Towards Secure and Flexible Optical Networks: A Tutorial on Quantum-Classical Coexistence

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***Abstract*—A growing trend in optical transport systems is the integration of quantum key distribution (QKD) into flexible optical networks (FONs) to meet increasing bandwidth demands and enhance security. Design, resource management, and scalability concerns arise from this combination. Several physical layer impairments, including nonlinear effects, crosstalk, and Raman scattering, occur due to the coexistence of quantum, companion, and data channels in shared optical resources, which might compromise secure key exchange and reduce quantum fidelity. These challenges need to be addressed with ultimate importance for future high-capacity secure optical transport systems. This paper discusses these issues. First, we start with the basic foundation of FONs and quantum communication. Then, our discussion focuses on physical-layer impairments and their modeling. The hybrid architecture that allows the coexistence of quantum, companion, and data channels is presented. Next, we discuss integrated resource allocation strategies considering crosstalk-avoided and crosstalk-aware approaches for the data channels, along with the coexistence of quantum and companion channels. We provide numerical results considering both crosstalk-avoided and crosstalk-aware approaches. Finally, we discuss open challenges and future directions for integrated QKD-enabled FONs.**

***Index Terms*—Flexible optical network, quantum key distribution, space division multiplexing, and hybrid architecture.**

I. INTRODUCTION

The explosive increase in network applications has dramatically increased Internet traffic, which demands a high-capacity transmission system. Traditional wavelength division multiplexing (WDM)-based optical networks are unable to handle the ever-increasing growth of traffic demand [1]. Flexible optical networks (FONs) have emerged as a promising solution that enables adaptive spectrum allocation and offers improved resource utilization [2]–[5]. As single-mode single-core fiber-based FONs are approaching the theoretical Shannon limit [6], an advanced technology is essential, which needs to offer better scalability. Space-division multiplexing (SDM) improves transmission capacity by utilizing many cores to utilize spatial dimensions [7], [8]. Integrating SDM with FONs is a promising improvement for future optical transport systems using multi-core fibers (MCFs), which forms the SDM-FONs technology [7].

The security of SDM-FONs is a critical concern owing to their substantially higher transport capacity. These networks are particularly vulnerable to physical-layer attacks and unauthorized access, which must be effectively mitigated to ensure secure operation [9]–[11]. Eavesdropping attacks are especially worrisome since malicious actors might pick up on data that is being sent [9], [10], [12]. Computational complexity underlies the security of classical encryption methods, such as integer factorization or discrete logarithms [13], [14], but these methods may become insecure with the advent of quantum computers. Indeed, Shor's quantum algorithm demonstrates that quantum computers can efficiently break these traditional encryption schemes [15]. Quantum key distribution (QKD) offers a fundamentally different security mechanism compared to traditional approaches, relying on the principles of quantum mechanics to ensure unconditional security. It detects eavesdropping attempts by exploiting quantum laws, including the Heisenberg uncertainty principle and the no-cloning theorem [16], [17]. The secret keys are transferred using photon polarization states through quantum channels by QKD-based protocols, such as BB84 [18]. For each request in QKD-enabled networks, three distinct channels are required: quantum, companion, and data channels. Among these channels, the quantum channel is used for secret key exchange, while the companion channel manages synchronization operations between nodes, and data channels are used for transmitting data. Both quantum and companion channels must follow the same routing path to ensure secure and synchronized operation, while the data channels follow different paths [19]–[22].

The physical layer presents additional issues for optical systems as spatial and spectral density grow. In SDM-FONs, inter-core crosstalk is a major issue due to optical power coupling between surrounding cores [23]–[25]. Signal loss, nonlinear distortion, and noise from crosstalk lower transmission quality and range. Large-scale transport networks need effective impairment management and spectrum and spatial resource allocation.

To achieve secure communication, QKD must coexist with regular data transfer via optical fiber infrastructure. However, quantum signals are weak and susceptible to high-intensity data channel interference, making cohabitation difficult. Quantum noise from crosstalk, Raman scattering, and nonlinear phenomena compromises quantum state integrity when data and companion channels propagate in the same fiber. Quantum and other channels require spectral and spatial coordination for safe key exchange [20].

Resource allocation is greatly complicated in QKD-enabled SDM-FONs. Multiple requirements, such as core, spectrum continuity, crosstalk, and noise, must be met when assigning

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three interdependent channels to each connection [24]. These channels must be shared in an effective way across routing, spectrum, and cores to reduce noise and synchronize nodes. Dynamic network scenarios with changing security needs, channel limitations, and traffic patterns make coordination difficult [26]. Errors in channel allocation or synchronization might raise quantum bit error rate (QBER) and undermine security, necessitating advanced resource management strategies [20], [26].

Table I summarizes recent studies on integrating QKD into optical networks. Due to their different properties and operating needs, optimizing quantum and classical resources simultaneously is difficult. To improve spectral efficiency and reduce noise coupling, joint routing, core, and spectrum allocation has been addressed. Despite these developments, a coherent architecture that combines security, scalability, spectrum efficiency, and coexistence performance is still a research challenge.

In this paper, we address the key challenges associated with integrating QKD into FONs and introduce a hybrid architecture. We begin with a brief overview of FONs and quantum communication, followed by a basic description of physical-layer impairments and their modeling. We then present a hybrid network architecture that enables the coexistence of quantum, companion, and data channels. Subsequently, we investigate integrated resource allocation strategies, considering both crosstalk-avoidance and crosstalk-aware approaches, and evaluate their performance under dynamic traffic conditions through numerical results. Finally, we outline potential future research directions for QKD-enabled SDM-FONs.

II. FUNDAMENTALS OF ELASTIC OPTICAL NETWORKS AND QUANTUM COMMUNICATION

A. Flexible optical network

The flex-grid technology or FON offers the flexibility to optimize optical spectrum capacity to create on-demand end-to-end lightpaths of varying capacities across an optical network [2], [4]. Unlike conventional fixed-grid WDM technology, where each wavelength channel is assigned the same rate in a predefined spectral grid, flex-grid technologies enable lightpath rates to be programmed individually for each lightpath to match the expected traffic load best [4]. Various bit rates can be achieved using several modulation formats, such as binary phase shift keying (BPSK), quadrature phase-shift keying (QPSK), 8-quadrature amplitude modulation (8-QAM), etc. The advantage of choosing from such a set of modulation formats is that one can trade spectral efficiency for OSNR and power. For example, a lightpath may have a long reach with a relatively low spectral efficiency modulation format or, conversely, have a high spectral efficiency at a relatively short reach, which is referred to as distance-adaptive modulation format selection. Interesting similarities can be found in radio access networks. However, achieving similar tradeoffs in optical networks is far more complex due to the multi-hop nature of lightpaths compared to the single-hop radio link. An additional level of spectral efficiency is attained by allocating the optical spectrum in a non-uniform manner rather than employing a predefined grid of evenly spaced wavelengths. By employing this method, lightpaths with high data rates can be allocated additional spectrum, which is obtained by reducing the spectrum allocated to low-rate lightpaths, as shown in Fig. 1 [4]. In addition, flex-grid allows parallel sub-wavelength lightpaths to be spectrally reserved inside a wavelength lightpath. Such sub-wavelength lightpaths can be switched individually and effectively used in campus/access networks to provide relatively small bandwidth granularity options. Flex-grid technology will likely be cost-effective for lightpath rates ranging from 10 Gbps to 1 Tbps (metro and core networks).

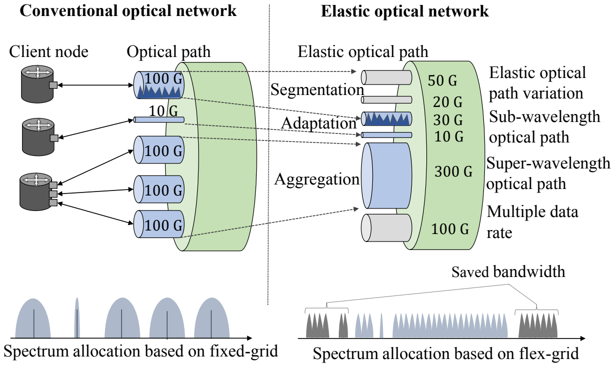

Fig. 1: Spectrum allocation in conventional and flex-grid optical networks.

B. Quantum key distribution (QKD)

QKD is a secure communication method that enables two parties, typically referred to as Alice and Bob, to share a secret key with security guaranteed by the laws of quantum mechanics [32]. The security of QKD relies on two fundamental principles: the Heisenberg uncertainty principle [16], which ensures that measuring a quantum state disturbs it, and the no-cloning theorem [17], which prevents an eavesdropper from perfectly copying quantum information. In QKD, key bits are encoded in quantum states of photons, commonly using polarization or phase encoding. During the key distribution process, Alice prepares and sends photons to Bob over a quantum channel, who measures them using randomly chosen bases. After transmission, both parties perform a sifting process to retain only measurements made with matching bases, followed by error correction and privacy amplification to generate a secure key. Eavesdropping causes QBER problems, allowing Alice and Bob to identify corrupted messages. Popular QKD techniques, such as BB84 and E91 use quantum features for information-theoretic security, ensuring key security without computational assumptions and robustness even with quantum computers.

III. PHYSICAL-LAYER IMPAIRMENTS AND THEIR MODELING

This section discusses physical-layer impairments, including linear and nonlinear effects, crosstalk, and fidelity, along with their modeling. The reliable coexistence of quantum

TABLE I: Summary of related works on QKD-enabled optical networks

Ref.	Focus Area	Technique/Approach	Key Contribution
[27]	QKD optical network survey	Resource allocation	Comprehensive review of routing, wavelength, and timeslot allocation in QKD-enabled optical networks.
[28], [29]	Quantum key resource allocation	Timeslot and key-number optimization	Introduced QKD architecture, analyzing effects of timeslot division and key count on utilization.
[30]	WDM/time-division multiplexing (TDM)-based QKD channeling	Classical-quantum coexistence, timeslot division	Enhanced key distribution via WDM/TDM integration for improved encryption and spectral efficiency.
[26]	Resource allocation in SDM-FONs	Crosstalk-avoided approach	Joint resource optimization considering crosstalk-avoided approach and QKD
[31]	Optical data center networks	Optimization problem	Investigate quantum key resource allocation in QKD-enabled optical data center networks

channels with companion and data channels in QKD-enabled SDM-FONs critically depends on effectively mitigating these impairments, which are addressed in the following subsections.

A. Linear and nonlinear impairments

Linear impairments in optical fibers are attenuation, chromatic dispersion, and polarization mode dispersion (PMD). These impairments significantly affect the performance of quantum channels. The number of photons in quantum channels is reduced due to attenuation, which increases the quantum bit error rate (QBER) and limits the maximum transmission distance. Chromatic dispersion broadens pulse durations, which can cause misalignment with detection windows. PMD impacts polarization-encoded QKD schemes by inducing misalignment and decoherence in the transmitted quantum states. The detailed descriptions of these linear impairments can be found in [33].

Nonlinear impairments, induced primarily by high-power classical signals, further threaten quantum fidelity. The Kerr effect, including self-phase and cross-phase modulation, modifies signal phases, while four-wave mixing generates new spectral components that can interfere with quantum channels. Spontaneous Raman scattering (SRS) is particularly critical, as scattered photons from classical channels can enter the quantum channel band, acting as a dominant noise source that degrades secure key rates. The detailed descriptions of these nonlinear impairments can be found in [33].

B. Crosstalk modeling and fidelity

In MCFs, crosstalk between cores becomes a key impairment. Inter-core crosstalk arises when the same spectrum of the adjacent cores is used simultaneously [24]. Crosstalk contributes to photon loss and state decoherence in quantum channels. Accurate crosstalk modeling is essential for predicting network performance and designing resource allocation strategies. The power of crosstalk often scales with neighboring channel power and depends on fiber length, core pitch, and the modulation format of classical channels. The detailed descriptions of crosstalk modeling can be found in [33], [34]. The total noise power affecting a quantum channel can be expressed as: $P_{\text{noise}} = P_{\text{IC-XT}} + P_{\text{SRS}} + P_{\text{other}}$, where $P_{\text{IC-XT}}$, P_{SRS}, and P_{other}, respectively, represent inter-core, Raman, and additional system noise contributions.

To quantify quantum signal degradation, fidelity is used as a key metric:

$$F = \langle \psi_{\text{ideal}} | \rho_{\text{out}} | \psi_{\text{ideal}} \rangle, \tag{1}$$

where ρ_{out} is the received quantum state, and $|\psi_{\text{ideal}}\rangle$ is the intended state. Fidelity $F = 1$ indicates perfect transmission. The QBER is directly related to fidelity as $\text{QBER} = \frac{1-F}{2}$, highlighting the sensitivity of quantum channels to even small levels of crosstalk or noise.

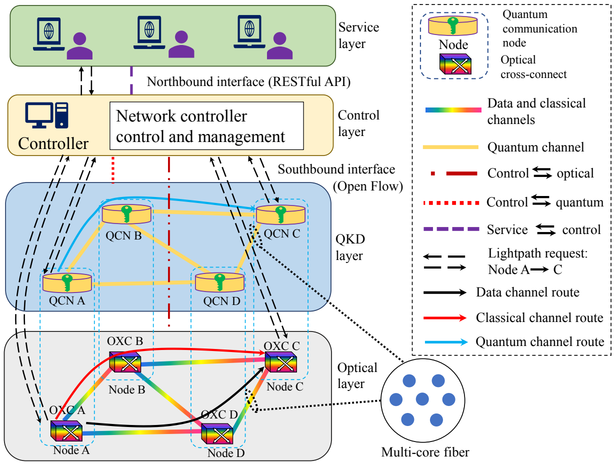

Fig. 2: Architecture of QKD-enabled SDM-FONs.

IV. INTRODUCED ARCHITECTURE FOR QKD-ENABLED SDM-FONS

The introduced architecture for high-capacity secure next-generation optical networks using QKD has four logical layers: the application layer, control layer, QKD layer, and data layer. The aim of this architecture is to include secure QKD methods with high-capacity SDM-FONs, ensuring both scalability and secrecy. The overall architecture is shown in Fig. 2, which facilitates the effective cohabitation of quantum and classical signals over shared optical infrastructure via coordinated resource management and communication operations.

A. Node architecture

Every network node in the introduced QKD-enabled SDM-FONs follows a hybrid architecture that amalgamates conventional and quantum communication capabilities. A node consists of two co-located components: a quantum communication node (QCN) and an optical cross-connect (OXC). The OXC regulates companion and data traffic by routing optical channels across various cores and spectral regions of MCFs. With advanced wavelength-selective switches (WSS) and reconfigurable optical add/drop multiplexers (ROADMs), it supports multi-core routing and transparent optical switching with low latency.

QCNs produce, receive, and route quantum signals. Its quantum transmitters (Alice modules), receivers (Bob modules), and optical switches (Q-OXC) manage sensitive quantum states with little loss and noise. QCN and OXC leverage spatial and spectral resources inside a single fiber to allow quantum and other channels to coexist while isolating them through spectrum filtering and spatial separation. The co-location of QCN and OXC allows software-defined control, switching, monitoring, and synchronizing quantum and conventional signals.

When a secure lightpath request is established from node A to node C, the software-defined networking (SDN) controller sets up data, companion, and quantum channels among the participating nodes. The data channel sends user traffic, the companion channel synchronizes QKD and sifts keys, and the quantum channel shares secret keys. The control plane sends configuration directives to each node, enabling secure optical connection establishment.

B. Link architecture

In an SDM-FON, the link architecture allocates physical and logical resources to quantum, companion, and data channels. An MCF is the underlying physical medium, which provides spatial dimensions for larger capacity and flexible channel allocation.

Low-noise cores and spectral slots decrease interference and maintain the QBER threshold in quantum channels. As companion channels offer synchronization, key filtering, and classical post-processing for QKD operations, they are near the comparable quantum channels in spectrum or space but segregated to avoid crosstalk. Data channels deliver high-bandwidth user traffic dynamically based on demand and network circumstances.

C. Control layer design

Under software-defined networking, the control layer coordinates and controls the architecture's resources. It centralizes intelligence and provides network resource visibility. The SDN controller computes routes, creates lightpaths, and allocates quantum, companion, and data channels. It monitors connection performance, QKD status, and impairment levels for dynamic reconfiguration and fault recovery.

Southbound interfaces, such as OpenFlow switches, allow the control layer to set up OXC and QCN components in real time. Figure 2 shows the signaling process: a lightpath request from the service layer identifies a source (node A) and destination (node C) with a defined security level. The SDN controller constructs an optimal path that fulfills data and QKD criteria. Next, it allocates resources for a data channel (black solid line), companion channel (light blue line), and quantum channel (red line). Dashed lines demonstrate how control signaling configures intermediary nodes to construct the end-to-end link.

The control layer also facilitates real-time synchronization between the data and QKD layers during operation. It facilitates the exchange of quantum keys and the encryption of data flow, enabling seamless key renewal and safe session administration. The SDN-based control layer ensures effective resource utilization, resilience, and safe service delivery in the QKD-enabled SDM-FONs via ongoing monitoring and reconfiguration.

V. RESOURCE ALLOCATION CONSIDERING QUANTUM-CLASSICAL COEXISTENCE

This section presents the resource allocation considering quantum-classical coexistence and both crosstalk-avoided and crosstalk-aware approaches [24], [35].

Figure 3 illustrates the allocation of requests considering quantum, companion, and data channels in SDM-FONs. The demonstration considers a four-node, five-link bidirectional network (Fig. 3(a)), where each link is an MCF, each of them containing five spectrum slots (Fig. 3(b)). Requests that use quantum channels are assigned to dedicated cores (c_1 and c_2) to ensure isolation and maintain link fidelity.

In this example, ten requests are considered; each of them consists of quantum, companion, and data channels. Quantum and companion channels occupy a single spectrum slot each, while data channels require a number of slots determined by the modulation format and the capacity class for data channels. Each companion channel follows the same path as its quantum counterpart, whereas data channels may traverse different paths.

For example, for request 1, the quantum channel (r^1_{qc}) with source-destination $(4,2)$ is routed via $4-1-2$, and its companion channel (r^1_{cc}) follows the same path. The corresponding data channel (r^1_{dc}) takes the path $4-3-2$. Similarly, r^2_{qc} is routed through $3-4$, with its companion channel r^2_{cc} following the same path, while the data channel (r^2_{dc}) follows $3-2-1-4$. Similarly, the quantum channels for requests (r^3_{qc}, r^4_{qc}, r^5_{qc}, r^6_{qc}, r^7_{qc}, r^8_{qc}, r^9_{qc} and r^{10}_{qc}) are allocated. The corresponding data channels (r^3_{dc}, r^4_{dc}, r^5_{dc}, r^6_{dc}, r^7_{dc}, r^8_{dc}, r^9_{dc} and r^{10}_{dc}).

Path selection of quantum channels accounts for node insertion loss ($L_{\text{node}} = 0.2\text{dB}$), maximum tolerable loss ($L_{\max} = 10\text{dB}$), and link fidelity threshold ($F_{\min} = 0.85$). Direct, low-loss paths are prioritized, and all successfully allocated requests meet these constraints. Guard bands ensure spectral isolation among the quantum, companion, and data channels.

The crosstalk-aware approach is used for resource allocation, as shown in (Fig. 3(c)). For both quantum and data channels, the crosstalk-aware approach allows spectrum reuse across adjacent cores if IC-XT remains below the maximum tolerable thresholds ($\text{XT}^{\text{dc}}_{\max}$) for data channels and ($\text{XT}^{\text{qc}}_{\max}$) quantum channels. For example, request r^5_{qc} on link $2-3$ cannot be assigned to core c_1 because the crosstalk contribution from adjacent core c_5 exceeds the permissible limit $\text{XT}^{\text{qc}}_{\max} = 0.05$. Therefore, the allocation is restricted to the next available slot or a non-adjacent core.

While the crosstalk-avoided approach is used for resource allocation, as shown in (Fig. 3(d)), which enforces a strict isolation policy between adjacent cores, whenever a quantum channel is allocated to a specific spectrum slot on one core, the same slot in its adjacent cores is marked unavailable to prevent any potential crosstalk interference. For example, if request (r^1_{qc}) occupies slot 1 in core c_1 on links $4-1$ and $1-2$, then slot 1 in the neighboring cores c_2, c_4 and c_5 is prohibited for use on the same links, since c_1 is physically adjacent

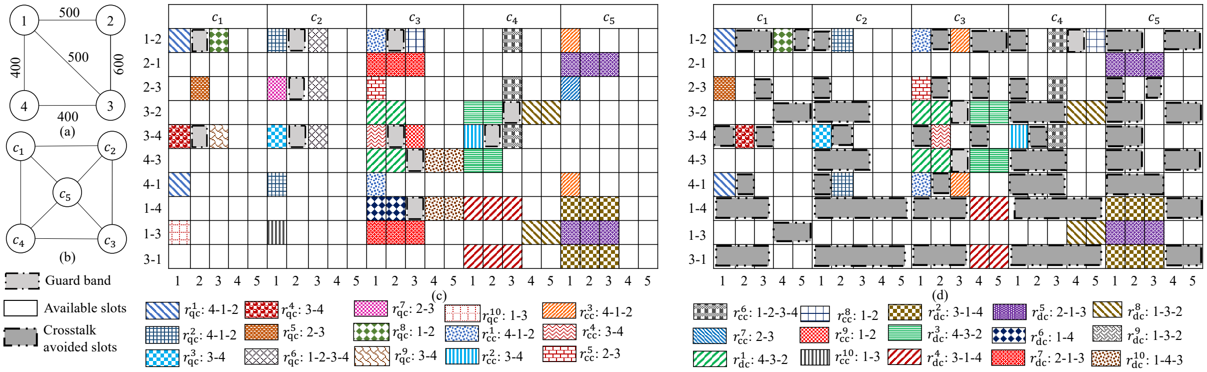

Fig. 3: Illustration of resource allocation: (a) sample network topology, (b) 5-core adjacency representation, (c) resource allocation using crosstalk-aware approach, and (d) resource allocation using crosstalk-avoided approach.

to c_1, c_4 and c_5 in the fiber cross-section. This approach guarantees that quantum signals remain isolated from classical interference, thereby maintaining high link fidelity above the fidelity threshold ($F_{\min}$) and keeping the total path loss below the allowed limit ($L_{\max}$).

Note that out of ten requests, the crosstalk-aware approach accommodates all ten, whereas the crosstalk-avoided approach accommodates only seven; the remaining three requests cannot be served due to resource unavailability.

VI. NUMERICAL RESULTS

This section presents the numerical results for crosstalk-avoided and crosstalk-aware approaches considering the coexistence of data, classical, and quantum channels. The simulations use the Tokyo TMN12 network model [36] shown in Fig. 4(a), where each link has five cores and 320 spectrum slots per core. Eight data channel classes with capacities uniformly distributed over $50, 100, 150, 200, 250, 300, 350, 400$ Gbps are generated, and source–destination pairs are randomly chosen. Six modulation formats—PM-BPSK, PM-QPSK, PM-8QAM, PM-16QAM, PM-32QAM, and PM-64QAM—are used. In the dynamic scenario, inter-arrival and holding times follow exponential distributions, with traffic load $\rho = \lambda_{\text{rate}} \times H$, where $H = 1/\mu$. A single guard band is applied between quantum, companion, and data channels to reduce inter-channel interference.

Figures 4(b) and (c) compare the XT-avoided and XT-aware allocation approaches, showing how blocking probability varies with traffic load and fidelity thresholds. In both cases, blocking increases with higher load due to limited cores and spectrum slots. Figure 4(b) shows that a relaxed fidelity threshold ($F_{\min} = 0.88$) yields lower blocking, while stricter thresholds slightly increase blocking until a saturation point is reached, where further tightening has minimal effect. In the XT-avoided case, crosstalk is eliminated, making path loss the main cause of blocking.

Figure 4(c) demonstrates that the XT-aware strategy achieves lower blocking at similar traffic loads, as it allows controlled spectrum reuse. For moderate XT thresholds ($\text{XT}_{\max}^{\text{qc}} = 0.035$, $\text{XT}_{\max}^{\text{dc}} = 0.07$) and $F_{\min} = 0.88$, blocking is minimized, but tighter XT limits increase blocking as assignment flexibility decreases. The flattening of high-fidelity curves in both cases indicates a fidelity-saturation point, where paths already approach loss and isolation limits.

VII. OPEN CHALLENGES AND RESEARCH DIRECTIONS

Although QKD offers theoretically invulnerable security, its integration with high-speed conventional data transmission in hybrid optical networks presents several practical obstacles. In the following, we discuss some of them.

A. *Physical layer challenges*

At the physical layer, quantum and conventional communications share the same optical fiber via wavelength, time, or space division multiplexing, which causes problems. Single-photon or weak-coherent-state quantum signals are especially susceptible to noise, scattering, and nonlinear effects from high-power conventional data channels. MCFs may suffer from spontaneous Raman scattering, ASE noise, and inter-core crosstalk, which can reduce quantum state fidelity. Additionally, fiber dispersion and PMD differences can cause temporal and phase shifts that affect QBER and KGR. Future research should focus on complex physical-layer models and mitigation techniques to address these effects.

B. *Resource allocation and network design*

Quantum and classical signal integration demands efficient spectral, spatial, and temporal resource allocation for best performance and security. Quantum channels need quantum-specific restrictions, including fidelity, key generation rate, and photon loss, making optical network resource allocation methods insufficient. The simultaneous optimization of quantum, classical, and data channel resources involves wavelength, core, mode, and temporal domains.

Cross-layer optimization models that maximize throughput, security, crosstalk, and energy efficiency are available for research. Deep reinforcement learning (DRL) and graph neural networks (GNN) are excellent heuristic and learning-based algorithms for dynamic and scalable resource management.

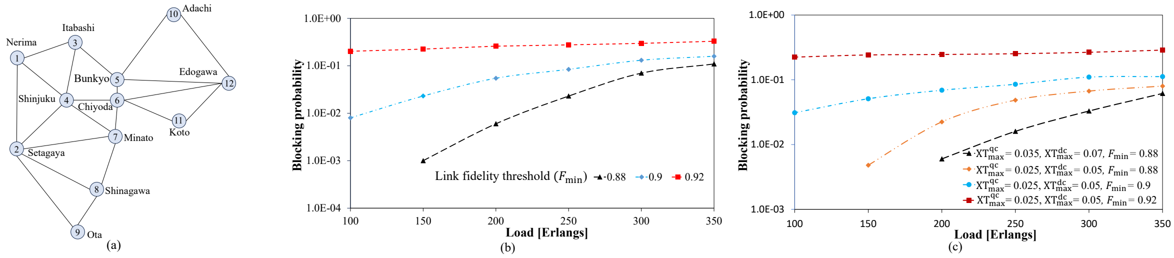

Fig. 4: (a) Tokyo TMN12 network model [36]. Blocking probability versus load using (b) crosstalk-avoided and (c) crosstalk-aware approaches.

In hybrid situations, quantum-aware routing and spectrum assignment algorithms for elastic and space-division multiplexed optical networks may help to establish efficient lightpaths. These models will enable automatic and configurable hybrid quantum-classical resource management in SDN setups.

C. Control and management layer challenges

The data, QKD, and control planes must be synchronized for hybrid quantum-classical optical network governance and administration. Most network control designs are designed for conventional communications and lack quantum-specific features, such as key generation, key storage, and quantum channel monitoring. Synchronization, scalability, and security concerns arise when adding these functionalities to SDN and network functions virtualization (NFV) systems.

Integrating SDN-based control systems to manage quantum and traditional network operations is a research priority. Such systems need application programming interfaces (APIs) and protocols to manage quantum information, such as key generation rates, fidelity metrics, and connection statuses. For easy interoperability, hybrid optical networks need standardized signaling protocols, such as quantum versions of OpenFlow and network configuration protocol (NETCONF). AI-based real-time telemetry and monitoring technologies and digital twins may improve control-plane intelligence by predicting network degradation and autonomously rearranging resources for safety.

D. Security and key management

QKD guarantees unconditional physical layer security, but network-scale implementation has security problems. Multi-hop, multi-domain hybrid networks require trusted nodes or quantum repeaters for key management and distribution, which pose security risks. To prevent man-in-the-middle attacks, network units must verify classical control signals. The simultaneous transmission of quantum and conventional signals exposes vulnerabilities, such as Trojan-horse and side-channel attacks, which employ crosstalk or power leakage.

Future research should focus on key management frameworks for hybrid optical networks that combine QKD and post-quantum cryptography for layered security. QKD systems based on entanglement and measurement-device-independent may reduce trusted node hazards. For complete security, the control and administration planes need lightweight, quantum-resistant authentication and encryption.

E. Network scalability and standardization

Hybrid quantum-classical networks struggle with scalability and interoperability. QKD systems are limited by transmission distance and key generation rate, making them unsuitable for large backbone networks without architectural changes. Without interfaces, performance assessments, and compatibility standards, adoption is limited. Network operators struggle to integrate equipment from several vendors and meet conventional and quantum performance criteria.

Current research must focus on scalable QKD methods that employ SDM, multi-band transmission, and quantum repeaters to improve secure communication ranges. Standardization activities should offer frameworks for interoperability, network administration, and performance evaluation. Assessing hybrid optical network viability and maturity in real contexts requires collaborative testbeds and field studies.

F. AI-enhanced network intelligence

The complexity of hybrid quantum-classical networks demands sophisticated management systems that can learn, adapt, and forecast. Artificial intelligence (AI) and machine learning (ML) might transform this sector. QKD performance, QBER, and channel behavior anomalies may be predicted using ML models. Automation for routing, spectrum allocation, and fault recovery is possible using reinforcement learning (RL). Interpretable AI may also show secure communications decision-making processes, boosting confidence and reliability.

Future research should study federated and edge learning models for distributed AI in large hybrid networks. Digital twin technology allows real-time modeling of hybrid optical networks for performance optimization, fault predictions, and resource management. AI-driven analytics and quantum-aware SDN control enable hybrid networks to self-optimize, self-heal, and self-secure.

G. Summary

Incorporating quantum and conventional communication into hybrid optical networks provides physical, technical, and management challenges. Research combining photonics, communication theory, quantum information science, and AI is needed to solve these problems. For seamless, high-speed, and secure quantum-classical coexistence, future hybrid optical networks will include adaptive resource management, integrated control-plane designs, better security protocols, and intelligent network analytics. Progress in these areas will enable a scalable and functional quantum Internet.

VIII. CONCLUSION

Quantum and conventional optical communication integration advances optical transport networks. The integration of QKD and SDM-FONs creates a unique architecture that provides security with great capacity and flexibility.

This paper focused on essential integration aspects. We began with FONs and quantum communication basics and discussed physical-layer limitations and modeling. A hybrid network design allowing quantum, companion, and data channels was then discussed. We explored and analyzed integrated resource allocation techniques, including crosstalk-avoidance and crosstalk-aware approaches, using numerical data. We observed that the blocking probability using crosstalk-aware approaches is lower than that of the crosstalk-avoided approaches. We discussed the insights for designing secure and scalable next-generation optical networks by highlighting open challenges and future research direction in QKD-enabled FONs.

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