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# Review on Next Generation WDM-PON Technologies

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***Abstract:We presented review on current advancement in WDM-PON technologies to standarized economical system implementation, and also discuss cost-effective solutions and potential areas of application.***

**Key-Words: WDM-PON, OFDM, OCDMA, RSOA.**

## I.Introduction

Recently, we have done many efforts to enhance the performance of the wavelength-division-multiplexed passive optical network (WDM PON) by utilizing the coherent detection technique. This is mainly due to the excellent receiver sensitivity and frequency selectivity achievable by using the coherent detection technique. In fact, these advantages have already been well exploited to increase the maximum reach and splitting ratio of WDM PONs. However, the typical coherent receivers developed for the high-capacitny backbone network are not suitable for the use in the optical access network due to their cost and complexity. To solve this problem, we have developed various techniques to improve the cost-effectiveness of the coherent receiver [1]-[3] . By using these techniques, we have demonstrated 80-km reach WDM PON operating at the per-wavelength speed of 1 0 Gbits without using any remote optical amplifiers [II]. For the cost-effective realization of a long-reach WDM PON based on the coherent detection technique, we assume that (1) the transmission of the downstream signals is achieved by utilizing directly-modulated single-frequency lasers (or a laser array) at the central office (CO) and PIN receivers at the optical network units (ONUs) and (2) the transmission of the upstream signals is achieved by using colorless light sources in the ONUs and coherent receivers at the CO. One of the plausible network configurations that can satisfY these assumptions is the WDM PON based on reflective semiconductor optical amplifiers (RSOAs)[4]. In this network, however, the maximum reach can be seriously limited by the power budget of the upstream signal due to the loopback configuration (i.e., the seed light sent from CO is modulated by the RSOA at the ONU and then sent back to the CO for the upstream transmission). Thus, in this paper, we focus our discussions on the issues related to the upstream transmission in the RSOA-based WDM PON [5].

To enhance the cost-effectiveness of the coherent receiver, we implement it by using a portion of the seed light as a local oscillator (instead of using an additional laser) and an inexpensive 3x3 fiber coupler as a 1200 optical hybrid (instead of using the 90° optical hybrid commonly used in the coherent receiver for backbone networks). In addition, in this receiver, the polarization stability is achieved simply by placing a Faraday rotator in front of the RSOA in the ONU instead of using the complicated polarization-diversity or polarization-tracking technique [8]-[9]. The results show that the network implemented by using this coherent receiver is extremely robust against the effect of the external reflection caused by fiber connectors and Rayleigh backscattering . This is an important feature for the WDM PON implemented in single-fiber loop back configuration. By using this coherent receiver, we have demonstrated the transmission of 2.5-Gb/s BPSK signal over 68-km long SMF link partially composed of buried and aerial fibers [10] and the transmission of lO-Gb/s QPSK signal over 80-km long SMF link in the laboratory environment [11] without using any remote optical amplifiers. These progresses will be described in details at the conference.

## II. WDM PON Architecture

Fig. 1 illustrates a typicalWDM PON architecture com-prising a CO, two cyclic AWGs, a trunk or feederfiber, a series of distributionsfibers, and optical network units (ONUs) at the subscriber premises. The first cyclic AWG located at the CO multiplexes downstream wavelengths to the ONUs and demultiplexes upstream wavelengths from the ONUs. The trunk fiber carries the multiplexeddownstream wavelengths to a second cyclic AWG located at a remote node. The second AWG demultiplexes the downstream wavelengths and directs each into a distributionfiber for transmission to the ONUs [3]-[5]. The downstream and upstream wavelengths allocated to each ONU are intentionally spaced at a multiple of the free spectral range (FSR) of the AWG, allowing both wavelengths to be directed in and out of the same AWG port that is connected to the destination ONU. In Fig. 1, the downstream wavelengths destined for ONU 1, ONU 2, ,and ONU ,are denoted $\lambda_1, \lambda_2, \lambda_3$ ... ... ... ,and $\lambda_n$ respectively. Likewise, upstream wave-lengths from ONU 1, ONU 2, , and ONU ,that are destined for the CO are denoted $\lambda_{1'}, \lambda_{2'}$ ... .... ,and $\lambda_{n'}$ respectively. In a typical WDM PON, wavelength channels are spaced 100 GHz (0.8 nm) apart. In systems classified as dense WDM-PON (DWDM), a channel spacing of 50 GHz or less is deployed[6]-[7]. Although a WDM PON has a physical P2MP topology, log-ical P2P connections are facilitated between the CO and each ONU. In the example shown in Fig. 1,

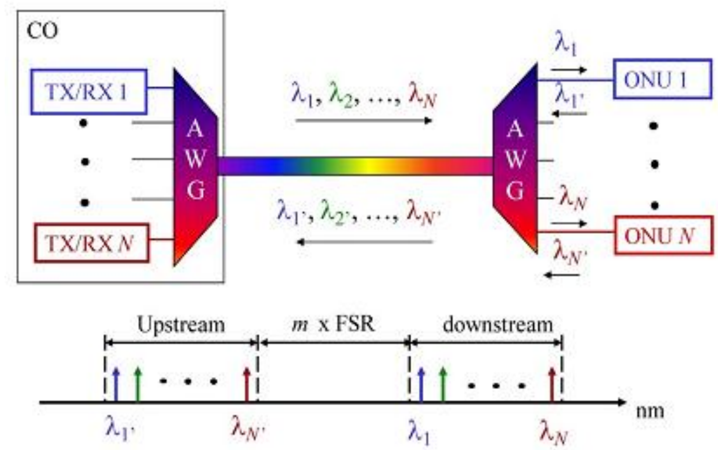


Fig. 1. Architecture of a WDM-PON. Allocation of upstream and down-stream wavelength channels into two separate wavebands.

ONU receives down-stream signals on $\lambda_n$ and transmits upstream signals on $\lambda_n'$. The capacity on these wavelengths is solely dedicated to that ONU. Commonly cited benefits of WDM PON resulting from this unique feature include protocol and bit-rate transparency, security and privacy, and ease of upgradeability and network management.

**III. Coherent Optical Access Networks**

Recent interests in applying digital coherent detection in the access segment have been fueled by the need to extend the system reach and to support high user density. Digital coherent detection combines optical coherent detection with electronic digital signal processing. In optical coherent detection, a six-port optical hybrid comprising linear splitters and combiners, outputs four vectorial additions of the signal of interest and ref-erence local oscillator (LO). The four out-puts are then detected by balanced photoreceivers. Using elec-tronic digital signal processing, the amplitude and the relative phase information between the signal of interest and the LO can then be extracted. Coherent detection can be classified into two categories depending on the LO source used [3]-[5]. In homodyne detection, the LO is derived from the same source as the signal of interest and hence is of the same frequency as the signal of interest. In heterodyne detection, the LO is derived from a dif-ferent signal source which is intentionally tuned to nearly the same frequency as the signal of interest There exist many properties of digital coherent detection that
makes it advantageous as a multiple access technology. Co-herent detection provides theflexibility of frequency selectivity and wavelength channel switching through the re-tuning of the LO. In a WDM PON, this wavelength selectivity feature allows the wavelength routing AWG to be omitted, thereby providing a smooth migration of an existing ODN to a coherent detection WDM PON through the upgrade of the end terminals. Addition-ally, coherent detection has the potential to reach quantum lim-ited receiver sensitivity thereby improving system reach, split ratios, and wavelength density. Further, dispersion com-pensation can be performed in the digital domain through dig-ital signal processing (DSP). An ultra dense WDM PON using digital coherent detection wasrecently demonstrated in . A 64 wavelength channel operation was demonstrated using het-erodyne detection to differentiate between channels spaced at 2.5 GHz. The LO source used at both the ONUs and OLT is a tunable laser that also serves as the light source for down-stream and upstream transmissions respectively. A 1.244 Gb/s data rate is achieved using differential quadrature phase shift keying (DQPSK) format[8]-[11]. Clock recovery and data processing is done in real-time usingfield programmable gate arrays (FPGA) at the OLT and ONUs. The use of coherent detection in PONs has also been reported in long-reach applications, whereby amplification is eliminated altogether, thereby achieving a truly passive network. A 2.5 Gb/s RSOA based WDM PON with a maximum reach of 68 km. Self homodyne coherent receivers at the CO were demonstrated for the upstream transmission. To enhance its cost-effectiveness,the coherent receivers were real-ized using a fraction of the seed light as a LO and an inexpensive 3 3fiber coupler as a 120 degree optical hybrid. To achieve the polarization stability of the upstream signal at the input of the coherent receiver and without having to use costly polariza-tion diversity receivers, a 45 degree Faraday rotator was placed in front of the RSOA in the ONU. As a result, the state-of-polar-ization of the upstream signal will always be orthogonal to that of the linearly polarized seed light at the input of the coherent re-ceiver located at the CO, regardless of the birefringence in the transmission link[5]-[7].

Field trials were carried out using the pro-posed coherent receiver in a 68 kmlink to realistically evaluate the effects of polarizationfluctuations occurring in the installed fibers. No significant degradation in receiver sensitivity was re-ported during the 10 hour trial despite large polarizationfluctu-ations in the installedfiber. Often, advanced modulation formats are also utilised to en-hance channel capacity. Maximum reach of 100 km and an operating speed of 5 Gb/s were achieved in a RSOA based WDM PON that combined digital coherent detection and quadrature phase shift keying (QPSK) modulation. The use of QPSK signal generated by directly modulating the ROSA with a 4-level electrical signal allowed the increase in operating speed of the RSOA from 1.25 Gb/s to 5 Gb/s. The optical coherent detection technique used was similar to the self-homodyne re-ceiver. Error free transmission over the 100 km link was achieved without the use of optical amplification and electronic equalizers, symmetrical data rates of up to 10 Gb/s was achieved with source free ONUs through a combination of OFDM-16QAM modulation format and coherent detection[8].

The uplink and downlink signals of the PON resided on dif-ferent RF bands. For uplink signal generation, the downstream RF-OFDM-16QAM signal was remodulated at the source free ONU with an independent RF-OFDM-16WAM. At the OLT, heterodyne detection with an LO tuned to the corresponding uplink band, was utilized to down-convert the uplink signals to baseband

**IV. Orthogonal Frequency Division Multiple Access (OFDMA)Access Networks**

Originally used as a modulation method for copper and radio OFDM is currently being considered by many research groups as one of the strongest candidate for future PON implementa-tion due to its attractive features that satisfy the needs of next generation access networks [10], [12]. In OFDM, multiple low bit rate orthogonal subcarrierscarrying different QAM symbols, are simultaneously transmitted in parallel. A major benefitof OFDMA is that the complexity oftransmitters and receivers is transferred from the analog to the digital domain using advanced DSP [11]. For example, practical and cost-efficient implementa-tion of the orthogonal subcarriers is achieved at the transmitter via the Inverse Fast Fourier Transform (IFFT) algorithm and at the receiver via FFT algorithm [11]. Another advantage of OFDM lies in the orthogonality oflow bit rate subcarriers, thus allowing high spectral efficiency. A high aggregate transmission bandwidth can be maintained using low bandwidth transceivers. Further, advanced modulation formats can be implemented to achieve high-speed transmission. In OFDM, different subcarriers can be assigned to different users, thereby making this technology particularly suitable as a multiple access scheme. The bandwidth of subcarriers can be dynamically provisioned to different services in both frequency and time domains. The implementation of OFDMA capability in a PON wasfirst demonstrated in [12]. Communication between the OLT and ONUs was through the transmission of OFDMA frames in which subcarriers were either dedicated to ONUs or shared between multiple ONUs in time. In the demonstration, 256 sub-carriers were generated over a 2.5 GHz channel band-width and equally split into 2 subchannels, each assigned to an ONU [12]. The OFDM-16QAM modulation format was imple-mented at the OLT and ONUs, achieving a data rate of up to 10 Gb/s/ over the 2.5 GHz channel bandwidth when all 256

subcarriers were assigned to one ONU [12]. polarization multiplexing (POLMUX) in combina-tion with direct detection wasimplemented, achieving a record of 108 Gb/s/ over 20 km single modefiber(SSMF)with 1:32 passive split. Downstream transmission from the OLT to the

ONUs was demonstrated. In POLMUX, the OFDM signal is transported via two orthogonal POLMUX bands, thereby fur-ther increasing the spectral efficiency of the system. Direct de-tection at the ONU was proposed through a combination of two separate photodiodes, followed by two OFDM receivers and a polarization demultiplexing receiver [88]. The proposed re-ceiver alleviates the complexity and cost associated with dig-ital coherent detection normally used in POLMUX-OFDMA systems. Another benefit which stems from the orthogonality of subcarriers in OFDM is the superior tolerance to chromatic dispersion. This feature makesOFDM particularly appealing for long reach deployments without the need for dispersion compensation. Most recently, a record rate-distance product of 1.2 Tb/s ( Gb/s/) symmetric WDM-OFDMA-PON was demonstrated over 90 km SSMF with 1:32 passive split and without optical dispersion compensation [9]. Similar to [8], uplink transmission from source free ONUs was achieved through the remodulation of CW upstream carriers from the OLT. Uplink reception of the 16-QAM modulation format OFDM signals at the OLT is through digital coherent de-tection. The demonstrated system supports 800 ONUs with 1.25/10-Gb/s guaranteed/peak rates [9]. For practical implementation of OFDMA PONs, the fea-sibility of real-time end-to-end transmission is crucial. Many demonstrated laboratory experiments use off-line DSP ap-proaches, which do not fully account for the limitations imposed by the precision and speed of practical DSP hardware A 41.25 Gbs real time variable rate DSP-based OFDM receiver was demonstrated. End-to-end real-time OOFDM transceivers at 11.25 Gb/s with essential functionalities for adaptive operation such as on-line per-formance monitoring and live parameter optimization were reported. The same research group also demonstrated Gb/s real-time OFDM transceivers using off-the-shelf, low-cost electrical/optical components in simple intensity modulation and direct detection (IMDD) transmission systems. In trying to reduce transceiver costs, the un-cooled, low power VCSEL has been investigated recently as a potential

alternative to the directly modulated DFB laser [13]-[14]. Results re-ported in show the feasibility of using VCSELs to directly modulate OFDM signals at signal bit rates of up to 11.25 Gb/s for end-to-end real-time transmission over 25 km SSMF IMDD systems. The use of SOA and RSOA were also investigated as potential substitutes to the DFB, achieving 23 Gb/s downstream and 8 Gb/s upstream over 40 km SSMF when single sideband subcarrier modulation is adopted in downstream. When deploying OFDM over a common wavelength, optical carrier suppression ofupstream transmission is necessary to al-leviate inter-ONU optical carrier beating noise at the OLT[17]-[19]. Optical carrier suppressed modulation can be achieved using a Mach–Zehnder modulator biased at its null point. The modulator connects the two PM branches of a po-larization beam splitter/combinerto overcome polarization sen-sitivity and to make the ONU configuration reflective. Each polarization component of the incoming optical signal travels through the loop in opposite directions and is modulated inde-pendently though the MZM. In [21], the combination of optical carrier suppression at the ONU and coherent detection at the OLT successfully demonstrated the elimination of both in and cross polarization beating noise,thereby improving upstream performance. UpgradinganexistingPON toinclude OFDMA capability involves the upgrade of the OLT and ONUs with advanced modulation and DSP capabilities, thereby allowing the reuse of theexistingODN.However,as transmission bit-rate increases, the complexity and cost for hardware implementation of FFT, and the challenge to achieve realtime end-to-end transmission will increase accordingly. Electronic component integration and mass production may provide a solution in alleviating transceiver costs and in making OFDMA competitive in the business and residentialmarkets in the future[22]-[24].

**V. Optical Code Division Multiple Access (OCDMA) Access Networks**

Optical code-division multiple access (OCDMA) is based on the spread-spectrum technique used in satellite and mobile com-munications. In a time-spread OCDMA system, the bits to be sent to each user are divided into chip time periods. Each chip is represented by a temporal waveform referred to as an optical code sequence. With each user designated a unique optical code sequence, the coded bits are transmitted over the ODN and then decoded using the exact optical code sequence at the receiver of the destined user. OCDMA is a promising multiple access technology especially for customers that require symmetric ac-cess and stringent data confidentiality and privacy[5][9]. Other bene-fits include full asynchronous operation, low end-to-end delay, flexibility in either coherent or incoherent detection, guaranteed bandwidth per unique code user, and increased system reach. Asynchronous operation allowed by OCDMA enables all users to access the network without contention and with minimal access delay [13]. Though early laboratory demonstrations of OCDMA for local area network applications took place in the 1980s , it was the progress in optical en/decoder and optical thresholding devices in the past decade that has enabled OCDMA to be potentially competitive in the access segment [13]. Recent investigations of OCDMA PONs have demonstrated 10 Gb/s capacity and an unamplified system reach of 100 km. At present, many demonstrated high-speed PONs using OCDMA technology are complex and require unconventional optical devices (e.g., optical decoders and encoders). Recent efforts are therefore focused on reducing implementation mcomplexity while maintaining high per user bandwidths.

An example is reported in the demonstration of a 10 Gb/s WDM-OCDM-PON. Key to the architecture is the use of a single multiport encoder/decoder (E/D) at the CO, which cost can be shared by all subscribers [15]. The multi-port encoder with periodic frequency response can simultaneously process multiple optical codes in multiple wavelength bands. At each ONU, WDM demultiplexing and OCDMA decoding is simultaneously carried out by employing a low cost multi-level phase-shifted super structurefiber Bragg grating (SSFBG) de-coder. The compact phase-shifted SSFBG E/D has the ability to process ultra-long time spread optical codes with polarization independent performance. Other benefits include low loss and code-length independent insertion loss. Field trials using the single multiport E/D and SSFBG E/D in a 10 Gb/s 8OCDM 2 WDM system over a 100 km loopback configuration with dispersion compensatingfiber, have been successfully demonstrated. In the implementation

complexity of the ONUs is further simplified by employing a single multiport E/D at the remote node between the CO and the ONUs, thereby eliminating the need for an individual E/D at each ONU.

## VI. Conclusion

A review of the emerging trends in next generation passive optical networks and technologies have been presented. In meeting increasing capacity demands, standardized 10 Gb/s PON systems, namely XG-PON and 10 GE-PON, were discussed. The main reasons behind the push for these TDM/TDMA PON systems are to extend the longevity of existing ODNs and to allow co-existence with the current generation PONs such that the operational impact on existing users will be minimized. The basic architecture of the WDM PON and its various colorless schemes to alleviate inventory problems, were also presented. The advantages of the pure WDM PON system are its ability tofacilitate symmetric appli-cations and itsflexibility in future scaling of bandwidth, reach, and user count. In combination with TDMA, an overview of the long-reach PON was presented with particular focus on key reach extender technologies and challenges in deploying these networks. The main reasons behind the deployment of such networks are to meet increasing capacity demand and user density requirements, while ensuring that the cost per unit

bandwidth is minimized. Technologies that complement the WDM PON such as digital coherent detection, OFDMA, and OCDMA were also discussed. In order to successfully deploy these technologies, the implementation complexity must be minimized to a level that is comparable to existing commer-cialized systems and with a cost that is sufficiently low to meet the cost constraints of the access market.

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