Large-Scale Deterministic Networks: Architecture, Enabling Technologies, Case Study and Future Directions

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***Abstract*—Driven by the continuous growth of network demands, Large-scale Deterministic Network (LDN) has been proposed to deliver deterministic services with improved latency and jitter, zero packet loss, configurable bandwidth, and high reliability across a broad geographical area. LDN serves as a bridge for businesses to connect and share information across different sectors with high-quality and customized network services. However, the conveyance of massive flows with stringent demands in a large topology poses technical challenges to LDN architecture, scheduling mechanisms, and operation methodologies. To shed light on the possible avenues for these issues, this article provides a comprehensive survey of LDN architecture and enabling technologies. The study begins with an overview of typical LDN architectures, including definitions, standards, and mechanisms, followed by an examination of the key technologies that support the LDN's performance characteristics and implementation processes. Additionally, a case study of LDN scheduling is presented illustrating its application in heavy-traffic scenarios. Finally, this article outlines the open challenges and future directions in this field, highlighting areas of potential growth and development.**

***Index Terms*—Large-scale Deterministic Network, TSN, DetNet, 5GDN, DIP.**

I. Introduction

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EMERGING applications, such as virtual reality games, robot control, and autonomous driving, demand network capabilities with millisecond-level delay and delay variation (jitter) and 99.9999% reliability. However, traditional networks, with their best-effort services, cannot guarantee Quality of Service (QoS) and hence fails to meet these stringent requirements. Therefore, the Deterministic Network (DN) was developed to deliver services with guaranteed End-to-End (E2E) QoS for data delivery. DN adjusts the service level according to network demands, co-transporting both best-effort and high-priority flows, and maintains specific QoS for respective traffic (e.g., timely services for time-sensitive flows). As the demand for ubiquitous and dependable networks continues to grow, DN is poised to become the core infrastructure, delivering customized services to various industries and catalyzing the evolution of new applications.

DN stands out from traditional best-effort networks due to its certainty and dependability, which are attributed to deterministic QoS features. Bounded latency and jitter ensure maximum time for E2E data delivery and its variation, a crucial requirement for time-sensitive applications such as industrial process control and real-time video streaming. High reliability and zero packet loss guarantee on-time delivery of all data, making DN an ideal solution for improving data transmission capabilities in data centers utilized for Cloud Computing and Big Data platforms. Additionally, its adjustable bandwidth facilitates precise resource allocation based on service requirements, aligning various applications and data streams with suitable network environments. During the past decade, DN standards, protocols, technologies, and methodologies have been established around these QoS characteristics.

Table I provides a comprehensive comparison of typical DN architectures and technologies, specifically designed for vari-

TABLE I
COMPARISON OF TYPICAL DN TECHNOLOGIES AND ARCHITECTURES

Types	Layers	Use cases	Advantages	Current limitations
Flex E [1]	L1.5	High-bandwidth applications Network slice for 5G networks	On-demand differentiated services Improved bandwidth utilization	Poor inter-vendor component compatibility Fine-grained slot scheduling and bandwidth allocation
TSN [2]	L2	Automotive Ethernet Industrial Ethernet	Comprehensive standard system for DN High compatibility for component interoperability	Network scale constrained by time synchronization Network service level cannot adaptive control
DetNet [3]	L2-L3	Industrial control system in WANs	Comprehensive network framework E2E deterministic transmission across LANs and WANs	DetNet cannot serve large groups of domains
DIP [4]	L1-L3	IP bearer network Remote communication system	Long-distance delivery High scalability	Incomplete architecture and mechanisms of DIP
DetWiFi [5]	L1-L2	Wireless industrial control system	Good compatibility and high flexibility	Services performance affected by link unreliability
5GDN [6]	L1-L3	URLLC applications	High reliability, flexibility and availability	5G network cannot offer deterministic services alone
LDN	L1-L3	Integration of multiple DNs Long-distance/large-area services	High scalability and compatibility Broad coverage and ubiquitous connection	Heterogeneous DNs, devices, and mechanisms Difficult deployment of devices at large scale

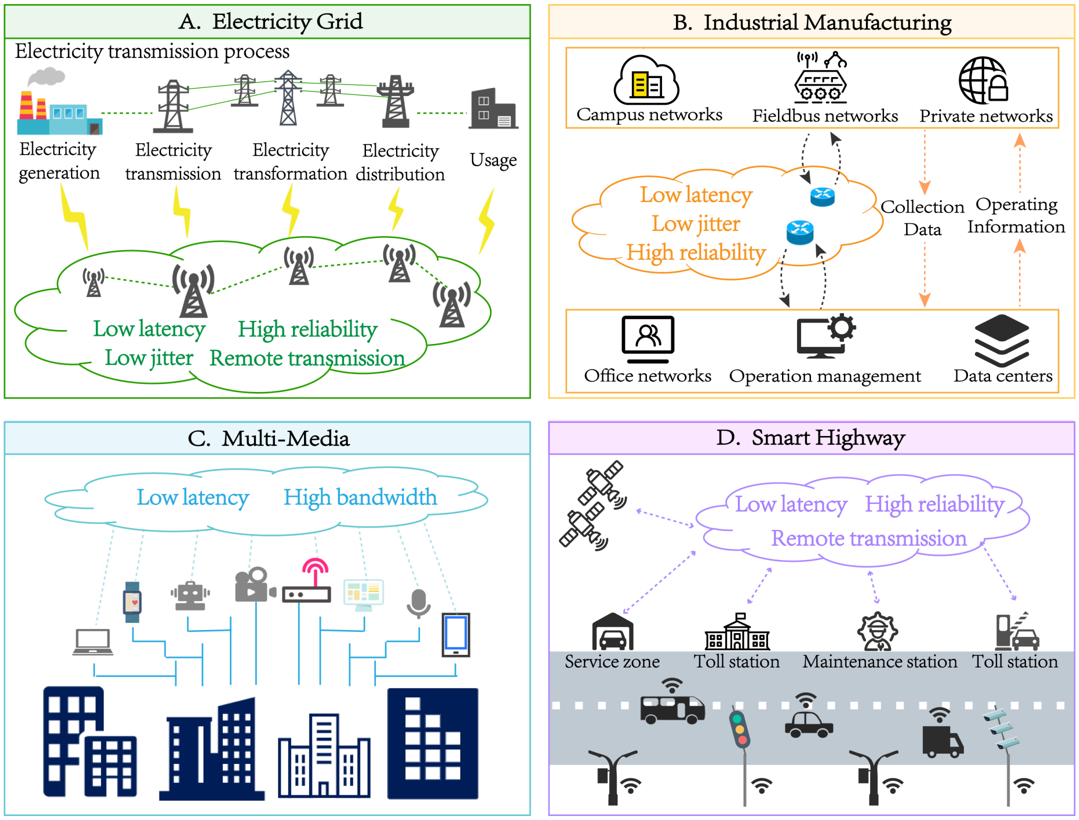

Fig. 1. LDN application scenarios. LDN provides high-quality, customized deterministic network services with low latency, low jitter, high reliability, and remote transmission, catering to various large-scale applications, such as industrial manufacturing, smart highways, multimedia, and power grids.

ous network layers and applications. While DN technologies have been implemented in campus-size networks, with applications in industrial field buses and vehicular communication, they may not yet be suitable for large-scale networks that span across different network levels, cover vast geographical areas, involve a massive number of connections, and cater to various network demands. To expand the utilization and accessibility of DN, network designers are exploring the potential of LDN. LDN is envisioned to support deterministic services for large-scale networks through its capabilities of long-distance deterministic transmission, E2E QoS guarantee across DNs in different layers, and customized services for various applications leveraging bearer networks (i.e., 5G and DIP networks). As shown in Fig. 1, LDN has the potential to drive growth across numerous sectors by facilitating seamless interconnections among businesses, processes, and applications over expansive areas.

As a cutting-edge technology with great potential, LDN has garnered significant interest from both academia and industry. Some studies depict possible LDN network architecture, scheduling mechanisms, and traffic management methods, while others focus on deterministic long-distance transmission [7]. However, LDN research is still in its early stages. Also, a comprehensive overview of LDN has yet to be established. This article aims to fill this gap by providing a comprehensive survey of LDN, identifying open challenges and potential applications for future research. Our key contributions are:

- A comprehensive review of the definition, standards, and mechanisms of LDN networking architectures.
- A summary and categorization of the technologies that enable the realization of LDN properties.
- A case study of LDN scheduling that efficiently handles heavy traffic in complex network scenarios.
- An outline of future directions in LDN research by highlighting challenging issues and potential applications.

II. Typical Large-Scale Deterministic Networks

In this section, four typical network architectures for LDN are reviewed, where Time-Sensitive Networking (TSN) and Deterministic Networking (DetNet) are briefly summarized as the standard frame, and Deterministic IP (DIP) and 5G deterministic networking (5GDN) are identified as the future developing technologies.

A. TSN

The TSN working group presents IEEE 802.1 standards to enhance Ethernet-based networking properties on timely and guaranteed delivery. TSN mechanisms strictly maintain time synchronization when scheduling and forwarding traffic at the link layer bridge, providing stringent timely delivery assurance. However, the maximum E2E latency of time-sensitive traffic classes is guaranteed up to only seven hops, limiting TSN's scalability. Although TSN is incompatible with large-scale networks, its comprehensive mechanisms can still be applied to implement LDN in flow forwarding and scheduling, reliability guarantee, and resource management.

B. DetNet

The DetNet Working Group concentrates on enabling deterministic delivery across Layer 2 bridges and Layer 3 routed segments, thus providing high reliability, bounded latency, loss, and jitter. Although DetNet standards are still under development, current research is developed based on published Request for Comments documents and technical guidance drafts. DetNet architecture is designed to transport specific unicast or multicast data streams within limited network domains, such as campus-wide networks. However, Its research into IP layer deterministic services lays a foundation for network integration and expansion. Additionally, its Software-Defined Networking (SDN) solutions may offer a scalable network and efficient management of a large number of flows. These suggest that DetNet has the potential to be an expandable E2E architecture for LDN.

C. DIP

DIP, proposed by Huawei and Purple Mountain Laboratories, is a scalable three-layer DN that has the potential to become an LDN architecture due to its support for remote deterministic transmission services and substantial traffic management. Segment Routing IPv6 (SRv6) provides explicit routing and flexible tunneling capabilities for DIP, while Network Cloud Engine controls the packet transmission process and assigns passageways and resources by exchanging information with the network entities. Moreover, DIP effectively eliminates long-tail effects by controlling the behavior of flow (i.e., identifying the sending/receiving period for each packet) at nodes along the path. This results in a fixed delay of T at each hop, and the E2E latency is proportional to the number of hops, with jitter accounting for $2T$ in long-distance transmissions. Moreover, DIP has already achieved the world's first successful delay and jitter control over a transmission distance of more than 2,000 km [8].

D. 5GDN

5GDN integrates DN and 5G networks to deliver deterministic mobile services for supporting communication missions with Ultra-reliable Low-latency Communication (URLLC), such as unmanned vehicles/drones and augmented/virtual reality. There are two main approaches for 5GDN, considering the 5G system either as a cable link between DNs or as a logical DN device. The former solution connects existing DN systems (i.e., TSN, Flexible Ethernet (Flex E), DetNet) to the 5G network, efficiently and flexibly providing deterministic services. Most current studies focus on the second option. Release 16 of the 3rd Generation Partnership Project proposes an integration strategy that views the 5G system as a pass-through bridge. Release-17 upgrades 5GDN with further supporting IEEE 802.1. In the upcoming Release-18, 5GDN will target the integration of 5G with DetNet to enhance the QoS of URLLC and broaden its applicability in a large-scale domain. Furthermore, through the standardization and evolution of 6G, seamless integration of wired and wireless DNs will be achieved. For example, 6G leverages machine learning technologies to understand and anticipate the characteristics of wired and wireless DNs, employs precise time management to design efficient schedulers, and establishes dynamic interfaces between networks to swiftly adapt. This approach thereby ensures stability and determinism in data transmission and expands the scope of E2E deterministic transmission.

III. Enabling Technologies for Large-Scale Deterministic Networks

The distinctive features of LDN pose novel technical challenges, as outlined in Table II. A thorough investigation of current DN technologies is essential to address them. Consequently, we review the technologies enabling QoS realization, with a particular focus on the characteristics of LDN.

A. Enabling Technologies for Timeliness Capability

LDN sets itself apart from best-effort networks by confining latency and jitter within a specific range, thereby ensuring consistent and timely communication. In emerging applications, low latency and jitter are often measured in milliseconds or even microseconds, such as industrial process control requiring delays of 1-50 ms and jitter of $1\,\mu$s-20 ms. To meet these requirements, LDN needs to adopt stringent scheduling and forwarding principles. The technologies described below can help fulfill these objectives.

Timing and synchronization: DNs require precise synchronization of devices to maintain consistent traffic scheduling through time slots at each hop, particularly in high QoS scenarios. TSN employs the IEEE 802.1AS protocol to achieve time synchronization across all network devices [9]. Nevertheless, this protocol may be unsuitable for LDN as network scales increase and clock data errors grow. As an alternative, DetNet can employ frequency synchronization. This method schedules traffic through periodic mapping connections between neighboring nodes, thus overcoming the constraints imposed by link length and the number of hops, and enabling LDN to support long-distance and large-domain communication. Additionally, periodic synchronization can help achieve synchronization among multiple existing DNs within LDN, which is primarily challenged by the varying length and misalignment of time slots.

Flow scheduling: LDN coordinates large volumes of time-sensitive streams through admission control, priority scheduling, and load balancing. Therefore, time-sensitive scheduling techniques are deployed to meet these service requirements. Time-Aware Shaper (TAS) is proposed to manage time-sensitive traffic using a cyclical gate-opening mechanism, which is essential for real-time control and instant messaging in industrial manufacturing. However, if a high-priority packet is too large to fit in a slot, relying solely on TAS could lead to task failure. The guard band method is thus introduced to reserve link resources after the time slot. This provision allows unfinished delivery to continue by blocking the entry of subsequent flows, ensuring that an uncompleted flow is not interrupted. Cyclic Queuing and Forwarding (CQF) fixes the bridge data processing time by cyclically receiving and sending two odd-even queues within the same cycle T [10], enabling E2E latency calculation. However, CQF requires rigorous time synchronization and dictates that bridges must receive and transmit frames within a time slot interval of T. This means the link delay must be shorter than T, which constrains the network expansion.

Several schemes have been developed based on CQF to overcome link length limitations. Multi-CQF extends the number of queues from two to Q but increases the hop delay to $(Q-1)T$. Scalable Deterministic Forwarding employs a cyclic hop-by-hop forwarding mechanism with frequency synchronization, providing scalability for traffic flows and resource reservation. Another promising scheduling approach for LDN is Cycle Specified Queuing and Forwarding, which integrates with Segment Routing to enforce explicit routes. As a result, this method naturally enables flow aggregation and efficient handling of large traffic volumes in LDN.

Traffic scheduling research has predominantly focused on the principles of queuing and forwarding within a single network, where a central controller pre-calculates and pre-configures the behavior of each flow in each node along the path to ensure E2E QoS. However, the scheduling of cross-network traffic in LDN becomes complex due to varying rules across multiple DNs. Furthermore, as networks expand in number and scale, reliance on centralized scheduling computations exacerbates this complexity, leading to prolonged computation times and increased calculation difficulty. Consequently, such a scenario negatively impacts the network's scalability, adaptability, and robustness. A potential solution to this issue is distributed scheduling, which allows for an independent scheduling policy for each DN. However, synchronizing time and configuring flows across networks present difficulties that necessitate addressing issues such as network traffic times alignment, flow shaping between DNs, and traffic admission controls.

B. Enabling Technologies for Reliability Improvement

With the increasing demand for high-quality data transmission, emerging applications are pushing for the standardization of network reliability. In particular, certain critical scenarios, such as autonomous driving, energy system management, and real-time robot control, require a network reliability of 99.9999%. Unlike traditional best-effort networks that focus on network connectivity, LDNs prioritize the timely and complete arrival of data. Here are some optimization, management, and protection technologies that can help achieve this.

Explicit routing: In LDN, traffic transmission often requires traversing multiple complex networks, making explicit routing essential. Guided by routing policies, such as Shortest Path Bridging, explicit routing allows for the pre-computation and pre-configuration of packet routes across different DNs. This arrangement takes into consideration multiple factors, including QoS requirements, traffic modes, network topology, and network conditions. Specifically, compared to a single network, LDN routing requires a more comprehensive acquisition of network information and a broader consideration of these factors. This complexity significantly increases the difficulty of route computation, optimization, and management across multiple DNs.

SRv6, a combination of IPv6 and Segment Routing, is a promising carrier protocol for LDN. By utilizing the extension header of IPv6 to specify data packet paths, SRv6 offers a flexible approach to the definition and management of network paths. The integration of SDN architecture with SRv6 yields programmable network functions and services with scalability, reliability, compatibility, and low latency, rendering SRv6 highly appropriate for large-scale network deployments. Furthermore, the programmability and global coordination of SRv6 enable LDN to seamlessly connect with heterogeneous networks and devices. This capability is anticipated to cater to specific service requirements in mixed-load scenarios, such as live video streaming, where co-transportation of best-effort, time-sensitive, high-reliability, and other specific-attribute flows is needed.

Flow management: LDN is vulnerable to failure when handling massive and diverse traffic, making traffic management essential. To prevent abnormal traffic, Per-Stream Filtering and Policing can act as firewalls, with Stream Filters recognizing abnormal frames according to predefined flow information (i.e., Stream ID, Label). Meanwhile, Stream Gates block unqualified frames, and Flow Meters restrict or stop exceeding frames. Additionally, Ethernet Operations, Administration, and Maintenance protocol can serve as a monitor to track network performance and identify and locate defects in LDN. Its fault management functions and performance monitoring functions can be performed either proactively or on demand to protect LDN. Traffic Engineering is a tool used to optimize network performance, scalability, and reliability by controlling network data flow. It is envisioned as a highly scalable, programmable, and plug-and-play tool for LDN, but its implementation is challenging and requires further investigation.

Redundancy mechanism: LDN is prone to higher error rates due to its large-scale topologies and heavy traffic, making redundancy mechanisms crucial. In TSN, Replication

TABLE II
LDN CHARACTERISTICS AND TECHNICAL CHALLENGES

Characteristics	Technical challenges
Long-distance transmission	E2E transmission over kilometers degrades time synchronization and increases latency and jitter
Vast and unstable network	Uncontrollable microbursts from changing topology and instant messages impair deterministic QoS
Various unpredictable services	Customized services demand LDN co-transfer diverse flows and configure network resources to them
Heterogeneous connections	Heterogeneous DNs and thousands of hosts in LDN require time domain and traffic information synchronization
Heavy traffic management	LDN strictly classifies, operates, supervises, and optimizes massive flows to guarantee their deterministic QoS

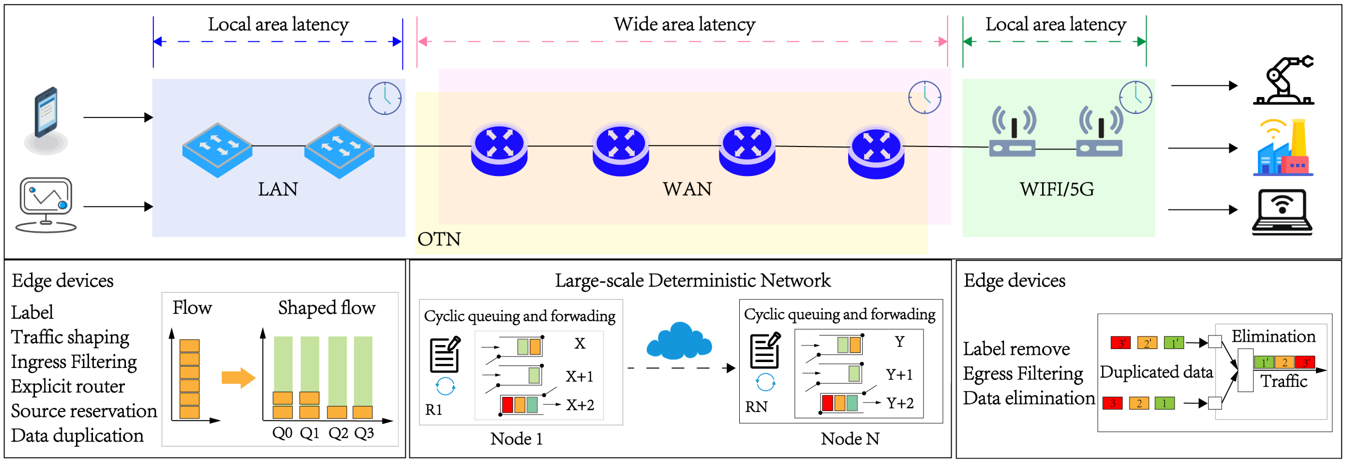

Fig. 2. LDN transportation processes. LDN delivers E2E deterministic services across multiple networks with strict flow scheduling, network configuration and management, and guaranteed mechanisms.

and Elimination for Reliability provides seamless protection against data losses by delivering duplicate frames over different paths [11]. Similarly, DetNet incorporates Packet Replication, Elimination, and Ordering Functions to enhance its fault tolerance. In this proposal, the transport of replicated packets and IP encapsulation is accomplished through "UDP tunneling", which facilitates flexible packet delivery across a large domain. However, The selection of redundancy paths in LDN involves balancing between protection path length and bandwidth consumption. Although longer redundancy paths provide improved reliability in the event of primary path failure, they result in increased bandwidth usage due to the duplication and transmission of data across multiple routes.

C. Enabling Technologies for Customized Services

The applications carried by LDN pose various stringent service requirements, resulting in diverse flows co-transmit within the network. Consequently, It is essential to classify, label, and maintain flow information and allocate, reserve, and manage the corresponding network resources by their requirements.

Flow prioritization: In LDN, specific flows may be provided with various QoS services, and a higher-priority flow may take the resources of a lower-priority flow. For instance, real-time communication messages are sent first in V2X, even though multimedia streams may consume a larger portion of the available bandwidth. Classification and grading are effective strategies for managing diverse traffic in LDN. As previously noted, flow priority is considered in scheduling, administration, and operation, but these techniques prioritize flows differently. In QoS, flows are categorized into eight levels, whereas in DN, the emphasis is on the co-transportation of best-effort and high-priority flows. Scheduling techniques also prioritize flows based on their roles. CBS, commonly used in Audio/Video Bridging networks, categorizes traffic into Class A, B, C, and Best-effort flow, while TAS separates flows into time-triggered and event-triggered, focusing on time-sensitive considerations. Given the variety of flows that LDN may encounter, it is crucial to establish unified classification standards. The rating information should also be standard and wrapped in the traffic (i.e., in IP headers and labels). Moreover, the standardization of flow information conversion across different networks is a key requirement. In this way, LDN can accurately identify the flows and match them with available resources accordingly.

Network slicing: Many vendors and users desire an LDN to host various applications. Network slicing can thus be implemented to create several logical networks (e.g., URLLC) on a single network infrastructure [12]. Each logical network can establish its own topology and services to meet the specific needs of applications. Specifically, diverse applications within LDN allocate exclusive time slots, enabling the isolated co-transfer of flows for services like operating system separation, private network extension, and communication security.

Flex E is a significant network-slicing technology in DNs that enables dynamic bandwidth allocation. Flex E has three modes of operation: Bonding, Sub-rating, and Channelization. The Bonding mode combines multiple standard Ethernet interfaces to form a logical channel with a higher transfer rate, which is suitable for high-bandwidth use cases, such as 5G services, ultra HD video, and VR/AR applications. Conversely, the Sub-rating mode reduces the flow delivery rate. This mode permits multiple customers to share a single physical channel when one customer's service cannot fully utilize it, thereby optimizing bandwidth usage. By using Flex E channelization technology, services are distributed across distinct time slots of individual physical channels, enabling multiple customers to share several physical channels freely.

Resource reservation: To ensure E2E QoS of LDN, network resources must be allocated and reserved in advance in each node along the explicit route. This precautionary approach helps to prevent delays or packet losses that could result from resource competition or scarcity. However, This process can present significant challenges, mainly due to the vast, unstable network topology and heterogeneous connections among devices and DNs.

In TSN, several standards have been established for the

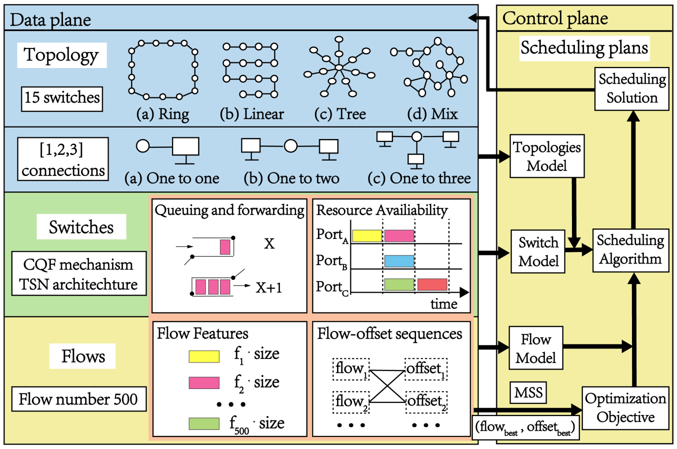

Fig. 3. Scheduling heavy traffic in an LDN using the MSS algorithm. The global information of the topology, switches, and flows is modeled to calculate a scheduling solution in the control plane. In this process, the MSS algorithm strategically selects potential optimal flow-offset sequences to optimize the scheduling plan.

distribution of resource reservation information. Stream Reservation Protocol (SRP) reserves resources on Ethernet switches through the distributed management of stream reservation information (i.e., registration, de-registration, and maintenance messages). To extend the capabilities of SRP, SRP Enhancements and Performance Improvements is proposed to support more streams and configure their characteristics to flexibly respond to varying network conditions and traffic demands. Link-local Registration Protocol is another method that allows applications to establish point-to-point, bi-directional associations between instances, facilitating the distribution of stream reservation information across a network or a portion thereof.

However, these protocols primarily govern the sharing and management of messages within LANs. To effectively manage resource reservation in LDN, novel protocols guiding intra-controller resource distribution and allocation are necessary. Further protocols are needed for multi-controller information exchange across DNs. Then, their challenges lie in ensuring interoperability across varied networks, responding swiftly to network status changes, and supporting complex resource optimization algorithms. These considerations are vital for enhancing existing or developing new protocols for LDN.

IV. Case Study

The primary goal of this case study is to demonstrate the capability of effective heavy-traffic scheduling in an LDN, as illustrated in Fig. 3. Our main interest lies in achieving efficient and successful traffic scheduling in such extensive network environments.

In our experiment, we adopt the load balance scheduling algorithm of Mapping Score-based Scheduling (MSS). This algorithm, implemented within a CQF-based TSN architecture, strategically selects potential optimal flow-offset sequences based on flow features, and available resources, to ensure load balance across the network and improve overall network performance. To demonstrate the effectiveness of scheduling across various network scenarios, we conducted experiments on four typical topologies widely used in the industry: ring, linear, tree, and mix. Each topology comprises 15 switches, with the number of hosts connected to each switch randomly selected from the set $\{1, 2, 3\}$, thus generating large-scale topologies of varying sizes and shapes. Moreover, we simulated heavy traffic conditions in this network. We set the number of flows to 500 to create a high-load situation and set the link bandwidth to 1000 Mb/s to achieve high-speed transmission. In addition, to test time-sensitive flow, the frame size is randomly selected between 64 to 1500 bytes, and the deadlines for all flows are randomly generated within 2 to 5 milliseconds.

We evaluated the scheduling experiment 50 times for each scenario to determine average performance. As a scheduling plan is an optimal solution under various constraints (i.e., topology, devices, traffic, and algorithm), not all traffic flows may meet the set delay requirements. Therefore, we define 'success rate' as the proportion of flows that meet these requirements. This average success rate was used as an index to assess the performance of the scheduling plan in the repeated estimations. The experimental results show that the MSS algorithm demonstrates excellent versatility and scalability when dealing with large-scale and variously shaped networks. Specifically, in intricate network scenarios consisting of 500 flows and 15 switches, the average success rates of the MSS algorithm for ring, linear, tree, and mix topologies were found to be 77%, 68%, 78%, and 79% respectively.

This case study shows that it is possible to schedule heavy traffic in LDN. This could facilitate the LDN to be well-extended in complex heavy traffic scenarios, such as handling large volumes of data transmitted between different networks and devices for telecommunications networks, enabling real-time data processing for industrial control systems, improving data transmission capabilities for video streaming services, and supporting mission-critical applications for healthcare systems.

V. Future Research Visions

From a long-term perspective, we highlight some open challenges and the potential future visions in LDN.

A. Open Challenges

Flow scheduling: LDN aims to create an SDN architecture for scheduling flows, managing resources, and providing policies for deterministic data transfer [13]. However, current scheduling solutions are inadequate for heavy traffic, ever-changing connections, and long-distance transmission. LDN needs a flexible traffic scheduling mechanism with high scalability and robustness. CQF-based scheduling methods have been proposed to address these issues, but further efforts are necessary to solve specific problems such as time interval settings, traffic granularity, and queuing mechanisms.

Services guarantee: Various network services and applications in LDN result in the co-transportation of flows with varying QoS demands, leading to sharp fluctuations in bandwidth and latency across a wide range. Additionally, aperiodic tasks can cause microbursts and poor network compatibility. Therefore, further research on resource allocation and reservation, traffic scheduling and coordination, network configuration and administration is needed to ensure QoS for data flow in LDN.

Heterogeneous network: The integration of heterogeneous networks is a significant study area in LDN [14]. The deterministic large-scale backbone network of DIP and the deterministic wireless networks of DetWiFi suggest practical ubiquitous connection schemes for LDN. Moreover, The 5GDN technologies of 5G+TSN, 5G+Flex E, and 5G+DetNet are exploring an even broader coverage for LDN. Thus, the combinations of heterogeneous networks in LDN help to connect the business processes of various industry sectors.

Hardware cost: In addition to the technical challenges, financial constraints pose a significant hurdle to the widespread implementation of LDN. While some network architectures and technologies, such as Flex E, TSN, and 5GDN, have achieved commercialization, others, including DetNet and DetWiFi, are still in stages of standardization or research and development. The availability of LDN-supporting hardware devices is limited, and the high cost of certain devices, such as TSN switches, in the market adds to the substantial cost of upgrading or implementing LDN. This cost factor presents a critical challenge that must be addressed to encourage broader adoption of LDN, particularly among smaller entities or those with limited resources. Therefore, further research and development efforts are crucial in reducing the cost of LDN-compatible hardware and making these technologies more accessible to various organizations and networks.

B. Future Visions

LDN will serve as an extensive core infrastructure, integrating IPV6 and optical networks to become the next-generation backbone network. This large-scale network will cover local, metropolitan, and wide areas, connecting multiple DNs and expanding the scope of deterministic service applications. As a result, LDN will help to reform and upgrade conventional sectors, such as agriculture, industry, logistics, and transportation, by making them more connected and intelligent. Moreover, LDN has the potential to increase the value of goods and services and spur new economic growth.

LDN has immense potential across multiple sectors, particularly in scenarios requiring long-distance, large-scale, and intricate network configurations, such as autonomous vehicles, industrial control systems, drone collaborative control, and video streaming services. With the increasing number of devices connected to the network, their operation and connection post a strong demand for URLLC services. Public networks and traditional Ethernet have fulfilled some needs but are often limited by latency, reliability, and security issues. LDN, on the other hand, will serve as an on-demand tunnel that offers various levels of URLLC services, enabling advanced communication with greater connectivity, security, and reliability.

LDN may enable many cross-industry applications because it lets technologies related to calculating, connecting, and controlling can communicate with various procedures, such as telesurgery [15], traffic guiding, and building automation management. Especially, LDN can greatly incentivize combining the Internet and other sectors, such as Industrial Internet of Things, Internet of Services, and Internet of Energy. In the future study of these interaction fields, we need to study not only the incorporation between two technologies but also their intercommunication by LDN.

VI. Conclusion

In this article, we provide a comprehensive survey of LDN. At first, the typical LDN architectures of TSN, DetNet, DIP, and 5GDN are introduced. We then summarize and categorize the LDN enabling technologies for the specific QoS and LDN features. Besides, we present a case study of LDN scheduling highlighting its potential applications in complex network scenarios. Finally, open challenges and future applications in LDN are discussed, concluding that LDN will significantly boost the development of industries.

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