概括了边缘云网络在5G前传和工业4.0的应用，以及其对网络能力、时延、抖动、动态性、切片和数据发送能力的保证，
介绍了以太网、工业以太网、OTN(Optical Transport Network)、FlexE、PONs(Passive Optical Networks)、TSN、
OSS(Optical Slot Switching)、DDN(Deterministic Dynamic Networks)等解决方案

End-to-End Time-Sensitive Optical Networking: Challenges and Solutions

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(Invited Paper)

***Abstract*—Time-sensitive applications, most notably, for 5G fronthauling and Industry 4.0, require deterministic (jitter-free) low-latency, highly reactive, and trustable networks, as opposed to today's best effort Internet. We review existing solutions, both established and at the research stage, and compare them for key next-generation 5G fronthauling and industrial requirements.**

***Index Terms*—Edge cloud, Industry 4.0, network automation, optical network performance, time sensitive networks, 5G fronthaul.**

I. Introduction

EDGE cloud is a network architecture that aims at bringing processing power closer to the end user, as shown in Fig. 1. In particular, 5G networks aim at covering a large spectrum of wireless networking use cases ranging from standard high-throughput broadband mobile access to ultra-low latency applications (with possibly low data rates) for sensor networks or the Internet of Things in general. The 5G use cases also include Ultra-Reliable Low-Latency Communications (URLLC) for Industry 4.0 and high-throughput, low-latency vehicle-to-anything (V2X) communications. In addition, 5G fronthauling itself will require very low latency to carry data from the antenna to the closest data center for baseband processing. This diversity calls for a novel end-to-end network architecture, whereby network functions enabling low-latency applications are located closer to the end-users to decrease the latency due to the physical propagation of the signals [1], [2]. In addition, virtualization of network functions is a key feature of 5G networks, whereby some functions are no longer located on dedicated hardware at the base stations but run on standard computing hardware located in data centers. Cloud Radio Access Network (CRAN), which centralizes network functions, was already proposed for latter LTE network generations, and is typically implemented by installing relatively small data centers in the metro area. Edge cloud brings processing power closer to the end users to reduce latency. Such an implementation is depicted in Fig. 1(a): user elements or things access the radio unit (RU) through the air interface (left), signals coming from a RU (for instance encapsulated in standardized Common Public Radio Interface–CPRI–frames, or through a latter protocol) are carried across a first network over less than 10 km to a metro node where a small (mobile) edge cloud data center (Distributed Unit / DU) is located and processes time-critical data. Non time-critical data is transported across a second network to the core network where for processing within a Central Unit (CU). In edge cloud networks, all latency-sensitive functions – even those not related to 5G digital signal processing such as support for virtual or augmented reality – can be located within the DUs, or even within the CUs if those are located close enough to the end users.

Clearly, both time-critical and non-time-critical data is carried by the fronthaul and mobile edge cloud intra-data center network. In addition, operators are seeking to leverage their past network deployment investments and are reluctant to deploy new networks; convergence of fixed access and mobile access networks is one example of such convergence and exacerbates the diversity of the traffic multiplexed in both the fronthaul and intra-data center networks.

As another application of edge cloud, the factory of the future will be massively connected to facilitate automation, such as part delivery between already largely autonomous robots and machines [3]. Industry 4.0 encompasses communication across several factories; here, we focus on the floor of a single factory. Indeed, the factory floor is where networking constraints are the most stringent. We depict such a factory floor in Fig. 1(b). Just as user elements and buildings were connected to an access node in the previously considered 5G network, robots, autonomous vehicle and other "things" are connected to a factory floor network (see Fig. 1(b)), whether through an air interface or a wired interface. This last-meter access part is outside of the scope of this paper, but the interested reader is referred to [4], [5] for ultra-reliable and low-latency communication in the wireless access segment. The factory floor network interconnects all "things" in the network to an edge cloud data center, which is in charge of processing latency sensitive traffic. For instance, the edge cloud data center network may be used to virtualize the Programmable Logic Controllers in charge of controlling factory robots [6]. In the Industry 4.0 context an edge cloud

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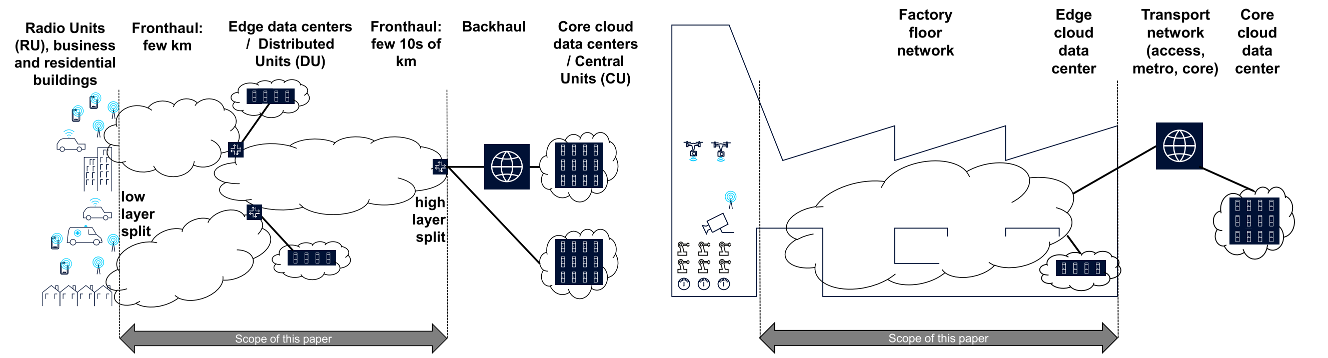

(a) 5G mobile edge cloud architecture.

(b) Industry 4.0 network architecture.

Fig. 1. Architectures for two time-sensitive networks.

data center may be within the factory or very close to minimize latency. The factory floor network may, in some cases, be converged and shared with the regular Internet traffic used for non-time-sensitive traffic, such as data analytics or even office traffic such as email. Non-latency-sensitive traffic can then be handled by a cloud outside of the factory, depicted in Fig. 1(b) as a core cloud data center.

Although we focus here on the 5G mobile edge cloud and on the factory (floor) of the future, determinism (controlled low-latency with reliable packet delivery) is also needed for several other related use cases, including the professional audio and video industry, electrical utilities, and potentially others, which are described in [7], [8].

In this paper, we summarize the key requirements for edge cloud networks, first for mobile 5G (Section II) then for Industry 4.0 networks (Section III). We show how those challenges are addressed today, at least partially, in Section IV. Then, in Section V, we summarize promising technologies that close the gaps identified in today's technology and could address the foreseeable evolutions of the requirements of edge cloud networks, focusing on 5G mobile edge cloud and Industry 4.0, but that are still at the research stage. Finally, we compare all solutions (present and future) in Section VI.

II. Challenges for 5G Mobile Edge Cloud

A. Capacity

Transport: The 3GPP standardization organization identifies several "functional splits," which characterize which (digital signal processing) functions are implemented locally to the antenna, and which functions are implemented in a centralized fashion in the edge data center [9]. Low-layer splits separates functions that are implemented near the antenna (at the RU) from those implemented at the DU while the high-layer split separates functions that are implemented at the DU from those implemented at the CU. Depending on the functional split and base station physical parameters including number of sectors, MIMO size, and radio bandwidth of the signals, the capacity of the network between antenna and mobile edge cloud data center ranges between 2.5 and 150 Gb/s [10]. The fronthaul design problem is compounded by fact that, depending on how the splits are defined, the RU-DU segment could require simultaneously higher capacity and lower latency such that the digital signal processing hardware is better utilized, or low capacity and less latency may be needed at the expense of requiring a larger amount of costly non-shared digital signal processing equipment directly located on the antennas. Latency requirements will be reviewed further.

Edge data centers: The traffic not processed at base stations is processed within the edge data centers, which can also implement higher layer highly latency sensitive network functions, for instance, to support virtual or augmented reality. In addition, edge data centers should have the capacity to process the traffic from potentially several fronthaul networks, yielding capacities potentially up to the Tb/s scale, which may seem large but are several orders of magnitude below that of "mega" core data centers (which can reach the Pb/s scale.)

B. Latency

The one-way latency sustained by sampled data from the antennas sent to the DU should not exceed 100 μs (CPRI 7.0 and eCPRI [11], [12]). This includes propagation over the fiber network, which is thus limited to 20 km. Reducing any latency component other than propagation yields more budget for propagation, hence network radius and amount of data center resource multiplexing. Hence, it is desirable to decrease latency, even if that is only by a few microseconds. Observe this latency is end-to-end, i.e., it encompasses both the fronthaul and the intra-data center segments, and the latency on both segments should be minimized.

C. Jitter Control

Jitter, i.e., the latency variation with time (expressed here as the maximum tolerable latency excursion, but alternatively sometimes as the second moment of the latency probability density function) that is tolerable in a 5G edge cloud network for standard radio functions (including synchronization), is capped for several reasons, but a jitter constraint of $+/-130$ ns including $+/-100$ ns for transport is generally accepted [13].

5G could additionally be used for accurate positioning. Achieving meter-scale positioning accuracy (which would for instance position cars in the right lane for the connected automobile use case), requires base stations to be synchronized with an error of less than 10 ns, which would translate into a jitter constraint for the fronthaul segment in the same order of magnitude.

D. Dynamics

Networks where resources are statically allocated are prone to over-dimensioning to cover any traffic variation over the network life, which translates into higher CAPEX. For this reason, networks that can adapt to the load are preferred. This should be understood as "put the capacity where the load is," which is already done in transport networks through transponder (e.g., wavelength tuning or data rate adaptation through a change of symbol rate, modulation format or Forward Error Correction – FEC) or network management (e.g., through routing) reconfiguration, rather than "put the load where capacity is" which is done in data center networks through load balancing but is clearly incompatible with jitter control. In addition, the current trend is to centralize network operation through Software Defined Networking (SDN) so that dynamic capacity re-allocation can be further optimized. As network load may change very fast, possibly at the hour to minute or even second to millisecond timescale, the network should also be sufficiently flexible to handle such a frequency of reconfiguration. For instance, within data centers, Facebook reported in [14] that 80% of the web servers flows and 95% of the cache followers flows last more than 1 ms, but only 25% of the web servers flow last more than 1 s. Distributed computing is even more dynamic: 75% of the Hadoop flows last less than 1 s. Inter-data center traffic is even more dynamic: 75% (resp. 65%) of the flows last less than 10 ms (resp. 1 ms). Given that technologies and applications once confined to the mega data center tend for decentralization and "cloudification" it is easy to extrapolate such numbers to the future of the end-to-end edge cloud network, which will then need ms-timescale (or even faster) reconfigurability.

E. Slicing

Network slicing refers to the isolation of resources such that the same physical infrastructure can be seen as a set of several independently managed virtual networks. Network slicing can be hard: the slices are physically independent (while possibly sharing the same wavelength); or soft: there may be interaction among the slices under certain network operation such as congestion, e.g., the performance such as latency over a slice depends on the traffic on the other slides. Slicing enables multi-tenancy whereby several operators share the same network infrastructure, and the cohabitation of several services with different requirements on the same network infrastructure. Only hard slicing provides guarantees as soft slicing makes any slice performance prone to dependence upon the performance of the other slices.

F. Guaranteed Delivery

Data should be delivered from antenna to the processing unit without resorting to upper layer mechanisms such as TCP, which timers and retransmission mechanisms are not compatible with sub-millisecond latency networks. For this reason, the frame loss rate is capped to 10^{-7} in 5G fronthaul [15]. This loss rate should be maintained from antenna to processing server. In addition, network availability (the probability that the network is operational over a long duration) is paramount, but is not a novel requirement in 5G mobile edge cloud and will not be discussed further in this paper.

III. Challenges for Industry 4.0

A. Capacity

Factory floor: as the factory floor network may support a wide variety of different applications, capacity requirements inherit from the most demanding ones. At one end of the spectrum, robots may send kb-long monitoring messages every second, to thousands of real-time video flows to assist autonomous vehicles. Hence, capacity requirement may range from kb/s to Tb/s in the future.

Edge data center: the edge DC should be able to process all latency-sensitive traffic from the factory floor, and hence should have at least the same capacity, and, in the context of convergence with the regular IT network, additional capacity to process the factory's office traffic.

B. Latency

Low latency is critical in Industry 4.0, as messages missing their delivery deadline may result in stopping machines/robots out of safety concerns. In addition, the performance of some machines directly depends on the network latency. In particular, for motion control systems, the latency requirement is 100 μs [3]. For high speed sensor automation control, the latency requirement varies between tens of microseconds to tens of milliseconds, while for motor drive control, the latency requirement is tens of microseconds [16]. This latency is end-to-end, e.g., from sensor to server, i.e., it includes the factory floor network and the intra data-center network.

C. Jitter Control

According to Texas Instruments, "future industrial Ethernet protocols will continue to evolve and converge to deliver hard real-time, deterministic communication links with better reliability and integrated safety" [17]. The word "determinism" is further qualified in [3], [16], with values ranging from 30 ns to a few microseconds depending on the application. Again, jitter is end-to-end.

D. Dynamics

As with 5G networks, the mobility of user elements such as autonomous vehicle delivering parts leads to a dynamic network load, which in turn has to be borne by the network. As an example, the reprogramming or migration of virtualized Programmable Logic Controllers impact how capacity is allocated on the factory floor network, which then requires to be flexible and dynamic. Unlike 5G networks, dynamics is not required at the second timescale; however, networks should be designed to be sufficiently flexible such that reprogramming a robot controller as the production line is changed to handle customized production does not require a manual reprogramming of all switching equipment on the factory floor [6].

E. Slicing

As with 5G, in the case of a converged network, office traffic should not impact latency sensitive, mission critical traffic, making hard slicing between those two types of traffic desirable. More generally, an incident in a part of a factory, e.g., a surge of traffic from one machine, should not impact other machines and disrupt the whole factory. Hence, slicing is an important feature for Industry 4.0 [7].

F. Guaranteed Delivery

As mentioned above, for safety reasons, a machine may stop when message delivery takes too long; this may happen in case packets are lost. Assuming a factory floor holds 1000 machines and each machine generates a safety message every millisecond then almost 10^{11} messages are generated each day in the factory. Assuming a packet loss ratio of 10^{-5}, the two consecutive-loss probability is 10^{-10}, which yields $10^{11} \times 10^{-10} = 10$ factory halts per day. In such context, this means that even a 10^{-5} packet loss probability is too high to ensure smooth operation of a large factory [7].

IV. Current Solutions

The trade-off between flexibility (dynamics) and performance determinism (e.g., no jitter) has long been recognized, with Ethernet being flexible and non-deterministic (Section IV-A), and Industrial Ethernet (Section IV-B) and SONET, now superseded by Optical Transport Networks (OTN, Section IV-C), being deterministic and inflexible. Passive Optical Networks (PONs, Section IV-D) come in two flavors, each addressing either flexibility or determinism but not both at the same time. Despite the recent introduction of Time Sensitive Networks (TSN, Section IV-E) the trade-off between flexibility and determinism persists, albeit with the new low-latency, low-jitter, high-speed, and guaranteed delivery use cases.

A. Ethernet

Although plain Ethernet is never used as-is for edge cloud applications, it is a very mature technology and it is tempting to think that a very lightly loaded Ethernet network will yield a low latency and small jitter. This is unfortunately not the case, as is shown by the trivial experiment described below. We injected several flows with constant bit rate into a commercial (professional) 10G Ethernet switch and measured latency for one of those flows at the output of a second identical switch directly connected to the first switch. Fig. 2 shows the resulting latency for a varying load (the ratio between the intensity of the input flow and the port capacity, here, 10 Gb/s). Note that we capped the latency axis as latency was unbounded for 100% load (and some packets were lost). Observe that, even for a load of 25%, jitter (defined by the excursion of the latency) is

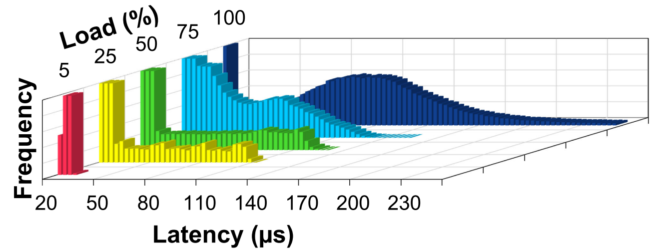

Fig. 2. Lack of determinism with Ethernet—sample experiment.

already in the same order of magnitude as the latency itself, here, tens of microseconds. The reason for such behavior is of course that multiple flows contend for the same output port and hence experience random latency, hence jitter, as shown in Fig. 3(a). Latency determinism would be achieved if packet arrivals were synchronous and regularly interleaved (Fig. 3(b)) but that would require synchronizing the clients (on the left of the switch) to the network (on the right of the switch). Hence, Ethernet is generally not deterministic. The solutions below provide, to some extent, the determinism that plain Ethernet cannot provide.

B. Industrial Ethernet

Industrial applications have long sought for determinism, for the reasons already outlined above, and protocols have been developed to enhance Ethernet and make it industry-grade, i.e., capable of carrying safety-critical messages over an Ethernet network. PROFINET, for instance, implements real-time communication on top of Ethernet, typically at very low (sub-Gb/s) data rates. TCP is also supported for non-time-critical applications. Real-time is achieved through static scheduling data over cycles of 0.25 to 512 ms. Jitter can be as low as 1 μs by synchronizing clocks of all equipment connected to the network [18]. Other protocols, for instance, EtherCAT, POWERLINK, Sercos III, and CC-Link IE have similar features.

In general, Industrial Ethernet protocols achieve determinism (with sub-μs jitter) but static scheduling hinders their dynamics and flexibility.

C. Optical Transport Network: OTN, and FlexE

Optical Transport Network (OTN) enables the multiplexing of several circuits in the time and wavelength domain over an optical transport, Reconfigurable Optical Add-Drop Multiplexers (ROADMs) infrastructure. OTN is designed to scale to several hundreds of Gb/s per wavelength, with up to 100 wavelengths per link. However, each circuit is statically allocated sub-wavelength capacity through time division multiplexing. OTN supports any mesh network topology and advanced resilience mechanisms, including both optical protection (a backup circuit is pre-computed, and traffic is switched from the working to the backup circuit in only a few ms after a failure is detected) and restoration (backup circuits are computed and established after failure detection, saving resources but incurring additional service restoration delay). Although NG-PON2 and OTN rely on highly different technology (for instance, PON only needs a passive coupler where OTN relies on ROADMs), topologies (PON

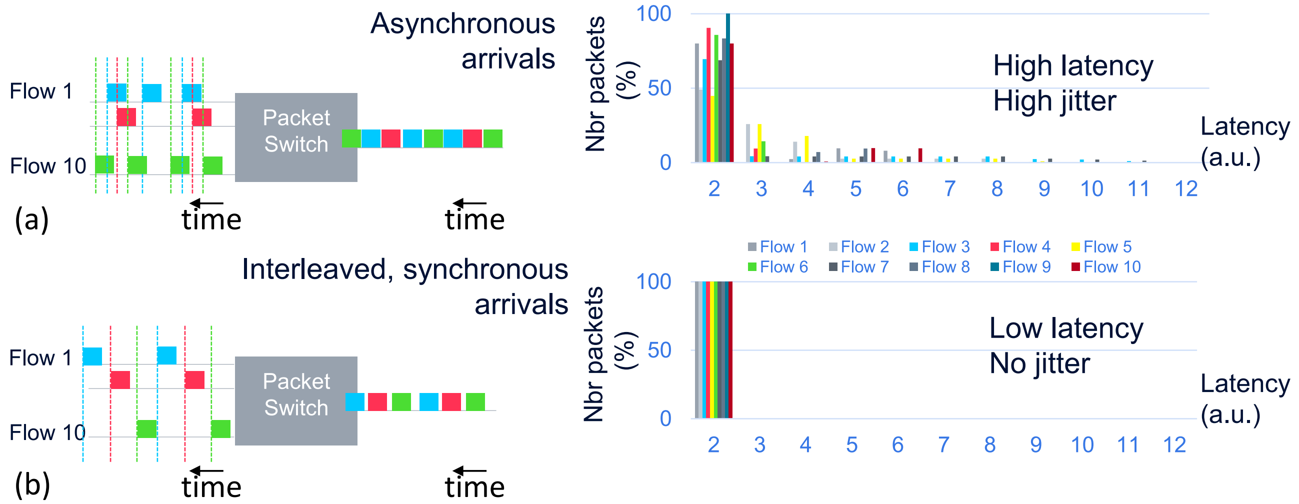

Fig. 3. (a) Lack of determinism with Ethernet is caused by asynchronous ingress frames arrivals. (b) Only perfectly synchronously interleaved ingress frame arrivals would result in a deterministic Ethernet switch.

is a star with asymmetry between down- and upstream, OTN is symmetric and assumes no underlying topology), capacities (tens vs. hundreds of Gb/s per wavelength), they share a large number of similarities when applied to fronthauling: de facto latency determinism, latency essentially constrained by physical distances – propagation; however, OTN usually requires Forward Error Correction (FEC) module, which can consume up to 10 μs of latency [19], – slicing via time and wavelength reservation, static allocation of resources preventing support of highly time-varying traffic and lack of fast reconfigurability in general. Indeed, OTN provides a limited amount of network dynamics – service establishment can take seconds or minutes due to the physics of the underlying components (e.g., laser tuning, optical switching matrix reconfiguration). Nevertheless, the support of CPRI by OTN was standardized in [20].

As a connection-oriented approach, OTN does not distinguish between traffic types, i.e., resource reservation is required via signaling prior to data transmission even for best effort (BE) traffic. This contrasts with asynchronous packet-based networks. In addition, for network synchronization, OTN must rely either on client signals to provide timing information or on IEEE 1588/PTP. But due to asymmetries in links lengths or even within network equipment, the required timing precision of a few hundreds of nanoseconds for instance for audio/video synchronization, power networks and mobile fronthaul or backhaul is difficult to achieve.

FlexE [21], a connection-oriented technology that implements TDM on top of an Ethernet network (and which in turn can be mapped to an OTN infrastructure for transport), adds additional features such as bandwidth allocation with 5 Gb/s granularity (although implementations may limit bandwidth assignment to coarser granularity, e.g., 25 Gb/s), bonding of channels, sub-rating of links, etc., it is conceptually similar to OTN and brings the same advantages and drawbacks [22]. In particular, FlexE is fully scheduled with static allocation and does not support best-effort traffic other than through static scheduling.

Although OTN or FlexE can meet the current fronthaul requirements, they currently suffers from a lack of standardization to carry CPRI traffic and limited dynamics, and their relatively high cost makes it an unlikely choice for local networks such as for factory floors.

D. *Passive Optical Networks: PONs*

Passive Optical Networks (PONs) have widely been proposed for 5G fronthauling and could also be adapted to fit the factory floor context. A survey of PON proposals for fronthaul can be found in [23] and we focus here on 2 flavors of PON: wavelength division multiplexed (WDM)-PON and time-division multiplexed (TDM)-PON.

WDM-PON dedicates a full wavelength for each cell site, resulting in a network of point-to-point dedicated links. Since the whole capacity of each wavelength is dedicated to a cell site, latency is deterministic and only due to propagation, and data delivery is guaranteed. Slicing can be implemented at a coarse granularity (a full wavelength). The drawback is of course the lack of statistical multiplexing with traffic from other cell sites or even residential traffic in case of a converged scenario, driving costs up. Obviously, such a network is also very static.

Those drawbacks are removed by adding time division multiplexing to wavelength division multiplexing, resulting in TWDM-PON standardized for instance in NG-PON2. NG-PON2 offers up to 40 Gb/s capacity downstream (from cell site to edge cloud) and 10 Gb/s upstream, shared by several cell sites. Slicing can be implemented through resource reservation (in time and/or wavelength.) Latency can be driven down to 100 μs per direction including a few km of propagation, while jitter can be virtually removed by using a Fixed Bandwidth Assignment (FBA) scheduler, rather than a Dynamic Bandwidth Assignment (DBA) scheduler [10]. Of course, using a fixed schedule i.e., FBA, offsets the benefits of statistical multiplexing and reduces the dynamics of the network, which is then essentially static. Hence, NG-PON2 provides, through the selection of the scheduling technique, a trade-off between jitter and adaptation to traffic changes, i.e., network dynamics.

E. Time-Sensitive Networks: TSN

The lack of high-speed, deterministic, dynamically reconfigurable networking solution led the Industry to leverage and build upon a previous standard, IEEE 802.1BA, designed for audio/video bridging, leading to the IEEE Time-Sensitive Networks task group. TSN relies on several standards, 2 of which are especially relevant in the context of this paper: 802.1Qbu (frame preemption) and 802.1Qbv (traffic scheduling). With frame preemption (802.1Qbu/802.1br), each node interface is able to support a limited number of classes of service (CoS), one of which with absolute priority over the other classes. Upon arrival of a high priority frame at a TSN switch, in case a lower priority frame is already been forwarded to the same destination port as that of the high priority frame, forwarding of the low priority frame stops so that the high priority frame can be forwarded; this preemption process is however not instantaneous and causes a delay of 124 ns at 10 Gb/s [24]; since, in a chain of switches this delay occurs at those switches where there is contention between low and high priority traffic, this additional latency translates into jitter. In addition, jitter is accumulated along the data path and increases further if there are competing high priority flows due to the lack of per-flow QoS management.

Such limitation is mitigated, although not fully removed, by 802.1Qbv, which relies on a network-wide schedule (and network-wide sub-μs clock synchronization for both devices and network elements, usually done with IEEE 802.1AS or IEEE 1588/PTP (precision time protocol) [25] for up to 8 classes of service. Both latency and jitter are reduced to a few microseconds for a relatively simple topology in [26].

Although 802.1Qbv enhances 802.1Qbu it suffers from two scalability issues. First, since only 8 classes of service are defined, if any interface needs to process more than 8 flows, then at least two flows will belong to the same class, contention is likely to occur and latency determinism will be lost. Second, the network-wide schedule is not defined in the standard, and schedules proposed in the literature are very time consuming, in the order of seconds per flow to schedule, making the network relatively static [24]–[27].

Nevertheless, a subset of the TSN effort is considered for 5G fronthauling, namely, P802.1CM (which defines profiles for Ethernet Transport for CPRI/eCPRI [11]), 802.1Qbu and ITU-T G.827x for time synchronization. Other industrial (non-telco) applications leverage additional TSN standards, for instance, 802.1Qbv as described above. An early paper concluded that frame preemption alone was not sufficient to meet the CPRI requirement, but that Ethernet with enhancements for scheduled traffic (802.1Qbv) might be sufficient to meet the jitter constraint [28].

TSN chipsets are readily available [29]. Despite the aforementioned limitations, it has to be noted that company Digital Design Corporation was able to implement a 60000-flows, 46-Tb/s data center based on TSN for broadcasting company ESPN [30].

V. Research Solutions

In the following, we review solutions that are still at the research stage. Some are more disruptive than others, and for all of them, standardization (if any) is highly preliminary, complicating their adoption in future networks. However, edge cloud, as a new paradigm, introduces new challenges on the optical networks, opening new business opportunities not only for incremental but also for disruptive solutions.

A. Ethernet "Fusion"

Fusion [31], [32] is a network concept building on top of Ethernet and aiming at providing determinism for a class of traffic even in the presence of best effort traffic. Incoming traffic which requires determinism is delayed by a fixed amount of time, during which the gap between incoming packets is analyzed, and best effort traffic can then be inserted within those gaps. Hence, Fusion implements a strict priority scheduling policy to enable a hybrid network where some traffic (requiring determinism) is circuit-switched and the remaining traffic (best effort) is packet-switched. Each client interface is able to multiplex several incoming deterministic flows at lower rate (e.g., 1 Gb/s) over a higher rate (e.g., 10 Gb/s) line interface. A 10 Gb/s (line rate) prototype was built and 15 ns jitter for the deterministic traffic was measured, at the expense of a latency of around 8 μs per hop, in addition to propagation. Fusion provides a similar service as 802.1Qbu but avoids the residual jitter of packet preemption. Virtual container encapsulation enables time preserving multiplexing of several flows in the deterministic traffic class.

B. PON

As mentioned in Section IV-D, current implementations of PONs do not meet the latency, constraints and dynamics requirements for future edge cloud networking. Several teams proposed gateways to map CPRI traffic over PONs, keeping in mind the strict constraints of 5G fronthauling.

In particular, in [33], a gateway called CPRI-Ethernet converter (CEC) is proposed. A CEC is located at each end of a PON network. Fixed Bandwidth Allocation is used rather than Dynamic Bandwidth Allocation, as discussed in Section IV-D, to decrease jitter, at the expense of reduced dynamics. Jitter is further reduced using a timestamping and buffering mechanism called "jitter absorber" and capacity requirement of CPRI is reduced using real-time (lossy) compression. Over a sample, FPGA-based implementation running at 2.5 Gb/s, latency overhead of 10.5 μs is due to processing (essentially, compression and decompression), leading to a total one-way latency of less than 50 μs (excluding propagation) as long as the number of cell sites remains small (latency increases to more than 150 μs for 4 cell sites), for a ns-timescale jitter.

Another CPRI-PON gateway was proposed in [34] and interfaced with a commercial 10 Gb/s bidirectional XGS-PON

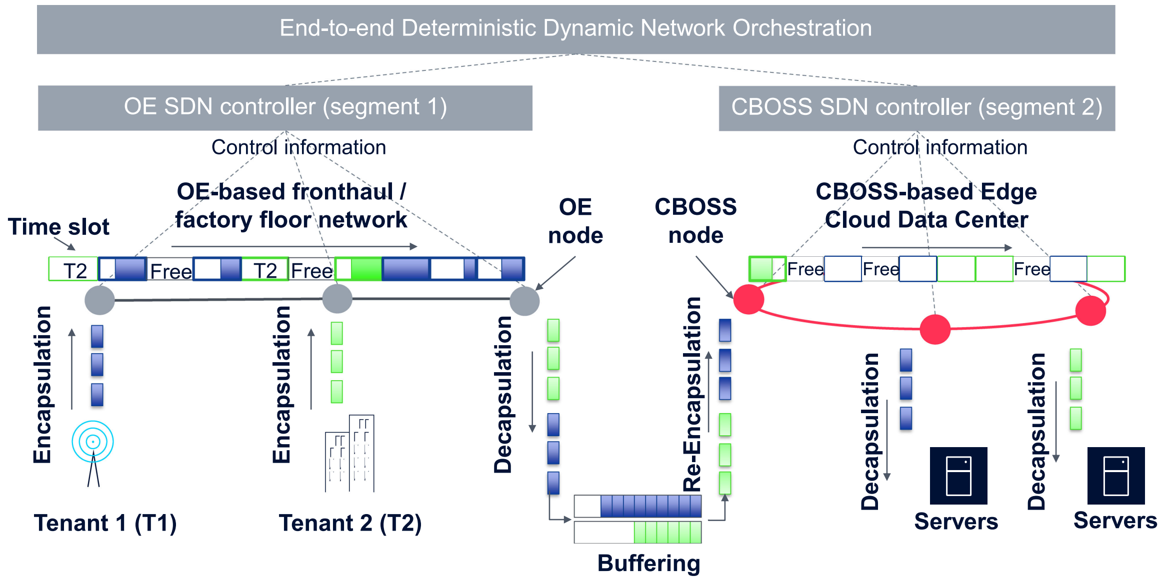

Fig. 4. Architecture for an end-to-end optical Deterministic Dynamic Network. Each segment (for instance, a 5G fronthaul or a factory floor network, left, and an intra-data center network, right) are deterministic and dynamic, guaranteeing a resulting DDN end-to-end, even if (control layer) the networks are controlled independently, and (data layer) if carried frames are decapsulated and re-encapsulated at the interface nodes.

network, again leveraging Fixed Bandwidth Allocation. The gateway performs media conversion and handles synchronization and jitter reduction/compensation through buffering. The overall measured round-trip latency was 115 μs excluding propagation, and, in presence of competing best-effort flows (emulating a converged mobile/fixed access scenario), jitter of up to 8 μs fully compensated through buffering. A third such CPRI-PON gateway was proposed in [35], again with similar features, notably, a 45 μs one-way latency excluding propagation.

C. *Optical Slot Switching: OSS*

Optical packet switching, whereby client frames/packets are switched in the optical domain with no or limited (e.g., for packet header processing) electronic processing, has been widely proposed in the past, both for data centers and transport networks, see for instance [36], [37] and references therein, typically to optimize cost (through reduction of the number of costly electrical interfaces), power consumption and latency. Optical Slot Switching moves all or most electronic processing and buffering to the ingress node. Such networks are typically highly dynamic but offer little to know guarantee or determinism other than through reservation of complete wavelength when combined with optical circuit switching in a hybrid optical packet/circuit switching architecture. Indeed, the switching of arbitrarily sized packets in a sequence of nodes with arbitrary degree inherently leads to contention, which is difficult to annihilate. Determinism is then enabled using fixed-duration packets or "slots" over either a single-node star-shaped network (à la PON) or a bus or ring network where all nodes have a degree of at most two.

Thus, similar to TWDM-PON with fixed bandwidth allocation, many ring- or bus-based (rather than tree-based) optical slot switching (OSS) networks were proposed in the past, including HOPSMAN [38], POADM [39], OBTN [40], OPST [41], FOADM [42] and TSON [43]. All of those solutions multiplex data encapsulated within time slots, carried by one of several (data) wavelengths. Capacity is reserved through time-wavelength slot reservations. In addition to the data wavelengths, a separate control channel may carry the headers of the (synchronous) data channels to provide transparency: once inserted on the fiber, optical slots remain in the optical domain when transiting through intermediate nodes, and conversion to the electrical domain occurs only at the destination node. The lack of electrical regeneration of optical slots at intermediate nodes between source and destination decreases the number of costly and energy-hungry transponders and moves all latency/jitter to the ingress node: once data is inserted on the ring, it sustains a deterministic latency typically driven by propagation. We observe here that all those solutions were proposed for transport networks before the (mobile edge) cloud era, typically in the metro segment, at a time when 5G was barely envisioned. Therefore, latency determinism was not a design requirement; capacity was usually limited to 10 Gb/s per wavelength (typically, 40-80 wavelengths can be multiplexed in transport networks), due to the lack of key components, notably, burst mode reception at higher data rates. Network slicing, however, was already provided de facto through optical slot reservation.

Optical slot switching was also proposed within data centers [44]–[46] and scalability to very large data centers (hundreds of thousands of servers) was investigated; in NEPHELE [45] the data center network fabric can be reconfigured every fraction of a second (e.g., ca. 200 ms) limiting dynamics to around that value. Although not investigated, those two networks clearly also ensure latency determinism through time and wavelength slot reservations.

For all network concepts listed in this section, prototypes were built, and, in the case of [40], a network was even deployed [47], however, the technology has always been in search

FH: fronthaul
FF: factory floor
DC: intra data center

	Network segment: FH	FF	DC	Characteristics: Total Network capacity	Latency (excl. propagation)	Jitter	Resource reservation dynamics	Hard Slicing	Guaranteed delivery	Maturity
Standard Ethernet (Section IV-A)	✓	✓	✓	Pb/s	~µs per hop	Unbounded	N/A	No	No	Production
Industrial Ethernet (Section IV-B)	✗	✓	✗	Typ. Gb/s	0.1-100 ms long schedule; sub µs per hop	Tens of ns to µs timescale	Static	Yes	Yes, depending on class of service	Production
TSN (Section IV-C)	✓	✓	✓	Gb/s	Similar to Ethernet	ns timescale (few classes of service)	Static	Limited to few (8 in 802.1Qbv) classes of service per node interface	Yes, depending on class of service	Standardization ongoing, products exist
PON – current (Section IV-D)	✓	✗	✗	~100 Gb/s	~100 µs	N/A	Static (FBA)	Yes (per flow time-wavelength slots allocation)	Yes	Production
OTN / FlexE (Section IV-E)	✓	✗	✗	Tb/s	Dominated by propagation	Nearly jitterless (circuit switching)	Slow (second)	Yes (frame allocation, coarse multi-Gb/s granularity)	Yes	Production
Ethernet / FUSION (Section V-A)	✓	✗	✗	~100 Gb/s	8 µs per hop	10 ns timescale (few classes of service)	N/A	Limited to few classes of service per node interface	Yes	Lab
PON – research (Section V-B)	✓	✗	✗	~100 Gb/s	~10-100 µs	ns timescale	Static (FBA)	Yes (per flow time-wavelength slots allocation)	Yes	Lab
OSS for FH/FF (Section V-C)	✓	✓	✗	Tb/s	ns to µs per hop	ns timescale possible	Fast (sub-second)	Yes (per flow time-wavelength slots allocation)	Yes	Lab
OSS/DC (Section V-C)	✗	✗	✓	Pb/s	ns to µs per hop	ns timescale possible	Fast (sub-second)	Yes (per flow time-wavelength slots allocation)	Yes	Lab
DDN (Section V-D)	End-to-end (FH/FF: OE; DC: CBOSS)			Designed for 1.6 Tb/s per bus (OE); Pb/s in torus configuration (CBOSS)	1-100 µs timescale	ns timescale	Fast (ms-timescale)	Yes (per flow time-wavelength slots allocation)	Yes	Lab

Fig. 5. Overview of the technologies reviewed in this paper in terms of targeted segment and performance for key edge cloud metrics.

of an application and has not enjoyed commercial success. Although those highly promising concepts had the capability to tackle networking issues relevant to 5G and Industry 4.0, determinism (and often latency, at least for the pre-2015 papers) were not specifically investigated or optimized, and were left for further research.

D. Deterministic Dynamic Networks: DDN

The concept of DDN (Deterministic Dynamic Networks) builds upon recent optical slot switching activities and extend those into a consistent, homogeneous end-to-end optical network vision, as depicted in Fig. 4 [48]. DDN creates an end-to-end virtual optical circuit switched network at a traffic flow granularity to provide deterministic low latency and bandwidth on demand. To meet this goal, DDN relies on and combines two complementary degree-2 (ring or bus) slot switching technologies: Cloud Burst Optical Slot Switching (CBOSS) [49] for intra-data center and Optical Ethernet (OE) [50], [51] for inter-data center transport; each segment is driven with a Software Defined Network (SDN) control plane (which manages resource allocation in each segment through scheduling – each schedule is computed to respect latency and bandwidth requirements of each time sensitive traffic flow) and an end-to-end orchestrator. In order to take advantage of statistical multiplexing, and reduce slot reservation complexity, best effort traffic accesses the channel in an opportunistic way – the first non-reserved slot is used. Overall, the network architecture achieves deterministic latency and bandwidth only for flows which deserve it. Fig. 4 also depicts an example of inter-segment slots reservation and synchronization for two flows or tenants. Even if tenant traffic goes through buffering at segments interconnection (client frames encapsulated in the first segment are decapsulated then re-encapsulated by the first node of the second segment), the queuing time is controlled. DDN was experimentally shown to provide end-to-end latency below 100 μs (without propagation), sub-microsecond jitter and millisecond-timescale schedule dissemination for high dynamics [48].

VI. Conclusion

Edge cloud networks, which will be used for future 5G fronthaul networks and Industry 4.0 networks, will have very strict requirements on capacity, latency, jitter, dynamics, slicing and data delivery guarantees. We reviewed current and future networking technologies prone to meeting most (current) or all (future) requirements. Fig. 5 summarizes the contents of the paper through the comparison of all reviewed technologies. It should be noted that no mature technology is able to meet the requirements of next generation edge cloud networks; in addition, further (somewhat niche) applications envisioned in 5G such as indoor positioning will have even more stringent requirements in particular in terms of jitter (e.g., femtosecond timescale) which are not envisioned with any of the reviewed technologies. Hence, progress has to be made at least on two fronts: maturing technologies proposed in the lab that are able to meet the foreseen requirements of future edge cloud networks, and proposing new technologies to cater to some of the less mainstream yet important use cases of 5G.

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