6 Technical Feasibility of NG-EPON

6.1 System Capacity

In order to increase the aggregate system capacity (expressed as aggregate bandwidth supported per OLT port), several approaches are possible, including the following options:

- increase the effective ~~line~~ data rate ~~by going~~ from 10 Gb/s ~~as used today in~~ (as supported by 10G-EPON) to ~~the effective data rate pf~~ 25 Gb/s or even 40 Gb/s per wavelength channel, while maintaining the NRZ modulation scheme, or
- reuse existing 10G-EPON PHY components, but increase the effective data rate to 25 Gb/s or even 40 Gb/s by ~~, or~~ applying advanced modulation schemes (e.g., duobinary, PAM4, OFDM), to increase the number of bits carried per baud ~~of transmitted data~~, or
- increase the number of wavelength channels per direction to more than one, while keeping the effective data rate unchanged ~~per transmission direction~~ (either symmetric or asymmetric data rate systems could be supported), or
- implement a hybrid approach, increasing the number of wavelengths per transmission direction, while simultaneously employing a more advanced modulation scheme to increase the effective data rate per wavelength channel to 25 Gb/s or even 40 Gb/s.

Commented [MH1]: This option needs to be clarified – it is possible to continue increasing the line rate using NRZ, but there are challenges to it.

Commented [MH2]: Data rate increase can be also achieved via advanced modulation schemes, reusing same optics

Commented [MH3]: Another option is wavelength stacking

Commented [MH4]: And the final approach is wavelength stacking

~~Hybrid approaches are also possible. Hybrid approaches employ two or more techniques to increase the aggregate capacity of the optical access system. For example, the line rate could be increased to 25 Gb/s, while simultaneously 4 downstream and 4 upstream wavelength channels may be used to reach the aggregate (symmetric) system capacity of 100 Gb/s.~~

Commented [MH5]: Too detailed in here and makes assumptions

The requirements for NG-EPON capacity for both residential and business applications are listed in **Error! Reference source not found.** and **Error! Reference source not found.** for the OLT and ONU, respectively. ~~Requirements for business services are more stringent in terms of aggregate system capacity when compared with residential applications, yet they are more difficult to quantify given a different deployment model from residential services. In business scenarios, typically customers are added on demand, as connection requests come from the given area. Moreover, typically only guaranteed bandwidth is delivered, eliminating altogether any over-subscription.~~

Commented [MH6]: This is covered in 5.1 and 5.2 already where we list requirements. No need to repeat

6.2 Architectures

There are ~~multiple~~ several possible architectures for NG-EPON, including higher-speed, single wavelength TDM-PON, hybrid PON systems, as well as more exotic solutions like CDM-PON, or OFDM-PON systems. The following sections focus on technical challenges of individual solutions, especially in terms of component maturity and ability to reach the total system capacity in excess of 10 Gb/s ~~per port~~.

6.2.1 TDM-PON

TDM-PONs ~~systems~~ with one downstream and one upstream wavelength channel have only two ways of achieving higher aggregate system capacity:

- increase the line rate ~~to at least~~beyond ~~40~~ 10 Gb/s~~ in at least the downstream direction~~, or
- employ advanced ~~non-NRZ~~ modulation schemes achieving higher spectral efficiency, while keeping the baud rate unchanged.

It is also possible to use hybrid approaches, where higher line rate (e.g., 25 Gb/s) is ~~coupled~~ combined with ~~non-NRZ~~ an advanced modulation scheme to achieve a higher ~~throughput~~effective data rate. Discussion on alternative modulation schemes can be found in **Error! Reference source not found.**.

The increase in the ~~line~~ data rate and with NRZ modulation directly affects both optical transmitters and receivers, mainly by shortening the bit time, and effectively decreasing the amount of light (number of photons) transmitted when the laser is on. ~~This~~ This increase in the data rate decreases the effective receiver sensitivity. ~~directly affects the observed effective received sensitivity, following the equation:~~

$$\cancel{P_{min} \propto B^{7/6}}$$

~~where P_{min} is the minimum observed receiver sensitivity and B is the baud rate.~~ The sensitivity of optical receivers ~~capable of~~ operating at 25 Gb/s is 4 dB lower and ~~sensitivity of optical receivers capable of~~those operating at 40 Gb/s is 7 dB lower when compared with sensitivity of optical receivers used in 10G-EPON today. Effectively, ~~this means that~~ in order to ~~achieve~~ support the same power budgets as 10G-EPON, optical transmitters for TDM-PON operating at 25 Gb/s or 40 Gb/s need to have 4 dB or 7 dB higher output, respectively. In practice, such transmitters ~~immediately adding a~~ need ~~for~~ integrated or external amplifiers, increasing the cost of ~~such~~ a solution.

The sensitivity penalty for optical receivers is not the only impairment when moving to higher ~~TDM speeds~~data rates. The increase in line rate also increases the dispersion penalty for propagating optical signals, resulting in ~3.5 dB penalty at 20 km for 25 Gb/s and ~9.5 dB penalty for 40 Gb/s operation at the same distance. In 10G-EPON, operating at the line rate of 10.3125 Gb/s, the dispersion penalty is equal to ~0.13 dB after 20 km of signal propagation.

Adding both of these penalties together, a TDM-PON operating at 25 Gb/s suffers from ~7.3 dB in penalties when compared with 10G-EPON operating at the same distance and over the same fiber plant, while the same penalty for 40 Gb/s TDM-PON would reach ~16.3 dB~~, immediately putting the technical feasibility of even PX10-compatible power budgets in question~~ [hw1]. The operation at 100 Gb/s with NRZ modulation would exhibit excessive transmission penalties, limiting the operation range of TDM-PON to a few kilometers

~~Note that the above analysis does not consider operation at 100 Gb/s, where both penalties would effectively prevent the proper operation of the access system at distances exceeding 1 km,~~, making them impractical for any deployment.

~~It is expected that if NG-EPON is built around higher line rates, operation at 25 Gb/s, though challenging, could be technically feasible in the downstream direction, where a single OLT transmitter could employ an amplified externally modulated laser (EML), compensating for the observed ONU receiver and dispersion penalties. A link budget above the PX10 level would be very difficult to meet with NRZ modulation [hw1].~~

~~The technical feasibility of 40 Gb/s operation in the downstream direction remains to be demonstrated, especially in terms of reliable operation at power budgets exceeding PX10-class.~~

Commented [MH7]: This section needs to be generic and not focused on specific implementation choise

Commented [MH8]: No need to repeat – advanced modulation implies non-RZ already

Commented [MH9]: This information is missing

Commented [MH10]: Additional clarification + wording improvement

Commented [MH11]: Equation is not needed in the report – it is well known

Commented [MH12]: Unnecessary wordiness …

Commented [MH13]: This was not clear

Commented [MH14]: Repeated information, just using different words to express the same concepts

Given the technical challenges related with the development of cost-effective high power laser sources, it is not clear whether operation at data rates exceeding 10 Gb/s per wavelength channel with NRZ modulation ~~in the upstream direction~~ is ~~technically~~ economically feasible. Technical challenges in the downstream could be addressed by the addition of transmitter amplifiers, adding to cost and complexity of the resulting system. However, in the upstream direction there is ~~The~~ additional burst mode penalty ~~(not included in the above analysis of link rate related penalties)~~ to consider, ~~would only~~ further ~~complicate~~ complicating already challenging operation at data rates beyond ~~25~~ 10 Gb/s.

Commented [MH15]: Convert it into a simple summary on TDM-PON

~~At this time~~Considering the data available at this time, the feasible and cost effective data rates for higher speed TDM-PON are ~~therefore~~ as follows:

Commented [MH16]: We cannot exclude some sort of a breakthrough in the future where either receiver sensitivity or /and transmitter output power is dramatically improved. Based on what we know today, this is the situation

- 25 Gb/s ~~operation~~ in the downstream direction (continuous mode) ~~with PX10 link budget~~, and
- 10 Gb/s ~~operation~~ in the upstream direction (burst mode).

6.2.2 WDM-PON

WDM-based access solutions achieve higher aggregate system capacity by using more than one downstream and upstream wavelength channel in parallel. In such ~~an~~ access systems, each wavelength channel is typically dedicated to a single subscriber. The total number of connected subscribers and the aggregate system capacity is proportional to the number of wavelength channels operated in parallel. There are many different ways to implement a WDM-PON access solution, depending on the complexity of light sources, target distance, supported line rates, and other factors. [ma1] provides a detailed survey of available WDM-PON access solutions, their advantages, and technical challenges.

In order to achieve an aggregate system capacity of 100 Gb/s, a WDM-PON system operating at 10 Gb/s (using, for example, 10GBASE-LR optics) would require 10 wavelength channels in the downstream and 10 wavelength channels in the upstream, but would be able to connect only 10 ONUs (subscribers).

Commented [MH17]: Just to clarify what these subscribers really are …

One of the obvious drawbacks of the WDM-PON architecture, especially for residential applications, is that each ONU is provided with dedicated data channel to the OLT, which remains idle most of the time, apart from periods of peak activity when bursty data is being exchanged. On the positive side, subscribers with low data requirements can be serviced with lower cost P2P optics running at 1 Gb/s or even 100 Mb/s.

6.2.3 Hybrid PON

The hybrid PON access systems ~~take advantage of~~combine the best features of both TDM-PON as well as WDM-PON~~, and combine them~~, allowing the access system to achieve high aggregate capacity (100 Gb/s and more) while still taking advantage of the TDM-based sharing of a wavelength channel among connected ~~multiple~~ subscribers.

In the simplest form, a hybrid TDM-PON / WDM-PON system can be implemented by stacking multiple TDM-PON systems, each operating at a slightly different wavelength in the downstream and upstream directions. The assigned wavelength grid for each direction is unique, allowing complete reuse of the currently existing TDM-PON solutions per wavelength (either 1G-EPON or 10G-EPON). Depending on the way ~~TDM~~ scheduling domains are created across available wavelength channels, MSD-WDM-PON, ~~or two types of~~ SSD-WDM-PON, and WA-PON can be supported.

Figure 1 shows an example of ~~such~~ a simple MSD-WDM-PON system, with four ~~TDM~~ scheduling domains, where each wavelength channel is TDM-shared among a number of connected subscribers. In this scheme, each ONU has access to only one wavelength pair at a time, transmitting and receiving on pre-assigned upstream and downstream wavelength channels. The assignment can be either fixed (fixed optics) or dynamic (tunable optics), depending on the requirements for the ONU's flexibility, ability to move between individual TDM domains for load balancing, etc. Each TDM domain is scheduled independently by the dynamic bandwidth allocation (DBA) process on the OLT. The number of connected ONUs ~~can~~ may vary per wavelength channel.

Commented [MH18]: We decided at the last meeting to call these "scheduling domain" and not TDM domain

It is also possible to create just one large ~~TDM~~ scheduling domain, where all connected ONUs have access to all downstream and upstream wavelength channels at the same time, and are scheduled via a single DBA process on the OLT – see Figure 2. In this way, an SSD-WDM-PON system is created. In this scheme, the ONU can utilize fixed optics, but its electronics needs to process all data transmitted by the OLT.

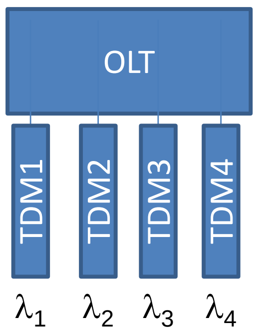

Figure 1: MSD-WDM-PON with multiple TDM domains [bhn1]

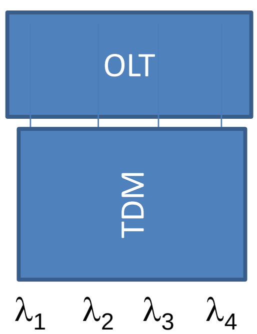

Figure 2: SSD-WDM-PON [bhn1]

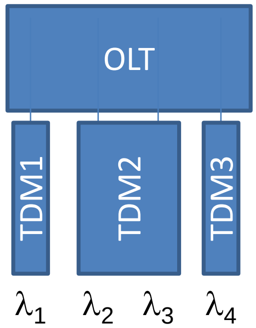

Figure 3: MSD-WDM-PON with dynamic TDM domains [bhn1]

A more flexible ~~MSD-WDM-~~hybrid PON approach is shown in Figure 3, where two wavelength channels are combined to create a larger ~~TDM~~ scheduling domain with the aggregate throughput exceeding the throughput of a single wavelength channel. In ~~this~~ the WA-PON scheme, advantages of the first MSD-WDM-PON system are applicable, while it is also possible to support customers with services requiring throughput exceeding the capacity of a single wavelength channel. This particular arrangement is therefore ideal for supporting both residential and commercial services on a single access platform.

Hybrid PON access systems are natural candidates for stacking multiple 10G-EPON systems in either symmetric or asymmetric configurations. Given the flexibility of this scheme, it is possible to operate some wavelength channels in the asymmetric 10/1G-EPON configuration and dedicate these wavelengths for residential access. Simultaneously, it is possible to aggregate multiple wavelength channels of 10/10G-EPON to create symmetric data channels with aggregate throughput exceeding 10 Gb/s. Such data channels are ideal to provide multi-Gb/s access service to commercial customers.

If TDM sharing is used, simulation models have shown that due to statistical multiplexing (see *[add reference to section on statistical multiplexing when added]*), it is possible to serve the same number of ONUs (compared with WDM-PON) with fewer wavelength channels, while simultaneously observing similar SLAs.