TRENDS AND CHALLENGES OF OPTICAL CONVERGED NETWORKS FOR SMART CITY AND INDUSTRY 5.0: A SYSTEMATIC REVIEW

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KEYWORDS

optical converged networks; smart city; industry 5.0; agentic generative artificial intelligence; digital twins; quantum-safe security; AI-native networks

ABSTRACT

This paper presents a systematic review of trends, enabling technologies, and key challenges in optical converged networks for smart city and Industry 5.0, based on studies published between 2023 and 2026. The analysis identifies major trends, including AI-native architectures, agentic generative artificial intelligence, digital twins, quantum-safe security, and optical–wireless (FiWi) convergence, indicating a shift toward intelligent and autonomous network infrastructures. It also highlights critical challenges related to latency, reliability, scalability, energy efficiency, security, and standardisation. The findings reveal a key research gap in the absence of a unified framework integrating these technologies. This review provides a foundation for future research on intelligent, scalable, and resilient optical converged networks.

I. Introduction

Smart city and Industry 5.0 paradigms impose new requirements on telecommunication infrastructures, shifting from basic connectivity toward intelligent, adaptive, and human-centric service delivery [1, 2]. Smart city environments demand scalable, low-latency networks for massive IoT and real-time analytics [16, 23], while Industry 5.0 requires deterministic latency, high availability, and resilience in industrial systems [8, 22].

Optical fibre networks, including FTTx, PON, and DWDM, form the backbone of these infrastructures due to their high bandwidth, low latency, electromagnetic immunity, and scalability [9, 10]. However, conventional optical networks lack the intelligence required for autonomous operation in complex environments.

Recent advances integrate AI-native control planes, agentic generative artificial intelligence (Agentic AI), digital twins, and quantum-safe security mechanisms [1, 5, 11, 13, 18, 19, 20, 26], enabling real-time monitoring, predictive decision-making, and autonomous network management.

Despite these advances, key challenges remain, including latency and reliability, scalability, energy efficiency, security, and lack of standardisation. Existing studies also address these technologies in isolation, without a unified framework for smart city and Industry 5.0 optical converged networks.

This paper analyses recent trends (2023–2026), identifies enabling technologies, and highlights key challenges and research gaps.

II. Main part

1. Related Work

Recent studies have examined optical and converged telecommunication infrastructures for smart city and Industry 5.0, emphasising fibre-based backbones and passive optical network (PON) technologies for high-capacity, low-latency communication [9, 10]. FiWi-based architectures demonstrate improved throughput and coverage in

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urban environments. However, these works primarily focus on physical-layer performance and scalability, with limited attention to intelligent control integration required for autonomous operation.

Artificial intelligence has been widely applied to network management, enabling traffic prediction, resource allocation, and autonomous control [1, 26]. For example, Zhang et al. (2025) proposed a generative AI-based multi-agent framework achieving up to 98% task completion in optical network operations [20], while Sun et al. (2025) introduced local AI agents for lifecycle management [11]. Nevertheless, existing studies remain fragmented, focusing on isolated functionalities rather than unified integration within optical converged architectures.

Digital twin technology enables real-time modelling, monitoring, and predictive maintenance [5, 19]. Projects such as ALLEGRO demonstrate physical-layer digital twinning for quality-of-transmission estimation [19]. Similarly, quantum-safe security mechanisms, including post-quantum cryptography and quantum key distribution, address emerging threats in optical networks [13, 18]. Despite these advances, these technologies are typically investigated independently, without integrated frameworks combining AI-driven management, digital twins, and security.

Optical–wireless convergence (FiWi) improves flexibility and coverage in large-scale smart city and industrial deployments [9, 10], as demonstrated in projects such as NEWTON and PROTEUS-6G [4, 6]. However, these approaches introduce significant management complexity that remains insufficiently addressed.

Table 1

Summarises the scope and limitations of existing studies

Domain	Key References	Focus	Limitation
Optical networks	[9, 10]	Physical layer, scalability	Lack of intelligent control integration
AI/ML for networking	[1, 11, 20, 26]	Traffic prediction, resource allocation	Fragmented solutions
Digital twins	[5, 19]	Modelling, monitoring	Limited integration with AI
Quantum-safe security	[13, 18]	PQC, QKD	No unified framework
Optical–wireless convergence	[9, 10]	FiWi architectures	High management complexity

In summary, substantial progress has been achieved across optical networking, AI-driven management, digital twins, and quantum-safe security. However, existing research remains fragmented, and no unified, agentic AI-driven framework has been proposed for smart city and Industry 5.0 optical converged networks. This study addresses this gap by providing a systematic analysis and conceptual foundation for integrated optical converged networks.

2. Methodology

This study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [7] to ensure transparency, consistency, and reproducibility.

2.1. Search Strategy

A comprehensive literature search was conducted across IEEE Xplore, Scopus, ScienceDirect, Google Scholar, and arXiv. The search was limited to publications from 2023 to 2026 to capture recent developments in optical converged networks for smart city and Industry 5.0. Relevant keywords related to optical networking, convergence technologies, and intelligent network paradigms were used. The applied search string is given below:

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("optical converged network*" OR "FiWi" OR "PON")

AND ("smart city" OR "Industry 5.0")

AND ("AI-native" OR "agentic AI" OR "digital twin" OR "quantum-safe")

2.2. Study Selection

The initial search identified 127 records. After removing duplicates (n = 31), 96 studies remained for screening. Based on title and abstract evaluation, 52 articles were selected for full-text assessment, of which 38 met the inclusion criteria and were included in the final analysis.

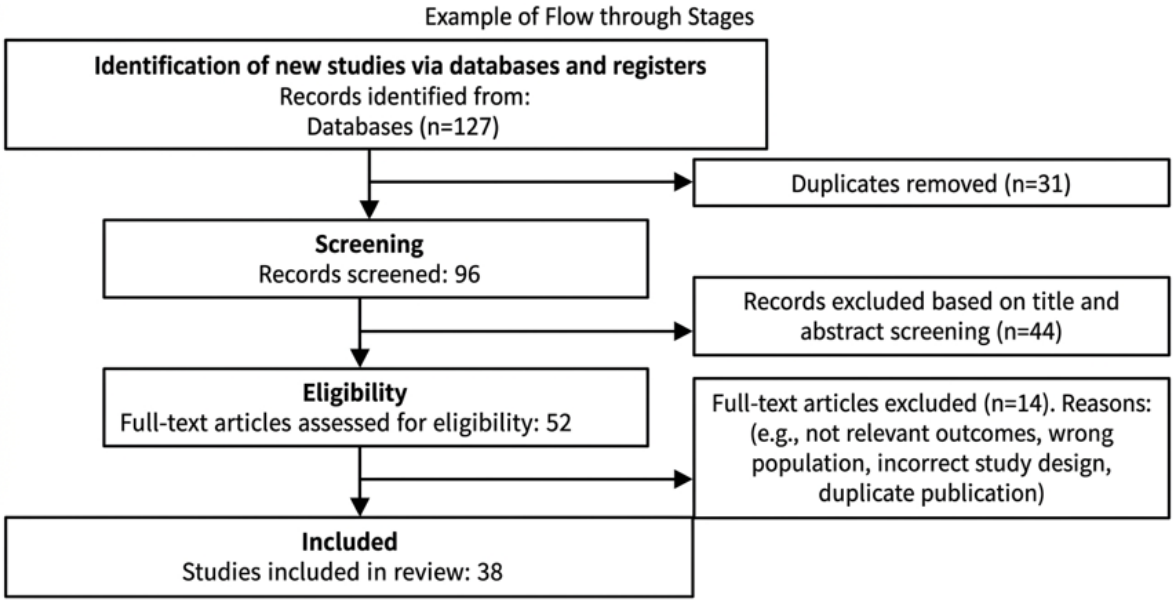


Fig.1. PRISMA flow diagram of the study selection process

2.3. Inclusion and Exclusion Criteria

Included studies were peer-reviewed journal articles, conference papers, or authoritative technical reports related to optical or converged telecommunication networks in smart city or Industry 5.0 contexts. Only English-language publications from 2023 to 2026 were considered. Studies were excluded if they focused solely on wireless systems without optical components, lacked technical validation, or were published prior to 2023.

2.4. Data Extraction and Analysis

A thematic analysis approach was employed to analyse the selected studies. Key information, including research focus, applied technologies, and outcomes, was systematically extracted. The studies were categorised into major domains such as AI-native networking, optical–wireless convergence, digital twins, and quantum-safe security, enabling the identification of dominant trends, classification of enabling technologies, and extraction of key challenges and research gaps.

3. Results

3.1. Technological Trends

The analysis of selected studies reveals several dominant trends shaping the evolution of optical converged networks for smart city and Industry 5.0, indicating a transition toward intelligent, autonomous, and adaptive architectures.

A key trend is the emergence of AI-native network architectures, where intelligence is embedded within the control plane rather than applied externally. In this paradigm, agentic generative artificial intelligence (Agentic AI) enables autonomous decision-making, self-configuration, and self-healing, with multi-agent frameworks demonstrating high automation and operational efficiency in optical networks [20, 26].

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Another major trend is optical–wireless convergence (FiWi), which combines high-capacity optical backbones with flexible wireless access to support scalable and heterogeneous deployments. Projects such as NEWTON and PROTEUS-6G highlight its role in enabling next-generation and 6G communication systems [4, 6].

Digital twin technology is increasingly adopted for real-time modelling, monitoring, and predictive maintenance. By creating virtual replicas of physical networks, digital twins enable accurate performance estimation and proactive fault management, as demonstrated in ALLEGRO and IOWN 2.0 [15, 19].

Quantum-safe security has emerged as a critical requirement due to the risks posed by quantum computing to traditional cryptography. Approaches based on post-quantum cryptography and quantum key distribution are being developed to ensure long-term data protection in optical infrastructures [13, 18].

Finally, Industry 5.0 drives the need for deterministic and ultra-reliable communication. Hybrid optical–wireless architectures and time-sensitive networking are being explored to guarantee strict latency, synchronisation, and reliability requirements in industrial and mission-critical environments [14, 22].

3.2. Technology Taxonomy

The identified technologies can be categorised into functional domains within optical converged networks, as summarised in Table 2.

Table 2

Identified technologies

Category	Technologies	Function
AI-Native Networks	Agentic AI, multi-agent systems	Autonomous control and decision-making
Converged Networks	FiWi, 6G x-haul	Scalability and coverage
Digital Twins	Network digital twins	Monitoring and prediction
Security	PQC, QKD	Quantum-safe protection
Optical Infrastructure	CPON, SDM, HCF, PICs	Capacity and latency enhancement

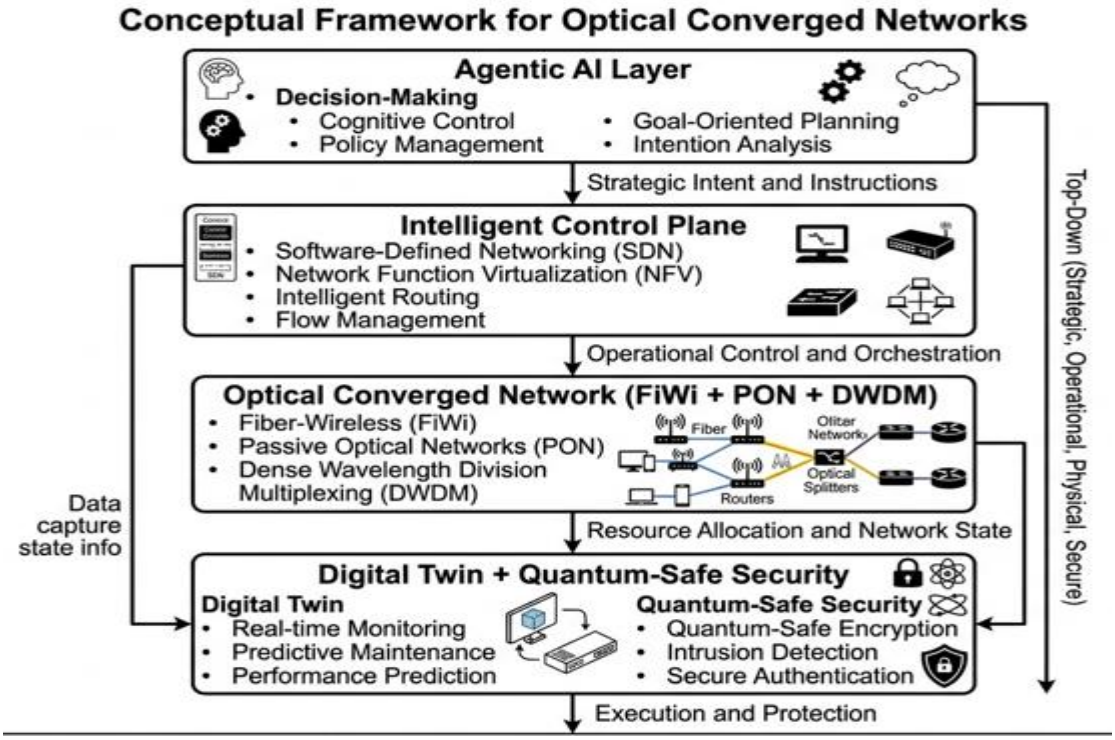


Fig.2. Conceptual Framework of Optical Converged Networks

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3.3. Synthesis of Trends

Overall, the identified trends indicate a transition toward intelligent, integrated, and autonomous network architectures. While each technology addresses specific performance aspects, their combined potential lies in enabling fully self-organising and adaptive systems. However, these technologies are still largely developed in isolation, and their integration into a unified framework remains an open research challenge.

4. Challenges and Research Gaps

Despite rapid advances in optical converged networks, several critical challenges limit their effective deployment in smart city and Industry 5.0 environments.

A key challenge is achieving ultra-low latency and deterministic reliability. Smart city applications require near-instantaneous processing, while Industry 5.0 demands strict timing guarantees for human–machine interaction. However, current architectures struggle to maintain consistent deterministic performance under dynamic, large-scale conditions.

Scalability is another major issue, particularly in massive IoT environments involving millions of devices per square kilometre. These systems generate heterogeneous, high-volume data streams that existing architectures cannot efficiently manage under real-time constraints.

Energy efficiency is also a growing concern. Although optical networks are more efficient than wireless systems, they still consume significant energy at scale, and the lack of standardised metrics limits the development of sustainable solutions.

Security remains critical due to emerging quantum threats. Traditional cryptographic methods are increasingly vulnerable, requiring post-quantum cryptography and quantum key distribution. However, their integration into optical infrastructures remains immature and lacks standardisation.

Interoperability and standardisation challenges further complicate deployment. Heterogeneous components—including optical, wireless, AI-driven, and digital twin systems—often rely on incompatible protocols, leading to fragmentation and limited scalability.

Most importantly, a key research gap lies in the absence of a unified theoretical and architectural framework integrating AI-native control, digital twins, quantum-safe security, and optical–wireless convergence. Existing studies address these technologies independently, without considering their interaction within a single system.

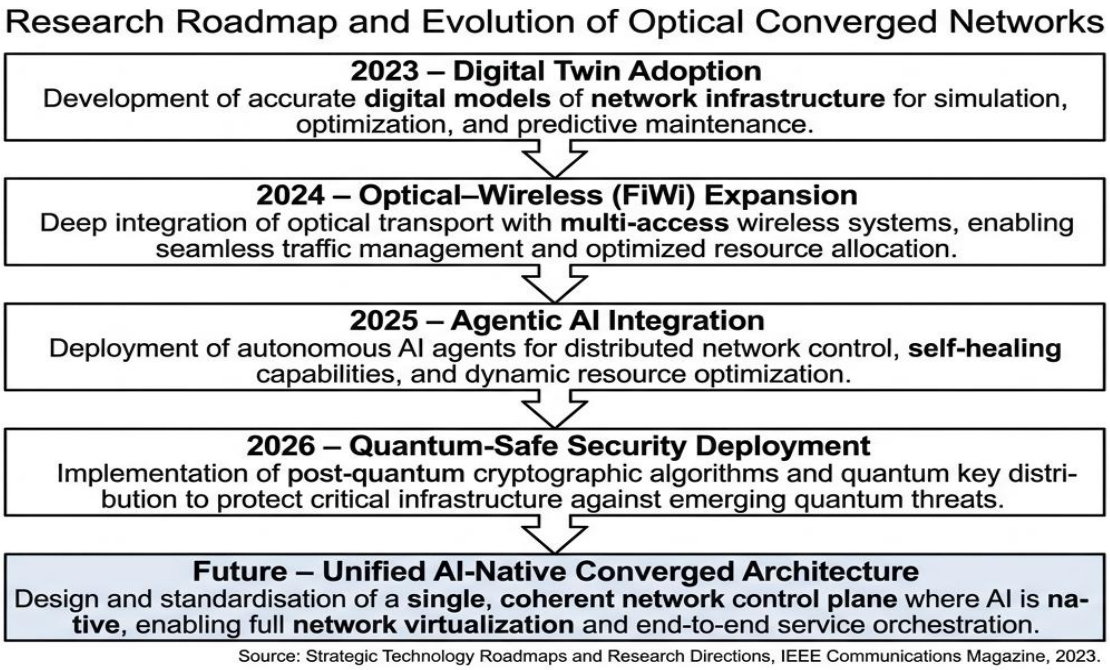


Fig.3. Evolution and Research Roadmap of Optical Converged Networks

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Addressing the identified gap requires integrated, multi-layered architectures capable of autonomous decision-making, real-time adaptation, and cross-domain optimisation. Future research should focus on agentic AI-driven frameworks that unify these technologies while ensuring scalability, security, and energy efficiency.

III. Conclusion

This paper presented a systematic review of optical converged networks for smart city and Industry 5.0, based on the analysis of 38 studies published between 2023 and 2026. The review identified key trends, including AI-native architectures, agentic generative artificial intelligence, digital twins, quantum-safe security, and optical–wireless convergence, indicating a transition toward intelligent, autonomous network infrastructures.

The analysis also highlighted major challenges related to latency and reliability, scalability, energy efficiency, security, and standardisation. Despite significant progress, existing research remains fragmented, with technologies typically addressed in isolation.

The main contribution of this study is the identification of a critical research gap in the absence of a unified framework integrating AI-driven control, digital twins, quantum-safe security, and optical–wireless convergence within a single architecture. Addressing this gap is essential for enabling autonomous, scalable, and secure communication systems for smart city and Industry 5.0.

Future research should focus on integrated, multi-layered architectures driven by agentic AI, enabling real-time decision-making, adaptive control, and cross-domain optimisation. The development of standardised performance metrics, particularly for energy efficiency and reliability, remains a key direction for further investigation.

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