Coherent passive optical network for 5G and beyond transport

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Building low-latency and high-capacity optical networks is vital for new high-speed cellular technologies. Coherent wavelength division multiplexing passive optical networks (WDM-PONs) are expected to play a key role in these applications. In this article, an overview of PON technologies for the 5th generation (5G) transport systems has been given. Moreover, a modified scheme based on coherent WDM-PON has been investigated using a dual polarization quadrature phase shift keying (DP-QPSK) transceiver. The aim of the scheme is to build a 1 600 Gbit/s network that will be used in the construction of the transport architecture of 5G and beyond cellular networks either in mobile front haul (MFH) or mobile back haul (MBH). The results indicate that the proposed scheme offers a promising solution for future 5G transport systems.

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The 5th generation (5G) technology promises to drive economic growth to the highest level more than all generations of mobile technologies. It goes with connecting machines as internet of things (IoT) in addition of connecting people[1]. The transport (or transmission) system plays an active role in reliable 5G wireless new radio (NR) and beyond 5G (B5G) wireless deployments. Several technologies are competing to be proposed for 5G transport systems. From these technologies, flexible Ethernet, point-to-point fiber access, optical transport network (OTN), and passive optical network (PON) were discussed in standards organizations. Which one of mentioned technologies will satisfy 5G requirements? In fact, it depends on each 5G operator, since these operators have different business models and various deployment plans built on their own budgets and markets. Technology availability and market needs will play a big role in choosing appropriate transport technology by an operator. Firstly, and before going on deep discussion of various transport technology choices, we need to discuss 5G requirements and their impact on the transport system. Among the competing technologies, PON is a good choice because of the following features: point to multi-point topology (P2MP), good utilization of fiber resources resulted from its topology, and current wide deployment of PONs around the world for fixed access services[2]. As a result of the increase of bandwidth demand initiated by recent applications such as mobile front-haul (MFH) for the 5G, the IEEE 802.3ca task force had evaluated the standards for 100 Gbit/s-based PON technology named 100G Ethernet PON (100G-EPON)[3]. In this paper, we will review optical access technologies, which are adequate for 5G transport system. Moreover, 5G transport system requirements will be presented. Finally, a scheme to evaluate the deployment of coherent PON technology in 5G transport system will be presented.

Fig.1 shows the required bandwidth for 5G transport based on PON technology[4]. This bandwidth will be allocated for the 5G MFH and mobile back haul (MBH) and is needed for connecting small cells and base band unit (BBU). For each individual small cell shown in the figure, a maximum of 100 Gbit/s data rate can be supported between the optical link terminal (OLT) and an optical network unit (ONU). Therefore, the data rate in 5G MFH/MBH can be up to 1 600 Gbit/s for a macro cell containing 16 small cells.

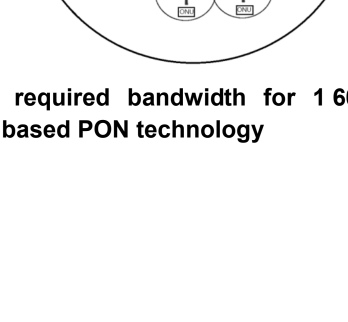

Fig.1 The required bandwidth for 1 600 Gbit/s 5G MFH/MBH based PON technology

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In this article, a significant data rate will be achieved (1 600 Gbit/s) using coherent WDM-PON with dual polarization (DP) technique and quadric phase shift keying (QPSK) modulation. With DP-QPSK, one symbol will carry 4 times the on-off keying (OOK) bits. This will highly utilize the fiber optic link resources to the maximum.

Before 5G, PONs with 10 Gbit/s seems to be very sufficient for current market. But in 5G era, higher speed PONs will be required. Several papers have studied 100 Gbit/s PON and below. In this article, a demonstration of 100 Gbit/s/λ with 16 wavelengths (1 600 Gbit/s) employing WDM PON system with coherent detection and simplified digital signal processor (DSP) will be presented.

PON is a point to multipoint network, where optical distribution network (ODN) with passive optical (power or wavelength) splitters is used to broadcast the transmitted optical signal from the OLT at the central office (CO) to ONUs at subscribers' premises.

Time-division-multiplexed passive optical networks (TDM-PONs) have been extensively deployed to deliver the enormous bandwidth needed for broadband services. TDM-PONs offer cost effective solution, however they suffer from the limited bandwidth[5,6]. WDM-PON increases the utilization of the optical fiber bandwidth[7-11]. In WDM-PON, high data rate transmission in both uplink and downlink directions can be simply achieved for each ONU near end users; where a dedicated pair of wavelengths is allocated to each ONU. Moreover, WDM-PON provides a direct optical point-to-point link between each ONU and the OLT at the CO; because of this, it is not required to deal with complex PON-over-Ethernet mapping and network management.

The coexistence of TDM-PON and WDM-PON is preferable[12]. So that existing TDM-PON users are unaffected and the previous investment on the network infrastructure can be preserved. Moreover, the full service access network (FSAN) has proposed time- and wavelength-division multiplexed passive optical network (TWDM-PON) as a main technology for next-generation PON stage 2 (NG-PON2) offering an aggregate network capacity of 40 Gbit/s. Tab.1 shows the standards, data rates and the increase in capacity offered by next-generation PON technologies[13]. These PON standards are set by the ITU and IEEE groups. For the ITU, they include gigabit PON (GPON), XG-PON, and NG-PON2 standards. While for the IEEE, they include GEPON, 10GEPON, and 100GEPON.

Tab.1 PON standards[13]

	GPON (2003)	XG-PON (2010)	NG-PON2 (2015)	GE-PON (2004)	10GE-PON (2009)	100GE-PON (2019-TBD)
Standard	ITU-T G.984	ITU-T G.9807	ITU-T G.989	IEEE 802.3ah	IEEE 802.3av	IEEE 802.3ca
DL/UL data rates (Gbit/s)	2.5/1.25	10/2.5 or 10/10 (XGS-PON)	40/10	1.25/1.25	10-Oct	Up to 100/100
Wavelength	1 490 nm and 1 550 nm DL/ 1 310 nm UL	1 577 nm DL/ 1 270 nm UL	1 596—1 603 nm/ 1 532—1 539 nm/ 1 610—1 625 nm	1 550 nm DL 1 310 nm UL	1 550 nm DL/ 1 310 nm UL	TBD
Splitting ratio	Up to 1:64	Up to 1:128	Up to 1:128	Up to 1:64	Up to 1:128	TBD
Coexistence	With the GPON			With the GE-PON		

Two significant factors must be considered in future high-speed PONs that will support 5G, which are latency and bandwidth[14]. In this section, we will review PON technologies that can address these two factors. High speed PON can be achieved by either multiplexing several wavelengths or increasing the data rate per wavelength. NG-PON2 has the ability of channel bonding and wavelength tunability. For example, by aggregating eight 10 Gbit/s wavelengths, use TWDM to achieve a bandwidth up to 80 Gbit/s. Moreover, 160 Gbit/s more bandwidth can be gained using sixteen 10 Gbit/s point-to-point (P-t-P)-WDM overlay wavelengths as reported in the ITU-T (G.989.2)[15]. Hence, NG-PON2 can be a good candidate for 5G transport. However, wavelength tunability, channel bonding, and strict crosstalk requirements will increase the complexity of transceiver design and the total cost of the network[2]. On the other hand, there is more interest in increasing the data rate of a single wavelength TDM-PON. A target of 25 Gbit/s data rate is becoming essential to meet the minimum transport bandwidth required in 5G for functional split 7a.

To achieve the 29-dB power budget class (called PR30) as reported in the IEEE 802.3ca draft standard that released in March, 2018, a 25 Gbit/s per wavelength PON system using non-return-to-zero (NRZ) modulation with the support of advanced forward error correction (FEC) is the preferred choice. Moreover, a 50 Gbit/s Ethernet PON (50G-EPON) can be achieved by ponding two 25 Gbit/s wavelength channels. Additional insertion loss of wavelength MUX and De-Mux in a wavelength ponding system can be compensated using semiconductor optical amplifiers (SOAs) in a 50G-EPON system[16]. A better solution can be achieved if a single wavelength of 50 Gbit/s using NRZ coding has been introduced instead of using two-25 Gbit/s wavelengths. This will not only require fewer optical components and lower system costs, but also saves wavelength resources[17]. Duobinary[18], pulse amplitude modulation with 4-level (PAM4)[19], and discrete multitone (DMT)[20] are other advanced modulation formats that can be combined with advanced DSP equalization to produce such system. Recently, NRZ/duobinary or PAM-4 with over 29 dB power budget using SOA and DSP has been used to demonstrate the benefit of 50 Gbit/s TDM-PON single-wavelength system[19].

5G specifications allow a minimum overall latency in the transmission system. TDM-PON bandwidth allocation schemes increase the overall latency beyond this level. OLT implements dynamically bandwidth allocation (DBA) to allocate time slots for specific ONUs upstream signals and avoid upstream data collisions in conventional TDM-PON. This process and the corresponding grant processing time (GPT) increase the total latency. So that, simplifying the handshake process or GPT is essential to minimize the latency. Fixed-length DBA[21] and traffic-load dependent DBA[22] have been proposed to minimize latency issue in TDM-PON. The quiet window (over 200 μs) is the total interruption time when new ONUs are invited to join the upstream traffic during TDM-PON ONU registration process. This interruptions time will be added to the latency, which will cause an extra delay of the allowed values in 5G. Various solutions were introduced in this regard either by using a second wavelength for ONU discovery and ranging, or by modifying the current activation process time to minimize the interruptions in TDM-PON[23].

WDM-PON is expected to play a key role in 5G MFH applications thanks to its operational simplicity, fiber resources saving, high capacity, and low latency. WDM-PON with a dedicated wavelength for each user with 25 Gbit/s or more has been proposed for 5G deployment[24]. There are two expected key technologies for WDM-PON. Firstly, colorless ONUs employ tunable transceiver technology. Recently, a 25 Gbit/s colorless ONU including reflective electro-absorption modulator with semiconductor optical amplifier (REAM-SOA) to support 5G fronthaul has been reported[25]. Currently, building cost effective tunable transceiver technologies for 25 Gbit/s and higher is a big challenge. It is conceivable that tunable transceivers can find more applications and usage in 5G business services than in other markets as 5G business services can tolerate higher cost. Stability of wavelength, integration of photonics to reduce cost, and tuning range of wavelength are main challenges that require more study.

The second key technology is the auxiliary management and control channel (AMCC), which is used to transmit assignment information, operation, administration, management (OAM) data, and wavelength allocation. There is a work related to wavelength adjustment method for the upstream signal using the AMCC in WDM-PON for 5G presented in Ref.[26].

In general, single-wavelength data rate 25 Gbit/s and 50 Gbit/s are the target for next PON innovations regardless of the PON type. On the transmitter side, novel modulation formats such as duobinary, discrete multitone, and PAM-4, are being introduced with the conventional NRZ method. On the receiver side, for a wireless service dedicated PON, the ODN loss budget is much more relaxed compared with the conventional fixed access PON, which results extra cost saving. For TDM-PON, the latency issue has been investigated to minimize the time delays due to DBA and quiet window during the activation of ONU[23]. For WDM-PON, there are innovations for cost-effective tunable transceivers, which are big challenge especially for 25 Gbit/s data rates and higher.

WDM-PON appears to be a best choice for reliable 5G and beyond transport system. WDM-PON is very attractive for future broadband access network due to its capability of providing practically unlimited bandwidth to each end node. WDM-PON can be paired with high-speed technologies such as digital coherent detection to provide improved tolerance to system impairments, greater capacity, and enhanced spectral efficiency[4]. There has been a great interest in coherent access networks recently. This has been driven by the need to expand the system reach and to support increased number of users. Digital coherent detection involves optical coherent detection with electronic digital signal processing (DSP)[4]. Coherent technology will allow the use of ultra-dense wavelength division multiplexing (UDWDM) by densely spacing channels whilst avoiding filtering and introducing the "wavelength-to-the-user" concept, thanks to the excellent selectivity of coherent receivers[12,27]. Moreover, coherent receivers offer significantly higher receiver sensitivities compared with direct detection (DD) receivers[28,29]. This will allow higher loss budgets, enabling higher split ratios and longer reach[6]. However, the complexity and cost of conventional digital coherent receivers have prevented their use in PON applications. Recent advances in low complexity coherent transceiver technology can play a significant role in future access PONs[30,31].

Phase and polarization diverse digital coherent receivers have the potential to increase the capacity of current optical fiber networks, where all four optical carrier dimensions (the in-phase and quadrature-phase components of two orthogonal polarizations) are used for modulation[32-34]. Spectrally efficient modulation techniques such as M-ary phase shift keying (PSK) and M-ary quadrature amplitude modulation (QAM) can be employed for coherent optical links[35,36]. Modulation formats with k bits of information per symbol can achieve a spectral efficiency of up to k bit/s/Hz/polarization compared with 1 bit/s/Hz/polarization for binary modulation formats. For example, modulation formats with 2 bits of information per symbol such as QPSK can realize up to 2 bit/s/Hz/polarization of spectral efficiency using half the symbol rate while keeping the bit rate. The reduced symbol rate offers numerous gains with regard to tolerance to chromatic dispersion (CD) and polarization-mode dispersion (PMD). Moreover, since the phase information is preserved after detection, linear equalization methods can be used to compensate linear optical impairments, such as CD and PMD. In addition, advanced FEC techniques can be applied to increase reach and robustness of the system.

However, nonlinear interactions between closely spaced multiple WDM wavelengths with large launching power occur. Theses nonlinear effects include self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). Currently, dispersion unmanaged systems are the industry standard, where the effect of SPM and XPM is eased due to fast broadening of the optical pulses during transmission. However, the effect of fiber nonlinearity remains a limiting factor for increasing the transmission capacity. Several technologies for reducing fiber nonlinearity have been reported including digital back-propagation (DBP), subcarrier multiplexing, and total intensity directed phase modulators (TID-PMs) XPM compensator[37-39].

As the needs in 5G transport architecture are increasing to at least 25 Gbit/s and beyond, the coherent detection technique seems to be more attractive method to be considered than direct detection. It enables a higher spectral efficiency and greater tolerance to CD and PMD. Several coherent PON system demonstrations that can be employed for 5G transport have recently been demonstrated. A 10 Gbit/s class TWDM-PON was demonstrated using a self-coherent coherent technique with a commercial distributed refractive laser (DFB)[40]. Afterwards, 20 Gbit/s to 100 Gbit/s class digital coherent PON systems were investigated[41,42]. These demonstrations indicated the capabilities of much higher bit rate of 100 Gbit/s/wavelength class PON systems, offering several times higher capacities than the current PON systems with 10 Gbit/s/wavelength. A DP-QPSK with 100 Gbit/s/λ for 100 km distance was demonstrated recently in Ref.[43].

Fig.2 shows the proposed coherent WDM-PON architecture employing 100 Gbit/s/λ DP-QPSK signals for a 100 km fiber span to achieve a total capacity of 1.6 Tbit/s.

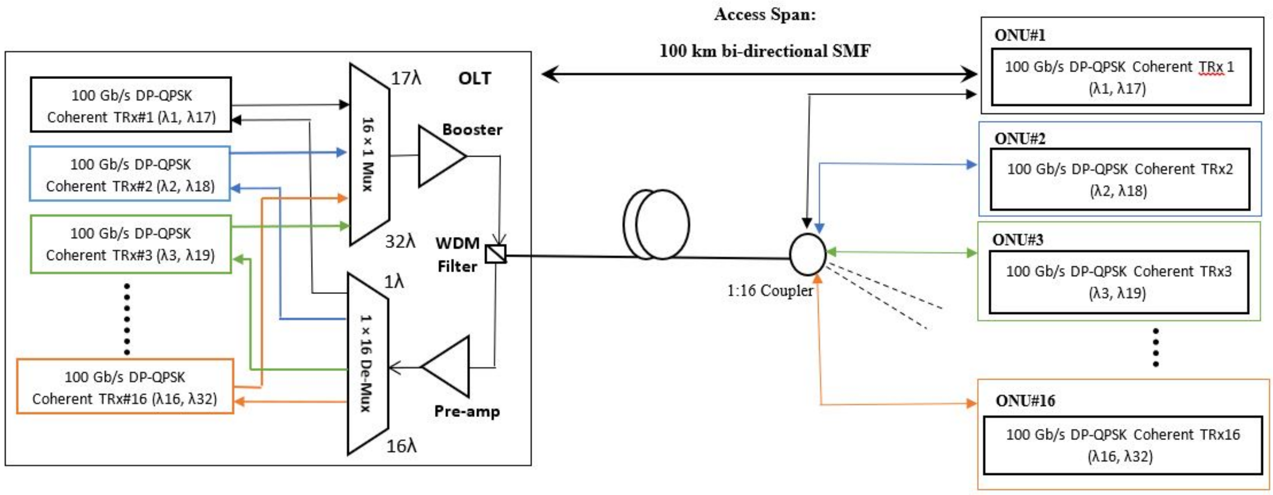

Fig.2 Architecture of the 1 600 Gbit/s coherent WDM PON system

A symmetric 16×16 coherent DP-QPSK WDM-PON system has been employed. Each OLT/ONU link of the sixteen can handle up to 100 Gbit/s data rate in both directions. Each ONU/OLT path is identified by an individual wavelength (λ). The upstream wavelengths (from ONU to OLT) were allocated from 1 537.79 nm (λ1) to 1 543.73 nm (λ16), while the downstream wavelengths (from OLT to ONU) were allocated from 1 558.17 nm (λ17) to 1 564.27 nm (λ32). The channel spacing in both cases was 50 GHz. At both ends, a 100 Gbit/s NRZ DP-QPSK real-time optical coherent transceivers (TRXs) were used. At the OLT, a booster amplifier for downstream, a preamplifier for upstream, an optical MUX/DEMUX with 50 GHz grid and a WDM Gaussian optical filter were employed. Both booster and preamplifier are EDFAs. At ONUs side, a 1:16 coupler was used to connect the 16 ONUs.

The coexistent advantages of low-cost and high sensitivity receiver make the proposed scheme an attractive candidate for 5G transportation. The optical coherent dual-polarization PSK receiver consists of a homodyne receiver design. It has an LO laser polarized at 45° relative to the polarization beam splitter, and the received signal is separately demodulated by each LO component using two single polarization PSK receivers. Cost effective simplified coherent receiver for high splitting downstream transmission was employed, where a simple half power coupler was used to replace 90° optical hybrid and the electrical LO was used to down-convert the signal. Moreover, single balanced photodiode was required for each polarization. This simplified coherent PON receiver enables high capacity, long reach and large-scale NG-PONs[44].

The performance of the DP-QPSK modulated signal in the downlink is investigated by measuring the variation of bit error rate (*BER*) with optical signal-to-noise ratio (*OSNR*)[45]. The *BER* results after 100 km SMF and at back-to-back (B-T-B) and the corresponding constellation diagrams of downlink 100 Gbit/s DP-QPSK modulated signals are shown in Fig.3. λ17, λ24 and λ32 were chosen to be viewed in the figure to show the results of first, middle, and last wavelengths of the downstream spectrum. It is clear from the results that the *BER* declines with the increase of the *OSNR*. Moreover, the perfect constellation diagram indicates that the fibre impairments do not have a major effect on the DP-QPSK-modulated signal. Furthermore, it can be seen that the power penalty is negligible (less than 2 dB).

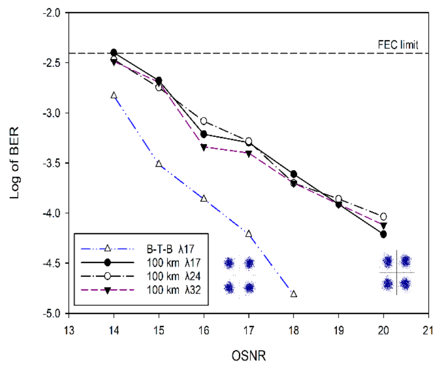

Fig.3 *BER* curves for DL at B-t-B and 100 km span (Inset: *λ*17 corresponding constellation diagrams)

The variation of *BER* with *OSNR* for the DP-QPSK modulated signal in the uplink 100 km span of SMF is shown in Fig.4). λ1, λ8, and λ16 were chosen to be viewed in the figure to show the results of first, middle, and last wavelengths of the upstream spectrum. It is clear from the results that the *BER* declines with the increase of the *OSNR* for both uplink and downlink respectively. Moreover, the *BER* is slightly better for the downlink compared with the uplink, which is expected because of the usage of booster in downlink before the 100 km SMF. For uplink, the pre-amplifier amplify both the signal that carries the information and the noise generated by dispersion and nonlinear effects of fiber span.

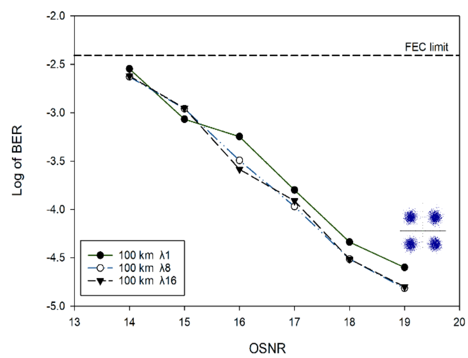

Fig.4 *BER* curves for uplink at 100 km span of SMF (Inset: *λ*16 corresponding constellation diagram)

Several DSP functions and algorithms to aid in recovering the incoming transmission channel(s) after coherent detection have been performed. These include Bessel filter, resampling, quadrature imbalance, nonlinear compensation, timing recovery, adaptive equalizer, down-sampling, frequency offset estimation, and carrier phase estimation.

Assuming that the DP-QPSK optical TRx has an output power (*PT*) of 0 dBm, the insertion loss of 16 splits is 14.5 dB, and fiber attenuation loss of 20 dB (0.2 dBm/km ×100 km). Then the total power loss (*PL*) for the link will be 34.5 dB. The total gain (*G*) of the link that is generated by the EDFA is 18 dB. Considering link degradation, a power margin (*PM*) of 6 dB should be added as well. Then the required receiver's sensitivity (*PR*) at the end of the optical path can be calculated using the equation ($PT-PR<PL-G+PM$). Hence, the optimum receiver sensitivity *PR* should be more than −22.5 dBm.

Tab.2 summarizes the loss budgets calculations. Uplink had a 35.01 dB loss budget with an OLT output power of +8.01 dBm/ch while downlink had a 35.16 dB loss budget with an OLT output power of +2.76 dBm/ch. It is clear from the results that the proposed 100 Gbit/s/λ-based coherent WDM-PON system has a feasible loss budget that can support a 1 600 Gbit/s symmetric bi-directional MFH suitable for 5G.

Tab.2 Summary of loss budget

Parameter	Unit	Upstream	Downstream
Bit rate per λ	Gbit/s	100	100
OLT output power	dBm/ch	8.1	+2.76
ONU input power	dBm/ch	−27	−32.4
Distance (max loss)	km (dB)	100 (20.0 dB)	100 (20.0 dB)
ONU splits (max loss)	# (dB)	16 (14.5 dB)	16 (14.5 dB)
Loss budget	dB	35.01	35.16

A review of the evolving and future PON technologies for 5G transport systems has been given. To accommodate the aggregate capacity demands for 5G and beyond cellular networks, coherent WDM-PON system employing DP-QPSK transceiver was investigated, whereas a total transmission capacity of 1.6 Tbit/s (100 Gbit/s/λ × 16 wavelengths) has been achieved. The *BER* results show that 100 km SMF transmission can be realized with minimum errors and without dispersion compensation. The results verify that the proposed scheme of coherent WDM DP-QPSK PON offers a promising solution for future 5G and beyond MFH and MBH networks.

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