Applicability of a new generation of photonic devices in backbone network scenarios

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***Abstract*— This article presents the characteristics of the transponders and optical nodes developed by the QAMeleon project and illustrates an example of application of these systems in an optical backbone. A scalability study shows how with traffic increasing at a rate of 30% per year, high flexible and spectral efficient QAMeleon devices allow the network to scale to carry all the traffic up to 2030 as long as multiple systems are used in parallel on the most heavily loaded nodal degrees. Scalability extends beyond 2030 with the use of nodes with a greater number of ports and with the possible use of C + L band systems instead of C band only. (*Abstract*)**

Keywords—Optical networks, Sliceable Bandwidth Variable Transponder (S-BVT), ROADM

I. Introduction

The global and continuous increase in connectivity needs and the reduction in footprint, power consumption and costs imposed to photonic technologies for telecom applications by current environmental challenges and by a very competitive market are the main drivers of the research activities carried out in the European funded project QAMeleon [1]. The project is developing a new generation of photonic devices, in particular very innovative integrated optical switching elements [2] and sliceable bandwidth variable transponders (S-BVT), as well as a software defined networking (SDN) framework for their control [3]. In this article, after having summarized the vision and technology of the QAMeleon project, we present a study of applicability of the devices being developed in the project to the backbone transport network of Telecom Italia [4]. The increase in traffic on the national backbone at a rate of +30% per year poses scalability challenges to current technologies. With the limits of spectral efficiency and number of fiber degrees on the reconfigurable optical add and drop multipexer (ROADM) nodes of the current equipment, the saturation of the systems will be reached soon, in one or two years, and technological upgrades are necessary to cope with traffic increase. The article will show how, leveraging QAMeleon technologies that allow the development of two-carrier sliceable transponders, with bit rate per carrier up to 1 Tb/s and spectral efficiency up to 7 (bit/s) / Hz over short distances, line systems based high port count wavelength selective switch (WSS) and multicast switch (MCS) , it is possible to achieve the network scalability up to 2030 with the possibility of going further if such devices will be scaled up and with the possible use of the L + C bands instead of the C band only.

The rest of the article is organized as follows. Section II presents an overview of the QAMeleon project. Section III presents the topology, the architecture and the traffic demand of the Italian photonic backbone of TIM. Section IV introduces the problem of scalability and discusses the applicability of QAMeleon devices to TIM photonic backbone. Finally, Section V illustrates the results of the scalability study and Section VI draws the conclusion remarks.

II. Overview of QAMeleon project

The project QAMeleon started in 2018 and it will end in October 2022 with a field trial that will take places in the TIM labs and infrastructure.

The project consortium is leaded by National Technical University of Athens (NTUA) and includes academic partners, systems vendors and component makers, in both the optical and electronic fields, packaging companies, system integrators and TIM as Telco operator.

A. QAMeleon vision

The vision of the project QAMeleon can be summarized by the following four concepts. First, scaling the capacity of metro and core optical networks to Terabit per λ range. This is achieved by transceivers operating at 128 Gbaud together with high order modulation formats. Second, improve resource utilization through flexibility in a. modulation format, b. baud rate, c. use of C bandwidth (with the resolution of 12.5 GHz as specified in ITU-T Rec. G94.1) and d. use of multiple optical flows that can be configured separately or together in a superchannel, implementing the sliceability feature in the transceivers. Third, enhance the spectral efficiency by using novel modulation format (4-D modulation, probabilistic shaped (PS) constellations, Digital Sub Carrier Multiplexing (D-SCM)) and technological upgrades in the devices like narrow linewidth lasers for Signal to Noise Ratio (SNR) and transmission reach improvement, and high-resolution Digital to Analog Converters (DACs) with an effective number of bit (ENOB) of 6.Fourth, automate the network with an efficient control and network orchestration via software defined networking (SDN).

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B. QAMeleon devices, systems and tools

The vision of the project presented above translates into the design and physical implementation of the following devices, systems, and tools:

- dual carrier BVT/S-BVT transponders based on innovative DP m-QAM transceivers working up to 128Gbaud;
- ROADM nodes for Metro-regional and Backbone application based on 1x24 flexgrid WSS (the combination PIC and LCoS technologies enabling a considerable footprint reduction with respect to 1x20 available products) and 8x24 transponder aggregator (TPA), obtained by 8 1x24 WSS and 24 1x8 broadcast&select multicast switches;
- ROADM nodes for Metro Access application based on 1x4 fast (low latency) flexgrid WSS;
- DSP toolbox which allows evaluation of different Tx/Rx algorithms for advanced modulation schemes (e.g., probabilistic shaping based DP PS m-QAM) and their comparison with spectral efficient equivalent DP m-QAM;
- holistic SDN solution: following the "disaggregation" paradigm the optical devices are seen as aggregation of optical functions or subcomponents, individually modelled and controllable.

It is outside the scope of this article to go in the details about the technologies used by the project to fabricate the devices and implement the systems. For further information please refer to the project site [1] and the available publications highlighted on it.

III. Topology, Architecture and Traffic in Optical Transport Backbone

In this section we introduce the TIM's national photonic backbone that has been chosen as application scenario for the devices developed in the QAMeleon project.

A. Topology and architecture of photonic and IP backbones

The photonic backbone of TIM spans over the entire Country, and it is made of about 50 nodes and 80 links, as shown in Fig. 1 (a). Nodal degree spans from 2 to 6 while links are a mix of G.652 and G.655 fibers with lengths ranging from 20 to 500 km. Currently TIM has two photonic backbones that have a similar topology, named Kaλeidon and Kaλeidon Evolution, respectively. They adopt two different generations of equipment. Kaλeidon, the older, is a fixed grid network (96 channels at 50 GHz in C band) and it is made with colorless and directionless (CD) ROADMs built with 1x9 WSS and equipped with coherent transponders at 40G or 100G. Such transponders have reaches of the order of 600 Km (regenerations are required on longer paths). The spectral efficiency (SE) is 2 (bit/s)/Hz at maximum. Kaλeidon Evolution, the newer photonic backbone still under development, is a flexible grid network (384 12.5 GHz flexgrid slots in C band) based on colorless directionless and contentionless (CDC) ROADMs built with 1x20 WSS and 8x16 add drop blocks based on MCS. The current system limitation allows the use of 8 fiber degrees and 12 MCS A/D blocks at maximum in each ROADM. Please note that this limitation holds even if in principle a different distribution of the WSS ports assignment between lines and A/D modules would be possible. The transponders of Kaλeidon Evolution are in continuous evolution and the current state of the art is shown in TABLE I. . The models are listed with their main characteristics, including the total net client rate (which coincides with the net line rate), the required optical band, the reach and the spectral efficiency. Reaches take into account the appropriate system and end-of-life margins used in network design. Client rate for Kaλeidon Evolution is always 100G and clients at lower rates (e.g., 1G, 2,5G and 10G) are groomed through the OTN layer or by muxponders.

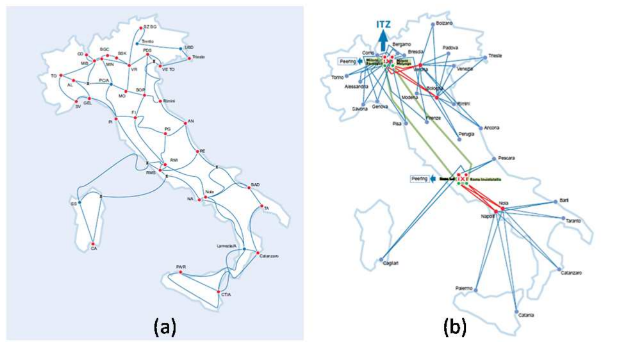

Fig. 1. Toplogies of (a) photonic backbone and (b) IP backbone of TIM. Both topologies are taken from [5].

Kaλeidon Evolution carries the circuits between routers of the National IP backbone, whose topology is shown on Fig. 1 (b), and traffic for other internal and external clients. The IP backbone has a three tiers hierarchical structure (blue, red and green links in Fig. 1 (b)). A dual homing redundancy with physical path diversity is applied in the interconnection of each tier to the next: this relaxes the requirement on protection of the IP links in the optical layer as in case of failure the traffic protection is made at IP level. Link length between routers ranges from ~20 km to ~1100 km, with an average of ~400 km. A huge amount of traffic is exchanged between higher layer nodes, while much less traffic is exchanged between peripheral nodes and the central nodes.

In Kaλeidon Evolution the amount of bandwidth (data rate) of circuits interconnecting IP backbone routers are approximately 65% of the total, while for the remaining 35% of the bandwidth, 2/3 are carried with unprotected circuits and 1/3 with 1+1 protected circuits. Looking at the distribution of the load in the photonic backbone, it results a very uneven traffic distribution over different nodes and links: this because, especially in the IP backbone, heavily loaded short and medium paths coexist with very long paths bearing small amounts of traffic. It turns out that very big and complex photonic nodes terminating traffic generated from higher tier nodes of the National IP Backbone network located in Milan and Rome, coexist with very small and simple peripheral nodes.

TABLE I. State of the art Transponders.

Device	B.width GHz	12.5GHz slots	Line rate Gb/s	Reach km	SE (Bit/s)/Hz
T1	50	4	100	1800	2.00
T2	75	6	200	1600	2.67
T3	75	6	300	900	4.00
T4	75	6	400	350	5.33

With the current traffic demand (year 2022 values), it results that in the most loaded nodes of the network all nodal degrees require only one fiber degree; however, the most loaded links are close to saturation (more than 70% of utilization). This means that at current traffic growth rate, and relying on current transponder technology, multiple fiber degrees on the same nodal degree (i.e., multiple parallel line systems between ROADMs) will be necessary in one/two years from now.

B. Traffic projections

To consider the evolution of traffic demand in the next decade we assume for the applicability and scalability study presented in this paper that the traffic will increase, starting from 2022 values, with a growth rate of 25% (standard) or 30% (more aggressive). Fractions of traffic types (IP, other clients unprotected, and other clients protected) and patterns are assumed the same as in 2022 for all the subsequent years, only the total volume is assumed to change.

Even if quite realistic, the current and future traffic data used in the study tare to be considered purely indicative and may be subject to significant updates.

IV. APPLICABILITY OF QAMELEON DEVICES

As we have observed in Section III, the photonic backbone equipped with the current technology is close to saturation on the most heavily loaded links and nodes.

The growth margin is strongly limited by the maximum number of fiber degrees of the systems (that is 8) compared to the nodal degree (that is 5 or 6 in the most critical nodes), so a scalability problem that needs to be addressed emerges.

A. Scalability Issue

In general, scalability issues in optical networks due to the traffic increase, can be addressed with the following solutions:

- Increase the channel capacity by enhancing the spectral efficiency, introducing the higher order modulation formats and their variants like PS;
- Increase the number of channels / bands used on the same fiber;
- Introduce the Spatial Division Multiplexing (SDM) with the use of multi mode fibers, multi-core fibers or simply using more fibers in parallel on the same nodal degree (i.e., a node to node link) [7].

In this applicability and scalability study we take into consideration the use of QAMeleon transponders to increase the channel capacity/spectral efficiency, and the extended use of parallel fibers on link, that is enabled by the high port count of QAMeleon WSS (see Fig. 2 (a) for an example of CDC ROADM with multiple fiber degree). Concerning the QAMeleon transponders, the two-carrier S-BVT can be flexibly configured to have two single carrier flows or a single dual carrier flow. The selection of configurations considered in the study are the ones shown in TABLE II. Changing the baud rate, the modulation format (only conventional modulation have been considered, higher performances could be achieved with advanced modulations) and the number of carriers (one or two), the configurations have the characteristics shown in TABLE II. Reaches are obtained with simulationsto be validated by experimental tests..

TABLE II. SELECTED CONFIGURATIONS OF QAMELEON DUAL CARRIER S-BVT TRANPONDERS. MODULATIONS ARE IN DUAL POLARIZATION AND CAN USE A SINGLE OR DUAL CARRIER (SC OR DC).

Mod. Format S/D Carrier	B. rate GBaud	12.5GHz slots	Line rate Gb/s	Reach km	SE (Bit/s)/Hz
16QAM SC	32	4	200	3000	4.00
64QAM SC	32	4	300	600	6.00
QPSK SC	128	14	400	3000	2.29
16QAM SC	64	7	400	1800	4.57
64QAM DC	32	7	600	600	6.86
64QAM SC	64	7	600	100	6.86
QPSK DC	128	26	800	3000	2.46
16QAM DC	64	13	800	1800	4.92
16QAM SC	128	14	800	800	4.57
64QAM DC	64	13	1200	100	7.38
16QAM DC	128	26	1600	800	4.92

Fig. 2 (b) shows on the bars (left y axis) the percentage of the total traffic to be carried in the photonic network in function of the distance range of the path. On the same diagram the SE achieved with standard 100G in 50 GHz (2 (bit/s)/Hz), current technology and QAMeleon S-BVT is plotted. A significant amount of traffic has paths under 600 km, almost all traffic with paths higher than 1200 km while 15% of total traffic has paths under 100 km. Path length lower than 600 km benefit of the high SE (⩾ 6 (bit/s)/Hz) achievable with higher order MF as the ones used in QAMeleon S-BVT. The plots highlight the gap in SE between the current and QAMeleon technologies.

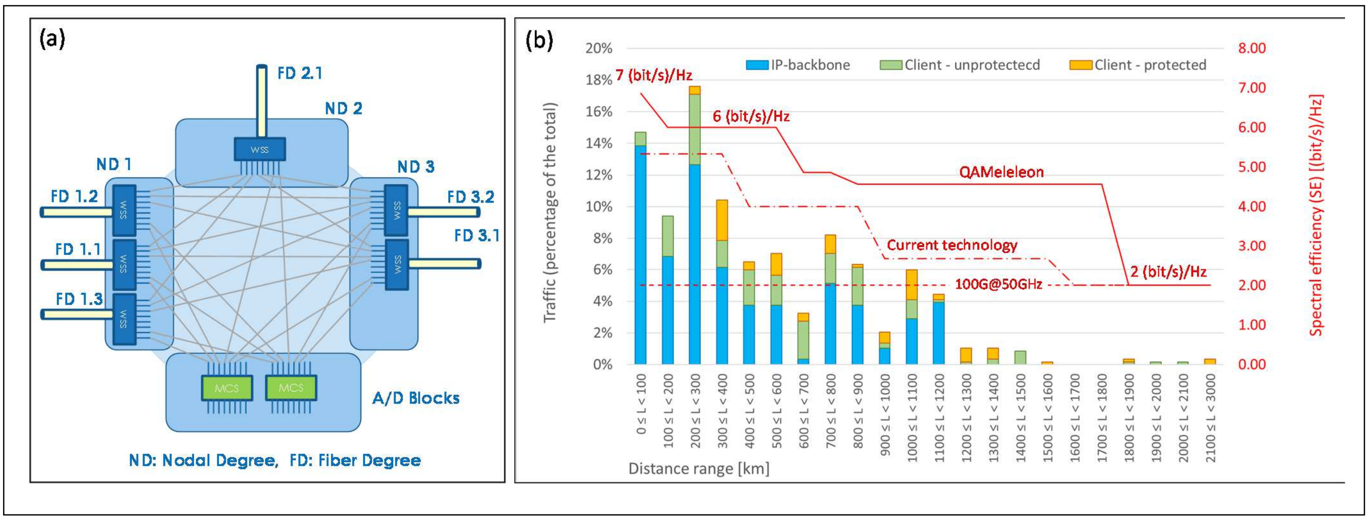

Fig. 2. (a) CDC ROADM with parallel fiber degrees and (b) diagram with the percentage of total traffic to be carried on photonic backbone in year 2022 (left Y axis) and the spectral efficiency of current and QAMeleon technologies (right Y axis), in function of path distance range (X0 axis).

CAGR = +30% — Current technology

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Total traffic (referred to year 2022 value)	*1.00*	*1.30*	*1.69*	*2.20*	*2.86*	*3.71*	*4.83*	*6.27*	*8.16*	*10.60*	*13.79*
Total Fiber Degrees	80	83	88	96	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Fiber Degrees on max loaded node	5	6	7	9	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Max Parallel Fiber Degrees on MAX loaded node	1	2	2	3	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Num 8x16 MCS A/D modules on MAX loaded node	6	8	9	12	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Max Num 1x20 WSS ports used on MAX loaded node	10	13	15	20 (max)	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Average Fibre Degree Utilization	22%	31%	33%	39%	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Weighted Spectral Efficiency [(bit/s)/Hz]	3.81	3.81	3.81	4.06	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.

CAGR = +30% — QAMeleon technology

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Total traffic (referred to year 2022 value)	*1.00*	*1.30*	*1.69*	*2.20*	*2.86*	*3.71*	*4.83*	*6.27*	*8.16*	*10.60*	*13.79*
Total Fiber Degrees	N. Y. A.	N. Y. A.	80	92	94	99	122	136	165	N. F.	N. F.
Fiber Degrees on max loaded node	N. Y. A.	N. Y. A.	5	8	9	9	11	13	17	N. F.	N. F.
Max Parallel Fiber Degrees on MAX loaded node	N. Y. A.	N. Y. A.	1	2	2	3	4	4	5	N. F.	N. F.
Num 8x16 MCS A/D modules on MAX loaded node	N. Y. A.	N. Y. A.	4	4	4	4	5	6	8	N. F.	N. F.
Max Num 1x20 WSS ports used on MAX loaded node	N. Y. A.	N. Y. A.	8	11	12	14	15	17	24 (max)	N. F.	N. F.
Average Fibre Degree Utilization	N. Y. A.	N. Y. A.	25%	35%	36%	41%	49%	54%	61%	N. F.	N. F.
Weighted Spectral Efficiency [(bit/s)/Hz]	N. Y. A.	N. Y. A.	4.77	5.12	5.32	5.00	5.33	5.06	5.10	N. F.	N. F.

CAGR = +25% — Current technology

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Total traffic (referred to year 2022 value)	*1.00*	*1.25*	*1.56*	*1.95*	*2.44*	*3.05*	*3.81*	*4.77*	*5.96*	*7.45*	*9.31*
Total Fiber Degrees	80	84	87	91	100	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Fiber Degrees on MAX loaded node	5 (6)	7	7	8 (9)	8 (11)	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Max Parallel Fiber Degrees on MAX loaded node	1	2	2	2	2 (3)	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Num 8x24 MCS A/D modules on MAX loaded node	6 (5)	8	9	10 (7)	13 (9)	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Max Num 1x24 WSS ports used on MAX loaded node	10	14	15	17	20 (max)	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Average Fiber Degree Utilization	22%	30%	32%	33%	39%	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.
Weighted Spectral Efficiency [(bit/s)/Hz]	3.81	3.63	3.76	3.9	4.06	N. F.	N. F.	N. F.	N. F.	N. F.	N. F.

CAGR = +25% — QAMeleon technology

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Total traffic (referred to year 2022 value)	*1.00*	*1.25*	*1.56*	*1.95*	*2.44*	*3.05*	*3.81*	*4.77*	*5.96*	*7.45*	*9.31*
Total Fiber Degrees	N. Y. A.	N. Y. A.	80	81	86	96	98	125	131	142	175
Fiber Degrees on MAX loaded node	N. Y. A.	N. Y. A.	5 (6)	5 (7)	7 (7)	8 (10)	8 (9)	11 (11)	13 (14)	13 (16)	18 (20)
Max Parallel Fiber Degrees on MAX loaded node	N. Y. A.	N. Y. A.	1	2	2	2	2	3	4	4	5
Num 8x24 MCS A/D modules on MAX loaded node	N. Y. A.	N. Y. A.	4 (3)	4 (3)	4 (3)	4 (3)	4 (4)	5 (4)	6 (4)	6 (5)	9 (6)
Max Num 1x24 WSS ports used on MAX loaded node	N. Y. A.	N. Y. A.	8	9	10	12	12	14	18	19	28 (>max)
Average Fiber Degree Utilization	N. Y. A.	N. Y. A.	25%	26%	30%	39%	41%	48%	50%	55%	60%
Weighted Spectral Efficiency [(bit/s)/Hz]	N. Y. A.	N. Y. A.	5.50	5.52	5.63	5.00	5.03	5.35	5.35	5.09	5.23

Colour and acronym legenda: CDC Feasible with one FD per ND; CDC Feasible with more than one FD per ND; CpDC Feasible; CpDC Feasible with system upgrade; N. F. Not feasible; N. Y. A Not yet commercially available

Fig. 3. Scalability results for current and QAMeleon technologies for +30% and for +25% of compound annual growth rate (CAGR) of traffic..

V. RESULTS OF THE SCALABILITY STUDY

Fig. 3 presents the comparison in scalability between currently used technology and QAMeleon for an annual growth of 30% and of 25% of the traffic for ten years from 2022. Tables include some general parameters as total fiber degrees, the maximum number of parallel fiber degrees and the number of WSS ports used on the one or two most critical nodes (the ones with the greatest sum of fiber degrees and/or A/D blocks). Cells filled in green refer to feasible solutions respecting full CDC functionality. Light green indicates that multiple fibers are needed on some nodes. Cells filled in yellow refer to solutions that are not CDC fully compliant but allows to a partial directionless property only [8]. Due to the quasi-static nature of the traffic demand the partial directionless property (i.e., CpDC) can be considered acceptable for the network under study, although an in-depth analysis would be recommended to assess the actual risk of traffic blocking in case of high level of resource utilization. Cells filleld in red mean that the technology does not allow to satisfy the traffic demand.

Current technology scales up to 2024 but require 2 fiber degrees from year 2023 for both +25% and +30% CAGR. In 2025 the number of WSS ports would be sufficient but the constraint on maximum fiber degrees is violated (9 instead of 8). In any case the directionless property would be partial. To scale up 2025 (2026 for CAGR =+25%) the current technology would require an upgrade. QAMelon technology has a more extended scalability. Traffic of year 2025 and year 2026 can be carried with full CDC property, while if we relax the full directionless feature QAMaeleon is suitable to carry the traffic up to 2030 (CAGR=+30%, all 24 WSS ports used in most loaded node) or 2031 (CAGR=+25%). The scalability would extend to 2032 if WSS were upgraded to 28 ports.

VI. CONCLUSIONS

An applicability and scalability study is performed to evaluate the introduction of QAMeleon devices (dual carrier S-BVT, 1x24 WSS and 8x24 TPA) in the Italian Photonic Backbone of TIM. With current technology and without spatial division multiplexing the saturation of single fibre links is quickly approaching (≈2023). Assuming a yearly traffic increase of 30% and relying on multiple fiber degrees on nodal degrees, the use of QAMeleon devices would allow to carry all traffic up to 2030 (with CpDC-F property). The scalabilty would extend to 2032 if yearly increase rate of traffic were 25% instead of 30% and with an upgrade of WSS from 1x24 to 1x30 on max loaded nodes. To guarantee the full CDC-F property in ROADM, the MCS should be upgraded to have at least ≈20 line-side ports instead of 8 (current R&D QAMeleon prototypes). Exploiting the same number of fibers a further extensions of scalability for a couple of years and could be achieved with C+L systems [8], which would allow a doubling of the bandwidth and therefore of the capacity, at the expense of higher complexity and cost.

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