Sabella, R., Iovanna, P., Bottari, G. y Cavaliere F. (2020). Optical transport for Industry 4.0. *Journal of Optical Communications and Networking*, 12(8), pp. 264-276..

DOI: https://doi.org/10.1364/JOCN.390701

JOURNAL OF
Optical Communications
and Networking

Optical transport for Industry 4.0 [Invited]

Roberto Sabella,[†],* **Paola Iovanna, Giulio Bottari,** and **Fabio Cavaliere**

Ericsson Research, Pisa, Italy
**Corresponding author: roberto.sabella@ericsson.com*

Received 14 February 2020; revised 23 June 2020; accepted 23 June 2020; published 10 July 2020 (Doc. ID 390701)

Industry 4.0 represents a new industrial revolution that will dramatically change the landscape in many sectors, including manufacturing and logistics. Robotics, machine intelligence, and new forms of connectivity are key ingredients of this paradigm. 5G mobile networks are expected to play a crucial role, supporting a lower cost per transported bit in air and a lower latency compared with 4G. 5G radio ensures different performance levels in very heterogeneous coverage situations, including a mix of indoor and outdoor contexts. Mobile network evolution requires new transport networks to address the new challenging requirements: increasing transmission capacity, compatibility with latency-critical applications, significantly reduced cost with respect to conventional metro network segments, lower energy consumption, and, in some cases, switching capabilities. Optical communications and networking will play a key role in these new transport scenarios, where tailored transmission techniques and network architectures are needed. This paper discusses the requirements and challenges that Industry 4.0 scenarios pose to optical communications and networking architectures. Performance of optical transmission schemes, tailored to support these new radio access networks, are detailed and benchmarked. A network test bed, focused on transport for vertical use cases, is described. Experimental results demonstrate the compliance of the proposed optical transport network with a latency-critical cloud robotics application, which presents industry-grade connectivity needs.

https://doi.org/10.1364/JOCN.390701

1. INTRODUCTION

The advent of 5G networks is enabling a true revolution in all industrial segments, providing a new way to wirelessly connect all elements in a factory plant or in a complex logistics system. It is the world of Industry 4.0, a concept that has evolved from a German initiative in 2011 [1] to a globally adopted industrial transformation paradigm enabled by digitalization. The initiative has developed many revolutionary concepts [2] that have resulted in a quantum leap in the networking of humans, machines, robots, and products. Leading companies, especially in the manufacturing sector, are combining information and operation technology to create value in entirely new ways.

Providing guaranteed real-time communication between humans, robots, factory logistics, and products is a fundamental prerequisite to unleash the full potential of Industry 4.0. A new telecom network, namely, the 5G network and its future evolutions, meets the challenging requirements of huge capacity, extreme low latency, dense connectivity, and different types of mobility needs [3–6]. To operate in that context, 5G has the requisite performance capabilities to ensure such industry-grade expectations. Distributed edge cloud [7] and network slicing [8] are also important concepts to serve different traffic profiles over the same network infrastructure.

Optical technologies will also play a role in addressing these requirements in terms of bandwidth, latency, and reliability within the radio access network (RAN). This application goes beyond the "traditional" segments where optical communications and networking technologies have typically been deployed, such as backbone networks, metro networks, and passive optical networks (PONs). This means that vertical industries, such as manufacturing plants and logistics systems (airports, maritime ports, warehouses, etc.), will require specific telecom architectures based on new forms of optical transport, which will be detailed in this paper. Specifically, Section 2 describes relevant vertical use cases for Industry 4.0 and introduces the concept of the "non-public network." Section 3 goes through the evolution of RANs with various deployment options. Section 4 describes challenges and solutions in using optical transport in support of 5G for vertical applications such as those described in Sections 2 and 3. Section 5 explores photonic technologies and components that are expected to play a relevant role in this context. Finally, Section 6 reports on experiments and associated research results.

2. TELECOM NETWORK FOR INDUSTRIAL SCENARIOS

There are many different industrial applications, each one having its own set of requirements in terms of necessary radio coverage, type of machine communications (massive, critical, etc.), and overall complexity. Regarding coverage, it can be indoor, outdoor, or mixed. The coverage area can range from a limited local area to a broader geographical area. For example, in manufacturing, local indoor coverage is the most essential aspect, but outdoor areas may also be present in this use case, e.g., to reach a warehouse in the vicinity of the manufacturing plant. Likewise, logistics in maritime ports, airports, or even energy/water distribution networks have a core parameter in their use case to include regional or even national coverage. Examples of intermediate coverage scenarios are represented by manufacturing companies having several sparse production plants with the need to be interconnected and linked to suppliers and logistics systems. In these cases, there is a clear mix of indoor and wide area outdoor scenarios, as well as a mix of various types of human/machine communications, each with their own specific requirements.

One of the most important industrial sectors, which is taking the lead in driving the Industry 4.0 concept, is manufacturing. In this context, a typical factory floor in a production/assembly plant includes robots, systems, and machineries of various kinds, automated guided vehicles (AGVs), physical controllers, sensors (including cameras), and tools. From the Industry 4.0 perspective, this "physical layer" in the plant is enriched by a "cyber layer," constituted by virtualization of some control functionalities in a cloud platform, typically on the premises. This is in contrast to more traditional manufacturing settings where individual industrial robotic cells are deployed, each with a local computer [a programmable logic controller (PLC)], which costs money, takes up space, and generates heat that requires cooling. Such isolated robot controllers also have limitations on their coordination. Moving control functionalities to a cloud environment allows for reduced footprint for robots, higher density production, lower robot cost (as the local control computer is not required), and simpler cross-robot communication. Redundancy for resiliency purposes is also facilitated.

5G technologies, if supported by an appropriate transport layer based on optics, can provide the connectivity for all of these elements and thus enable the gradual introduction of Industry 4.0 features.

In 2018, Ericsson, Comau (the industrial automation company of the FCA group), and Telecom Italia (TIM) began deploying a smart-manufacturing proof of concept (PoC) [4,9], illustrated in Fig. 1. It is permanently hosted in the Comau headquarters, in the same factory in which commercial robotic cells are built and tested. The PoC consists of two industrial robots (a manipulator and a welding gun), a conveyor, and control logic that manages all of these elements. The control logic, driving the robotic station responsible for the concurrent actions of the two robots and the conveyor, would normally reside in a control cabinet named "Station PLC." In the PoC, the functionalities of the control logic were moved to an on-premises cloud platform by transporting ProfiNet [10] control signals over cellular links with an appropriate framing. Moving this portion of the control to the cloud enables the virtualization of the associated functionalities, which can then run as virtual machines on commercial-off-the-shelf (COTS) hardware instead of on dedicated industrial computers. This essentially creates a virtualized PLC. Figure 2 indicates the various components of such a cloud environment, focusing on the latency of the various control functions.

Fig. 1. 5G-connected smart manufacturing pilot deployed by Ericsson, Comau (FCA), and TIM in Torino, Italy.

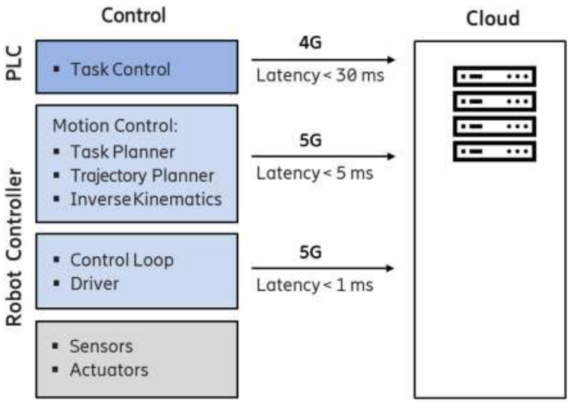

Fig. 2. Virtualization of control in the cloud: cellular technology generations and maximum tolerable latency values.

Before performing experiments on the wireless connectivity between robots and the PLC, we determined the maximum latency values that could be tolerated if task control, motion control, and lower control functions (e.g., the control loop) were migrated to the cloud. The values of 30, 5, and 1 ms were obtained in our tests, respectively. Those values can be mapped to the performance of 4G and 5G networks as reported in Fig. 2. As indicated, 4G is sufficient for task control but not the other functionalities. The actual *measured* values in the PoC with wireless connectivity are reported in Section 6. The most challenging requirement comes from migrating the control loop (used for control of motor stability), which would require a reduction of latency to less than 1 ms. Currently, this may not be achievable, even with 5G. In fact, this requires supporting the transmission of isochronous real-time (IRT) [6] type of communication. Having the control loop in the cloud, however, might not be useful for most robot implementations, as this functionality is typically integrated on the same card as the robot driver.

Although there are different requirements for different industrial applications, it is possible to summarize the general requirements imposed on cellular connectivity for the manufacturing use case as follows:

- Data rates to be supported are very much use case specific and will vary from a few kilobits per second (Kb/s) to tens or even hundreds of megabits per second (Mb/s). Some use cases require massive data transfer with gigabit per second (Gb/s) throughput. Moreover, in contrast with traditional consumer mobile traffic, which is typically heavier in the downlink direction, the data traffic from the industrial shop floor is generally uplink intensive (due to, for example, massive distribution of sensors and high-definition cameras in the field).
- End-to-end (E2E) latency with a guaranteed upper bound and controlled jitter is essential for critical automation use cases and, in particular, to connect a robot to a remote-control system. Safety applications, such as transporting the ProfiSafe [10] protocol, require no more than 1 ms latency.
- A need to guarantee traffic separation and quality of service assurance per device, per service, and even per location of the device.
- Mobility is a feature needed by all of the equipment and devices that need to move freely around indoor and outdoor environments covered by a cellular network.
- Scalability, since the number of industrial devices supported by the connectivity must be able to scale from a few devices to thousands.
- Some industries show particularities as well with respect to network roll-out and planning requirements due to special conditions like metal walls, high ceilings, heavy electromagnetic interference, etc.
- Perimeter protection and access control have been widely used to protect the confidentiality of processes, operational data, users, and equipment in manufacturing plants. With 5G, this physical isolation is no longer maintained, and specific protections of the radio layer are needed [11]. These protections include robust networks that can withstand attacks (e.g., radio jamming) and secure control of cyber-physical systems (e.g., remote control in a factory environment). Both the signaling traffic and the user plane traffic can be encrypted and integrity protected. User plane integrity protection is a new feature that is valuable for small data transmissions, particularly for constrained Internet of Things (IoT) devices.
- Finally, reliability and availability of the connectivity layer are crucial in the industrial environment, since any network downtime can lead to non-negligible production lags with consequent economic damage. In this regard, independent of the specific radio access technology (4G or 5G), special care must be given to network and system design, often requiring dedicated coverage and equipment redundancy schemes as well as proper fault management procedures. This is needed to increase network availability to service levels (up to five nines) not normally assured in traditional commercial networks for retail services.

Logistics is another large industrial sector where Industry 4.0 concepts will apply intensively (in this context, “logistics” is the process of managing how resources are acquired, stored, and transported). A practical example is represented by a maritime port and its operations. In this scenario, digital transformation driven by 5G has a large impact, providing new opportunities to enhance the productivity, efficiency, safety, and sustainability of port operations. It is crucial here to create transparency in the data exchange among the different actors of the chain. This calls for aggregation and translation of data flows in a specific logistics node, such as the port terminal, and across geographical distances. The H2020 Corealis Project [12] is experimenting with the application of 5G to logistics in the Port of Livorno, Italy, for the optimization of the unloading of goods from trucks and loading them to cargo ships and vice versa. The goal is to minimize the transit time of goods in the port, which in turn helps to cut down on emissions.

The port use case is supported by a 5G dedicated network covering the port terminal area. The radio network is provisioned to ensure a minimum throughput of 15 Mb/s for each HD camera installed on the docks with a latency less than 15 ms to provide an immediate view of reality to port operators through an augmented reality/virtual reality (AR/VR) application. The 5G network must support a large and densely distributed number of connected objects in the area (e.g., sparse sensors and cameras). Moreover, operations in the port are considered mission critical so that deterministic and resilient network behavior must be guaranteed. This imposes the use of a connectivity solution with dedicated network coverage, with local gateways to terminate the user plane traffic and the direct interconnection of the application layer running on the premises.

The two aforementioned scenarios (smart manufacturing and port logistics) are based on a non-public network (NPN). An NPN is a “dedicated” cellular network for the sole use of a private entity, which can be an enterprise or an authority, i.e., it is essentially a network that provides a specific service in a private or public area.

In contrast to public networks that offer mobile connectivity to the general public, a 5G NPN provides 5G network services to a private or institutional organization on their premises, such as a factory or campus. This approach allows compliance with the stringent industry-grade requirements described above. The private approach also provides the security level required for transporting confidential and critical data and avoids malfunctions in the public networks from affecting operations in the vertical premises. The 5G NPN topic has been addressed by multiple standards developing organizations (SDOs). The 3rd Generation Partnership Project (3GPP) body has studied this topic, for example in [13]. The 5G Alliance for Connected Industries and Automation (5G-ACIA) [14] has been very active in this field, being the most representative vertical association. 5G-ACIA proposes four scenarios of 5G NPN deployment: the first scenario is a standalone 5G private network, whereas the other three scenarios partially reuse some network functions from a public network with different levels of sharing. Shared scenarios are intended to reduce the total cost of ownership (TCO), while still ensuring acceptable levels of quality of service, isolation and security. While increasing the level of sharing reduces the cost, it also reduces the network guarantees and isolation.

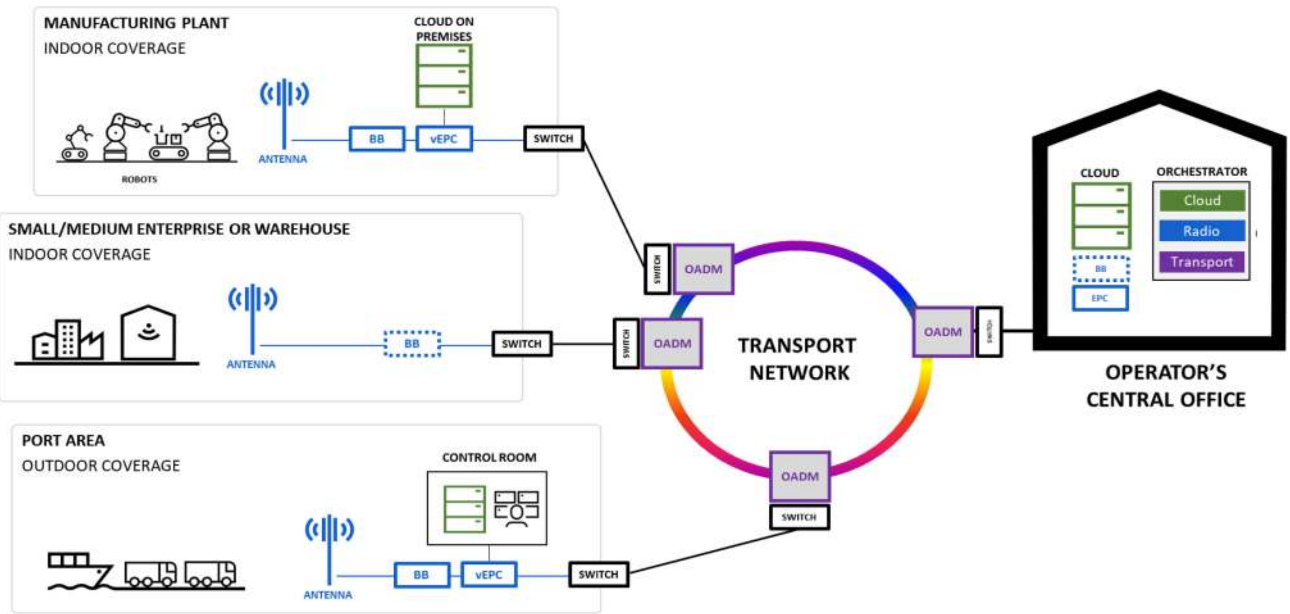

Fig. 3. Example of a transport network scenario [28] to serve different vertical needs.

Figure 3 illustrates three generic vertical services sharing the same transport network, which is depicted as an optical add/drop multiplexer (OADM)-based optical fiber ring in the figure. There are several reasons to use a ring topology, e.g., add/drop connectivity, protection; this will be discussed further in Section 4. A first use case is constituted by a manufacturing plant where a standalone NPN offers wireless connectivity to a robotic cell. In this setup, both a baseband (BB) and a virtual evolved packet core (vEPC) are on the plant premises. The same transport network can also serve a small/medium enterprise or a warehouse with an indoor network. In this case, the vEPC is hosted in an operator's central office (CO), while the BB can be hosted on the premises or similarly located in the CO (dashed box in the figure). Finally, the same transport infrastructure can also serve as backhaul for operating a third use case in a port area in support of a logistics scenario.

The architecture in Fig. 3 also contains the orchestration building blocks, located in the CO of the network operator, in charge of the automation of radio, transport, and cloud resources. Its task is to set up, operate, and monitor each vertical service. It also handles the 5G network slicing, which is used to support different traffic profiles over the same physical radio network.

3. EVOLUTION OF RADIO ACCESS NETWORKS

It is important to understand the evolution of RANs, as it has led to a need to introduce optical transport capabilities to support this portion of the network. We review this evolution here.

The advent of 5G networks has led to a dramatic increase of capacity requirements and more complex network topologies. A significant change is represented by the transformation of the radio base station (RBS) architecture. A base station essentially consists of a baseband unit (BBU) and a radio unit (RU). The former includes all processing functions performed on the BB signal (e.g., digital BB computation for beamforming), whereas the latter works on the radio frequency (RF) signal and contains the antenna element, the RF power and low-noise amplifiers, and the circuitry for digital-to-analog and analog-to-digital conversion of the downlink and uplink signals. In the traditional monolithic implementation, both the BBU and RU are integrated in the same rack and connected via a RF cable. However, as RANs evolved, the RBS was split such that one BBU handles multiple remote RUs (RRUs), saving equipment cost. This transformation simplifies the deployment because the RRUs are simpler to install and configure, reducing the operational expenditures (OpEx); it also allows better coordination among the RRUs connected to the same BBU. The typical distance between the BBU and RRU is of the order of a few hundred meters up to a few kilometers.

To enable that transformation, it was necessary to introduce a new type of interface, referred to as *fronthaul*, and related communication protocols. The most common fronthaul protocol is the Common Public Radio Interface (CPRI) [15], based on a frame able to carry digitized in-phase and quadrature (IQ) antenna samples while respecting tight requirements in terms of clock and frequency accuracy as well as latency and synchronization of data in both the uplink and downlink. That interface can adapt to any radio standard but is bandwidth hungry. For example, to carry 40 MHz of radio bandwidth, corresponding to about 150 Mb/s of true traffic, requires a 2.5 Gb/s CPRI data rate. For this reason, the 5G new radio (NR) interface [16] requires efficient fronthaul interfaces based on a different split of functions between the BBU and RRUs to prevent bandwidth explosion. A functional split determines the amount of functions left locally at the antenna site and the amount of functions centralized at the CO. Several different functional splits are possible in 5G NR [17]. No single optimal splitting solution can be found that meets the trade-off between RAN performance and transport network requirements. Realistic deployments will therefore likely need to adapt to the available transport infrastructure on a case-by-case basis. For this reason, 5G networks should ideally support different functional splits.

One relevant split specification is evolved CPRI (eCPRI) [18]. While CPRI is basically a time division multiplexing (TDM) transmission of antenna signal samples, which poses tight requirements in terms of latency, synchronization, and bandwidth, eCPRI transmits the modulation symbols and thus reduces the amount of required bandwidth while making use of statistical multiplexing. This enables scaling up the radio bandwidth by 1 order of magnitude without a dramatic increase in the bit rate to be transported between the BBU and RRUs as compared to CPRI.

If advanced antenna array systems (AASs) are considered, where many radiating elements of the antenna must be fed, it is possible that a global transmission capacity of many hundreds of Gb/s may be required. To get an idea of the fronthaul bandwidth requirements, consider the following examples: A 5G system operating below 6 GHz of carrier frequency, with a radio band of 200 MHz, and with an antenna array of 64 elements (8 × 8), would require a fronthaul capacity per sector of about 100 Gb/s, assuming an eCPRI fronthaul interface. Such fronthaul capacity requirements would explode to 600 Gb/s in the case of a classic CPRI interface. Furthermore, if carrier frequencies at millimeter waves (mmWave) were used, to enable larger usable bandwidth, those numbers significantly increase. For example, a 400 MHz radio bandwidth, in the mmWave band, with 256 radiating elements (16 × 16), would lead to a global fronthaul required capacity in the range of 400–800 Gb/s assuming an eCPRI interface. With a CPRI interface in the fronthaul, those numbers [e.g., more than 2.5 Tb/s for a multiple-input multiple-output (MIMO) system with 256 antenna ports and 100 GHz bandwidth] would further explode and become difficult to manage [19].

A second step of transformation of RAN architectures was the introduction of the centralized RAN (C-RAN) paradigm [20]. In a C-RAN, all BB processing (including RAN L1, L2, and L3 protocol layers) is located at a central location that serves multiple distributed remote radio sites. The hybrid automatic-repeat-request (HARQ) loop, such as the Packet Data Convergence Protocol (PDCP), is centralized, as well as most of the radio control functions (RCFs). The RCFs are in charge of load sharing among system areas and different radio technologies, the policies to control the schedulers in the BB, the packet processing functions, the negotiation of quality of service (QoS), etc. The centralization of those functions allows network operators to simplify their network architecture and management as well as to reduce the number of sites, resulting in further cost reduction, especially in terms of OpEx. Packet processing and control functions can eventually be virtualized on generic purpose processors (GPPs), for example, hosted in a data center, leading to the concept of cloud RAN. Even time-critical BB processing functions can be centralized, but virtualization is more critical in this case, and thus they are more suitable for specific purpose processors (SPPs). Depending on the time sensitivity of the fronthaul interface between the RRU and BBU, the maximum distance between the RRU and BBU ranges from a few kilometers up to a few tens of kilometers. C-RANs represent the relevant parts of some network scenarios considered in Section 6.

These transformations of RAN architecture and of the RBS have important implications for the underlying transport network. The most important one is that fronthaul, which was typically arranged as a point-to-point link between one BBU and one RRU, becomes a new transport segment that must support stringent 5G requirements. Moreover, based on the above examples, we conclude that any fronthaul segment of a 5G (and beyond) network requires a very high transmission capacity in this network segment. The role of optical fiber communications is essential as discussed in the next sections.

4. OPTICAL TRANSPORT FOR VERTICAL INDUSTRIES

Section 2 described some relevant vertical use cases for Industry 4.0 and the concept of NPN. Section 3 described the evolution of RANs with various deployment options. It is worth returning to Fig. 3, which depicts several relevant vertical scenarios and the related radio network architecture. This figure also illustrates a possible optical transport deployment that will be described later in this section.

The heterogeneity of use cases highlights the fact that the transport network will have to concurrently meet all of the stringent requirements associated with each of the scenarios. First, there will be huge growth in traffic volume that will be generated by the different services, resulting from a mix of high-quality video (e.g., coming from high-definition cameras placed in different locations in manufacturing plants) and a massive number of devices that communicate with the cloud. Second, there are stringent latency requirements associated with various critical machine communications (e.g., the communication between a PLC and the machineries associated with it) and with remote control of elements that need to have a somewhat tactile reaction.

To meet these requirements, optical communications and networking is a suitable option. In fact, optical transmission can support these very high capacity requirements. However, the true challenge is to support these capacities while at the same time drastically lowering the cost-per-bit of transport. To achieve low latency, it will be necessary to avoid multiple stages of electronic switches. While electronic packet switches are very useful tools to flexibly connect the different elements of a network, they introduce latency at each stage [e.g., a few microseconds (μs) to hundreds of μs in some cases] that accumulates along the path from source to destination. Furthermore, this latency is typically a function of load, leading to variations in the delay. To avoid these issues, wavelength division multiplexing (WDM) optical switches, by operating directly in the optical layer and avoiding packet processing, can significantly alleviate this problem [e.g., stable sub-nanosecond (ns) delays are possible]. WDM allows the combination of many wavelength channels onto the same fiber and enables the possibility to transmit and route each of those channels without any packet processing that, unavoidably, would introduce latency.

In this way, the wavelength-routed transport segment is equivalent to a point-to-point wire with a deterministic propagation delay.

In Fig. 3, wavelength channels travel along the transport network (e.g., an optical ring, as shown); a channel is added/dropped by the OADMs at the channel's endpoint nodes, while bypassing the intermediate OADMs. With cost-effective fixed transmitters or OADMs, optical channels (i.e., wavelengths) are assigned and cannot be reused for other source-destination pairs so that the number of remote sites connected through a single ring could be limited. Of course, more optical rings can serve more remote nodes if needed. Such a topology is well matched to the C-RAN scenario where multiple RRUs are connected directly to the BBU located in a CO. RRU interaction is not needed, but currently RRUs have the possibility to be daisy-chained. Optical channels spanning the same length in both the downstream and upstream directions, i.e., traveling on the same arc along the ring, will ensure a symmetric delay in both directions.

If optical transmission and switching are fundamental tools for the transport infrastructure, the real challenge is to implement links and nodes whose cost is an order of magnitude lower than corresponding elements in conventional optical transport networks. For instance, hundreds of Gb/s transmission and wavelength selective switch (WSS)-based optical switches have already been commercialized for metro networks for many years. However, those systems are too costly for the radio access segment. One order of magnitude of cost reduction for optical transceivers and one or two for optical switches [21] represent typical research challenges [22] (e.g., a cost target of \$0.5/Gb/s for fronthaul links and \$0.05/Gb/s for intra-board interconnect). New integrated photonic technologies can in fact enable low-cost transmission and switching systems in different segments of the network, simplifying the architecture of some of those systems while performing better than electronics for some key features [23].

The previous section focused on the architecture of the RAN itself. In the following, to better highlight the role of photonics in the radio access space, the significant changes of the *transport* architecture of 5G networks are discussed.

In the past 5 years, several architectures have emerged to support the needs of 5G transport. Relevant examples are the XHaul network architectures defined and deployed in the European projects 5G Crosshaul [24] and 5G-XHaul [25], addressing both data and control plane evolutions. In both projects, optical technologies constitute the key elements of the transport layers expected to support any radio split option of 5G [17]. These architectures are typically based on a switched network, characterized by a variety of topologies (ring, tree, or low-degree mesh) and covering a distance up to about 20 km between BB site and antenna site, encompassing both fronthaul and the first aggregation stage of backhaul. This creates the conditions for the convergence of mobile and fixed services on the same infrastructure, in either of two possible directions: a RAN can be extended to support fixed access services, through appropriate segregation of the different types of services, or a fixed access infrastructure, e.g., a PON [26], can be used to connect antenna sites at some of its optical network terminals (ONTs). The "Xhaul" term was introduced to indicate a transport network able to support both backhaul and fronthaul needs, based on any possible radio split option [17]. Later, the concept evolved to include the support of other types of services, not necessarily mobile ones, e.g., an operator using the mobile access infrastructure to provide dedicated fixed connections to enterprise premises.

The net result is that the same transport infrastructure can be used to convey both 5G radio traffic and fixed enterprise traffic so that an operator can exploit any existing transport infrastructure (such as a metro ring) to smoothly introduce 5G radio [27].

Now, two aspects are crucial for a transport network. The first one is that, to meet low E2E latency (the fiber introduces a delay of 5 μs/km), some of the core network functions need to move closer to the access site, i.e., from a few big operator sites, sparsely distributed in a wide area, to more densely distributed, small data centers (as core functions are virtualized). The second aspect is the virtualization of the network functions, which paves the way to a more efficient orchestration of radio, transport, and cloud resources. In this scenario, the same CO hosts nodes with different functions such as centralized BB processing, cloud functionalities dedicated to specific vertical applications, switching, and routing.

To serve these needs, we have defined and demonstrated an optical-based transport architecture for 5G [28,29] covering up to 20 km from the CO to the antenna site and dedicated to carrying both fronthaul and backhaul signals. To deal with time-sensitive fronthaul interfaces, this transport solution guarantees low latency (of the order of 100 μs), symmetric delay in the two propagation directions (i.e., asymmetries of the order of 10 ns), support for tight synchronization both in frequency (a few parts-per-billion) and phase (of the order of 1 ns) between the two end points where, for example, an RRU and a BBU are attached.

As stated in Section 3, eCPRI shows significant capacity savings with respect to CPRI. The maximum bit rate of a single eCPRI channel is lower than 25 Gb/s, which is compatible with state-of-the art technology for small form-factor pluggable (SFP) optical transmission modules based on non-return-to-zero (NRZ) on–off keying (OOK) modulation, which is the most simple and cost-effective modulation format.

The use of dense wavelength division multiplexing (DWDM) enables a clear separation of the resources for the different slices. Moreover, the combined use of DWDM with deterministic framing/switching enables the separation of resources with subwavelength granularity, while preserving the deterministic approach needed for latency control. In this context, the main challenges for the optical transport network for access are i) that the cost should be reduced by 1 order of magnitude with respect to metro and aggregation networks and ii) manageability. With regard to the second aspect, traditional optical networks were quite static as compared to current traffic behavior where, with the virtualization of some network functions, the dynamicity of the traffic increases and traffic forecasting becomes difficult. Hence access optical networks should be easily reconfigurable and readily monitored. The monitoring topic is addressed in several H2020 projects. For example, METRO-HAUL [30] addressed monitoring for advanced optical node architectures (e.g., open reconfigurable

OADMs (ROADMs), disaggregated nodes, new photonic technologies). However, today's optical networks require fast reaction and configuration time, which are for future study.

5. ENABLING OPTICAL TRANSMISSION TECHNOLOGIES

Manufacturers of photonic-based equipment are challenged to reduce the cost and size of their products; a simple evolution of current technologies and hardware architectures is not sufficient to meet these challenges. Today, optical technologies are mostly used for transport in long-distance or metro networks and in PON-based access systems. The use of photonics for transporting radio traffic and its evolutions, as well as the construction of components and modules for next-generation radio, will occur only if the costs are much lower than those of the components and optical systems currently in use.

Figure 4 provides a simple mapping of the field of application of current optical transport to its corresponding place in the "new optical transport" space where radio applications and silicon photonics are served. One of the key technologies is integrated photonics. As occurred with microelectronics, integration is a way to increase the system complexity without a proportionate increase in cost. Integrated photonic technology on silicon, namely, silicon photonics [31–33], will play a fundamental role in meeting the challenging requirements with lower costs.

The first industrial sector to use silicon photonics was the data center world, whose volumes pushed for important investments in that technology in order to have the desired devices and modules ready for use in real systems. Silicon photonic transceivers were adopted in data centers due to the need for higher bandwidth, lower costs, and lower power consumption with respect to transceivers used in transport networks. The telecom world evolution associated with the advent of 5G networks share most of the datacenter requirements with some important differences. Data centers are more bandwidth hungry as compared to telecom networks but are less sensitive to cost and temperature tolerances. Data center equipment is deployed in controlled environments, i.e., with controlled temperature and humidity; thus, the transceiver operating temperature is not an issue. In contrast, telecom equipment is less bandwidth hungry, but more sensitive to cost and much more to temperature. In addition, small-sized transceivers are required, which requires new fiber-attachment techniques with silicon photonic chips [34]. A relevant example of this is a radio unit that must operate in a harsh environment where the temperature can be very high (in some cases greater than 100°C or even 120°C). In 5G mmWave antennas, and even more in future mobile systems, the radio unit will consist of RF, radiating antenna elements, and photonic interconnects intimately integrated in a single hardware unit. This means that the photonics must be more and more miniaturized, and the design of the entire system must consider the operating conditions of the different devices. This illustrates why there is a need for co-packaged photonic transceivers integrated in a multi-chip module with digital application specific integrated circuits (ASICs) and other analog frontends.

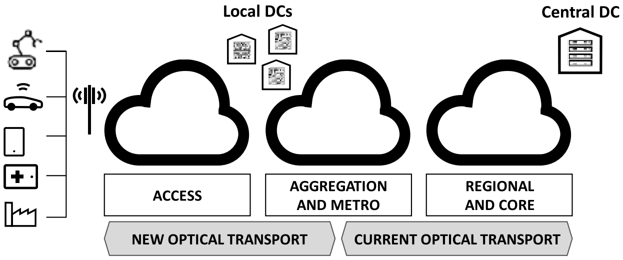

Fig. 4. Transport network evolution across network segments. (DC, data center).

Current silicon photonic transceivers based on pluggable modules or on-board mounted optics lack bandwidth density and scale of integration while costs and power consumption are not adequate to meet the needs of 5G deployment [35]. Thus, new highly integrated photonic transceivers must be developed with terabit throughput, power consumption of few pJ/bit/s and a bandwidth density >50 Gb/s per mm^2, co-packaged in the same substrate with high processing capacity digital ASICs. Solutions based on silicon photonics achieving these power and density goals were demonstrated in the H2020 TERABOARD EU project [36]. Moreover, the maximum operating temperature range of such transceivers will be much higher than for currently commercial devices, reaching 120°C, which requires placing the laser (the most sensitive component) external to the transceiver [37]. Current commercial lasers cannot withstand very high temperatures; thus, fully integrated transceivers are not currently feasible under these conditions. While there are promising technologies to withstand the heat, such as quantum dot lasers, they are currently not mature enough. In contrast, silicon photonic devices such as modulators and photodetectors are tolerant to high temperatures. Active cooling may be used as in WDM, but this is cost intensive and consumes power.

Moreover, low-cost highly integrated optical switches represent attractive devices to replace fixed filters in WDM-based C-RAN to fully exploit the functionality of the fronthaul transport network. They will simplify planning and deployment of interconnects, improving utilization of scarce fiber assets and reducing the need to stock spare parts.

Overall, we see that the fundamental use of silicon photonic devices and modules in 5G and future mobile networks will present different technological challenges, which will be suitably addressed by further research [38].

Recent technology advances in enabling optical transmission technologies for 5G transport are illustrated hereinafter. It has already been highlighted that integrated photonics is the key to obtaining the target cost reduction of 1 order of magnitude, for both distributed-RAN based on point-to-point optical interconnects and more complex centralized architectures based on WDM. A roadmap for integrated photonic transceivers for interconnect applications is outlined in [39]: in the 2025 timeframe, optical bandwidths >80 GHz will be supported, as well as driving voltages <1 V [to eliminate the modulator drivers and provide the modulation signal directly from the CMOS integrated circuit (IC)] and hybrid silicon photonic integration with InP lasers. In the 2030 timeframe, the bandwidth will increase to 150 GHz to decrease further the cost per bit per second (bit/s).

The roadmap also makes clear that the photonic packaging technology must improve substantially to achieve better energy efficiency, for example, by introducing co-packaging solutions. Several transceiver vendors are moving in this direction, although with different technologies. Multimode transmission is used in [40] for a 2 × 400 Gb/s photonic engine, based on 56 Gb/s 4-level pulse amplitude modulation (PAM4), relying on 16 nm IC technology and GaAs vertical cavity surface emitting lasers (VCSELs) [41]. Other vendors are betting on single-mode transmission based on silicon photonics and III-V laser integration, to overcome the capacity bottleneck of directly modulated lasers. For example, in [42], a co-packaged solution for 1.6 Tb/s (4 × 400 Gb/s) silicon photonic engines, interfacing a 12.8 Tb/s programmable Ethernet switch, is described. A second silicon photonics co-packaged engine for multiterabit interconnect solutions in data center and communications networks is proposed in [43]. It provides from 800 Gb/s to 3.2 Tb/s in a single chip, with a granularity of 100 Gb/s NRZ or 200 Gb/s PAM4 per wavelength. It uses silicon photonics monolithic integration on a large-scale wafer with a III-V quantum dot laser. The above examples show how integrated photonic solutions for radio applications can benefit from the current datacom trend: the industry belief is that co-packaged optics offers energy and bandwidth density advantages for supporting ICs working at terabit per second (Tb/s) and higher.

Moving to C-RAN, the starting point is represented by WDM metro and long-haul networks, where aggregate capacities of the order of 10 Tb/s are already in place, based on 100 Gb/s dual polarization quadrature phase shift keying (DP-QPSK) standardized optical interfaces [44]. Standards exist for 400 Gb/s [45] WDM optical interfaces and some vendors already offer digital signal processing (DSP) capabilities to support 800 Gb/s on a single wavelength [46], to increase the system capacity. Recent research works show the possibility of boosting the capacity further: In [47], 1.1 Tb/s was transmitted over a single wavelength, with a spectral efficiency of 9.8 bit/s/Hz, over a distance of 80 km, based on 64-quadrature amplitude modulation (QAM), probabilistic constellation shaping (PCS), and low-density parity check (LDPC) coding. Although the capacities and distances reported above for coherent systems are more than enough to fulfill even the most challenging requirements of 5G transport, dramatic cost reductions are necessary before they are suitable for this network segment; integrated photonics will again be the key enabling technology.

A step in this direction, exploiting the advantages of integrated photonics, is reported in [48], where two optical transmitters and receivers are integrated in a monolithic InP interfaced with a SiGe ASIC. The transceiver delivers 800 Gb/s per wavelength over a 50 GHz bandwidth using digital subcarrier multiplexing at 100 Gb/s per carrier and PCS 64-QAM, yielding 4.5 bits/symbol. DSP simplification is another way to reduce the cost of coherent optical systems. This is the case with self-coherent systems, where the local oscillator frequency is sent together with the optical carrier used for data transmission. This leads to remarkable DSP simplification, especially if the polarization is recovered by optical means, to fully replace the equalizer [49]. A silicon photonics realization of the polarization recovery photonic IC (PIC) introduced in [28] has been demonstrated in [50]. In all aforementioned works, cost/bit/s reduction is pursued by increasing the bit rate carried by a single wavelength, assuming that the higher implementation cost is compensated for by a larger amount of transmitted information, i.e., number of bit/s. The opposite approach is to accept a reduction in the bit rate carried by a single wavelength, e.g., from 100 to 50 Gb/s, in order to simplify the implementation and reduce the cost. This approach is adopted in [51], where 50 Gb/s wavelengths are transmitted over more than 20 km using PAM4 and a simplified coherent receiver based on a silicon photonics 120° hybrid.

Despite all of the discussed advances, it will be several years before coherent optical transmission will be sufficiently cost-effective for RAN applications. Meanwhile, alternatives based on direct detection are under investigation. Direct-detection systems are known to be simpler and more cost effective compared to coherent systems (approximately an order of magnitude lower in cost), especially those using binary modulation, such as OOK and differential binary phase shift keying (DBPSK). However, binary direct-detection systems suffer from poor robustness to fiber chromatic dispersion. Increasing the number of modulation symbols leads to higher spectral efficiency, i.e., more tolerance to the chromatic dispersion, but impairs the receiver sensitivity and adds implementation complexity and thus cost. Identifying the right trade-off is still under investigation.

Figure 5 shows measured received optical power penalty versus link distance for various direct-detection modulation formats, at a bit rate of 50 Gb/s and a bit error rate (BER) of $10^{\ 3}$ [$10^{\ 3}$ is an acceptable pre-forward error correction (FEC) BER]. The penalty is compared to the OOK received optical power with 0 km of fiber. The fiber attenuation and chromatic dispersion coefficients are 0.22 dB/km and 17.5 ps/(nm/km), respectively. As expected, OOK shows a sudden increase in penalty with the fiber length. Power penalty and chromatic dispersion tolerance are both slightly better for DBPSK. PAM4 starts with 4 dB of penalty compared to OOK but it recovers the gap within the first 5 km of fiber, due to its better spectral efficiency. PAM8 is even more tolerant to the chromatic dispersion, but it suffers from a back-to-back penalty of 8 dB, too high for practical links.

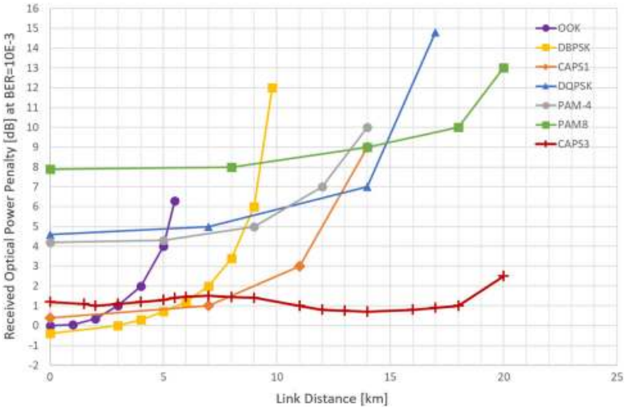

Fig. 5. Optical power penalty of various direct-detection modulation formats versus link distance.

Differential quadrature phase shift keying (DQPSK) shows a marginal improvement compared to PAM4 for distances longer than 11 km, which is not enough to justify the increase of complexity and cost compared to PAM4.

The other two modulation formats reported in Fig. 5 belong to a family of signals known as combined amplitude phase shift (CAPS) [52], designed to be tolerant to the chromatic dispersion. Optical duobinary is a special case, not shown because its performance is similar to CAPS1 (both are generated by narrow filtering of a binary modulated differential signal). CAPS1 has negligible back-to-back penalty compared to OOK but extends its reach from 4 to 10 km, considering 2 dB of dispersion penalty. CAPS3 further extends the reach to 20 km, but it requires an IQ modulator to be generated [53], which increases its cost.

Due to the variety of design options, the list of modulation formats is far from exhaustive. For instance, discrete multi-tone (DMT) was also investigated for access applications. DMT is known to have good robustness to chromatic dispersion (40 km at 49.6 Gb/s was shown in [54]), but the need for a negotiation procedure between the transmitter and receiver, the need for configuring the subcarrier power, the number of subcarriers and modulation format per subcarrier, and the high peak-to-average power ratio, which limits the receiver sensitivity, make it unsuitable as a multivendor standardized solution. Recent dispersion-tolerant evolutions of PAM4 are more promising [55]. Finally, as for coherent optical transmission, with direct detection it is possible to increase the bit rate per wavelength by accepting a higher implementation complexity. In [56], 218 Gb/s is transmitted over 125 km of fiber using a Kramers–Kronig receiver, and in [57], 224 Gb/s is transmitted over 10 km of fiber using a Stokes receiver and an integrated silicon nitride optical dispersion compensator.

6. OPTICAL NETWORKING EXPERIMENTS FOR INDUSTRIAL APPLICATIONS

In the H2020 5G-TRANSFORMER project [58], Ericsson led the realization of a PoC integrating cellular-ready radio systems with an optical-based transport layer to support vertical use cases and, specifically, cloud robotics (CR) applications for industrial automation. This PoC, schematically represented in Fig. 6, represents robot operations, in a production scenario, remotely monitored and controlled in a cloud on the premises, exploiting the use of industry-grade cellular connectivity to minimize infrastructure cost, optimize processes, and implement lean manufacturing. The project has validated a scenario of a shared transport network by integrating an optical network with the cellular infrastructure.

The CR setup includes an autonomous mobile vehicle (AGV) shuttling materials between two work cells in a factory by means of image processing navigation algorithms. A factory control tablet is used to select a customized set of factory tasks, e.g., a pallet transfer from one cell of the factory to another. The request is handled by a main control server that orchestrates multiple robots' tasks as well as executes image processing for visual navigation of the AGV. The setup includes two robotic arms, which are used to load/unload material on/from the AGV.

As stated, the entire activity is monitored and controlled by a remote server located in a cloud on the premises through cellular radio communication. Radio traffic flows over an optical network infrastructure, which includes novel photonic technologies complemented by dedicated agnostic framing, a deterministic switching module, and a flexible control entity. The optical transport architecture is reported in [58], basically a C-RAN scenario with the transmission of CPRI traffic. As reported in Section 3, CPRI is the most demanding traffic profile for radio transmission both in terms of bandwidth and latency. Hence, such an experimental setup allows stressing the optical network especially for the latency requirement. A DWDM system and deterministic framing are used and a single lambda connects the CO with the antenna sites. Such a configuration essentially provides a point-to-point connection with deterministic delay due only to transmission in fiber that is of the order of μs. The fiber length between the CO and the remote site where the robot is connected is 6 km. The upstream and downstream transmissions are on two different wavelengths on the same arc of the ring to guarantee symmetric latency. The use of deterministic framing ensures a certain

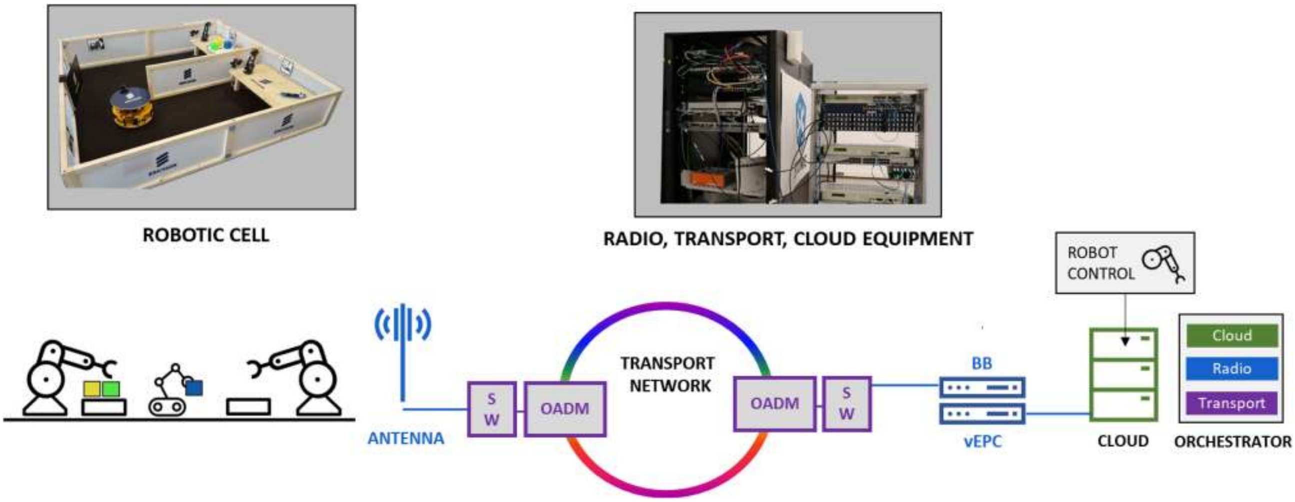

Fig. 6. The cloud robotic proof-of-concept setup and pictures of the robotic cell and of the infrastructure hardware.

level of flexibility because it is possible to aggregate in the same wavelengths more traffic flows and, if necessary, dynamically move the wavelengths from the CO to multiple remote nodes (i.e., OADMs on the optical ring). The PoC includes a platform to orchestrate the radio and transport infrastructure with the applications running in the cloud in an automatic fashion. Configuration of the E2E connection between the AGV and the PLC application is requested dynamically by means of a graphical user interface (GUI). The orchestrator automatically triggers the control for the radio, transport, and cloud to configure the said connection. The setup is based on a preliminary 4G installation (one cell with 2 × 2 MIMO support) because the 5G user equipment was not commercially available at the time of the experiment. To achieve industry-grade radio performance, a licensed spectrum portion of 15 MHz in the 2.6 GHz band (B7) has been used, dedicated to the experimental traffic.

Such a setup enables an E2E latency of 20 ms with stable jitter, which overcomes the typical performance limitations of commercial 4G (e.g., average latencies of the order of 60 ms and a variation range quite high depending on the traffic load, which cannot be controlled, and no guaranteed jitter control). As reported in Fig. 2 in Section 2, these achievable latency values and jitter control allow the centralization of the PLC that coordinates a set of robots in a production cell.

Measurements have been done to verify the E2E latency between the ingress point of the vertical services (i.e., the antenna) to the egress point of the services (i.e., the output of the vEPC). Figure 7 presents a histogram of measured E2E latency over the setup of Fig. 6. The average value in the downlink direction is 20 ms (as reported in Deliverable 5.4 of [58]). The resulting round-trip time (RTT) spans from a minimum of 13 ms to a maximum of 47 ms. Actually, as Fig. 7 reveals, the spikes of latency higher than the 30 ms limit of Fig. 2 are very rare. We have experimentally verified, in a four-weeks' time frame, that such spikes are tolerated by the PLC. The same results were obtained when the optical network is replaced by a point-to-point link. This result demonstrates that the optical transport network does not impact the E2E delay of the radio network.

A specific test [59] was conducted to assess the delay introduced by the optical transport in relation to the overall E2E latency budget. A single commercial Ethernet traffic generator was attached to both the remote node (i.e., where the RRUs are connected) and the CO (i.e., where the BBUs are located), creating a loopback. Ethernet frames were injected by the traffic generator into the remote node and transported to the CO through the fiber ring. Through the loopback, the traffic was sent back to the traffic generator. This allowed the traffic generator to measure the one-way delay for each packet and collect delay statistics. Figure 8 reports the total number of frames transmitted as a function of line load, where the latter is defined as the percentage ratio between the actual traffic load and the maximum channel bit rate (10 Gb/s). Multiple Ethernet ports were used to adjust the line load. The measurements were performed at three different Ethernet packet frame sizes, ranging from 64 bytes to 1500 bytes, and the line load ranging from 50% to 100%. No frame loss was detected under any measurement condition.

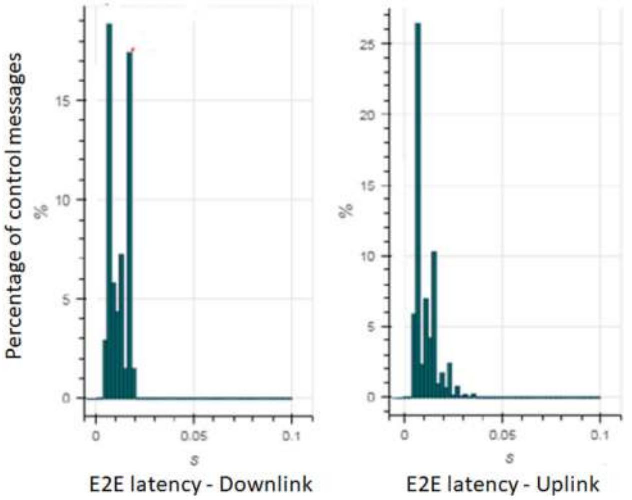

Fig. 7. Histogram of the E2E latency experienced by the control messages, in downlink and uplink directions.

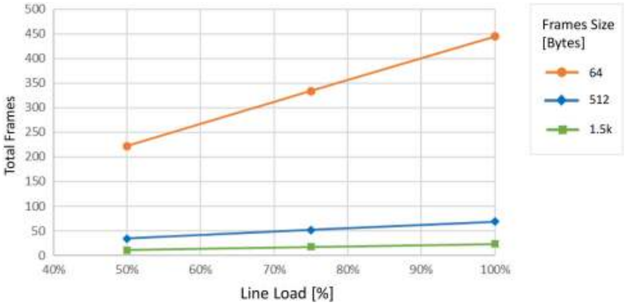

Fig. 8. Number of total frames versus line load resulting in a latency range of [35.1 μs, 35.2 μs], for different frame sizes.

In all of the measurement points corresponding to Fig. 8, the measured latency was in the range [35.1 μs, 35.2 μs]. For example, these latency values have been achieved with 52 frames with a frame size of 512 bytes and a line load of 75% (i.e., 7.5 Gb/s of traffic). The measured latency includes fiber propagation delay (about 30 μs, corresponding to 6 km of fiber), the delay introduced by the FEC (about 4 μs), and the delay introduced by the two switching nodes (about 1 μs). The packet delay variation, estimated by subtracting the above contributions to the overall latency, is about 0.1 μs. These results show that the optical network, on a realistic distance for the fronthaul segment, does not introduce excessive delays for the specific application of transporting 5G traffic interfaces (i.e., eCPRI). In particular, it demonstrates that the delays introduced by the optical transport network are compatible with the delay targets indicated in Fig. 2.

The experiments carried out in the 5G-TRANSFORMER project are evolving in the H2020 5Growth project [60], whose goal is to experiment with more use cases on vertical premises using 5G NR interfaces. These experiments include a digital twin of a robotic cell, telemetry, and monitoring of the plant shop floor as well as remote support enabled by augmented reality. Initial tests in 5Growth, based on point-to-point transport connectivity, have measured an average latency value of 3.5 ± 0.1 ms achieved with preliminary 5G terminals (i.e., smartphones configured as 5G devices). As described in Section 2 and illustrated in Fig. 2, the use of 5G enables the centralization of the robotic motion control if the E2E latency is lower than 5 ms.

7. CONCLUSIONS

Industry 4.0 will be a key driving force for the evolution of cellular radio networks, spanning all industrial sectors. However, it poses challenges, especially with respect to the transport network and related technologies. In fact, transport is crucial to ensure the 5G performance levels that are required to serve diverse vertical services and deployment scenarios. An automated and intelligent coordination between radio and transport networks is vital to guarantee robustness, enabling operators to meet their requirements in multiple use cases, to keep OpEx under control, and to continue to support legacy services. The wide range of challenging industrial applications mandate that the transport segment cope with numerous challenges, including huge transmission and switching/routing capacity, latency control, low energy consumption, and high flexibility to enable the network to automatically react to changes. All of the above must be fulfilled at reasonably low costs. Optical networking and related technologies will be a cornerstone in realizing the transport infrastructure for Industry 4.0.

With regard to transmission capacity demand, it will require optical communication links at several hundreds of Gb/s (100G, 200G, 400G) in the radio access network space to feed advanced antenna units performing massive MIMO and beamforming techniques. This is quite a new requirement with respect to the conventional transport networks currently used. Different relevant use cases require a convergent optical transport able to satisfy, at low cost, all of the relevant vertical scenarios. This is made possible by using not only low-cost, high-capacity optical links but some form of optical switching.

The transport segment in the radio access space should be comparable to an "equivalent wire" to minimize the total latency and comply with the most challenging services such as cloud robotics. This means limiting the latency, possibly avoiding any form of intermediate switches introducing further delays. Without that, the only other option is deploying a dedicated network for each individual vertical industry, which would lead to unacceptably high cost.

In the paper, two main sets of results were reported, focused respectively on high-capacity and low-cost optical transmission and optical networking for latency-critical services. The former set was reported in terms of a comparison among different optical transmission schemes, in terms of link distance, receiver sensitivity, and implementation complexity (Section 5). These transmission schemes have different trade-offs between cost and performance, and it is not possible to assess which is the best one in absolute terms. Future research work and business development aspects will lead to a reduction in the number of options. The latter set of results was reported in terms of latency measurements on the cellular network, including the optical transport segment, serving a cloud robotic use case (latency critical) under different conditions. Results show that the developed optical transport segment introduces a latency contribution that is about an order of magnitude smaller with respect to the rest of the end-to-end radio network. Moreover, optical network latency is predictable and controllable, so it can be kept low enough to comply with relevant latency-critical applications in respective vertical services. This was demonstrated even in the case of the most latency-critical fronthaul interface (i.e., CPRI).

In summary, optical transport in the radio access space is a key enabler of 5G-based industrial applications. It will contribute to realizing the "one-network for all services" concept that network operators want to achieve in the long term. The optical transport role will be even more important in next-generation mobile networks, which will have to serve more complex and challenging industrial use cases.

Acknowledgment. The authors acknowledge Stephane Lessard, Teresa Pepe, Marzio Puleri, Eris Seder, Stefano Stracca, Francesco Testa, and Fabio Ubaldi, for relevant discussions and information about their research work.

This work has been partially supported by the EC H2020 5GPPP 5Growth project (grant 856709).

[†] Head of the Ericsson Research center in Italy

REFERENCES

1. H. Kagermann, W.-D. Lukas, and W. Wahlster, "Industrie 4.0: mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution," in *Hannover Messe* (2011).
2. K. Schwab, *The Fourth Industrial Revolution* (Crown Publishing, 2017).
3. M. Puleri, R. Sabella, and A. Osseiran, "Cloud robotics: 5G paves the way for mass-market automation," Ericsson Technol. Rev. **93**(2), 66–77 (2016).
4. R. Sabella, A. Thueling, M. C. Carrozza, and M. Ippolito, "Industrial automation enabled by robotics, machine intelligence and 5G," Ericsson Technol. Rev. **96**(1), 40–50 (2018).
5. B. Holfeld, D. Wieruch, T. Wirth, L. Thiele, S. A. Ashraf, J. Huschke, I. Aktas, and J. Ansari, "Wireless communication for factory automation: an opportunity for LTE and 5G systems," IEEE Commun. Mag. **54**(6), 36–43 (2016).
6. B. Chen, J. Wan, L. Shu, P. Li, M. Mukherjee, and B. Yin, "Smart factory of Industry 4.0: key technologies, application case, and challenges," IEEE Access **6**, 6505–6519 (2018).
7. Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A survey on mobile edge computing: the communication perspective," IEEE Commun. Surv. Tutorials **19**, 2322–2358 (2017).
8. P. Rost, C. Mannweiler, D. S. Michalopoulos, C. Sartori, V. Sciancalepore, N. Sastry, O. Holland, S. Tayade, B. Han, D. Bega, D. Aziz, and H. Bakker, "Network slicing to enable scalability and flexibility in 5G mobile networks," IEEE Commun. Mag. **55**(5), 72–79 (2017).
9. M. A. Marsan, N. B. Melazzi, and S. Buzzi, *5G Italy White eBook: From Research to Market* (CNIT, 2019).
10. "PROFINET System Description," Order Number 4.132 (PROFIBUS Nutzerorganisation e.V., 2014).
11. "Security aspects of 5G for industrial networks" (5G-ACIA, 2020), https://www.5g-acia.org/publications/security-aspects-of-5g-for-industrial-networks/.
12. H2020 European Project COREALIS, https://www.corealis.eu/.
13. 3GPP, "Study on enhancement of 5G system (5GS) for vertical and local area network (LAN) services (Release 16)," Specification 23.734, 2018.

14. "5G non-public networks for industrial scenarios" (5G-ACIA, 2019), https://www.5g-acia.org/publications/5g-non-public-networks-for-industrial-scenarios-white-paper/.
15. "Common Public Radio Interface (CPRI); Interface Specification," CPRI Specification Version 7.0, 2015.
16. 3GPP, "Technical Specification Group Services and System Aspects; Release 15 Description; Summary of Rel-15 Work Items (Release 15)," TR 21.915 (V0.6.0) (2019-02), 2019.
17. L. M. P. Larsen, A. Checko, and H. L. Christiansen, "A survey of the functional splits proposed for 5G mobile crosshaul networks," IEEE Commun. Surv. Tutorials **21**, 146–172 (2019).
18. "Common Public Radio Interface: eCPRI Interface Specification," eCPRI specification version 2.0, 2019.
19. "Transport network support of IMT-2020/5G," ITU-T Tech. Rep. GSTR-TN5G, 2018.
20. "Characteristics of transport networks to support IMT-2020/5G," ITU-T Recommendation G.8300, May 2020.
21. F. Testa, "Optical Interconnect for future radio systems," in *7th International Symposium on Optical Interconnect in Data Centers* (2009).
22. S. Nakamura, S. Yanagimachi, H. Takeshita, A. Tajima, T. Hino, and K. Fukuchi, "Optical switches based on silicon photonics for ROADM application," IEEE J. Sel. Top. Quantum Electron. **22**, 185–193 (2016).
23. R. Sabella, F. Testa, P. Iovanna, and G. Bottari, "Flexible packet-optical integration in the cloud age: challenges and opportunities for network delayering," IEEE Commun. Mag. **52**(1), 35–43 (2014).
24. H2020 European Project 5G Crosshaul, http://5g-crosshaul.eu/.
25. H2020 European Project 5G-XHaul, https://www.5g-xhaul-project.eu/.
26. B. Skubic, J. Chen, J. Ahmed, L. Wosinska, and B. Mukherjee, "A comparison of dynamic bandwidth allocation for EPON, GPON, and next-generation TDM PON," IEEE Commun. Mag. **47**(3), S40–S48 (2009).
27. P. Iovanna, S. Stracca, F. Ubaldi, F. Cavaliere, G. Vall-llosera, and L. M. Contreras, "Network convergence in 5G transport," in *Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego (2019), paper M1G.3.
28. P. Iovanna, F. Cavaliere, F. Testa, S. Stracca, G. Bottari, F. Ponzini, A. Bianchi, and R. Sabella, "Future proof optical network infrastructure for 5G transport," J. Opt. Commun. Netw. **8**, B80–B92 (2016).
29. P. Iovanna, G. Bottari, F. Ponzini, and L. M. Contreras, "Latency-driven transport for 5G," J. Opt. Commun. Netw. **10**, 695–702 (2018).
30. H2020 European Project METRO-HAUL, https://metro-haul.eu/.
31. A. Tzanakaki, M. P. Anastasopoulos, I. Berberana, D. Syrivelis, P. Flegkas, T. Korakis, D. Camps-Mur, I. Demirkol, J. G. Teran, E. Grass, Q. Wei, E. Pateromichelakis, N. Vucic, A. J. Fehske, M. Grieger, M. Eiselt, J. Bartelt, G. Fettweis, G. L. Lyberopoulos, H. Theodoropoulou, and D. Simeonidou, "Wireless-optical network convergence: enabling the 5G architecture to support operational and end-user services," IEEE Commun. Mag. **55**(10), 184–192 (2017).
32. R. Sabella, "Silicon photonics for 5G and future networks," IEEE J. Sel. Top. Quantum Electron. **26**, 8301611 (2020).
33. F. Cavaliere, L. Giorgi, and L. Potì, "Transmission and switching technologies for 5G transport networks," in *IEEE Optical Interconnects Conference* (2018).
34. L. Zimmermann, T. Tekin, H. Schroeder, P. Dumon, and W. Bogaerts, "How to bring nanophotonics to application silicon photonics packaging," IEEE LEOS Newsletter (Dec. 2008).
35. P. N. Goki, M. Imran, C. Porzi, V. Toccafondo, F. Fresi, F. Cavaliere, and L. Potì, "WDM PON photonic integrated receivers including SOAs," Appl. Sci. **9**, 2457 (2019).
36. H2020 European Project TERABOARD, http://www.teraboard.eu/.
37. F. Testa, L. Giorgi, A. Bigongiari, and A. Bianchi, "Experimental evaluation of silicon photonics transceiver operating at 120°C for 5G antenna array systems," Electron. Lett. **54**, 1391–1393 (2018).
38. F. Cavaliere and A. D'Errico, *Photonic Applications for Radio Systems Networks* (Artech House, 2019), pp. 36–37.
39. AIM Photonics Academy, "Integrated Photonic Systems Roadmap (IPSR)," https://aimphotonics.academy/roadmap/ipsr-roadmap.
40. Broadcom, "BCM81181 16-nm 400GbE PAM-4 PHY (8:8) Product Brief," https://docs.broadcom.com/doc/81181-PB100.
41. Broadcom, "AFCD-V61XT 25-Gb/s Oxide VCSEL Product Brief," https://docs.broadcom.com/doc/AFCD-V61XT-PB.
42. https://newsroom.intel.com/news/intel-demonstrates-industry-first-co-packaged-optics-ethernet-switch/#gs.zder1f.
43. https://www.businesswire.com/news/home/20200305005157/en/Ranovus-Launches-Single-Chip-ODIN%E2%84%A2-Silicon-Photonic.
44. "Amplified multichannel dense wavelength division multiplexing applications with single channel optical interfaces," ITU-T Recommendation G.698.211, Nov. 2019.
45. OIF Implementation Agreement 400 ZR, Feb. 2019.
46. https://www.ciena.com/insights/articles/800G-is-here-pushing-the-boundaries-of-what-your-network-can-do.html.
47. F. Buchali, V. Lauinger, M. Chagnon, K. Schuh, and V. Aref, "1.1 Tb/s/λ at 9.8 bit/s/Hz DWDM transmission over DCI distances supported by CMOS DACs," in *Optical Fiber Communication Conference (OFC)*, San Diego, March 8–12, 2020, paper Th3E.2.
48. V. Lal, P. Studenkov, T. Frost, H. Tsai, B. Behnia, J. Osenbach, S. Wolf, R. Going, S. Porto, R. Maher, H. Hodaei, J. Zhang, C. Di Giovanni, K. Hoshino, T. Vallaitis, B. Ellis, J. Yan, K. Fong, E. Sooudi, M. Kuntz, S. Buggaveeti, D. Pavinski, S. Sanders, Z. Wang, G. Hoefler, P. Evans, S. Corzine, T. Butrie, M. Ziari, F. Kish, and D. Welch, "1.6Tbps coherent 2-channel transceiver using a monolithic Tx/Rx InP PIC and single SiGe ASIC," in *Optical Fiber Communication Conference (OFC)*, San Diego, March 8–12, 2020, paper M3A.2.
49. M. Morsy-Osman, M. Sowailem, E. El-Fiky, T. Goodwill, T. Hoang, S. Lessard, and D. V. Plant, "DSP-free 'coherent-lite' transceiver for next generation single wavelength optical intra-datacenter interconnects," Opt. Express **26**, 8890–8903 (2018).
50. P. Velha, V. Sorianello, M. V. Preite, G. De Angelis, T. Cassese, A. Bianchi, F. Testa, and M. Romagnoli, "Wide-band polarization controller for Si photonic integrated circuits," Opt. Lett. **41**, 5656–5659 (2016).
51. M. G. Saber, E. El-Fiky, Z. Xing, M. Morsy-Osman, D. Patel, A. Samani, M. S. Alam, K. A. Shahriar, L. Xu, G. Vall-Llosera, B. Dortschy, P. J. Urban, F. Cavaliere, S. Lessard, and D. V. Plant, "25 and 50 Gb/s/λ PAM-4 transmission over 43 and 21 km using a simplified coherent receiver on SOI," IEEE Photon. Technol. Lett. **31**, 799–802 (2019).
52. E. Forestieri and G. Prati, "Novel optical line codes tolerant to fiber chromatic dispersion," J. Lightwave Technol. **19**, 1675–1684 (2001).
53. E. Forestieri, M. Secondini, F. Fresi, G. Meloni, L. Potì, and F. Cavaliere, "Extending the reach of short-reach optical interconnects with DSP-free direct-detection," J. Lightwave Technol. **35**, 3174–3181 (2017).
54. C. Lacava, I. Demirtzioglou, I. Cardea, A. E. Khoja, K. Li, D. J. Thomson, X. Ruan, F. Zhang, G. T. Reed, D. J. Richardson, and P. Petropoulos, "Spectrally efficient DMT transmission over 40 km SMF using an electrically packaged silicon photonic intensity modulator," in *European Conference on Optical Communication (ECOC)*, Gothenburg, Sweden, September 17–21, 2017.
55. M. Secondini, E. Forestieri, F. Fresi, L. Potì, T. Catuogno, and F. Cavaliere, "Bipolar pulse amplitude modulation with direct detection," in *European Conference on Optical Communication (ECOC)*, Dublin, Ireland, September 22–26, 2019.
56. X. Chen, C. Antonelli, S. Chandrasekhar, G. Raybon, J. Sinsky, A. Mecozzi, M. Shtaif, and P. Winzer, "218-Gb/s single-wavelength, single-polarization, single-photodiode transmission over 125-km of standard singlemode fiber using Kramers-Kronig detection," in *Optical Fiber Communications Conference and Exhibition (OFC)*, Los Angeles, March 19–23, 2017.
57. Md. S. Alam, M. Morsy-Osman, Kh. A. Shahriar, E. El-Fiky, S. Lessard, G. De Angelis, V. Sorianello, F. Fresi, F. Cavaliere, L. Potì, M. Midrio, M. Romagnoli, G. Vall-Llosera, and D. V. Plant, "224 Gb/s transmission over 10 km of SMF at 1550 nm enabled by a SiN optical dispersion compensator and stokes vector direct detect receiver," to be presented at the OSA Advanced Photonics

Conference: Signal Processing in Photonic Communications (SPPCom), July 13–16, 2020.
58. H2020 European Project 5G-TRANSFORMER, http://5g-transformer.eu/.
59. P. Iovanna, F. Cavaliere, S. Stracca, L. Giorgi, and F. Ubaldi, “5G Xhaul and service convergence: transmission, switching and automation enabling technologies,” J. Lightwave Technol. **38**, 2799–2806 (2020).
60. H2020 European Project 5Growth, http://5growth.eu/.

Roberto Sabella, (M’90–SM’98) is the leader of the Optical Systems unit of Ericsson Research, based in Pisa, Italy, and Montreal, Canada. His expertise covers several areas of telecom networks, such as packet-optical transport, optical solutions for mobile backhaul and fronthaul, and photonics technologies for radio and data centers. He has authored more than 150 papers published in international journals, magazines, and conferences, 2 books on optical communications, and holds more than 30 patents. He was an adjunct professor of telecom systems at the Sapienza University of Rome. He is a senior member of IEEE and has guest edited many special issues in several IEEE journals and magazines. He holds the “Laurea in Ingegneria Elettronica” degree from the University of Rome “La Sapienza,” Italy.

Paola Iovanna is a Master Researcher at Ericsson. Her competencies span several areas of network architecture and control for several technologies. In the past few years, she has been leading activities for Ericsson Research on transport solutions for 5G, including CRAN, convergence networks (radio and fixed access network), and orchestration solutions for verticals. She is responsible for joint work with operators for 5G solutions, realizing several prototypes. Since 2003 she has been working with different levels of responsibility in different EU projects and the Network of Excellence as a WP leader and an Innovation Manager. She holds more than 70 patents, is an author of 80 publications in either international scientific journals or conferences, and is a co-author of 2 books on transport solutions for 5G and 5G in Italy. She received the “Laurea in Ingegneria Elettronica” degree from the University of Rome “Tor Vergata,” Italy.

Giulio Bottari is a Master Researcher at Ericsson in Pisa, Italy. He has competence in 5G for industry technologies and applications. He has been a reference person of ER for the “5G for Italy” program which developed the first 5G manufacturing area in Italy, operating in the Comau (FCA) plant in Turin in June 2018. He was also responsible for the “Future Factories” area of the Ericsson booth at MWC2018. In 2019 he drove the “VR digital twin” proof-point at Hannover Messe and at MWC Shanghai. He is the Innovation Manager of the H2020 5G-TRANSFORMER project and is also involved in the H2020 5Growth project. He is an author of 80 patents and tens of articles in IEEE publications. He co-authored the “5G Italy Book 2019” illustrating 5G status in Italy. He holds the “Laurea in Ingegneria delle Telecomunicazioni” degree from the University of Pisa, Italy.

Fabio Cavaliere is an expert in photonics and responsible for the standardization of optical systems at Ericsson (Sweden). In 22 years of professional experience, his activity encompassed all aspects of optical networking. He is on the technical committees of international conferences on optical networks, the editor of ITU-T Recommendation G.698.4, and a member of the Board of Stakeholder of Photonics 21 and the Strategic Advisory Board of the Quantum Flagship. He has co-authored 130 patent applications and 80 scientific publications.