Flexibility in Future Optical Access Networks

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Abstract *Overview of using flexibility to increase overall PON throughput, to extend optical power budget, and to reduce energy consumption in future optical access networks. Standardization of flexibility features is also discussed. ©2023 The Author(s)*

Introduction

The peak line-rate of time division multiplexed passive optical networks (TDM-PON) based on intensity modulation with direct detection (IM/DD) has been continuously pushed higher because of emerging high bandwidth applications like cloud services, 5G/6G mobile transport, virtual reality, premium high peak-rate services, and ultra-high-definition video and gaming.

In 2020 a 25 Gb/s based TDM-PON was standardized by IEEE [1]. This standard describes a single wavelength 25 Gb/s PON and a dual wavelength 50 Gb/s PON. In that same year also a 25GS-PON multi source agreement (MSA) was defined for a single wavelength 25G TDM-PON with an ITU-T-based TC Layer [2].

One year later an asymmetric 50 Gb/s down and 25 Gb/s upstream TDM-PON was standardized by ITU-T [3]. And very recently, in April 2023 a standardized symmetric 50 Gb/s TDM-PON is in force [4].

A TDM-PON is inherently very flexible due to the TDM nature of sharing the bandwidth between users in this point-to-multipoint architecture. Bandwidth can be very flexibly allocated. However, additional flexible aspects are starting to appear in the most recently standardized PONs.

In this paper an overview of currently available and potential future flexibility features and their advantages are described.

Increasing Overall Throughput

Increasing the line-rate beyond 10 Gb/s in PON has been a topic of research for a while [5-8]. The target optical power budget in PON is fixed (and some operators even ask for larger budgets), due to the already installed optical distribution networks (ODN). Fibre installation is very costly, so PON operators request that legacy ODNs will be supported by every new generation of PON. However, in the case of IM/DD increasing the baud rate decreases chromatic dispersion (CD) tolerance and reduces the receiver sensitivity, making it difficult to continue supporting the installed ODN base in a cost-effective way [5-7].

One way to mitigate this stringent requirement is to make use of the fact that most optical network units (ONU) on a PON have an optical channel that is better than the worst case. This enables optimization of the data-rate for each ONU via flexible modulation and forward error correction (FEC). An ONU with a more relaxed optical channel (with respect to optical loss and total CD) can receive a higher order modulation and/or lower overhead FEC, which increases the overall throughput of the PON and enables the continued usage of cost-effective IM/DD. We investigated and demonstrated the flexible PON concept in [9-11].

In [12,13] we showed the feasibility of recovery of a mixed modulation signal without extra synchronization patterns, using an off-the-shelf 50Gbd clock and data recovery (CDR) with adaptive equalizer in a real-time experimental setup. In [14] we studied probabilistic (PS) and geometric shaping (GS) to enable higher resolution bandwidth adaptability to further optimize the transmission for each ONU. In [15] we studied PS in combination with flexible soft-input FEC to adapt the bandwidth per ONU. Finally, in [16] we examined training of an artificial neural network with data generated using a simulation of a realistic model of the PON physical layer to enable a generalized scheme to select the optimal shaping per ONU.

Recently, flexible modulation concepts are also being researched for future coherent PON to adapt the rate per ONU [17,18].

Extending Optical Power Budget

In addition to increasing the line-rate for ONUs that have a more relaxed optical channel compared to the worst case as defined in the PON standards, there can be ONUs that have an even poorer channel. This can be due to a temporary connection problem or due to an ONU being too far away in for example a rural area.

To support these use-cases we proposed to use an alternative line-code, Miller encoding, which provides increased CD tolerance as well as increased receiver sensitivity at the cost of halving the bitrate but with seamless recovery of the mixed modulated signal with an adaptive

CDR with equalizer. In [12,13] we showed up to 5 dB increased optical power budget for 25 Gb/s Miller versus conventional 50 Gb/s non-return-to-zero (NRZ) after worst case total CD.

Alternatively, and in addition, the power budget can be increased with a higher gain and higher overhead FEC, which we investigated in [15,19].

Reducing Energy Consumption

Energy consumption has become an issue that is becoming visible on the radar of many [20]. In current PON standards energy consumption reduction in the form of schemes based on sleep-modes has been accepted [21]. Sleep-modes enable flexibly turning off and on certain sections of the ONU and optical line termination (OLT) transceiver (TRx) equipment depending on the amount of traffic.

Energy consumption can be further reduced depending on traffic and channel conditions by introducing additional flexibility in the PON system.

In the past the bit-interleaved (Bi)-PON concept has been shown in the context of the GreenTouch project [22]. The Bi-PON concept is based on adapting the PON data-rate to the user-rate by using a decimating clock and data recovery (CDR) at the ONU. This enables all receiver functions beyond the CDR, like FEC, scrambling, to run at the (much) lower user-rate instead. More recently, we developed a scheme also based on just processing data closer to the user-rate at each ONU, namely FEC codeword (CW) grouping [15]. In this scheme ONUs are grouped, and each ONU will only decode CWs in its own group which enables significant complexity, energy- and power consumption reduction.

Doubling PON capacity by multiplexing of two channels (for example wavelengths) is attractive with respect to optical power budget and CD tolerance [23], but it might also be attractive for introducing flexibility to reduce overall energy and power consumption by enabling switching ONUs to fewer OLTs during low traffic (for example during night-time). Reassigning ONUs to fewer OLTs can be enabled with a time- and wavelength division multiplexed PON (TWDM-PON), like NG-PON2 [24] which has wavelength tuneable TRx or the 2x25G IEEE PON [1] which has fixed wavelength TRx. Reassigning ONUs to fewer OLTs can also be accomplished by switching in the spatial domain using an optical switch, which has been documented in [25] by British Telecom.

Fig. 1 illustrates the two described TWDM-PON architectures (A and B) and the spatial switching architecture (C), also indicating which TRx can be turned off during low traffic. Architectures A and B are based on two wavelength channels, architecture C on two fibres and all of them feature 50 Gb/s overall throughput per PON for easier comparison.

The energy consumption performance of the three architectures depends on many factors, like the extra introduced optical loss, the power consumption of the required DSP, and the specific traffic demands. For example, a traffic profile that mostly requires the 25 Gb/s rate will likely favour the two TWDM-PON architectures because they have more optimal 25 Gb/s TRx implementations. But a traffic profile that requires mostly the 50 Gb/s peak-rate will likely favour the architectures with the more energy efficient 50 Gb/s TRx implementations. However, the 25 Gb/s line-rate does not require DSP [6], so a 1x50 Gb/s implementation might have a similar power efficiency compared to the 2x25 Gb/s implementation depending on the power consumption of the needed DSP relative to power needed to provide the second channel. Note that

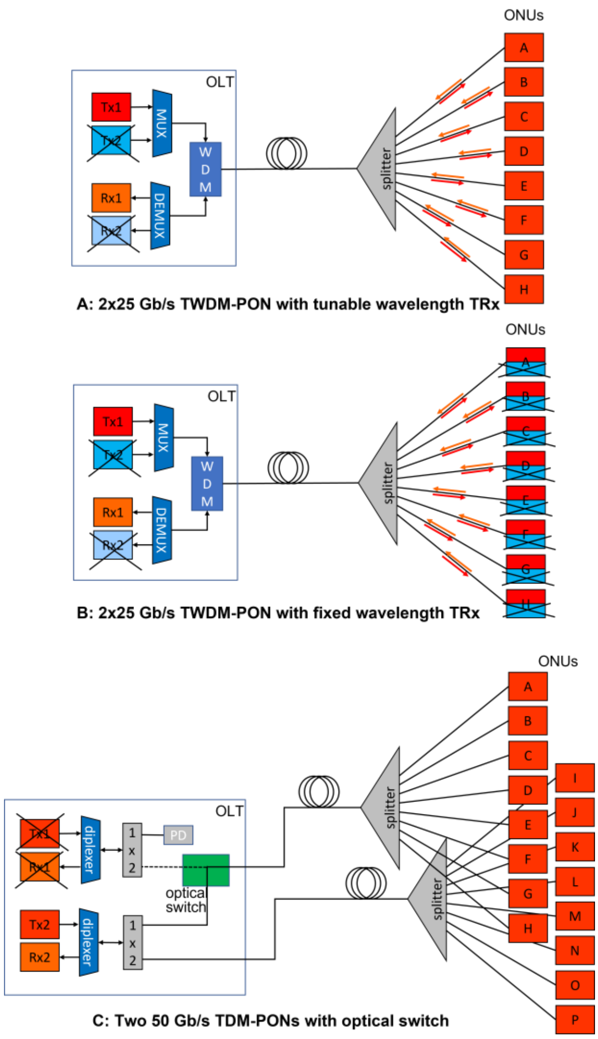

Fig. 1: A: Wavelength tunable TWDM-PON, B: Fixed wavelength TWDM-PON, C: Spatially multiplexed TDM-PON.

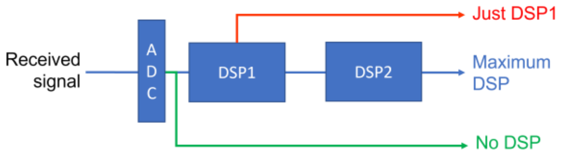

Fig. 2: Illustration of flexible DSP chain concept for optimized energy consumption.

the wavelength tuneable TWDM-PON architecture (A) cannot provide the maximum 50 Gb/s peak-rate). A more detailed quantitative analysis of the energy consumption of such wavelength- or spatial multiplexed architectures compared with the consumption of a conventional TDM-PON or the flexible TDM-PON architectures is ongoing.

Another method for optimizing energy consumption can be based on a flexible digital signal processing (DSP) chain to adapt to the received signal-to-noise (SNR) at the ONU. An ONU that receives a high SNR can reduce DSP complexity if the digital signal processing chain would be flexible resulting in lower energy consumption. See Fig. 2 for an illustration of the flexible DSP chain concept.

Finally, the most recent PON standards use a transmitter and dispersion eye closure (TDEC) test to qualify transmitters [1-4]. This enables a trade-off between launch power and transmitter quality because the required minimum launch power depends on TDEC. This flexibility enables a larger solution space and thus a lower cost and higher volume eco-system, but it also can support minimized optical launch power which will result in an overall lower energy consumption.

Standardization

As already stated, the standardized PONs are already very flexible due to bandwidth sharing via TDM and WDM.

Another recently added flexible feature available in the 50G PON standard is flexible upstream FEC [19]. And the already mentioned adoption of TDEC also introduces flexibility [26].

For several years flexible modulation has already been enabled for other standardized access networks, like DSL, DOCSIS, Wi-Fi, and mobile networks [27-30]. In these networks resources like frequency spectrum and energy are scarce and must be used optimally which is enabled via flexible modulation schemes (and flexible FEC).

As of now standardization of flexible modulation has not happened yet for PON. All standardized PONs up to now have relied on just one modulation scheme, NRZ because simplicity is still more important compared to optimal resource use.

However, it is expected that also for PON increased flexibility will be needed to accommodate required performance with the available resources. One crucial resource that might drive more flexibility into optical access is energy and power consumption. For operators, to accommodate rising energy costs and for equipment vendors to enable small form factors which enable higher density and thus more cost-effectiveness.

Conclusions

An overview of a wide range of flexible concepts that can be used in optical access is given.

IM/DD has always outperformed coherent detection with respect to power consumption, complexity and cost [31], so it is very advantageous to continue to use IM/DD in optical access. Flexible modulation can stretch the use of IM/DD while increasing overall throughput of the PON. Flexible modulation can also provide an extended optical power budget for ONUs that require this and to potentially reduce energy consumption in future optical access networks via switching ONUs to a lower rate with lower energy consumption when traffic permits.

Another scheme to extend the use of IM/DD is to multiplex two channels, for example two wavelength channels. This way gained flexibility can enable reassigning ONUs to fewer OLT TRx when traffic allows, resulting in reduced overall energy consumption. Reassigning ONUs can also be enabled via a spatially switched architecture based on optical switching with similar potential savings.

Finally, standardization of flexibility features is discussed. Several flexible concepts are already available in standardized PONs. The overall trend that can be seen is towards more flexibility which will likely be driven by the need to use resources in a more optimal way.

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