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# Experimental demonstration of time- and mode-division multiplexed passive optical network

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ABSTRACT

A time- and mode-division multiplexed passive optical network (TMDM-PON) architecture is proposed, in which each optical network unit (ONU) communicates with the optical line terminal (OLT) independently utilizing both different time slots and switched optical linearly polarized (LP) spatial modes. Combination of a mode multiplexer/demultiplexer (MUX/DEUX) and a simple $N \times 1$ optical switch is employed to select the specific LP mode in each ONU. A mode-insensitive power splitter is used for signal broadcast/combination between OLT and ONUs. We theoretically propose a dynamic mode and time slot assignment scheme for TMDM-PON based on inter-ONU priority rating, in which the time delay and packet loss ratio's variation tendency are investigated by simulation. Moreover, we experimentally demonstrate 2-mode TMDM-PON transmission over 10 km FMF with 10-Gb/s on-off keying (OOK) signal and direct detection.



## 1. Introduction

In recent years, the growth of personal communication demand and popularity of broadband services of terminal users, such as online gaming, internet video, high quality internet protocol TV, and so on urge on rapid increasing of bandwidth demands of end-customers in optical access networks, which drives the development of next-generation passive optical network. [1,2]. Besides current commercial PON based on time-division multiplexing (TDM) [1], various alternative researches has been reported to investigate high-speed, cost-effective, and flexibility bandwidth allocation. Among these techniques, time- and wavelength- division multiplexing PON (TWDM-PON) systems [3–6] have been selected by Full Service Access Network (FSAN) as the primary solution for next generation PON stage 2 (NG-PON2) supporting 40-Gb/s data rate. The TWDM-PON increases the overall transmission capacity of networks by bundling multiple wavelengths and reuses existing optical distribution network (ODN), which provides cost-effective way for practical implementation. Additionally, the TWDM-PON dynamically allocates wavelength and bandwidth resources to users, catering their bandwidth requirements, and achieve resource sharing among them [7,8]. However, there are still some challenges such as high speed low-cost optical module in ONU, which includes colorless transmitters for upstream transmission [9,10] and tunable optical filter for selecting wavelength [11,12].

Currently, mode-division multiplexing (MDM) has been an alternative technique for expanding transmission capacity by use of few-mode fibers (FMFs). Besides most of reports for long/short-haul transmission systems over FMFs [13–17], several works have been reported for MDM application in PON systems [18–20]. Xia et al. [18] propose a mode-enhanced TDM-PON architecture. Under this architecture a spatial mode is used to enhance upstream transmission of conventional TDM-PON to accommodate more ONUs and only one ONU transmits signal to the OLT at a specific time slot, which avoid the mode crosstalk among modes at the ODN. However, because of large intermodal dispersion and strong mode coupling in typical FMFs, signals will suffer severe differential mode group delay (DMGD). If direct detection is applied at the receiver, the DMGD-induced distortion may significantly degrade the signals. In our previous work, based on low-mode-crosstalk two-mode FMF and mode MUX/DEMUX, we have experimentally demonstrated MDM-PON transmission over two-mode FMF with 10-Gb/s optical OOK signal and direct detection [19,20], in which

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the two LP modes could be simultaneously transmitted and received without complex multi-inputmultioutput (MIMO) digital-signal-processing (DSP). A MDM optical distribution network (ODN) can be cascaded with multiple conventional TDM ODNs to effectively extend larger scale of current commercial PON systems based on TDM. Therefore, we also experimentally demonstrated cascaded MDM-TDM-PON transmission over 10 km two-mode FMF and 10 km standard single-mode fiber (SSMF) with 10-Gb/s optical OOK signal and direct detection [20]. These experimental results imply that mode is a next accessible dimension to increase the capacity of PON systems comparing to wavelength.

The cascaded MDM-TDM-PON can be an evolution scheme from TDM-PON in current deployed network with SSMF. But for new-deployed PONs, replacing SSMF with FMF is a better approach, because FMF can increase the capacity of PON systems and deploying FMF has similar cost with that of SMF. Moreover, the introducing of spatial modes can solve the problems of wavelength plan for optical access network [6]. As we know, PONs of different types or generations may have wavelength conflict. If they coexist in the same ODN based on FMF, we can adopt different modes to separate them. Thus, it is necessary to consider an effectively new PON architecture based on FMF.

In this paper, we propose a two-dimensional TMDM-PON architecture, similar to TWDM-PON architecture, in which signal for each mode can be transmitted or received at different time slots and switched LP modes. Combination of a mode MUX/DEMUX and a simple N $\times$ 1 optical switch is employed to select one specific mode in each ONU. A mode-insensitive power splitter (MIPS) is used for signal broadcast/combination of all the LP modes between OLT and ONUs. We theoretically proposed a mode and time slot assignment scheme based on inter-ONU priority rating (IOPR) on TMDM-PON, in which the time delay and packet loss ratio's variation tendency are investigated by simulation. Furthermore, we successfully demonstrate TMDM-PON downstream and upstream transmission over 10-km two-mode FMF with 10-Gb/s OOK signal and simple direct detection by experiment, in which two LP modes could be simultaneously transmitted or received. Compared to TWDM-PON, the proposed TMDM-PON does not need wavelength-tunable module and can achieve colorless ONUs. In order to increase the overall transmission capacity of networks and keep low cost in ONU, the proposed TMDM-PON is also a better candidate technique for a new deployed network with FMF in comparison with cascaded MDM-TDM-PON [20].

## 2. Principle of TMDM-PON architecture

The schematic of proposed bidirectional TMDM-PON architecture is shown in Fig. 1. For downstream transmission, at the OLT side, the signal from each transmitter is converted from $LP_{01}$ mode in SSMF into a specific mode in FMF by a mode MUX. Then the light beam carrying multiple modes is launched into the FMF. After FMF transmission, the signal is power-split by a MIPS and sent to ONUs. At the ONU side, the transmitted signals are demultiplexed and converted back into $LP_{01}$ mode by a mode DEMUX. For upstream transmission, signals from each ONU are multiplexed by the mode MUX and power-split by the MIPS. After FMF transmission, signals are demultiplexed by the mode DEMUX and received at the OLT side. Using an N $\times$ 1 optical switch, the ONU can select one branch to receive the signals from the OLT or send signals to the OLT. For downstream transmission, different modes can carry different data, in which the light beam is split into N branches by 1 $\times$ N power optical coupler and then different data in each branch are generated using optical IMs. Note that cascaded MIPS can further extend larger-scale PON. In this way, the network resources in TMDM-PON can be allocated in both time and mode domains. The two-dimensional resource allocation principle is similar to that in TWDM-PON. The all-fiber mode MUX/DEMUX are composed of passive mode selective couplers, which can be realized by heating and tapering technique [20]. Passive MUX/DEMUXs are indispensable for both MDM-PON and WDM-PON when cascading with TDM-PON structures. Since the mode MUX/DEMUX has similar insertion loss with AWG in WDM-PON, the MDM-PON will not induce serious influence on power budget of the TDM-PON, just like the WDM-PON. It is important to note that in TWDM-PON the wavelength of ONUs should be tunable to achieve colorless upstream transmission, which will greatly increase the ONU cost. On the contrary, TMDM-PON does not need wavelength-tunable module and the upstream transmission is naturally colorless. And both passive mode DEMUX and optical switch can be easily integrated. So the TMDM-PON will benefit from simple mode switching.

## 3. Simulation

In TMDM-PON, the upstream resource allocation is two-dimensional and consists of mode and time slots, which are shared by all ONUs. In our work, the ONUs are scheduled based on its priority, which consider the number of the delayed traffics and the new-coming traffics. The priority of each ONU may lead to situation that the traffics of ONUs with larger ids can be solved timely even the network is under heavy load. Taking into account the stability of signal carrying LP modes, the lower-order mode is preferentially assigned when allocating mode resource. In simulation, mode resource is scheduled sequentially in ascending order. In an assignment period, the priority of $ONU_i$ $P_i$ can be calculated as below:

$$P_i = \sum_{t=0}^{C} D_{i,t} + N_i \tag{1}$$

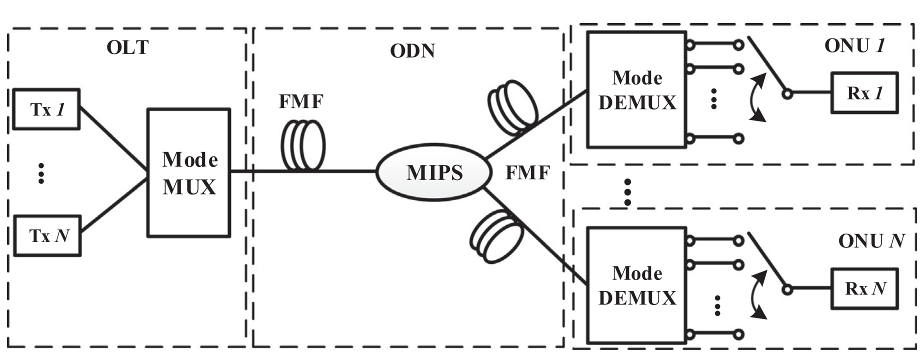


**Fig. 1.** Schematic of an architecture of proposed TMDM-PON.