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Terabit WSDM Optical Access Network Using Multicore Fibers and Advanced Modulation Formats

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Abstract— We proposed a hybrid wavelength-space division multiplexing (WSDM) optical access network architecture utilizing multicore fibers (MCFs) with advanced modulation formats. As a proof of concept, we experimentally demonstrated a WSDM optical access network with duplex transmission using our developed and fabricated multicore (7-core) fibers and fan-in/fan-out device with 58.7 km distance. With QPSK-OFDM modulation format, the aggregation downstream (DS) capacity reaches 250 Gb/s using 5 outer cores and it can be further scaled to 1 Tb/s using 16 QAM-OFDM. For upstream (US) transmission, wavelengths seeded from DS using the inner core are modulated with DMT signal adapted with the channel conditions and then transmitted back to the OLT through the 6th outer core. As an emulation of high speed mobile backhaul (MB) transmission, IQ modulated PDM-QPSK signal with 48 Gb/s per wavelength is transmitted in the inner core of MCF and coherently detected in the OLT side. Both DS and US optical signal exhibit acceptable performance with sufficient power budget.

Recently, the bandwidth demand for the access network has witnessed a sharp increase driven by various services like business IP traffic, super HD video, mobile traffic backhaul and social networking, etc. [1]. Multiple candidates have been proposed to satisfy the requirements, such as passive optical networks based on WDM [2], TWDM [3], and OFDM [4]. However, the access capacity, transmission distance and subscriber number are still limited just using conventional technical methods. The space division multiplexing (SDM) technique based on few mode fibers (FMF) or multi-core fibers (MCF) has been proposed to be a favorable solution to accomplish the fiber capacity crunch in both long-haul transmission [5] and short-reach access network [6, 7]. Although the FMF based access network example has been reported very lately [6], the differential modal dispersion and modal interference may hinder its deployment in the access network region and MCF is actually a better choice owing to its well-controlled inter-core crosstalk and almost identical transmission quality compared with standard single mode fibers (SSMF). Zhu et al. demonstrated a 7-core based optical access network using traditional TDM-PON technologies [7]. However, the access data rate and the fiber link distance are quite limited (2.5 Gb/s and 11.3 km). Moreover, as a universal platform for wired/wireless data services, the optical access network plays even more important role in the 4G/5G mobile data transmission [8] and it is also interesting to envision the application of MCF in the fiber/wireless converged networks.

In this paper, we proposed a hybrid wavelength-space division multiplexing (WSDM) optical access network architecture utilizing multicore fibers with advanced modulation formats, as shown in Figure 1. In our proposed architecture, the most prominent feature is that a physically isolated fiber channel (the inner core of a typical 7-core MCF for example) is allocated to the wireless data transmission such as the mobile backhaul transmission considering the mobile internet demand is booming. One of the outer cores of MCF is utilized to transmit US signal while the others are employed as the parallel channels for DS transmission, thus the Rayleigh backscattering noise can be eliminated even though the same wavelengths are reused for both DS and US. In the OLT block, m wavelengths are utilized as the laser source. For each wavelength in one subset OLT, it is power split by $N-1$ in which N representing the number of cores of MCF. $1/(N-1)$ of the signal power is left as the optical carrier for US signal modulation which is delivered to the ONU side via the inner core. In this way, this configuration can support $(N-1)\times m$ subscribers only employing m wavelengths that can lower the expense compared with the same situation in WDM-PON. To further enhance the capacity with affordable cost and complexity, downstream

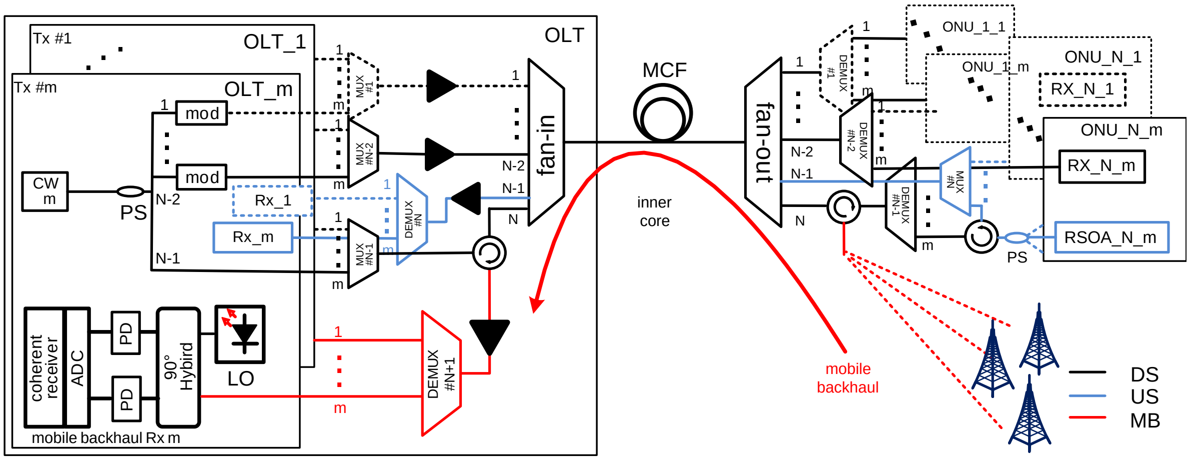


Figure 1: Proposed WDM/SDM optical access network architecture.

signal on each wavelength is suggested to be intensity-modulated with optical OFDM modulation format, which is spectral efficient and bandwidth flexible. After the modulation, the $(N-2)\times m$ branches from λ_1 to λ_m are multiplexed respectively by $N-2$ m-wavelength Mux devices like array waveguide gratings (AWGs). Afterwards, $N-2$ sets of WDM signals are amplified by erbium-doped fiber amplifiers (EDFAs). After getting through the circulators, the N sets signals are injected into the $N-2$ outer cores of MCF taking advantage of the fan-in device. Subsequently, the DS signals are transmitted in the MCF, and output to $N-2$ independent single mode fibers by the fan-out device. Signals from each core containing wavelength from λ_1 to λ_m are demultiplexed respectively and each ONU enjoys one dedicated wavelength. Therefore our proposed WSDM optical access network has the potential to deliver multi-giga-bit services to a substantial number of subscribers. For US transmission, the optical carriers distributed from the OLT side using the inner core can be amplified and modulated by a RSOA and then transmitted to the OLT side via the remained outer core. All the ONUs served by the same subset OLT must share the same wavelength for US transmission, in a TDMA or OFDMA manner.

To verify the feasibility of our proposed WSDM access network architecture, we conducted a proof of concept experiment using the setup depicted in Figure 2. The low-crosstalk MCF (with average loss of about 0.25 dB/Km) we developed and fabricated has seven cores in a hexagonal array (cross section view is shown as inset in Figure 2) and its geometrical and optical parameters are described in details in [9] and the low-loss fan-in/fan-out devices (shown as inset in Figure 2) are in-house developed using chemical etching process and fiber bundles manufacturing technique. For DS transmission, ten wavelengths with 25 GHz channel spacing are selected by a WSS (Finisar

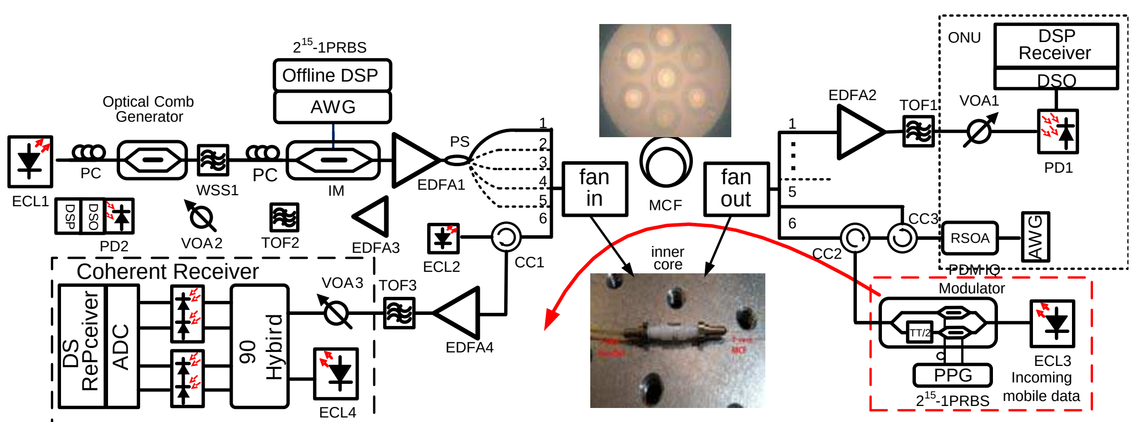


Figure 2: The experimental setup schematic diagram. (PS: power splitter, PC: polarization controller, WSS: wavelength selective switch, AWG: arbitrary waveform generator, IM: intensity modulator, VOA: variable optical attenuator, EDFA: erbium doped fiber amplifier, ECL: external cavity laser, TOF: tunable optical filter).

WaveShaper 4000 s) from an optical frequency comb generator (OFCG) seeded by an ECL centered at 1550.12 nm. Then the ten continuous waves (CWs) are intensity modulated with 5 Gb/s baseband OFDM-QPSK signal. Boosted by an EDFA, the optical OFDM signals are power split by a 1 : 8 power splitter and simultaneously injected into five outer cores of the MCF through the fan-in device, and the optical spectra of amplified optical OFDM signals is shown as inset in Figure 2. After 58.7 km MCF transmission, the signals are output into five single mode fibers through fan-out device. At the receiver side of every single mode fiber, after pre-amplification and de-multiplexing, one wavelength is selected and directly detected by a photodetector (PD) with 2.4 GHz bandwidth and then sampled by a 20 GS/s digital sampled oscilloscope (DSO, Tektronix CSA7404B). Demodulation and bit error ratio (BER) counting are implemented offline.

The BER performance of QPSK based OFDM DS signal centered at 1550.12 nm from 5 outer cores at various received optical power after MCF transmission and in OB2B setup is shown in Figure 3(a). The BER can be kept under 7% Forward Error Correction (FEC) limit at BER $= 3.8 \times 10^{-3}$ at the received optical power as low as -16 dBm. Therefore an aggregated 250 Gb/s DS capacity has been realized with 10 wavelengths and 5 cores, through a combination of spectral and spatial dimensions. A BER floor has been observed when the received optical power excess -15 dBm, which is mainly due to the relatively poor optical signal-to-noise ratio (OSNR, about 25 dB) of the OFCG. To demonstrate the scalable capacity, we use a single wavelength laser with higher OSNR to replace the OFC and employ 16 QAM modulation format in the same setup. As shown in Figure 3(b), with a single wavelength, the receiver sensitivity of 10 Gb/s 16 QAM-OFDM based DS transmission is about -11 dBm. Therefore, using 20 wavelengths from a high quality

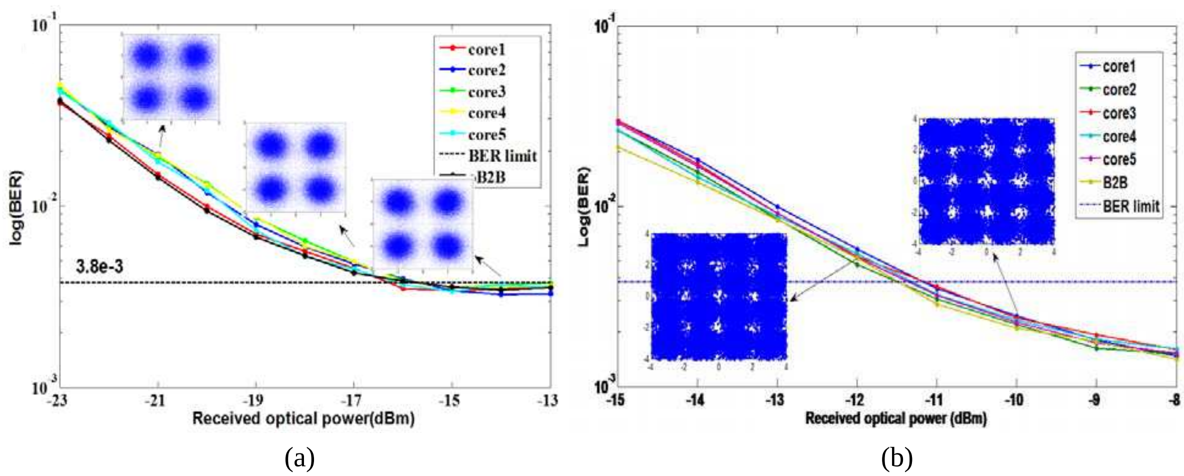


Figure 3: The BER curve for DS transmission with (a) optical frequency comb based QPSK-OFDM, (b) single wavelength based 16 QAM-OFDM

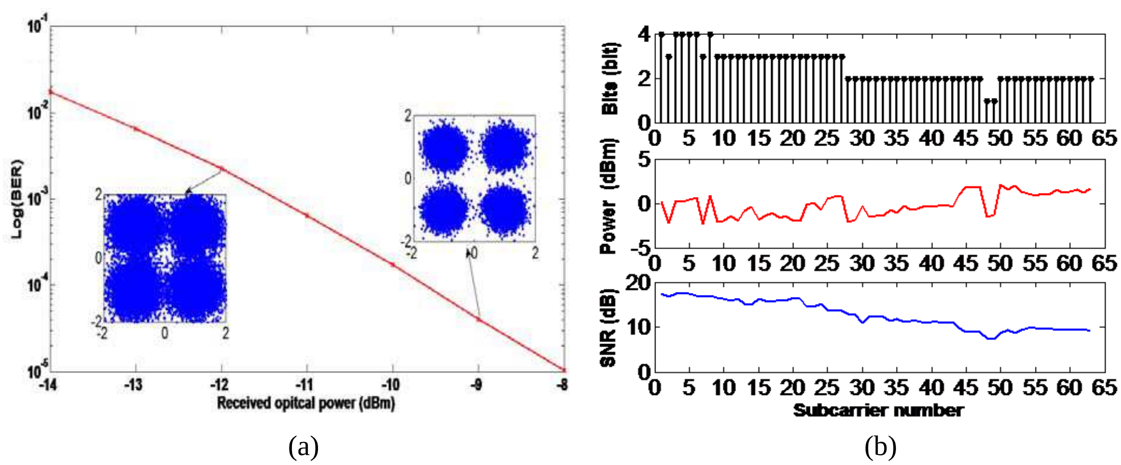
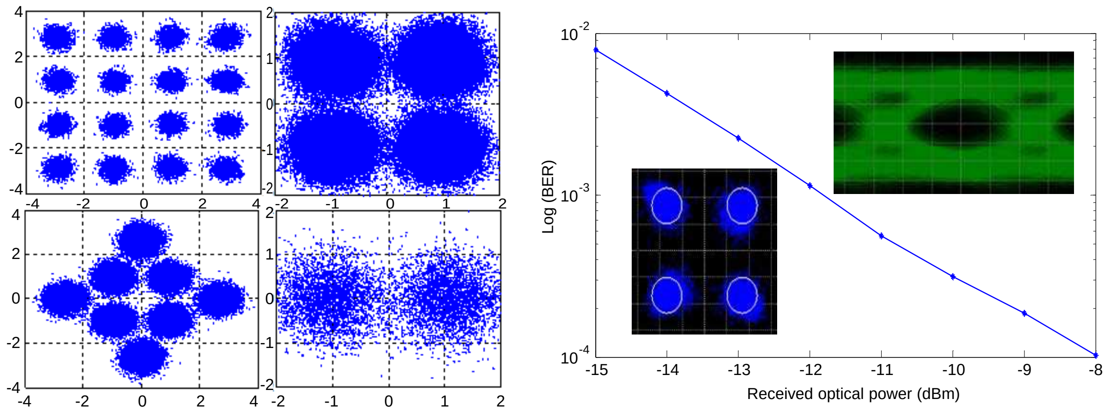


Figure 4: (a) The BER curve for US transmission using QPSK-OFDM, (b) bit and power allocation with adaptive DMT modulation and the estimated SNR for each subchannel.



(a) (b)

Figure 5: (a) The received constellation diagrams for US transmission using adaptive DMT, (b) BER performance for MB transmission.

OFC and 16 QAM modulation format, it is expected to realize terabit $(20 \times 10 \times 5)$ DS transmission optical access network based on MCF.

For the US transmission from the ONU, 3.12 Gb/s OFDM signal with adaptive modulation based on a 1 GHz bandwidth RSOA is coded on the optical carrier distributed from the inner core and then transmitted to the OLT side from core 6. During the adaptive modulation, 2.5 Gb/s uniform QPSK modulation on every subcarrier is firstly used to obtain the channel state information, and then the bit number and power allocation on each subcarrier will be rearranged based on Chow's rate-adaptive bit-loading algorithm using the estimated sub-channel SNR information. Figure 4(a) depicts the transmission performance when uniform QPSK is used. The results of number of bits per subcarrier and power allocation using the estimated SNR are shown in Figure 4(b). With adaptive modulation, constellations of different modulation formats after MCF transmission are shown in Figure 5(a), leading to 1.25 times increase in US data rate with BER under 3.8e-3.

For large capacity MB transmission, a CW laser from ECL centered at 1556.55 nm is modulated by a PDM-IQ modulator with 12Gbaud binary signal generated by BER tester (BERT). After amplification and filtering, the signal with 2 dBm power is coherently detected (Tektronix OM4006D) at the OLT. After coherent detection, the output electrical signal is digitalized by a real-time oscilloscope (DSA 72504D) and then offline digital signal processing is implemented using the traditional DSP flow [10]. The MB transmission result is shown in Figure 5(b) with enough power budget.

We have proposed and experimentally demonstrated a duplex WSDM optical access network utilizing our in-house developed 7-core MCFs and fan-in/fan-out devices. The proof of concept experiment proves the capability of the MCF based access network in terms of long reach transmission (58.7 km), large capacity(potential terabit aggregation DS data rate) and massive count of users (50 ONUs), compatible with 48 Gb/s coherent PDM-QPSK MB transmission and 3.13 Gb/s RSOA based adaptive DMT US signal.

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