2 Tbit/s based coherent wavelength division multiplexing passive optical network for 5G transport

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Future high-speed mobile communication systems require low latency and high capacity networks. Coherent wavelength division multiplexing (WDM) passive optical network (PON) scheme is expected to play a vital role in these systems. In this paper, coherent WDM-PON scheme based on dual-polarization 16-quadrature amplitude modulation (DP-16QAM) transceiver has been investigated. The aim of this scheme is to build a 2 Tbit/s (125 Gbit/s/λ×16 wavelengths) network that will be used in the construction of the transport architecture of fifth generation (5G) and beyond 5G (B5G) cellular networks either in mobile front haul (MFH) or mobile back haul (MBH). The results indicate that the proposed scheme is very adequate for both 5G and B5G cellular networks requirements.

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The transport network plays a vital role in reliable fifth generation (5G) and beyond 5G (B5G) deployments. Several technologies such as point-to-point fiber access, passive optical network (PON), Flexible Ethernet, and optical transport network (OTN) are competing to be proposed for both 5G and B5G transport systems[1-6]. Since 5G and B5G operators have different business models and various deployment plans built on their own budgets and markets. Technology maturity and market timing will play a big role in choosing appropriate transport technology by an operator. However, among these competing technologies, PON stands out as an attractive choice because of its efficient use of fiber resources and its wide deployment around the world for fixed access services[7]. 100 Gbit/s-based PON standard in the form of 100 G Ethernet PON (100G-EPON) has been proposed in 2017 to meet the growing bandwidth demand initiated by latest applications, such as mobile front haul (MFH) networks for 5G[8].

The bandwidth requirements for 5G MFH and mobile back haul (MBH) based on PON technology that are needed for connecting small cells and base band unit (BBU) are shown in Fig.1. The peak data rate is assumed to be 20 Gbit/s for each sector[9]. The integrated remote radio head (RRH) covers three sectors in a small cell. For each macro cell, the total peak wireless data rate for a single sector is assumed to reach 60 Gbit/s. Thus, the data rate between the optical line terminal (OLT) and the optical network unit (ONU) in 5G MFH/MBH can increase to 125 Gbit/s for a small cell and up to 2 Tbit/s for a macro cell containing 16 small cells as evaluated in Fig.1.

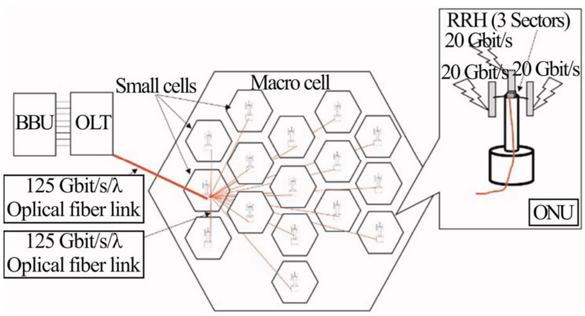

Fig.1 Bandwidth requirements (in red) for 2 Tbit/s 5G MFH/MBH based PON technology

Several papers have studied 100 Gbit/s PON and below[2,9]. Recently, coherent wavelength division multiplexing (WDM) PON system for 5G mobile network employing 100 Gbit/s/λ×8λ (800 Gbit/s) was demonstrated[2], whereas, dual polarization quadrature phase shift keying (DP-QPSK) transceiver was used. In this paper, a demonstration of 125 Gbit/s/λ×16 wavelengths (2 Tbit/s) WDM PON system employing dual polarization 16 quadrature amplitude modulation (DP-16QAM) transceiver with coherent detection and simplified digital signal processor (DSP) will be presented. This system could be utilized for 5G and B5G transport networks.

Recently, data traffic in the mobile communication systems grew exponentially, driven by the development

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of smart mobile devices and mobile Internet. To meet the huge bandwidth demand in the network, radio access networks (RANs) have been upgraded and arrived now to the 5G wireless networks which are envisioned to be the practical solutions for meeting the increasing demand for ultra-reliable low latency communications (URLLC)[4]. There are two main parts of the RAN transport architecture in the 4th generation (4G) (Known as long term evolution (LTE)). The first part is the backhaul, which connects between evolved packet core (EPC) and base band unit (BBU), and the second part is the fronthaul which connects between the BBU and remote radio head (RRH). The fronthaul in 4G is used to transmit the digitized in-phase/quadrature (IQ) data in a continuous bit rate irrespective of the availability of user traffic. Therefore, data rates over 100 Gbit/s are projected in 5G networks if the same protocols are used. Latency is an additional key factor, where the maximum end-to-end round-trip time (RTT) in 4G equals to 250 μs for BBU-RRH connection. This latency requirement does not cause a problem as optical fiber is used for BBU-RRH connection at the same cell[7]. However, this approach does not meet the 5G requirements for both low latency and high bandwidth. The centralized transport architecture for 5G system must support a large scale of connected devices. Therefore, all BBUs have to do the centralized processing at a common location, while all RRHs are left at the cell site with least power consumption. Moreover, the latency must take into account propagation time through the transmission media, for example the round-trip delay in optical fiber is 10 μs/km[1].

Consequently, these constraints can be mitigated by employing a new design that will keep network centralization. The basic idea of the new design is a reallocation of the radio signal processing functions in EPC and BBU of 4G/LTE to new functional elements in 5G, namely the next-generation core (NGC), centralized unit (CU), distributed unit (DU), and radio unit (RU). There are several features included in these functions such as: radio resource control (RRC), packet data convergence protocol (PDCP), radio frequency (RF), high/low layers of radio link control (RLC), media access control (MAC), and physical layer (PHY). Fig.2 shows the difference between 4G/LTE and new radio design of 5G architectures[7]. There are several ways to split the functions, one of these ways is split option 8, which is the conventional 4G/LTE common public radio interface (CPRI) for fronthaul interface, which provides full centralization processing functions. Other split options 1-7 offers to scale the data transported with user traffic. This leads to dynamically adapt to conditions of traffic in the transport network and efficiently aggregate traffic from multiple cells, when PON is used as a shared media.

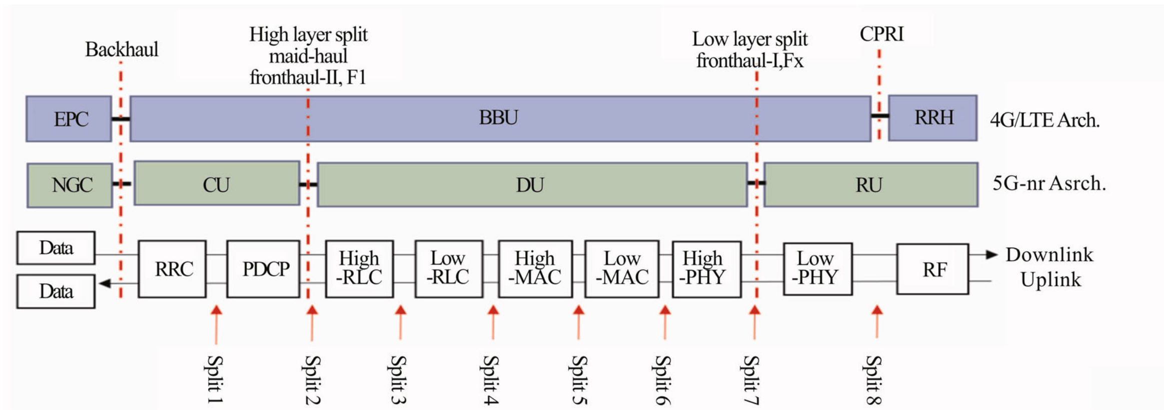

Fig.2 Network elements for both 4G/LTE and 5G-NR (top) and signal processing function chain (bottom)

The 5G requirements of transport bandwidth and latency is illustrated in Tab.1[2]. All stated splits under optimal settings indicate bandwidth peak values. The bandwidth values were computed based on these parameters; 100 MHz radio frequency bandwidth, 256-QAM modulation, up to 32 antenna ports for about 6 GHz, and 8×8 MIMO layers. The main property of 5G and B5G systems is throughput bandwidth or PON capacity. For example, less than 3.5 GHz radio bandwidth between backhaul and F1 is required at phase 1 of 5G system, growing to 6 GHz for phase 2[10], and about 86 GHz for the later phase[11]. Regarding the values of latency, Tab.1 presents a potential range of these values, which are enclosed in the standards development organizations (SDOs)[1].

PON is a point to multipoint network, where a passive optical splitter is used to broadcast the transmitted optical signal from the OLT at the central office to ONUs at subscribers' premises. For time division multiplexing PON (TDM-PON), in the uplink direction, each ONU burst transmits in a signed time slot and signals from all ONUs are multiplexed in the time domain. 5G specifications allow a minimum overall latency in the transmission system. TDM-PON bandwidth allocation schemes increase the overall latency beyond this level. In TDM-PON, OLT implements dynamically bandwidth allocation

(DBA) to allocate time slots for specific ONUs upstream signals, which could cause delay. Fixed-length DBA[12] and traffic-load dependent DBA[13] have been proposed to minimize latency issue in TDM-PON. 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 (as it does not need DBA). WDM-PON with a dedicated wavelength for each user with 25 Gbit/s or more has been proposed for 5G deployment[14]. Coherent detection technique is more attractive method for 5G transport architecture than direct detection. It enables higher spectral efficiency and greater tolerance to chromatic and polarization mode dispersions. Therefore, coherent detection can extend transmission distance and increase capacity compared with a traditional direct detection[15,16]. Consequently, coherent WDM system based on multi-level modulation formats will be able to meet the aggregate bandwidth demand. Tab.2 summarizes the results of coherent PON system demonstrations which can be employed for 5G transport[2,17-19].

Tab.1 Bandwidth and latency requirements for 5G

Split	Uplink bandwidth	Downlink bandwidth	One-way latency
1	4 Gbit/s	3 Gbit/s	1—10 ms
2 (F1)	4 016 Mbit/s	3 024 Mbit/s	
3	Lower than option 2		
4	4 000 Mbit/s	3 000 Mbit/s	100 to a few 100 μs
5	4 000 Mbit/s	3 000 Mbit/s	
6	4 133 Mbit/s	5 640 Mbit/s	
7a	10.1—22.2 Gbit/s	16.6—21.6 Gbit/s	
7b	37.8—86.1 Gbit/s	53.8—86.1 Gbit/s	
7c	10.1—22.2 Gbit/s	53.8—86.1 Gbit/s	
8 (CPRI)	157.3 Gbit/s	157.3 Gbit/s	

Tab.2 Demonstration results of Coherent PON systems[2,9]

Parameter	Unit	Ref.[16]	Ref.[17]	Ref.[18]	Ref.[2]	Ref.[19]
Bit rate per λ	Gbit/s	10	112	20	100	100
Modulation	n/a	OOK	DP-QPSK	SP-QPSK	DP-QPSK	DP-QPSK
Multiplexing	n/a	TDM	WDM	TDM	WDM	WDM
Distance	km	37	B-to-B	40	100	80
Evaluation	n/a	Offline	Offline	Offline	Offline	Real-time

The 16QAM modulation is one of the spectrally efficient modulation formats[20]. Researchers have investigated and compared the end-to-end latency in hybrid optical-wireless system for various modulation formats such as GMSK, DQPSK, 8PSK and 16QAM in real-time. The experimental results using software defined radio and optical links indicated that 16QAM modulation latency is the lowest[21].

Coherent WDM-PON scheme based on DP-16QAM has been investigated as it meets the requirement for high bandwidth and low-latency needed in 5G and B5G transport architecture. Coherent WDM-PON employing 16 wavelengths spaced at 50 GHz has been used. Each wavelength serves a small cell with 125 Gbit/s transport data rate. The 16QAM modulation increases the capacity by transmitting 4 bits per symbol. Moreover, using dual polarization duplicates the bit rate. Therefore, a significant data rate of 2 Tbit/s (125 Gbit/s/λ×16 wavelengths) can be realized for 5G and B5G transport networks.

The block diagram of the proposed 2 Tbit/s coherent WDM-PON scheme over 100 km single mode fiber (SMF) is shown in Fig.3. The architecture features a symmetric 16×16 WDM-PON system with 16×125 Gbit/s wavelengths in both downlink (DL) and uplink (UL) respectively. Each ONU is connected to the OLT on a dedicated wavelength via an optical coupler located at the end of 100 km SMF access span. In our work, the 16 UL wavelengths are allocated from 1 537.79 nm (λ_1) to 1 543.73 nm (λ_{16}), and the DL ones were allocated from 1 558.17 nm (λ_{17}) to 1 564.27 nm (λ_{32}). For both of UL and DL the channel spacing is 50 GHz. At the OLT side, a 125 Gbit/s non-return-to-zero (NRZ) DP-16QAM real-time optical coherent transceiver (TRx) was employed. Moreover, an optical multiplexer/de-multiplexer (MUX/DEMUX) with a 50 GHz grid spacing[22], a gaussian WDM optical filter, a booster amplifier for DL and a pre-amplifier for UL are used. The booster and pre amplifier are standard erbium-doped fiber amplifiers (EDFAs). Both amplifiers are located at the OLT to eliminate further power requirements in the optical distribution network (ODN), and hence, to achieve minimum power consumption at ONUs.

At the ONU side, 125 Gbit/s NRZ DP-16QAM real-time TRx was also employed. Furthermore, an optical 1×16 coupler was also utilized.

Fig.4 shows a simplified block diagram illustrating the functions of the DP-16QAM TRx employed in both OLT and ONUs. The diagram consists of an optical and electrical sections as shown in Fig.4. The optical part contains an optical DP-16QAM transmitter to modulate the pseudo-random binary sequence (PRBS) data, an optical circulator to isolate upstream from downstream signals, a gaussian optical filter and an optical coherent DP-16QAM receiver to receive the upstream signal. Second, the electrical side includes digital signal processor (DSP) to aid in recovering received signals. Moreover, there is a decision component that processes received I and Q electrical signal from the DSP stage then normalizes the electrical amplitudes of each them to the respective 16QAM grid, and then performs a decision on each received symbol based on normalized threshold settings. Furthermore, two 16QAM sequence decoders are utilized to decode the sequence generated by decision component, and finally a parallel to serial (P/S) converter to combine the two input sequences at bit rate *R* into one output sequence at 2*R* bit rate. The DSP is utilized in our scheme since its functions and algorithms can aid in recovering the incoming transmission signals. The DSP consists of several elements such as Bessel filter, quadrature imbalance, resampling, nonlinear compensation, chromatic dispersion, timing recovery, adaptive equalizer, and estimation of both carrier phase and frequency offset.

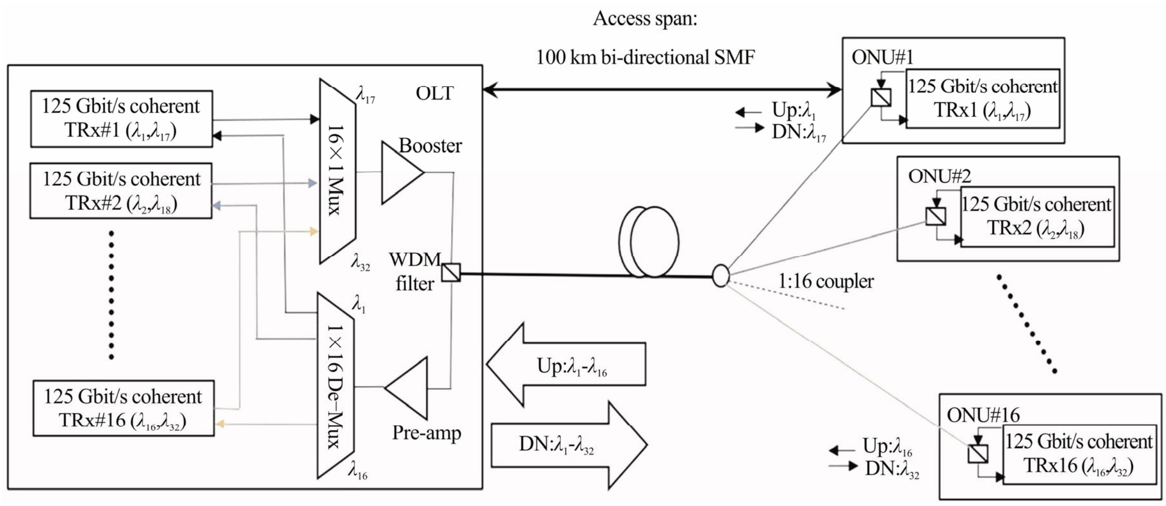

Fig.3 Block diagram of the proposed 2 Tbit/s coherent WDM-PON scheme

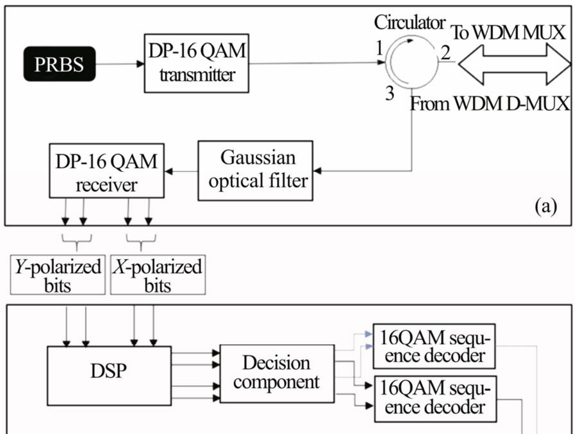

Fig.4 A simplified block diagram of the system with (a) optical part and (b) electrical part

The bit-error rate (*BER*) performance of the DP-16QAM coherent WDM-PON system is evaluated. The *BER* versus optical signal to noise ratio (*OSNR*) results after 100 km SMF and the corresponding constellation diagrams for selected UL signals (λ_{17}, λ_{20}), and DL signals (λ_1, λ_4) are shown in Fig.5. It is clear from the results that the *BER* declines with the increase of the *OSNR*. Moreover, the DL and UL signals have comparable results. Furthermore, the perfect constellation diagram (evaluated for λ_1 and λ_{17} respectively at *OSNR* of 24 dB) indicates that the fibre chromatic dispersion does not have a major effect on the DP-16QAM modulated signal.

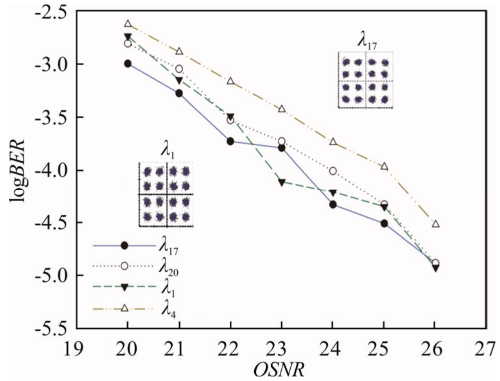

Fig.5 *BER* curves for uplink and downlink at 100 km span of SMF, where insets corresponding constellation diagrams for λ_1 and λ_{17}

A comparison between the performance of the system after 100 km SMF and at back-to-back (BTB) has been performed. The variation of *BER* with *OSNR* and the corresponding constellation diagrams for both schemes is shown in Fig.6. It can be seen from the results that the power penalty is negligible (less than 1dB). For example, the log of *BER* values are −4.3 and −3.8 at *OSNR* of 23 dB for BTB and the system, respectively.

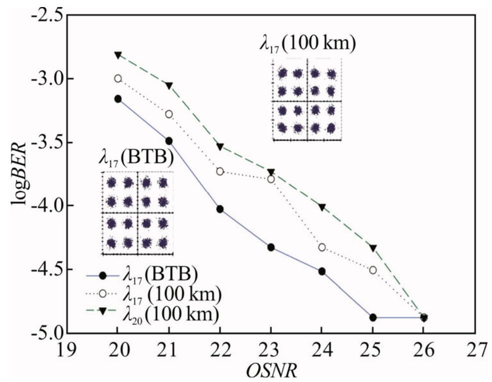

Fig.6 *BER* curves at BTB and 100 km span, where insets corresponding constellation diagrams for λ_{17}

Coherent DP-16QAM WDM-PON system for 5G transport networks has been evaluated over 100 km SMF. To meet the aggregate bandwidth demands for 5G and beyond cellular networks, 125 Gbit/s/λ × 16 wavelengths-based system has been proposed, whereas a total transmission capacity of 2 Tbit/s 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 both 5G and B5G transports networks.

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