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Review of Mode Division Multiplexed passive optical networks and its hybrid with TDM and WDM systems

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ABSTRACT
We review the use of Mode Division Multiplexing (MDM) as a multiplexing technology for the realization of passive optical networks. We start with approaches for MDM realization – with the use of complex MIMO digital signal processing or without complex DSP using few mode fibers. We proceed to explain basic architecture of MDM PON, and its hybrid with time division multiplexing - TDM MDM PON and hybrid of time, wavelength and mode division multiplexing – MDM TDM WDM PON. We then proceed to discuss recent progress in the field of Mode Division Multiplexing.
Keywords: Mode Division Multiplexing, Time Division Multiplexing, Wavelength Division Multiplexing, PON, Few Mode Fiber.

INTRODUCTION
With the rapid increase in population, the use of internet has increased rapidly. To cope up with this increased bandwidth requirement and to accommodate the huge amount of data traffic in the near future, we must greatly increase the transmission capacity of our systems [1]. Passive optical networks have seen large deployment to provide last mile connectivity to the users – providing services for fiber to the home and other such applications [2].

Most of the PON systems that are commercially deployed are TDM (time division multiplexing) PONs such as Ethernet PON and Gigabit PON. In these systems, the Optical Network Units (ONU) transmit/receive signals at different time slots and a power splitter is utilized to broadcast and combine signals. There are some alternate approaches also such as PON architecture based on WDM (Wavelength Division Multiplexing) [1], Orthogonal Frequency Division Multiplexing (OFDM) PON [3], Optical Code Division Multiplexing (OCDM) PON [3]. In last years, mode has been adopted as a spatial dimension to further increase number of channels to transmit data optically [4],[5]. Some multi dimension PON architectures have also been proposed such as hybrid TDM- WDM PON [3], WDM- MDM PON and TDM- MDM PON etc – thus significantly improving data capacity of PON systems.

In case of Mode Division Multiplexing, transmission capacity is increased by using higher order modes of a multimode fiber for transmitting channels. Early works of MDM [6] used commercial multimode fibers with core diameters of 50-62.5 um. These fibers supported hundreds of modes, but inter-mode coupling and crosstalk were very large - restricting their usage to short distances such as LANs. So practical demonstration of MDM uses Few Mode Fibers (FMF) with less than 10 linearly polarized modes rather than multi-

mode fiber. Few Mode Fibers can be used in large networks to increase the capacity of single mode fibers. It has low attenuation and mode selectivity is also high [1]

RECENT WORKS IN MODE DIVION MULTIPLEXING PON TRANSMISSION

There can be two approaches for MDM realization.

A. Mode division multiplexing using MIMO (multiple input multiple output) Digital signal processing

Modal crosstalk and dispersion are inevitable during long distance transmission using MDM. To compensate for this, complex coherent detection and computationally heavy Multiple Input Multiple Output (MIMO) digital signal processing (DSP) is used. It compensates for linear impairments and distance covered with MDM system is large but the DSP complexity increases heavily increasing the overall cost of the system.

[7] shows 6X6 MIMO transmission over 1000 km, 12X12 MIMO transmission over 708 km [8], 20X20 MIMO transmission over 125 km [9], 30X30 MIMO transmission over 22.8 km[10] using Graded index fiber , [11] reported 72tb/s transmission over 179 km all fiber using 6 modes with two in-line amplifiers.[12] 67.5 tb/s transmission with 30 wavelength channels on 87 km with 20X20 DSP.

B. Mode division multiplexing without using MIMO (multiple input multiple output) Digital signal processing

This is a less complex scheme and is better utilized in applications such as PONs. In this scheme, optical fiber and mode Mux/Demux with low modal cross talk are used. In this technique, mode coupling is minimized so that each mode can be detected separated with a mode mux/demux. The DSP complexity in this kind of system is less and is close to single mode fiber. So , these can be better deployed at reduced costs and without any additional circuitry with already deployed TDM PON systems.

In this regard, in 2015, a cost effective, energy saving MDM PON scheme was investigated using homodyne detection for high speed access based on low modal crosstalk few mode fiber and all fiber mode Mux/Demux [13]. In [14] LG modes were exploited for reducing modal dispersion and increasing data capacity. 5 LG modes were multiplexed with 5 wavelengths centered around 1550.12 nm for a distance of 800 m at rate of 25 Gbps

In 2015, Fazea et al [15] considered spot mode excitation for multi-mode fiber and also MDM of hybrid modes in a multimode fiber [16]. In 2017, in [17] WDM-MDM hybrid was considered for multi-mode fibers in access networks. In 2017, authors proposed [18] a wavelength technique to mitigate inter spatial channel crosstalk buy optimizing the direct detection MDM and WDWM system design. By 2018 [19], 40 Gbps speed with WDM MDM hybrid was being considered with LG mode. In 2020 [20], authors worked on high-speed optical transmission for next generation TDM, TWDM and WDM PONs based on low cost optical and DSP technologies., in [21], authors worked on reach extension of PON using fiber amplifiers. While [24] considered 100 km MDM- WDM system using orbital angular momentum fiber in the same year. In 2021, [22], a WDM PON with symmetrical 28 gbps OOK access signals was investigated. It had 3 Gbps Virtual Private Network link between ONUs. In [23], it was investigated how to use WDM MDM PON. In 2022, [25] authors considered a high capacity MDM utilizing 402.7-Tbit/s weakly coupled 10-mode-multiplexed transmission over 48 km and 50.47-Tbit/s standard cladding coupled 4-core fiber transmission over 9,150 km.

In this paper we discuss the concepts of MDM based PONs including MDM PON, MDM-TDM PON, MDM-WDM-TDM PON.

CONCEPT OF MODE DIVISION MULTIPLEXING AND OTHER HYBRID TECHNIQUES RECENT WORKS IN MODE DIVION MULTIPLEXING PON TRANSMISSION

MDM PON ARCHITECTURE

Figure 1 shows MDM PON architecture. for downstream transmission at the OLT, signals from N transmitters (Tx1-TxN) are taken, converted into different modes and multiplexed together by an all fiber Mode Multiplexer. These modes are then launched into a Few Mode Fiber. After the transmission through fiber, these modes are then converted back into fundamental mode by an all fiber mode Demux, launched to different Single Mode Fibers and distributed to N ONUs(ONU1 – ONU N)Units Similarly for upstream transmission, signals from N onus re multiplexed by another Mode Mux and launched into the Few Mode Fiber (FMF). After transmission through the FMF, signals are demultiplexed and launched into different Single mode fibers by the mode Demux and received at the OLT side. A pair of few mode circulators on both sides enables bi-directional transmission. This proposed structure of MDM PON can adopt conventional TDM PON transceivers and does not require colorless- ness solution as in WDM-PON i.e. it is compatible with the currently deployed PON architecture.

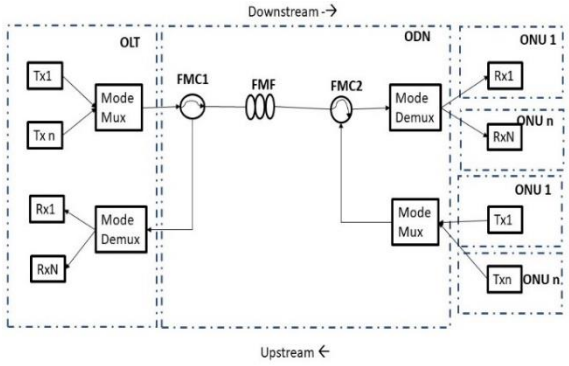

Figure 1 : MDM PON architecture.

The components used in MDM transmission should have low modal crosstalk for it to work effectively. Firstly, the few mode fiber used should have low modal crosstalk. For this the the difference of effective refractive index of modes travelling in the fiber should be large. Generally, difference in effective refractive index between modes of a step index fiber is greater than that of a graded index fiber

The realization of all fiber mode mux/demux is very important. There are several ways of realization of all fiber mode multiplexers like y-shaped , t- shaped couplers, long period fiber gratings, photonic lanterns. these can also be realized in the form of fused couplers fabricated by heating and tapering a single mode fiber and a few mode fiber together to achieve the phase matching condition. which have the benefit of low modal crosstalk. The fundamental mode LP01 in SMF can be converted into LP11 mode in FMF at a specific tapering ratio around 1550 nm. the reported coupling ratio is around 66%.

MDM-TDM-PON Architecture

The architecture of MDM TDM PON is shown in Fig. 2 for downstream transmission at the OLT, signals from N transmitters(Tx1-TxN) are taken and converted into different modes and multiplexed together by an all fiber Mode Multiplexer. These modes are then launched into a Few Mode Fiber. after the transmission through fiber, these modes are then converted back into fundamental mode by an all fiber mode demux and launched into each single mode fiber in conventional TDM- PONS. The power splitters are then utilized to send signal to each ONU at divided time slots.

The upgrade from TDM PON to MDM TDM PON is cost effective and simple and can be used to extend the scale of existing PONS. In case of WDM TDM pon the wavelength of the ONU should be tunable to achieve colorless upstream transmission which increases cost of the system. This requirement is not there in MDM TDM PON hence making this system a cost effective choice.[5] it is expected to

increase number of modes of FMF keeping cross talk among modes low.

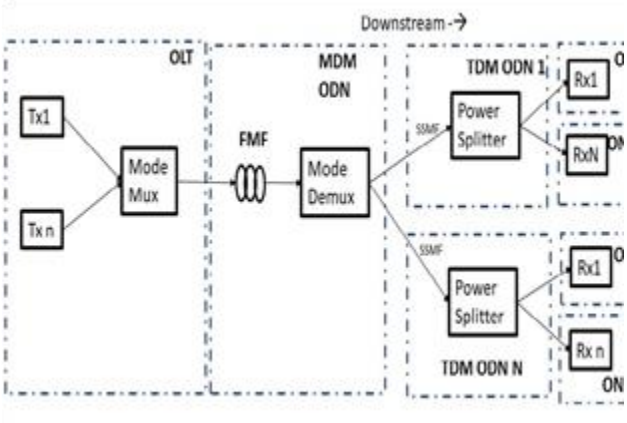

Fig. 2. Architecture of MDM TDM PON showing downstream trx.

C. MDM-WDM TDM-PON Architecture

The proposed architecture of MDM TDM WDM PON is shown in figure 3.the MDM structure consisting of low modal crosstalk FMF and all fiber mode Mux/Demux is cascaded with WDM TDM PON. Many transmitter units are associated with one wavelength sending signals at different time slots through TDM Mux after which all wavelengths are multiplexed by WDM Mux in a single fiber. Signals from different WDM muxes are then further converted into modes by mode MUX and transmitted through a FMF- thus the integration of TDM WDM and MDM. The output of MDM Mux/Demux is connected with WDM-TDM ODN.

If the modal crosstalk for Mode Mux/Demux, FMF and FMC is low the signals will not interfere with each other and the architecture of TDM WDM PON will be preserved. it will lead to smooth and cost-effective upgrading to TDM WDM MDM PON [26]. The bidirectional transmission is made possible by the Few Mode Circulator at MDM ODN and a single mode circulator at each ONU

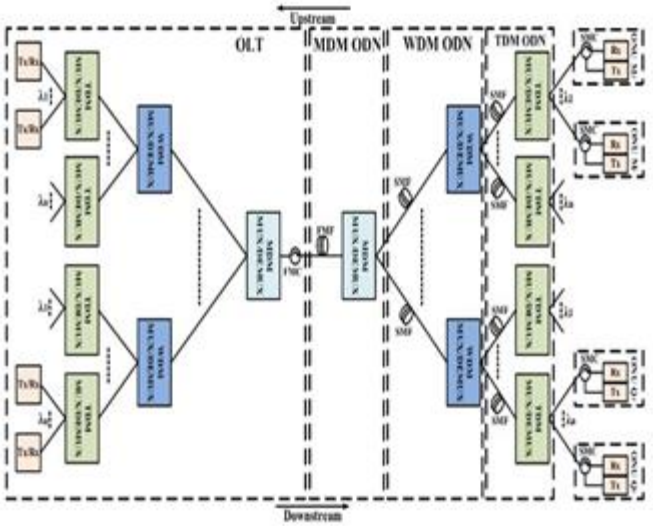

Figure 3 :MDM WDM TDM PON Architecture [26]

Table 1- Comparison table showing work done in field of mdm in recent years using simple receiver circuitry (without mimo).

WORK DONE	***MULTIPLEXING TECHNOLOGY***	***RECEIVER DSP***
MDM PON scheme was investigated using homodyne detection for high-speed access based on low modal crosstalk few mode fiber and all fiber mode Mux/Demux. [13]	MODE DIVISION MULTIPLEXING	SIMPLE - Few mode fiber (FMF) used
LG modes used for reducing modal dispersion and increasing data capacity. 5 LG modes were multiplexed with 5 wavelengths centered around 1550.12 nm for a distance of 800 m at rate of 25 Gbps. [14]	MODE DIVISION MULTIPLEXING	SIMPLE
spot mode excitation was	MODE DIVISION MULTIPLEXING	SIMPLE

done for multi-mode fiber and also MDM of hybrid modes in a multimode fiber [15]		
WDM-MDM hybrid was considered for multi-mode fibers in access networks [17]	MDM – WDM hybrid	SIMPLE
inter spatial channel crosstalk was mitigated using wavelength technique by optimizing the direct detection MDM and WDM system design [18]	MDM – WDM hybrid	SIMPLE
40 Gbps speed with WDM MDM hybrid was being considered with LG modes [19]	MDM – WDM hybrid	SIMPLE
high speed optical transmission for next generation TDM, TWDM and WDM PONs based on low cost optical and DSP technologies [20]	TDM- WDM – MDM hybrid	SIMPLE
a WDM PON with symmetrical 28 gbps OOK access signals was investigated. It had 3 Gbps Virtual Private Network link between ONUs. [22]	WDM	SIMPLE
Mode division multiplexed transmission of WDM signals over a single span 100 km orbital angular momentum fiber [24]	MDM – WDM hybrid using angular momentum fiber	SIMPLE

CONCLUSION

As we have discussed MDM PON offers a very good solution to increasing the scale of currently deployed PON schemes. Independently, it offers another dimension in which different signals can be sent thorough different modes in a few mode fiber. Further it can be well used to increase the capacity and scale of currently deployed PONs which are generally based on time division multiplexing as MDM PON can be easily used in hybrid with TDM. Further TDM WDM MDM hybrid offers really good solution in increasing the capacity further. In recent years these hybrid schemes have been researched as in [22], [23] but there is a lot of scope in increasing the capacity and bandwidth by further increasing number of modes and wavelengths in hybrid systems without increasing the crosstalk and complexity of receivers.

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