility.

Exclusions due to lack of access (15.8%) reflect practical constraints on evidence assessment. A further 14.3% of studies were excluded because the extracted data did not evidence physical fidelity of the QKD process e.g., no reporting of Secret Key Rate (SKR), Quantum Bit Error Rate (QBER), or finite-key effects, so their contributions were not directly usable for assessing QKD and quantum process behaviour and were instead focused on other performance objectives (e.g., power, coverage, or generic communication metrics). In a smaller subset of cases, exclusions were driven by satellite-oriented optimisation studies that prioritised orbital height, line-of-sight angle, and positioning parameters; these works do not align with the SLR's aim of a digital replica of the quantum networks. Smaller proportions of exclusions were associated with pure hardware-focused studies, non-English publications, or works falling outside the defined scope. Collectively, these results highlight a persistent gap between theoretical or device-level research and system-level digitalisation suitable for digital twin development.

In contrast, the inclusion rate distribution provides an empirical characterisation of the digital maturity of the retained studies. Based on the extracted evidence, including simulation type, coupling mechanisms, and interaction with physical systems, the included literature was classified into three maturity levels reflecting increasing degrees of digital twins and virtual–physical integration, as shown in Figure 6. Low-level, representing 35% of the included studies, corresponds to digital models that provide static or time-evolving virtual representations primarily used for conceptual design and system understanding. These studies remain decoupled from physical assets and serve as baseline digital artefacts, consistent with established digital twin taxonomies [64].

Medium-level, accounting for 24% of the studies, aligns with the notion of digital shadows, in which one-way data flow from physical or experimental sources is used to update the virtual representation. This level enables monitoring, diagnostics, and retrospective analysis, but does not support closed-loop control or bidirectional interaction [65].

High-level, comprising 41% of the retained studies, reflects contributions approaching digital twin behaviour. These studies typically employ dynamic or co-simulation frameworks in which live or near-real-time data synchronises the virtual representation, and model-derived insights can inform system configuration or operational decisions, supporting runtime adaptation and decision-making [66]. Importantly, the alignment between observed digitalisation levels and established digital twin concepts is used in this study as a maturity indicator rather than as evidence of fully realised digital models, digital shadows, or digital twins.

The analysed literature is organised into three principal pillars corresponding to distinct forms of digital representation in quantum network research: digital models, digital shadows, and digital twins. This structuring reflects how existing studies represent quantum network behaviour either at individual network layers or through cross-layer integration, as well as the degree of interaction established between virtual environments and physical or experimental systems. Within each pillar, studies are further categorised into recurring thematic groups, enabling a taxonomy-driven synthesis of modelling approaches and technical contributions. The following sections examine these pillars and their associated themes to clarify how current developments collectively advance the progression toward digital twin realisation in QCN.

V. TAXONOMY-DRIVEN SYNTHESIS

The literature is synthesised through a thematic lens categorised into three primary pillars: Digital Models, Digital Shadows, and Digital Twins. Rather than providing an isolated summary of individual studies, this section evaluates how collective bodies of work align with these pillars to demonstrate their contributions and inherent limitations. As illustrated in the taxonomy provided in Figure 7, the reviewed studies are mapped across three ascending levels of digitalisation and physical-system coupling.

Digital Models capture idealised, assumption-driven representations primarily used for theoretical analysis and offline simulation. Digital Shadows introduce one-way data flows from physical or emulated systems, enabling monitoring and updated performance estimation under evolving operational

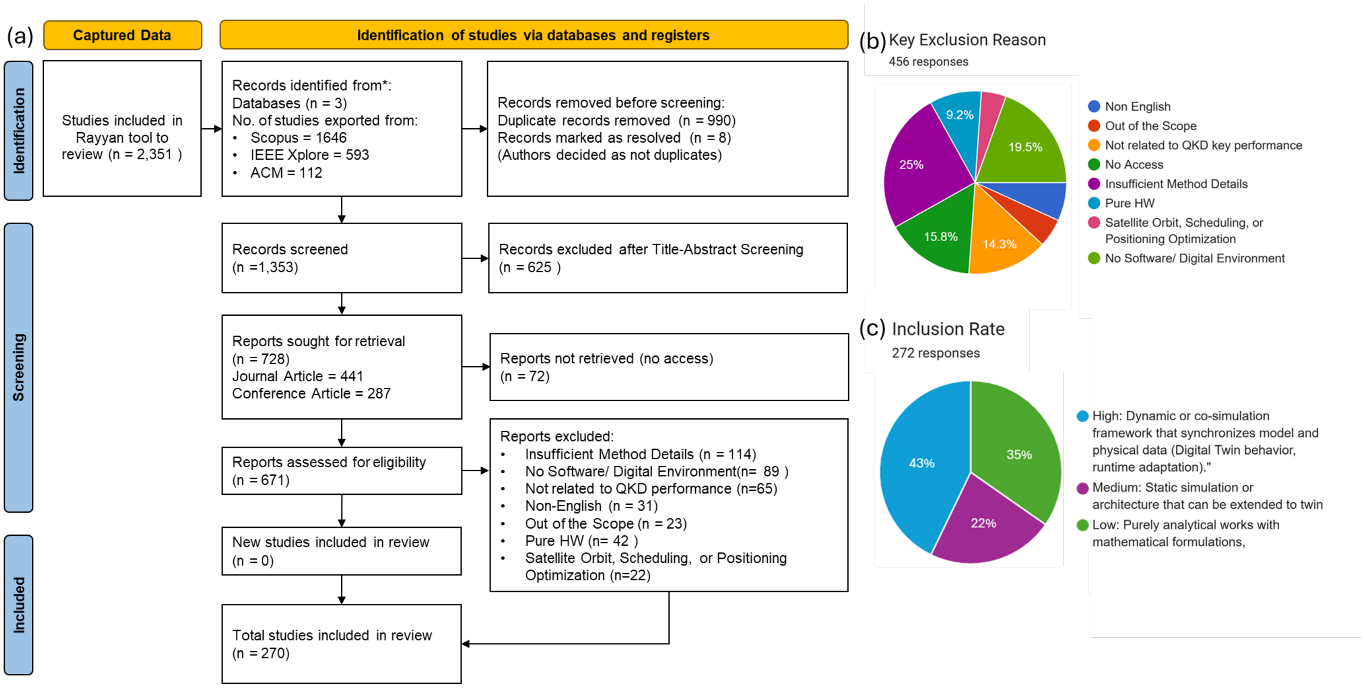

Fig. 5. PRISMA-guided study selection and screening results. (a) Flow diagram illustrating records retrieved from databases, exclusions with reasons, and the final number of included studies. (b) Distribution of key exclusion reasons during full-text assessment. (c) Inclusion rate classification showing the proportion of studies aligned with DT readiness levels

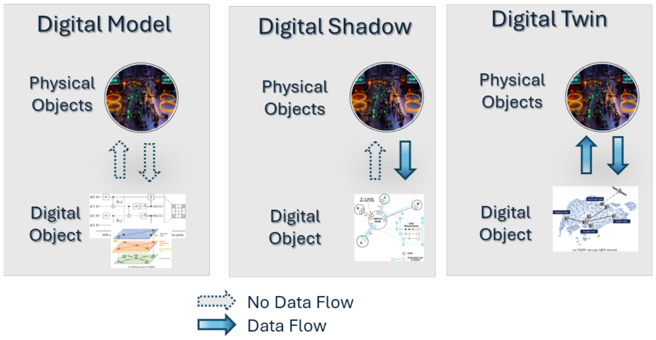

Fig. 6. Digital-Physical Integrations levels

conditions. Studies categorised under the Digital Twin pillar, while not yet constituting fully realised digital twins in the strict sense, exhibit a higher degree of architectural readiness through their support for interoperability, modular integration, and system-level data exchange with external simulators, controllers, or experimental testbeds. Rather than evaluating individual studies in isolation, this structured grouping highlights how their combined contributions progressively advance the digital representation of quantum communication networks.

A. Digital Model

From a digital model perspective, the studies in this pillar collectively operate at the level of design-time representation and exploration. Broadly, they can be divided into two forms of modelling. One group adopts *analytical models*, in which quantum networks are represented through numerical abstractions, optimisation-based workflows, or simulation environments to investigate behaviour, performance, and design trade-offs. The other adopts *descriptive models*, in which the focus is on formally capturing network architectures, functional structures, interfaces, and design variants without directly executing or simulating the network itself. Although different in form, both types remain at the level of offline without continuous, or bi-directional coupling to a physical system. These studies therefore align with the Digital Model maturity level.

Within this pillar, the analytical models can be further grouped into three recurring themes, which reflect the dominant approaches used to analyse and explore quantum networks. Descriptive modelling studies, while fewer, complement these by providing system-level representations that help organise, and evolve network architectures in a traceable manner. Rather than viewing these studies as isolated contributions, the synthesis in this review highlights how they form a set of complementary modelling capabilities that scaffold different layers of a future quantum-network digital twin.

1) Protocol-Level models derive and analyse security and performance metrics in order to assess how protocol behaviour changes under different parameters, channel conditions, and implementation assumptions.
2) Algorithmic and network-control models represent optimisation or control problems to evaluate how different policies affect network performance under varying traffic, topology, and channel conditions.
3) Simulators and digital-platform developments provide executable environments in which network architectures, protocols, and control strategies can be instan-

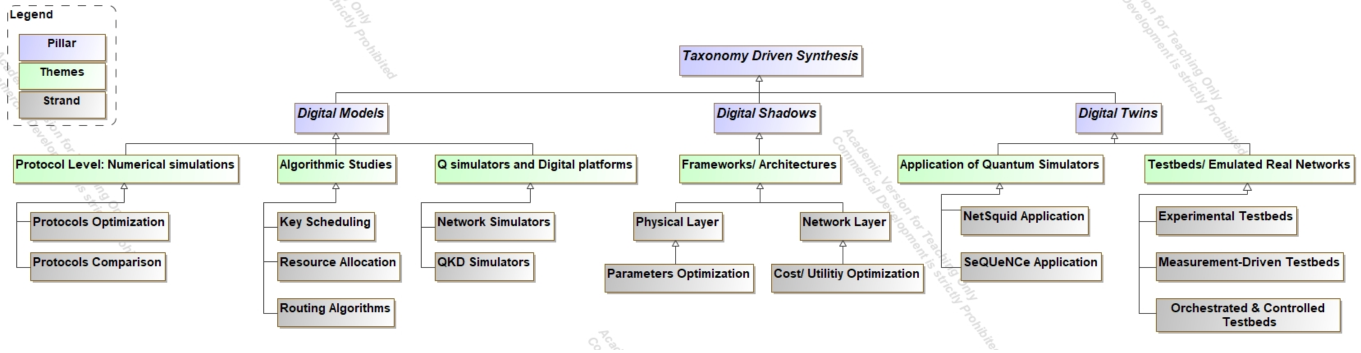

Fig. 7. Thematic Pillars from the Literature

tiated, combined, and systematically evaluated through scenario-based experimentation.

This layered progression is key to understanding both the current capability of the field and its readiness to support future digital-twin implementations.

Protocols-Level Performance:

This theme comprises studies that investigate quantum communication protocols through analytical and simulation-based representations to optimise protocol performance or evaluate protocol suitability prior to physical deployment. Within the Digital Model pillar, protocol behaviour is analysed with different operational constraints.

The first strand focuses on protocol-level optimisation targeting performance metrics such as SKR, robustness to noise, and implementation feasibility. Machine-learning-based optimisation is applied to tune modulation parameters in continuous-variable QKD, improving finite-size SKR performance [67]. Analytical protocol redesign, eliminating pilot-reference signalling, enhances key-generation efficiency while reducing implementation overhead [68]. Numerical modelling of modulation noise in multi-carrier CV-QKD identifies optimal subcarrier configurations under practical transmitter constraints [69]. Device-aware optimisation incorporating detector afterpulsing demonstrates performance recovery through advantage distillation [70], while architectural simulation of sending-or-not-sending twin-field QKD enables competitive SKR–distance operation with untrusted sources [71].

Security-oriented simulations further optimise protocol resilience under noisy or adversarial conditions by analysing depolarising-channel effects and adaptive state-preparation strategies that reduce QBER and eavesdropping success probability [72], [73]. CV-QKD integration within optical infrastructures is simulated to optimise wavelength allocation and coexistence conditions for network-level scenarios [74].

The second strand addresses comparative evaluation across alternative protocols and communication architectures. Simulation-based security comparisons assess robustness among major QKD protocols under implementation and attack scenarios [75], [76]. Post-processing comparison shows that polynomial-interpolation reconciliation maintains higher secret key fractions than Cascade under increasing QBER conditions [77]. Protocol suitability across deployment environments is further examined through comparison of multi-photon and conventional QKD schemes across network topologies, demonstrating scalability and transmission trade-offs [78], [79]. Beyond key distribution, numerical evaluation of Quantum Repeater (QR) communication protocols shows that entanglement-distribution performance strongly depends on protocol selection under hardware constraints [80].

Overall, this theme supports a coherent research direction in which QR and QKD protocols are investigated through analytical and simulation-based digital models, supporting systematic exploration of performance, security resilience, and deployment trade-offs prior to, or in parallel with, physical implementation.

Algorithmic Studies:

The second theme comprises algorithmic studies, forming the second-largest cluster of included works. Here, QKD and entanglement-based networks are modelled through algorithmic abstractions of routing, scheduling, key management, resource allocation, or protocol control, and evaluated in simulation under varying traffic, topology, and channel conditions. These studies are classified as digital models because quantum- layer behaviour is encoded as parameters (e.g., SKR, success probability, error rates) within optimisation or simulation workflows rather than implemented as full physical systems. In several cases, these parameters are calibrated using testbed topologies or measured link data, meaning that, when externally fed by operational data, such models begin to demonstrate shadow-like behaviour at the network-management layer.

As summarised in Table IV, the literature clusters around recurring optimisation targets. A major strand focuses on routing and path selection for trusted and partially trusted QKD networks, as well as entanglement-routing schemes that mitigate bottlenecks, improve fairness, or support mobility and multi-tree routing. A second strand addresses key-management and provisioning, where keys are treated as constrained resources and allocated via fairness-, priority-, or trust-aware scheduling, forwarding, and multi-constraint optimisation. Complementary work targets resource allocation and routing/wavelength assignment in QKD-secured optical networks, including noise-aware formulations, virtual-network embedding, and learning-based policies (e.g., DRL, DQN, GAT). Further studies examine entanglement distribution and connectivity optimisation (percolation, fairness, swapping feasibility) and protocol/parameter optimisation at the implementation layer, which act as design-time digital models rather than operational controllers.

A smaller subset of works performs testbed-driven orchestration and service abstraction, where realistic infrastructures are used as constraints for orchestration and assignment policies, placing these closest to shadow-like operation. Likewise, structural and analytical models provide design-time indicators of robustness and feasibility that inform, rather than replace, optimisation-based control. Overall, this theme shows that algorithmic simulation and optimisation are the dominant approaches for analysing and configuring QKD-enabled networks, and constitute a natural bridge toward digital-shadow capability when coupled with live network data.

Quantum Network Simulators & Digital Platforms:

This theme comprises studies that develop quantum simulators and digital experimentation platforms for QKD and quantum communication networks. Early consolidation of this research area was provided through a comparative survey of QKD protocols and simulation tools, evaluating platforms in terms of availability, implementation language, supported protocols, and validation approaches [39]. While this review captured the state of simulator maturity around 2021, the landscape has since evolved considerably. A broader and more specialised ecosystem has emerged, encompassing full-stack quantum network simulators, protocol- and application-level environments, QKD service and infrastructure platforms, channel- and fidelity-oriented tools, as well as meta-frameworks supporting programmability, orchestration, and hardware-assisted experimentation.

To reflect this progression, the simulators and platforms identified in this review are consolidated in Table V. The table highlights the modelling scope, network-layer coverage, intended application, performance outputs, and validation approaches of each platform, clarifying the functional role of these digital environments in quantum network design and evaluation. The platforms are organised according to increasing abstraction and system relevance, beginning with system-level simulators, followed by layered abstraction environments, and concluding with hardware-control platforms. This ordering illustrates how existing tools address different layers of the quantum networking stack and collectively enable architecture exploration, performance assessment, and pre-deployment experimentation.

Descriptive Models

Beyond analytical and simulation-based representations, a smaller set of studies within the Digital Model pillar adopts a descriptive modelling approach. Instead of numerically predicting behaviour, these studies focus on representing system structure, interfaces, architecture, and design alternatives in a reusable and traceable models. Their importance lies in providing higher-level abstractions that help manage design complexity, support interdisciplinary communication, and formalise architectures before implementation. Within this strand, UML-based modelling has been used for hybrid classical–quantum systems [144], SysML with variability modelling has been applied to evolving QKD network architectures and stakeholder-driven architectural exploration [145], and a dedicated quantum architecture description language has been proposed to connect architectural specification with implementation-oriented development [146]. Together, these studies indicate that descriptive modelling is becoming a relevant complement to simulation in the quantum domain, although it remains dispersed across different modelling traditions and levels of abstraction.

B. Digital Shadow

From a digital-shadow perspective, the included studies collectively demonstrate how realistic physical parameters, operational constraints, and empirical performance behaviour are embedded into simulators, optimisation frameworks, SDN controllers, and testbeds to support configuration, planning, and evaluation of QKD and quantum networks. The coupling remains one-way: physical-layer characteristics (loss, noise, QBER, fidelity, SKR, cost, device constraints, memory lifetime, etc.) are fed into digital environments. In this sense, the literature provides one-directional coupling that is practically valuable for proactive provisioning, survivability assessment, and service-level planning while also exposing the gap to a full Digital Twin. Conceptually, the papers are distributed across two complementary layers of this pillar: (i) network-level orchestration, control, and cost/utility optimisation, and (ii) physical-layer / channel-parameter calibration and optimisation.

Network Layer Identification:

A large subset of network-system studies realises a Digital Shadow by modelling network architectures, control planes, and orchestration mechanisms to evaluate how quantum-secured services behave under operational conditions. These works typically assume that network state information, such as topology, link availability, traffic demand, device capabilities, and policy constraints, can be captured and fed one-way into a digital representation, including analytical models, simulation frameworks, or optimisation engines. The resulting digital artefacts support planning, performance evaluation, and operational decision-making, while deliberately avoiding closed-loop actuation or continuous synchronisation with the physical network, as shown in Figure 8.

This architectural strand is most clearly manifested in Software-Defined Networking (SDN) enabled QKD service control and orchestration, where digital controllers translate network context into provisioning, switching, and management decisions. Foundational SDN–QKD integration is demonstrated through (Key on Demand)KoD and related SDN-based QKD service designs, which explicitly link key availability and provisioning workflows to software-defined optical network control. This line of work establishes a clear Digital Shadow mechanism in which operational key and network states are mirrored digitally to guide service-level decisions [147]. The

TABLE IV
PATTERNS IN THE ALGORITHMIC DIGITAL-MODEL SUBGROUP

Optimisation target	**Core optimisation logic**	**Algorithms used**	**Ref**
QKD routing and path selection (trusted / partially-trusted relays)	Determines which network path should carry keys or entanglement by modelling the network as a graph and selecting routes that balance key rate, trust, load, and blocking behaviour under simulated traffic.	Load-balanced routing; multi-path / multi-segment routing; time-driven routing evaluation	[81]–[86]
Metaheuristic routing (dynamic or trust-aware environments)	Treats routing as a multi-objective search problem, where candidate paths are iteratively refined using heuristic exploration to balance key rate, delay, and congestion.	Simulated Fish Swarm (SFS); Ant Colony Optimisation (ACO)	[87], [88]
Learning-based routing and resource assignment (QKD optical / hybrid networks)	Models routing and resource allocation as a sequential decision problem, training RL/DRL/DQN/GAT policies to minimise blocking and improve utilisation in optical and hybrid QKD networks.	Deep Reinforcement Learning (DRL/RL); Deep Q-Network (DQN); Graph Attention Network (GAT)	[89]–[91]
Key scheduling and dynamic assignment (fairness / priority / access-network slots)	Allocates limited key resources to users or services subject to freshness and availability constraints, with algorithms targeting fairness, service priority, or delay reduction and evaluated via blocking and completion metrics.	Quantum Generalised Processor Sharing (Q-GPS); priority-order assignment; controller-driven dynamic assignment	[92]–[94]
Key provisioning and key forwarding (partially-trusted relay environments)	Optimises how keys are provisioned and forwarded across multiple relay paths under trust and freshness constraints, using multi-path and collaborative provisioning to maximise success probability and utilisation.	Multi-Path Quasi-Real-Time Key Provisioning; collaborative provisioning; key-forwarding optimisation	[95]–[98]
Dynamic key-management optimisation (multi-constraint coordination)	Jointly optimises key generation, storage, and consumption as a coupled multi-constraint problem, using Lagrangian relaxation to coordinate key-lifecycle processes across the network.	Learning Reinforcement (LR)	[99]
Optical resource allocation and RWA / VONE (with QKD or CV-QKD constraints)	Jointly optimises routing and spectrum (wavelength) assignment while enforcing SKR feasibility, trading off blocking, throughput, spectrum use, and key availability in WDM/EON settings.	Routing and Wavelength Assignment (RWA); Virtual Optical Network Embedding (VONE); Elastic Optical Network; Mixed-Integer Linear Programming (ILP/ MILP)	[85], [100]–[103]
Entanglement routing, allocation fairness, and connectivity optimisation	Treats entanglement as a probabilistic resource with memory limits and optimises where it is routed, stored, or allocated to balance throughput, fairness, and bottleneck mitigation across users and topologies.	Destination-Oriented Directed Acyclic Graph (DODAG); SwappingBoost; Fair-EAS; entanglement percolation	[104]–[108]
Entanglement-swapping with wavelength / survivability constraints	Co-designs swapping feasibility with wavelength assignment to improve robustness and survivability.	Entanglement-swapping RWA with co-path selection	[109]
Protocol / configuration optimisation (parameter-level digital models)	Protocol parameters (decoy settings, grouping, coding, modulation) numerically optimised to improve SKR/QBER under realistic channels—design-time optimisation rather than live control.	Genetic Algorithm (GA); MDI-QKD tuning; Polar + Low-Density Parity-Check (LDPC) reconciliation	[110]–[115]
Testbed-driven orchestration and service abstraction (*algorithm-informed, shadow-leaning*)	Realistic topologies, devices, and services used as constraints for orchestration and assignment policies; models become shadow-like when driven by measured link data.	Testbed / inter-site orchestration policies; quantum VLAN-style service abstraction	[116], [117]

same architectural principle is extended through multi-tenant provisioning [148] and secret-key assignment mechanisms [149], [150], where an SDN controller manages tenant lifecycles and allocates key resources under shared-network constraints, enabling service-like operation through programmable abstractions rather than physical reconfiguration.

Complementary contributions further formalise this approach by introducing software-defined quantum network switching, which abstracts quantum switching and control functions under programmable control assumptions, and by positioning SDN as the coordination layer for integrated QKD and classical optical transport [151], [152]. Together, these studies reinforce the Digital Shadow concept as a network-context-to-control decision pipeline, rather than a bidirectional or self-updating twin. A similar one-way mapping is also observed in wireless settings [153], where SDN is proposed as an enabling layer for managing QKD services based on operational service conditions, again without implying continuous co-evolution between digital and physical systems.

Building on these architectural foundations, a second and often dominant stream within this pattern formulates the network as an optimisation-driven shadow, where operational constraints become inputs, and routing or resource allocation decisions become outputs. In this stream, the digital model

TABLE V
SYSTEMATIC COMPARISON OF QUANTUM NETWORK SIMULATORS, PLATFORMS, AND FRAMEWORKS

Simulator / Platform	Modeling Scope	Network Layer Coverage	Purpose	Outputs & Metrics	Validation Method	Language & Access
NetSquid [118]–[122]	Discrete-event platform for simulating all aspects of quantum networks and modular quantum computing	Physical layer and control plane up to the application level	Models hardware non-idealities, including time-dependent noise, decoherence, fibre loss, and gate errors	Fidelity, key and error rates, throughput, latency, duration	Experimental (NV centres) and theoretical validation	Python/C++; available upon request
SeQUeNCe [123]–[127]	Discrete-event simulator for full-stack photonic quantum networks with picosecond timing precision	Hardware, entanglement, resource, network, and application layers	Experiment planning, validation, and protocol design via photon-level and control-message modelling	Fidelity, resource distribution time, error rates	Experimental (metropolitan QKD and teleportation)	Python; open-source on GitHub
SeQUeNCe II [126], [127]	Parallel extension of SeQUeNCe enabling large-scale network simulation with up to 25× speedup	Hardware, entanglement, resource, network, and application layers	Introduces a Quantum State Manager (QSM) to manage shared quantum information across logical processes	Fidelity, resource distribution time, error rates	Performance comparison against sequential simulators	Python; open-source on GitHub
QuISP [128]	Large-scale quantum internet simulator for heterogeneous repeater networks	Physical realism via connection architecture and RuleSet protocols	Uses error-basis tracking instead of full state vectors for scalability	Fidelity, connection request completion time	Cross-validated with SeQUeNCe and analytical models	C++ (OMNeT++); open-source
SimQN [129]	Discrete-event network simulation platform for quantum networks	System-level / network layer	Enables large-scale investigation of QKD, entanglement distribution, and routing protocols	Average key utilisation, throughput, delay	Validated via routing algorithm performance	Python; open-source
qns-3 [130]	Quantum network simulator integrated with ns-3 using tensor-network techniques	Quantum physical entity, link, and application layers	Efficient protocol simulation via control-flow adaptation without Monte Carlo sampling	Runtime, peak memory usage, success probability	Compared against NetSquid results	C++ (ns-3); open-source
QuNetSim [131]	High-level framework for developing and testing quantum networking protocols	Network and application layers	Supports real-time simulation and hardware-in-the-loop experimentation	Protocol correctness, timing accuracy, throughput	Cross-validated with other simulators	Python; MIT license
SimulaQron [132]	Simulator for quantum internet application development without hardware access	Application layer via Classical–Quantum Combiner (CQC) abstraction	Acts as a hardware stand-in enabling portable application development	Application behaviour, CQC instruction outcomes	Software-focused validation	Python; open-source
SPARQ [133]	Extension of QuNetSim for Space–Air–Ground quantum networks	Integrated space, air, and ground network layers	Models mobility and heterogeneity via integration with Ansys STK	Fidelity, teleportation success, routing performance	Comparative validation with physical channel models	Python; open-source
QKDNetSim / QKDNetSim+ [37], [134], [135]	NS-3-based simulator for QKD network operation and management	Key management, control, and application layers	Evaluation of QKD resource management and Quality of Service (QoS) strategies	Key pool state, buffer utilisation, QoS indicators	Validated against experimental network deployments	C++ (ns-3); open-source; ETSI-compatible
SQUANCH [136]–[138]	Parallel agent-based simulator for noisy quantum and classical channels	Physical and link layers	Models realistic channel noise and distributed execution	QBER, secret key rate, latency, memory usage	Benchmarked against field-deployed QKD experiments	Python; open-source
QuanTACT [136], [139]	Extension of SQUANCH for tactical quantum networks	Physical layer and constrained edge resources	Integration with EMANE for field-deployed QKD scenarios	QBER, secret key rate, latency, memory usage	Experimental benchmarking	Python; specialised military framework
NuQKD [140]	QKD feasibility simulator for critical infrastructure environments	Physical channel and post-processing layers	Assesses real-time performance under equipment imperfections	Sifted key length, QBER, communication time	Benchmarked against experimental data	Python; modular research code
EnQuad [39]	High-speed BB84 simulator optimised for photon-intensive regimes	Protocol-level components	Accelerated simulation with integrated security testing	Secret key rate, execution time	Compared with QKD simulator benchmarks	MATLAB; publicly available
QFide [28]	Teleportation fidelity simulator built on Qiskit	Circuit and noise modelling layer	Evaluates fidelity degradation due to noise and loss	Fidelity deviation, BSM probabilities	Validated using experimental teleportation results	Python (Qiskit); open-source
QuIP [141]	Protocol prototyping framework using P4 abstractions	Data plane (link and network layers)	Decouples protocol logic from simulator implementations	V1Quantum architecture behaviour	Validated via NetSquid integration	P4 / Python; open-source
QNDK [142]	Cloud-based simulation development framework	Multi-layer via integrated backends	GUI-driven orchestration of multiple simulators	Unified metrics from integrated engines	Relies on backend simulator validation	Web-based; open-source
PnPQ [143]	Hardware control framework for automated quantum testbeds	Low-level hardware and driver layer	Abstracts device-specific experimental protocols	Coincidence counts, tomography data	Validated via physical testbed deployment	Python; open-source

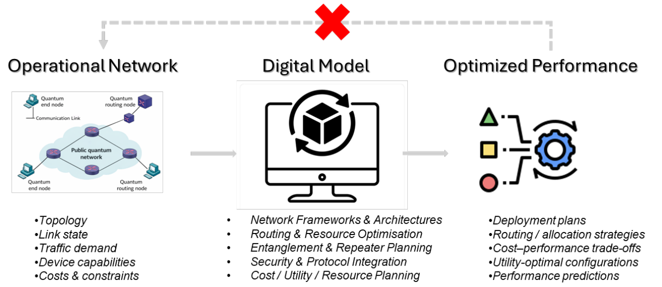

Fig. 8. Conceptual representation of network-level Digital Shadow implementations in quantum communication networks

computes optimised routing or allocation plans under explicit service objectives, such as improved key provisioning, reduced blocking probability, priority-aware service differentiation, or higher utility under security constraints, and evaluates their performance, thereby acting as a decision-support layer for provisioning and traffic engineering rather than a real-time control surrogate [154]–[156]. Application-aware and service-driven routing exemplify this behaviour through priority-ranked routing strategies and topology abstraction routing for secret-key provisioning, which treat application requirements and heterogeneous infrastructures as exogenous inputs to the digital routing logic [157], [158].

The same pattern appears in QKD-enabled optical infrastructures where key resources are allocated under explicit security-level constraints, as well as in high-capacity optical networking contexts such as space-division multiplexed datacenter networks secured by QKD [159], [160]. At a broader system-of-systems scale, cloud–edge collaboration for QKD-secured datacenter networks similarly employs digital optimisation models to map distributed demands and infrastructure constraints into allocation decisions and performance outcomes, maintaining a one-way "network state → optimisation → plan" relationship [161]. Additional network structuring approaches, such as cluster-based QKD with dynamic node selection, follow the same logic by representing operationally relevant constraints digitally and using them to compute improved system behaviour [162].

Beyond key provisioning and traffic engineering, the Digital Shadow paradigm also extends to entanglement distribution and repeater-network operation, forming a third stream within the network-system theme. In this case, the inputs to the digital shadow include network connectivity, candidate resource placement options, user demands, fidelity or quality constraints, and protocol parameters, while the outputs are path selection, resource placement, and protocol configurations that maximise entanglement distribution rate and/or fidelity. Concurrent entanglement routing formalises routing behaviour under quantum constraints [163], while resource placement optimisation explicitly determines where quantum resources should be deployed to maximise end-to-end performance [164]. Optimisation under fidelity requirements is likewise addressed in studies that allocate or share entanglement resources while meeting quality thresholds [165].

This perspective naturally connects to optimisation-based tuning of repeater protocols, such as Bayesian optimisation approaches, which use measurable or assumed network and device parameters to compute improved protocol configurations without closing the loop to physical actuation [166]. At larger spatial scales, satellite-assisted entanglement distribution extends the same principle to global architectures, where orbital connectivity and link availability are digitally represented to support network design and evaluation. [167] Similarly, multi-user quantum network security and association problems, including matching-based association and multi-user secure communication frameworks, model user demands and network constraints digitally to compute operational policies, again without implying continuous bidirectional synchronisation [168], [169].

Furthermore, several system-level studies reinforce the Digital Shadow paradigm by providing enabling mechanisms for secure operation and protocol–network integration. Modelling and simulation frameworks, together with key management system validation, support deployment-based evaluation [170], [171]. Complementary protocol and security contributions, including physical-layer authentication and integrated QKD protocol designs, encode deployment, and relevant assumptions into digital performance assessments that can inform higher-layer network decisions [172]–[174].

Finally, a further stream of network-level Digital Shadow studies focuses on cost-, utility-, and resource-aware network planning, where economic and infrastructure constraints are digitally abstracted to support deployment and evolution decisions. These works ingest information such as device and link costs, relay capabilities, protocol characteristics, and demand profiles, and formulate optimisation models to minimise deployment cost or maximise network utility under security and performance constraints. This approach is evident in topological and planning optimisation of hybrid QKD networks [175], [176], utility-driven planning of quantum repeater and entanglement-enabled networks [177], and cost-aware resource pooling and hybrid relay architectures [178], [179]. Cost-effective protocol upgrading further extends this Digital Shadow stream by digitally evaluating transition strategies and associated resource costs in metropolitan quantum optical networks [180]. Collectively, these studies establish economic and utility optimisation as a distinct network-system Digital Shadow, supporting strategic planning rather than closed-loop control.

Physical Layer Identification:

At the physical layer, Digital Shadow implementations differ fundamentally from their network-level counterparts by adopting a parameter-centric and component-focused abstraction scope. Rather than integrating multiple network functions, physical-layer studies typically isolate a single dominant element—such as the quantum channel, transmission medium, device behaviour, or protocol parameters—and feed its measurable or assumed characteristics one way into analytical or simulation-based models. These Digital Shadows are used to predict performance limits or to identify parameter settings that enhance key performance indicators, including SKR, QBER, fidelity, and transmission reach, without continuous synchronisation or closed-loop actuation, as shown in Figure 9.

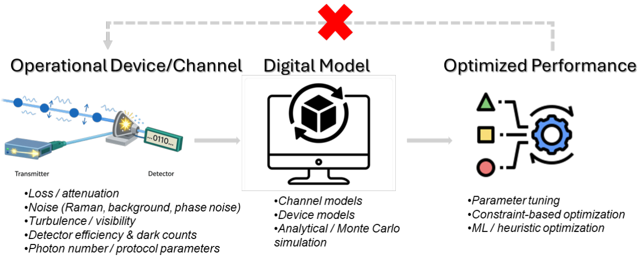

Fig. 9. Conceptual Representation of Physical Layer Digital Shadow

A first and dominant sub-pattern focuses on impairment-aware channel and device modelling, where physical effects such as fibre attenuation, Raman noise, phase instability, detector imperfections, multicore crosstalk, and protocol-specific vulnerabilities are digitally represented to forecast performance under realistic deployment conditions [181]–[185]. This predictive Digital Shadow is further extended to free-space and satellite-based quantum communications, where atmospheric turbulence, visibility constraints, pointing errors, and orbital geometry are modelled to evaluate link feasibility and operational margins at regional and global scales [186]–[190].

A second sub-pattern emphasises parameter optimisation within the physical layer, where controllable system variables, such as photon number, decoy-state settings, reconciliation efficiency, wavelength/core allocation, or switching strategies, are treated as optimisation variables rather than fixed inputs. In these studies, the Digital Shadow computes optimal operating points that improve robustness or throughput under fixed physical constraints, thereby supporting performance enhancement rather than real-time control [191]–[195]. Complementary simulation-driven and comparative studies further support this paradigm by providing exploratory Digital Shadows that allow protocol comparison, hybrid deployment analysis, and cross-technology evaluation prior to physical implementation [196], [197].

Collectively, these studies demonstrate that Digital Shadow implementations in quantum communication networks have matured across both the network and physical layers, albeit with distinct abstraction scopes and objectives.

C. Digital Twins

This section focuses on Digital Twin maturity from a thematic perspective. Rather than analysing explicit Digital Twin claims, it examines classes of approaches that demonstrate technical readiness to support Digital Twin realisation. Two dominant themes emerge: (i) the application of quantum network simulators, and (ii) virtual testbeds and emulated networks. While these approaches do not constitute full Digital Twins, they provide essential capabilities, such as realistic modelling, parameter calibration, and system-level integration, that enable future coupling between software models and physical quantum network infrastructure.

Testbeds & Emulated Networks:

This theme examines experimental quantum-network testbeds in which physical quantum communication systems operate together with monitoring, control, or digital service platforms. From a Digital Twin perspective, these studies demonstrate how physical quantum infrastructure becomes observable, measurable, and increasingly controllable through digital environments.

An initial group of studies develops hybrid quantum–classical testbeds to validate network feasibility and device interoperability under realistic conditions. These platforms combine quantum links with conventional networking and control planes to perform coexistence experiments, protocol validation, and performance measurements [198], [199]. Channel and environmental emulation testbeds further reproduce propagation effects such as atmospheric turbulence to generate calibrated physical data for system evaluation [200]. In these implementations, the digital environment primarily supports experimentation through measurement acquisition and offline analysis, rather than operational control, real-time synchronisation, or continuously mirroring the physical system.

A second group introduces measurement-driven operation, where running QKD networks continuously provides operational data to digital monitoring platforms. Reconfigurable and federated QKD testbeds enable multi-node experimentation while producing live performance measurements used to validate network behaviour [201], [202]. Synchronisation mechanisms and environmental field experiments support alignment between physical network states and monitoring platforms [203], [204]. These studies establish persistent physical-to-digital data flow, although configuration, optimisation and decision-making remain externally managed.

Further integration is achieved when testbeds are embedded within network-management or security platforms. Hybrid QKD–Post Quantum Cryptography (PQC) deployments and quantum-safe system integrations directly link physical key generation to operational digital services, allowing encryption and network functions to depend on measured quantum outputs [205], [206]. Metropolitan QKD infrastructures extend this capability through automated collection of service-level metrics such as delay, availability, and key delivery performance [207]. Here, physical data acquisition becomes automated, yet system adaptation follows predefined management logic rather than predictive digital control.

The closest transition toward Digital Twin behaviour appears in software-defined and orchestration-based testbeds. Quantum-secured service orchestration integrates QKD resources into SDN and virtualised control planes capable of dynamically configuring optical connectivity across domains [208]. Autonomic QoS assurance frameworks introduce closed monitoring–analysis–decision–action loops that automatically reconfigure network operation in response to measured conditions [209]. These platforms demonstrate bidirectional interaction between digital control systems and physical quantum networks, although control remains rule-based and limited to service or network layers.

Overall, the reviewed testbeds progress from experimental observation to continuous monitoring, and finally to digitally assisted control of physical quantum networks. As shown in Figure 10, current implementations therefore enable reliable physical data capture and partial real-time interaction, but typically lack continuously synchronised predictive models spanning all network layers. As a result, most platforms realise Digital Model or Digital Shadow capabilities, while orchestration-enabled environments indicate early readiness toward Digital Twin realisation.

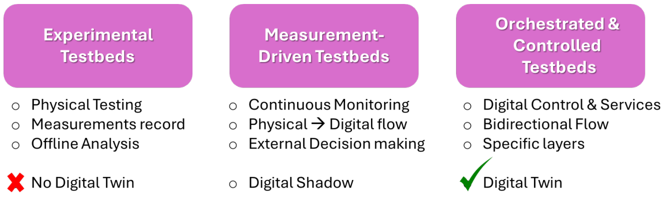

Fig. 10. Testbeds and experimental setups maturity level towards digital twins

Application of Quantum Simulators:

The design and evaluation of quantum network architectures increasingly depend on high-performance simulation environments. Among the available tools, Network Simulator for Quantum Information using Discrete events (NetSquid) and Simulator of Quantum Network Communication (SeQUeNCe) have emerged as two of the most widely adopted platforms in the literature. The prominence of these platforms is largely attributed to their shared reliance on discrete-event simulation and their modular full-stack architectures, which enable coordinated modelling across layered network structures. In particular, SeQUeNCE is organised into five functional modules, while NetSquid adopts a three-layer architecture, both aligning with the operational architecture of quantum networks proposed within the IEQNET initiative led by Fermilab [210], [211].

This integration allows interactions between hardware non-idealities, communication links, and protocol operations to be modelled consistently across multiple abstraction levels, supporting the evaluation of network behaviour under realistic operating conditions. As illustrated in Fig. 11, simulation configuration is defined within a unified workflow that coordinates device parameters, network topology, timing constraints, and protocol logic, thereby triggering state transitions throughout the system. Such an approach enables end-to-end performance assessment, including metrics such as fidelity, throughput, latency, and error rates, while maintaining consistency between physical-layer processes and network-level decision mechanisms. These characteristics are particularly relevant for digital twin development, offering a representative digital replica of the physical infrastructure capable of further real-time integration between physical system states and operational network dynamics within a unified simulation environment.

Although NetSquid and SeQUeNCE are both developed as Discrete Event Simulation (DES) platforms for quantum network research, their adoption across the literature reflects differing modelling perspectives and research objectives. Existing studies frequently employ these simulators to address complementary aspects of quantum communication systems, making direct interpretation of their respective capabilities non-trivial when considered independently. In this review, the technical distinctions between the two platforms are identified through analysis of their applications across different modelling aspects reported in the literature, an approach that has not been systematically examined in prior survey studies. Accordingly, Table VI presents a structured comparison that consolidates the capabilities of both simulators, providing a unified basis for understanding their respective roles in quantum network simulation and digital twin–oriented research.

Beyond NetSquid and SeQUeNCE, the reviewed literature introduces several simulation and emulation frameworks addressing complementary capabilities relevant to digital twin development. Some of these studies demonstrate important advances toward dynamic system representation and testbeds emulation; however, a detailed assessment of these platforms requires direct access to source frameworks and practical execution of simulation codes to reproduce and evaluate their operational behaviour capabilities. For transparency, the corresponding studies and extracted technical information are provided in the supplementary materials, as comprehensive capability analysis extends beyond literature interpretation alone and necessitates practical trials with the tools themselves.

While Digital Models and Digital Shadows demonstrate increasing maturity across quantum networking research as presented in this section, true Digital Twins enabling continuous real-time synchronisation between physical and digital quantum infrastructures remain rare, revealing clear maturity gaps that motivate the development of comprehensive Digital Twin frameworks.

VI. EVIDENCE-BASED SYNTHESIS

Within the reviewed literature, only a limited subset of studies explicitly employs the concept of a digital twin in quantum networking contexts. The introduction of digital twins is consistently motivated by common practical constraints associated with quantum communication infrastructures, including the high cost and limited availability of QKD hardware, interoperability challenges among heterogeneous systems, and the difficulty of safely evaluating network behaviour under dynamic or adversarial conditions [225] [226]. Digital twin environments are therefore introduced as virtual experimentation platforms capable of reproducing network operation, security scenarios, and integration processes without requiring direct access to physical quantum equipment [14].

This need is reflected in digital twin implementations that emulate QKD network behaviour for security analysis and controlled experimentation [220], as well as in deployable virtual infrastructures designed to support early-stage testing and integration studies while avoiding risks to costly operational systems [15]. In experimental networking scenarios, Yang et al. [16] further extend this justification by emphasising that operating entanglement distribution networks without continuous performance awareness can significantly degrade quantum services, thereby requiring a digital counterpart capable of monitoring and optimising system behaviour in real time.

Despite similar motivations, the mechanisms used to construct digital twin environments differ substantially in maturity. One implementation realises a digital twin architecture

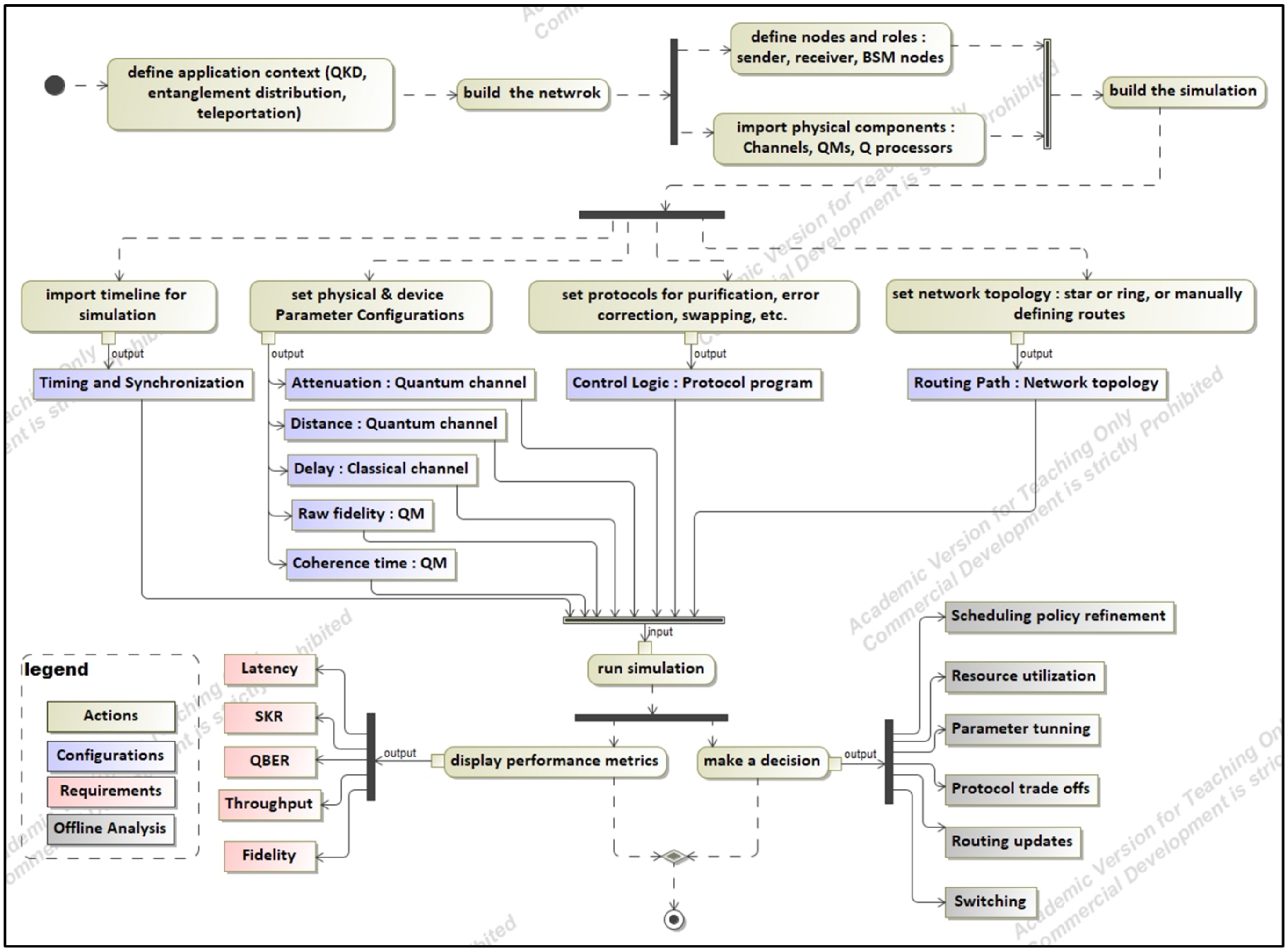

Fig. 11. Generic workflow of full-stack discrete-event simulation studies for quantum communication networks

through the integration of the Quditto orchestration framework, an open-access emulation platform designed specifically to deploy digital twins of QKD networks using classical computing infrastructure [227], with the NetSquid quantum network simulator, where virtual QKD nodes, configurable network topologies, and an eavesdropper simulation module collectively emulate quantum network operations. This environment enables controlled evaluation of routing adaptation, Quality-of-Service behaviour, and the security impact of adversarial attacks on key distribution processes within a fully emulated setting [220]. However, the presented twin operates entirely within an emulated environment initialised through configuration files rather than live physical data streams, indicating that the achieved system primarily functions as a high-fidelity experimentation platform.

A comparable software-centric realisation is introduced in a deployable digital twin service capable of automatically instantiating QKD networks using Network Functions Virtualisation (NFV) and standardised ETSI interfaces. Their contribution lies in enabling scalable deployment and lifecycle management of virtualised QKD nodes distributed across computing infrastructures. Validation experiments conducted, confirming the feasibility of rapid experimentation and infrastructure testing [15]. While this work successfully achieves its intended objective of providing an operational experimentation ecosystem, the digital twin remains detached from real quantum hardware feedback.

In contrast, stronger evidence of digital twin realisation is demonstrated in an experimentally coupled implementation where the digital replica is directly integrated with a field-deployed entanglement-based quantum network. Operational metadata, including photon source parameters, link losses, detector performance, and polarisation drift, are continuously collected to calibrate the digital model, enabling optimisation decisions such as wavelength allocation and pump-power control. Experimental validation shows improved network performance, reflected in coincidence rate and quantum bit error rate measurements, confirming partial behavioural alignment between physical and digital systems [16]. However, synchronisation still relies on manual tuning and correction factors, indicating remaining limitations toward fully autonomous digital twin operation.

TABLE VI
Capability Comparison of NetSQUId and SeQUeNCE Based on Reviewed Studies

Comparison Dimension	NetSQUId	SeQUeNCE
Primary Modelling Abstraction	Network and protocol-level simulation incorporating hardware-aware quantum state evolution and control processes [121], [212]	Physical-layer photonic network simulation focusing on photon transmission and optical component behaviour [124], [125]
Core Simulation Capability	Entanglement generation, storage, scheduling, and distributed protocol execution across quantum network nodes [213], [214]	High-fidelity modelling of photon propagation, optical channels, interferometers, and beam splitters for communication performance evaluation [124]
Hardware Representation	Explicit modelling of quantum memories, decoherence (T_2), relaxation (T_1), and gate imperfections [212]	Channel-oriented modelling including fibre attenuation, loss mechanisms, and polarisation effects in optical links [125], [138]
Network Intelligence and Control	Validation of routing and synchronisation protocols including Hybrid Quantum Routing Protocol (HQRP), Eventual Synchronisation Protocol, and Border Gateway Protocol (BGP) in distributed topologies [215]–[217]	Protocol abstraction primarily oriented toward transmission performance and link-level evaluation [218]
Supported Research Applications	Routing optimisation, entanglement management, resource allocation, and system-level coordination studies [214], [217]	Metropolitan QKD deployment analysis and photonic infrastructure feasibility studies [124], [218]
Security and QKD Evaluation	Security validation including eavesdropping analysis and Physical Unclonable Function integration [219]–[221]	Hybrid QKD–Post-Quantum Cryptography evaluation under metropolitan operating conditions [218]
Environmental and Deployment Modelling	Free-space, balloon-based, and satellite quantum communication simulations incorporating atmospheric and orbital effects [222], [223]	Primarily fibre-based metropolitan quantum communication infrastructure modelling [125]
Optimisation via Machine Learning	Surrogate-guided optimisation for protocol and hardware parameter tuning [224]	Machine-learning-assisted optimisation of quantum memory allocation and metropolitan resource management [224]
Computational Characteristics	Event abstraction enabling scalable large-network behavioural simulations [214]	Increased computational overhead due to pulse-level photonic modelling granularity [218]
Digital Twin Contribution	Supports behavioural and operational digital representations enabling end-to-end network evaluation and cyber–physical interaction studies [220]	Provides high-fidelity physical-layer representation supporting infrastructure-level digital replication [124]
Typical Modelling Layer	Network / Control Layer	Physical / Transmission Layer

A. *Maturity Analysis of The Existing Literature*

Although the taxonomy synthesis was originally organised by maturity readiness levels for supporting the digitalisation of QCN, an additional temporal lens is needed to capture how the field has evolved over time. This year-by-year perspective helps justify observed trends, relate them to broader technological advances, and motivate future research directions. Accordingly, the included papers were analysed and visualised in Fig. 12 to assess their evolution across publication years.

Figure 12(a) reveals that early studies were relatively sparse and primarily exploratory, with most contributions centred on modelling concepts and small-scale introductions to QCN simulations. As the field matured, research shifted increasingly toward quantum simulators, which have become the most visible and sustained theme V-A. This growth coincides with a broader transition from isolated protocol studies toward system-level research, where algorithms V-A and simulators V-C are utilised to study network architectures, control mechanisms, and end-to-end behaviour. More recently, the rise of testbed-related work signals a gradual shift from purely digital experimentation toward implementations capable of supporting validation under realistic physical conditions V-C.

In parallel, Figure 12(b) presents the maturity perspective of these developments. Early contributions aligned mostly with Digital Models and limited Digital Shadow capabilities. This was largely because physical quantum systems were scarce, forcing many inputs to rely on theoretical assumptions or highly controlled settings rather than continuous physical data. Over time, as experimental platforms and data availability improved, research moved toward the Digital Shadow phase, where models are informed by measured behaviour to provide a more realistic understanding of performance.

The most recent trends indicate the early emergence of Digital Twin maturity, driven by advancing testbeds and the integration of simulators with orchestration and control workflows. Overall, the transition captured across both figures suggests a field moving from static, offline representations toward operationally grounded, synchronised digital twins. In this evolving landscape, digital capabilities are progressively coupled to physical counterparts and constrained by real-world deployment conditions.

VII. RESEARCH CONTRIBUTION

A. *Research Questions Mapping*

The research questions are addressed through a taxonomy-driven and evidence-based synthesis of the reviewed literature. This mapping enables a structured assessment of (i) the capabilities required to achieve predictive digital representation and (ii) the extent to which existing simulation platforms currently fulfil these requirements. These identified gaps inform a set of research directions aimed at advancing the digital twinning of quantum communication networks.

Q1: *How can a digital twin framework be designed to enhance and predict the performance of quantum communication networks?*

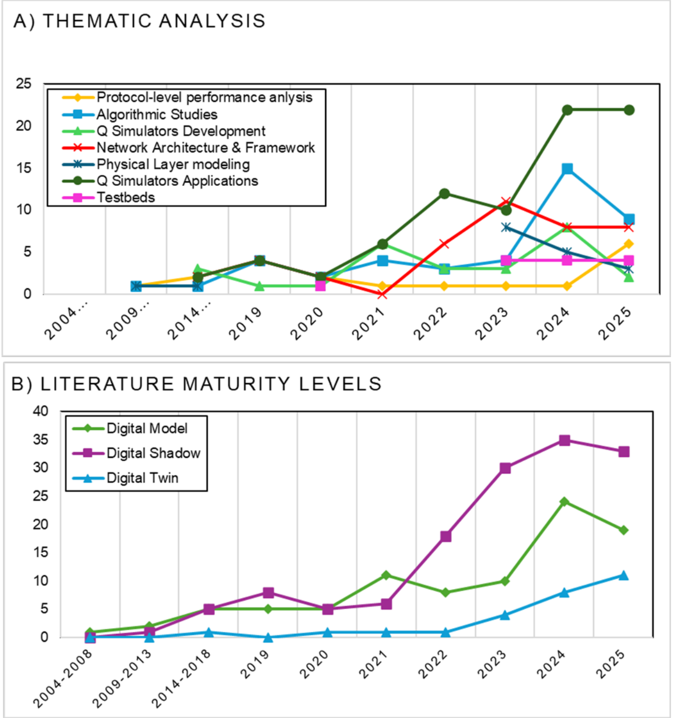

Fig. 12. Current status and maturity analysis of the included studies

To build a digital framework capable of twinning network behaviour, the layered architecture of quantum communication networks must be updated beyond the communication-oriented view introduced in the background section II. In particular, it should be aligned with the broader full-stack abstractions developed in quantum network simulators, since these environments are designed to capture how network behaviour emerges from interactions across application, control, management, and hardware-related functions. Figure 13 illustrates this architectural dependency, inspired by both quantum network simulations full stack representations and large-scale experimental deployments such as the Illinois Express Quantum Network (IEQNET), led by Fermilab, where entanglement distribution over existing telecommunications fibre infrastructure highlights the necessity of cross-layer coordination for stable quantum network operation [210], [211].

This transition is important because simulator-based architectures make explicit a key requirement for future deployable networks: users or applications should be able to request services, such as entanglement distribution between selected nodes, without needing to understand the underlying physical mechanisms. Once such a request is issued at the application layer, the network layer determines a suitable routing path, while resource-management functions verify the availability of quantum memories and other hardware resources needed to support the request. Following this, the lower control and physical-support functions coordinate synchronisation, signalling, and error-handling processes associated with entanglement establishment over the physical layer, and then report the resulting state of the resources back to the management layer. Only through this coordinated cross-layer interaction can the requested service be exposed to the application as a usable and abstracted network capability. For this reason, the development of a digital framework for quantum communication networks requires a revised layered architecture that explicitly includes application, network, resource-management, control, and physical-support functions, so that the full chain from user request to physical execution and feedback can be represented within a single coherent system model.

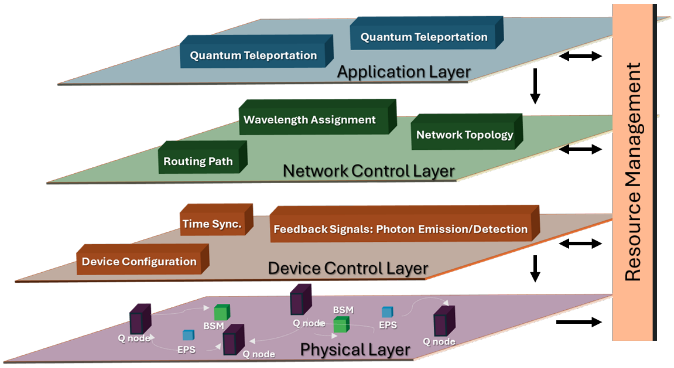

Fig. 13. Reproduced layered Architecture of Quantum Communications Networks developed by IEQNET, led by Fermilab, [210], [211]

Based on this layered architecture, quantum network simulators represent an important step beyond descriptive studies towards twinning network behaviour itself, as they capture the interdependent behaviour of cross-layer functions within a unified executable environment. However, when used as standalone tools, they do not yet constitute full digital twins, since their orchestration remains largely manual and static: network configurations, device constraints, and hardware parameters typically require explicit user setup rather than automatic updating. This reduces reproducibility and limits the exploration of evolving topologies, configurations, and operational scenarios in a way that reflects real network development.

Accordingly, these simulators are better understood as the computational core of a future digital twin rather than as complete twins in themselves. Realising such a twin requires interoperable data sources that can provide simulator inputs in a structured and updateable form, while also recording outputs to support systematic trade-off analysis across varying network conditions, for example, through application programming interfaces (APIs) and connected data pipelines. In parallel, software-controlled quantum testbeds provide a complementary pathway by allowing data collected from the physical counterpart to feed into the framework, thereby supporting monitoring, verification, and incremental improvement through tighter synchronisation between physical operation and digital representation. Taken together, full-stack simulators and software-controlled testbeds indicate a pathway towards digital twins in which executable network models are continuously informed by physical feedback, enabling ongoing analysis, validation, and performance enhancement.

Taken together, the evidence suggests that designing a predictive digital framework for quantum communication networks requires the coordinated integration of simulation capability, configuration management, and persistent cyber–physical synchronisation across all architectural layers. By unifying the capabilities emerging from the different digital representation pillars, such a framework enables validated experimentation and adaptive optimisation prior to deployment, thereby addressing the current gap between experimental quantum networking research and scalable system-level realisation.

Q2: *To what extent do existing experimental setups and testbeds enable cyber-physical coupling to optimise and predict quantum communication network behaviour?*

The synthesised evidence indicates that existing experimental quantum network setups enable cyber-physical coupling mainly through measurement collection, system monitoring, and parameter transfer between physical infrastructures and digital environments. In most cases, this coupling supports validation, calibration, or analysis of specific components or layers rather than the operation of a continuously synchronised virtual counterpart. As a result, current implementations do not yet realise digital twins capable of predictive optimisation or closed-loop control.

At the same time, the reviewed studies reveal an important intermediate capability. Several testbeds and emulation platforms demonstrate interoperability between experimental infrastructures and digital environments, allowing structured exchange of operational data, device parameters, and network conditions between physical and virtual domains. Although this remains insufficient for full digital twinning, it provides the basic mechanisms needed to incorporate physical measurements into digital representations and thereby forms an important foundation for future cyber-physical integration.

Taken together, existing work demonstrates early forms of cyber-physical coupling and establishes some of the required data interfaces, but falls short of the continuous, bidirectional, and system-wide integration needed for predictive and optimisation-oriented digital twins. Advancing towards this capability will require continuously synchronised cyber-physical environments in which operational measurements dynamically update virtual models, while model-based analysis informs network configuration, interoperability assessment, and performance optimisation throughout the network lifecycle.

Q4: *What performance metrics are most commonly employed in these hybrid experiments and emulated networks?*

The synthesised studies reveal strong convergence toward a common set of performance metrics used across simulated, emulated, and experimental quantum communication networks, as listed:

Fidelity: Measures how closely the transmitted quantum state matches the intended ideal quantum state after transmission, storage, or processing. It is commonly used to evaluate entanglement distribution performance, repeater efficiency, noise impact, and purification effectiveness within quantum communication networks [138], [214], [228], [229].

Secret Key Rate (SKR): Represents the rate at which secure cryptographic keys are successfully generated after error correction and privacy amplification processes. This metric evaluates the efficiency and practical performance of QKD protocols under realistic network conditions [138], [221], [230], [231].

Quantum Bit Error Rate (QBER): Quantifies the proportion of incorrectly received quantum bits caused by channel noise, device imperfections, or potential eavesdropping activities, serving as a key indicator of communication security performance in QKD networks [138], [231].

End-to-End Latency: Defines the total time required to establish entanglement or successfully deliver quantum communication services between network nodes, incorporating transmission, processing, and synchronisation delays [216], [232], [233].

Throughput: Indicates the amount of successfully transmitted quantum or classical control information per unit time, reflecting network capacity and protocol execution efficiency under varying traffic conditions [234]–[236].

Entanglement Generation Rate (EPR): Measures the frequency at which successful entangled quantum states are generated between communicating nodes, providing an indication of link reliability and repeater performance [119], [237], [238].

Entanglement Success Probability: Represents the probability that an entanglement generation attempt succeeds across a communication link or multi-hop network path, reflecting channel stability and protocol robustness [239], [240].

Resource Utilisation: Measures how efficiently quantum network resources, such as quantum memories, entangled pairs, and communication channels, are used during protocol execution, reflecting the effectiveness of resource allocation and scalability under constrained network conditions [213], [241].

Request Acceptance Ratio: Denotes the proportion of successfully served quantum communication requests relative to total service demands, reflecting service reliability and network operational efficiency [234], [242].

Routing Efficiency: Assesses the effectiveness of path selection mechanisms based on performance objectives such as latency, fidelity preservation, and resource consumption in distributed quantum networks [217], [232], [243].

These indicators are consistently employed to evaluate communication reliability, security performance, and operational efficiency across both virtual and physical environments. However, the literature also highlights the absence of standardised system-level requirements governing quantum communication networks and QKD deployments. As a result, performance metrics increasingly function as surrogate engineering requirements used to define and evaluate system objectives.

From a systems engineering perspective, the selection of requirements becomes dependent on the intended operational goal of the network. Consequently, the recurring performance metrics identified in the literature provide a flexible requirement framework that enables trade-off analysis between alternative devices, protocols, and architectural solutions. Their consistent use across experimental and simulated environments allows these metrics to serve as measurable system requirements within a digital twin framework, supporting objective-driven optimisation and informed decision-making throughout the quantum network lifecycle.

Q5: *What technical, architectural, and operational limitations currently restrict the digital twinning of quantum* *communication networks and hinder the integration between virtual and physical components?*

The synthesised evidence indicates that the primary limitations preventing the realisation of digital twins for quantum communication networks arise not from the absence of modelling and simulation tools, but from the difficulty of connecting these capabilities into a coherent cyber-physical system. A first challenge concerns *full-stack layer realisation*. While several studies model specific aspects of network behaviour, much of the literature remains focused on particular protocols, devices, or isolated layers. This fragmentation makes it difficult to establish a digital counterpart that reflects how behaviour emerges across the complete communication stack.

A second challenge is *real-time synchronisation* between the digital and physical domains. For a digital twin to remain meaningful during operation, the virtual representation must be updated using timely measurements from the physical network, while analytical outcomes should in turn inform monitoring, control, or adaptation. However, the literature shows that current approaches more often support offline simulation, post-experimental analysis, or periodic calibration than persistent bidirectional synchronisation. As a result, the digital representation does not yet function as a continuously evolving counterpart of the physical network.

The literature also highlights *scalability* as a major limitation, not only in the computational sense, but also in terms of model transferability and reuse. In many current studies, a simulation or modelling setup is tailored to a specific scenario, topology, or experimental assumption, making it difficult to reuse the same representation across different network conditions or deployment contexts. The large number of device-specific assumptions, protocol choices, and environmental constraints means that each new scenario often requires significant manual reformulation, which limits the ability of a digital-twin framework to scale across heterogeneous and evolving networks.

Closely related to this is the lack of *standard models*. Without shared abstractions, common data structures, and agreed interface definitions, it remains difficult to maintain consistency between digital models, simulator configurations, and physical network states. This also reduces comparability across studies and hinders the creation of reusable digital representations that could support lifecycle continuity from design to operation. In parallel, *interoperability* remains a persistent barrier, since simulators, control platforms, experimental testbeds, and physical devices are often developed in isolation and with limited compatibility. This prevents seamless data exchange and makes it difficult to establish the connected toolchain required for automated updating, configuration tracking, and integrated analysis.

Finally, *hardware scarcity* continues to constrain progress toward practical digital twinning. Access to quantum communication hardware remains limited, experimental platforms are often highly specialised, and many technologies are still evolving. This restricts the availability of continuous operational data needed to validate and update digital representations under realistic conditions. Taken together, these challenges show that the main barrier to digital twinning is not simply improving the fidelity of simulation models, but enabling persistent integration across layers, tools, and physical infrastructures. Addressing these limitations will require an interoperable and standardised framework capable of supporting a full-stack simulation, physical measurements, and adaptive synchronisation into a unified digital environment for quantum communication networks.

B. Research Directions

The following research directions address the gaps identified in the synthesis and outline opportunities to enhance, predict, and optimise QKD and quantum networks through digital twin principles. To reflect the expected maturation pathway, the directions are organised into three overarching domains that trace a trajectory from pre-development foundations and near-term requirements needed to enable full DT deployment, toward longer-term DT capabilities that support scalable, network-wide operation.

1) Architectural Prerequisites for Quantum DT Integration: This research direction focuses on the architectural foundations required to make quantum digital twin development and deployment feasible. A central limitation across the synthesis is the absence of standardised architectural representations that evolve with emerging quantum technologies. In practice, this leads individual technologies, such as devices, protocols, and management/control mechanisms, to be evaluated and refined in isolation, rather than embedded within a shared architectural baseline that supports consistent full-stack integration. As a consequence, studies rarely model how interactions between components and layers propagate to shape end-to-end behaviour. This obscures interdependencies between physical impairments, control and management policies, and higher-layer services, which hinders system-level realisation of quantum networks and, in turn, constrains their digitisation. These limitations limit the ability to construct credible digital representations that can consistently replicate and "twin" network behaviour across layered building blocks, and motivate two opportunities that support DT readiness:

Quantum Network Library Develop standard, reusable libraries of quantum-network building blocks such as architectural patterns, devices, channels, and protocol modules with defined parameters, constraints, and validation evidence, enabling consistent model assembly and systematic comparison of technology trade-offs.

Layer-Aware Simulation & Modelling Develop digital representations that explicitly encode cross-layer dependencies, enabling system-level prediction, verification, and optimisation of end-to-end network behaviour by linking physical-layer effects to network control, routing/scheduling feasibility, and application-level service outcomes.

2) Engineering Quantum Digital Twins:

This research direction concerns the engineering mechanisms that convert digital artefacts into DT-ready workflows. Across the synthesis, a recurring limitation is that quantum-network digitalisation is often technology-driven rather than engineering-driven: models and simulations are developed without a consistent requirements baseline, integration and verification are typically ad hoc, and links to physical infrastructure are commonly limited to monitoring or offline calibration rather than persistent, bidirectional synchronisation. In addition, workflows are frequently tool-bound, where scenario definitions, data formats, and assumptions are tightly coupled to a specific simulator or optimisation method, limiting reuse across scenarios and preventing systematic comparison under consistent conditions. Collectively, these limitations constrain traceability, repeatability, and operational credibility, and therefore hinder progression from digital models/shadows toward deployable digital-twin functionality. These gaps motivate four engineering research directions that, together, establish DT-ready workflows through requirement formalisation, repeatable integration and verification, continuous cyber-physical coupling, and interoperable toolchains and interfaces.

Requirement-Driven Optimisation Establish a requirements baseline that formalises non-functional requirements, such as reliability, availability, and maintainability, as traceable, verifiable system requirements linked to measurable Key Performance Indicators (KPIs). This enables objective-driven DT, where design and control decisions are evaluated against requirement satisfaction rather than informal performance targets.

Plug-and-Play Integration Engineer a modular integration DT environment where candidate technologies can be swapped as plug-ins within a preserved system context, enabling evaluation of compatibility through integration-scale, performance impacts, and failure modes prior to costly physical deployment.

Digital–Physical Coupling Systems Enable continuous, bidirectional cyber–physical synchronisation in which operational measurements update the virtual state and model-derived insights inform configuration and optimisation, shifting DT use from offline analysis toward operational prediction and assurance.

Interoperable toolchains and interfaces Define a stable, reusable DT toolchain with a shared information model and enforceable data contracts, allowing simulators and optimisation/ML modules to function as swappable back-end engines under consistent scenario definitions and configuration management.

Study of Emergence A validated DT framework can be deployed across infrastructures to reveal and quantify emergent system behaviours that only become observable when the network operates as an integrated whole. Component-level characterisation of loss and noise is insufficient because the same nominal hardware quality can yield very different network-level performance under contention, policy choices, and configuration effects that are not visible in isolated or small-scale tests.

3) Next-Generation Autonomous and Scalable DT:

This final research direction addresses longer-term capabilities required for scalable and autonomous DT operation at the network level. Across the synthesis, a common limitation is that most current approaches remain bounded by manual operation, offline analysis, and classical-compute scalability, which restricts DT functionality once networks grow in size, heterogeneity, and dynamism. Even when digital models and testbeds are combined, experimentation is frequently executed under predefined configurations with limited closed-loop feedback, making behaviour difficult to reproduce under time-varying conditions and slowing the design–test–learn cycle. In parallel, classical simulation becomes increasingly constrained as network scale and quantum-state complexity grow, limiting the feasibility of studying large-scale scenarios or running optimisation and assurance routines in near-real time. Collectively, these limitations motivate three longer-term research directions that enable autonomous, secure, and scalable DT operations.

Hardware-in-the-Loop (HiL) Advance automated HiL feedback loops that support repeatable, closed-loop experimentation with minimal human intervention, enabling rapid what-if evaluation, real-time state update, and accelerated validation of integrated network behaviour under changing conditions.

Network Simulation using Quantum Computers Integrate quantum computational resources into network simulation workflows to overcome classical scalability limits, enabling tractable simulation, optimisation, and design exploration for large-scale quantum networks as quantum hardware progresses toward fault-tolerant capability. However, this direction remains a forward-looking and currently unrealised capability, as the use of fault-tolerant quantum processors for large-scale network simulation is still speculative and depends on hardware advances that are not yet available.

Secure Digital Twin Framework While DTs create new assurance capabilities, they also introduce a security vulnerability: compromising the DT can threaten network operation and the integrity of operational data and decisions. Secure the DT as a security-critical component by threat-modelling its data pipelines, models, and interfaces, and enforcing integrity, access control, and auditability so the DT cannot be poisoned, manipulated, or abused for malicious actuation.

VIII. CONCLUSIONS

Owing to the rapid evolution and interdisciplinary scope of studies of quantum communication networks, this study adopted a literature survey approach inspired by PRISMA guidelines to ensure a systematic and transparent exploration of a broad and heterogeneous body of work. Through structured screening and synthesis, the literature was organised into thematic pillars reflecting progressive levels of digital representation, while evidence-weighted analysis enabled the identification of practically validated contributions within the digital twin context. This systematic consolidation allowed the research questions to be addressed through cross-study evidence.

The findings show that the literature on quantum communication networks has advanced beyond purely idealised digital models, but has not yet realised a true digital twin. Existing work already provides strong coverage in analytical protocol studies, optimisation-based network models, simulators, and descriptive system representations, establishing the main digital foundations for analysing and designing digital twins for quantum networks. More importantly, the state of the art is increasingly shifting toward digital-shadow-like representations, as many studies now ground their models in experimentally derived physical parameters, real network topology constraints, and testbed conditions, rather than relying only on abstract assumptions. These studies use such inputs to simulate, evaluate, and optimise network behaviour in a way that more closely reflects real system developments, revealing the trajectory that motivates future digital twin development and indicating that the field is already building the basis from which true digital twin frameworks may emerge.

Accordingly, the major gaps are now more precisely defined. What is missing is not digital representation in general, but the integration mechanisms that would transform current shadow-like and model-based approaches into genuine digital twins. These gaps are evidenced even in studies that developed mature algorithms and applied quantum network simulators, where the physical inputs remain predefined, periodically incorporated, or used for offline simulation and optimisation rather than through persistent real-time synchronisation with the running network. Consequently, the review not only clarifies the present maturity and gaps of digital representations in quantum communication networks, but also establishes research directions highlighting opportunities to address these gaps through integrated, interoperable, and lifecycle-oriented digital twin frameworks capable of enhancing, predicting, and optimising future quantum network systems.

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STATEMENT OF CONTRIBUTION

Amal Elsokary conceived the study, conducted the literature search, screened the papers, analysed and synthesised the findings, and drafted the manuscript. **Hayato Ishida** contributed to the study design and screening process. **Catherine White** contributed to the framing of the research questions, and validated, and reviewed the manuscript. **Stephen Powley & Maria Aslam** reviewed the taxonomy synthesis of the literature. **Michael J. de C. Henshaw** supervised the study and provided academic guidance. **Siyuan Ji** supervised the study, contributed to the conceptual framing and interpretation of the findings, and critically revised the manuscript. All authors read and approved the final manuscript.

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