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A Survey on Cost Effective Optical Network Unit Configurations

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ABSTRACT

The technology of Wavelength division multiplexing-Passive optical networks WDM-PONs is basically developed based on the approach of broadcast-and-select in which an identical aggregation of wavelengths is directed to different destinations using a power splitter. Later, it was developed based on the approach of wavelength routing in which an aggregation of wavelengths is separated and directed in such a way that each individual wavelength in the aggregation can reach a specific destination using an arrayed waveguide grating (AWGs). It is one of the highly nominated technologies for next-generation optical access network NG-OAN. This is due to its ability to overcome the limitation imposed in the currently standardized TDM-PONs (E-PON, G-PON, 10G-EPON, and XG-PON), such as their shared-traffic nature and allowable power budget. However, the inventory of wavelength-specific transmitters needed in this technology especially at subscriber premises (i.e. optical network unit ONU) where cost is most sensitive, and their associated operation, administration, and management costs remains a major issue that needs to be settled before widespread commercial success can be achieved. This attracts many researchers to concentrate their efforts to develop a cost-effective ONU. Many proposals were found in the literature that aims to realize this desirable goal with most of them agreed up on that it can be achieved by enabling ONU mass production. They also agreed up on that enabling the ONU mass production can only be achieved by unifying its design. In this paper, the author provides a review of various state-of-the-art configurations, proposed to unify the ONU design.

Keywords: Wavelength division multiplexing WDM; optical network unit ONU; Time division multiplexing-passive optical networks TDM-PONs; Fiber-to-the-home FTTH; Passive optical networks PON

INTRODUCTION

The shared-traffic nature and allowable power budget of the currently standardized Time Division Multiplexing Passive Optical Networks TDM-PONs are the two major obstacles that come against future widespread. The allowable power budget limits the splitting ratio (i.e. the number of accommodated users) and distance between the Optical Line Terminal OLT and ONU, whereas the shared-traffic nature prevents the desirable Optical Network Terminal ONU self-upgradeability (Ibrahim Mohamed & Mohammad Syuhaimi 2015). These limitations can be overcome by using the so-called Wavelength Division Multiplexing-PONs WDM-PON technology. For instance, in a WDM-PON system, each ONU can separately upgrade its speed via a dedicated couple of wavelengths assigned to it (achievable self-upgradeability). Moreover, the number of accommodated users can be increased by exploiting the virtually unlimited bandwidth of fiber optics (increasable capacity). WDM-PONs were basically developed based on the technique of broadcast-and-select, later they were developed based on a more enhanced technique which is the wavelength routing technique (Grobe & Elbers 2008).

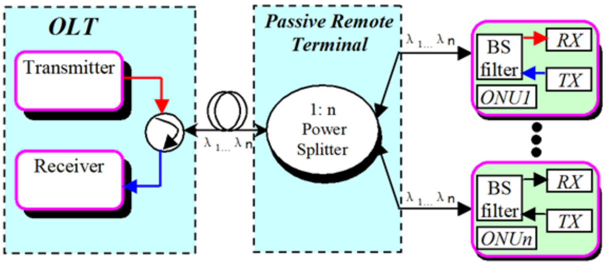

FIGURE 1. Schematic Diagram of a Broadcast-and-select WDM-PON

In the broadcast-and-select WDM-PON shown in Figure 1, an optical line terminal OLT is used to broadcast an aggregation of wavelength carriers ($\lambda 1 - \lambda n$) in the downstream direction, and a 1:n power splitter is used to direct the whole aggregation to a number of n ONUs. Each ONU can extract the wavelength intended to it by using a suitable band-pass filter. Another individual wavelength carrier is allocated to each ONU for handling transmission in the upstream direction. Even though, the broadcast-and-select technique can realize the desirable goal of self-upgradeability for each ONU, it suffers from a high splitter loss (splitting loss plus insertion loss). Additionally, it has a lack of privacy. Moreover, the system has a high cost because of the need for specific or tunable receiver and transmitter in each ONU. In the wavelength routing technique shown in Figure 2, the WDM-PON system makes use of an arrayed waveguide grating (AWG) instead of the power splitter.

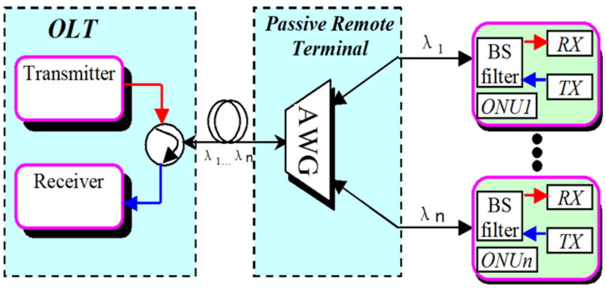

FIGURE 2. Schematic Diagram of a wavelength routing-PON

Compared with the broadcast and select-based WDM-PON, the wavelength routing-based WDM-PON has low loss as the AWG has only a specific amount of insertion loss regardless the number of output ports (no splitting loss is imposed). Additionally, It accepts the use of a simpler ONU (wavelength-selective receivers are no longer required).

However, separate or tunable ONU transmitters are still required. All of the aforementioned WDM-PON techniques were based on dense WDM (DWDM) technology in which a wavelength spacing of either 0.8 nm or 0.4 nm is considered. Alternatively, coarse WDM (CWDM) can be used in which a 20 nm wave-length spacing is used. In this aspect, an additional tolerance for wavelength drift is allowed due to the wider spacing used, which simplifies the transmitter requirements and thus reduces the cost. Although, WDM-PON technology can mitigate the aforementioned limitations, imposed in the currently standardized TDM-based PONs, the large number of wavelength-specific transmitters needed in this technology particularly at the subscribers' side would increase the cost, which leads to decrease its commercial deployment. This attracts many researchers to concentrate their efforts to develop a cost-effective ONU. While many proposals can be found in the literature that aims to realize this desirable goal, most of them agree up on that it can be achieved by enabling ONU mass production. They also agree up on that enabling the ONU mass production can only be achieved by unifying its design. The objective of this paper is to provide a review of various state-of-the-art configurations, proposed in the literature to unify the ONU design. It is organized as follows: Section 2 provides general categorization of cost effective ONU configurations. Section 3, 4, and 5 provides an individual detailed review of each particular cost effective ONU configuration. Section 6 concludes the paper.

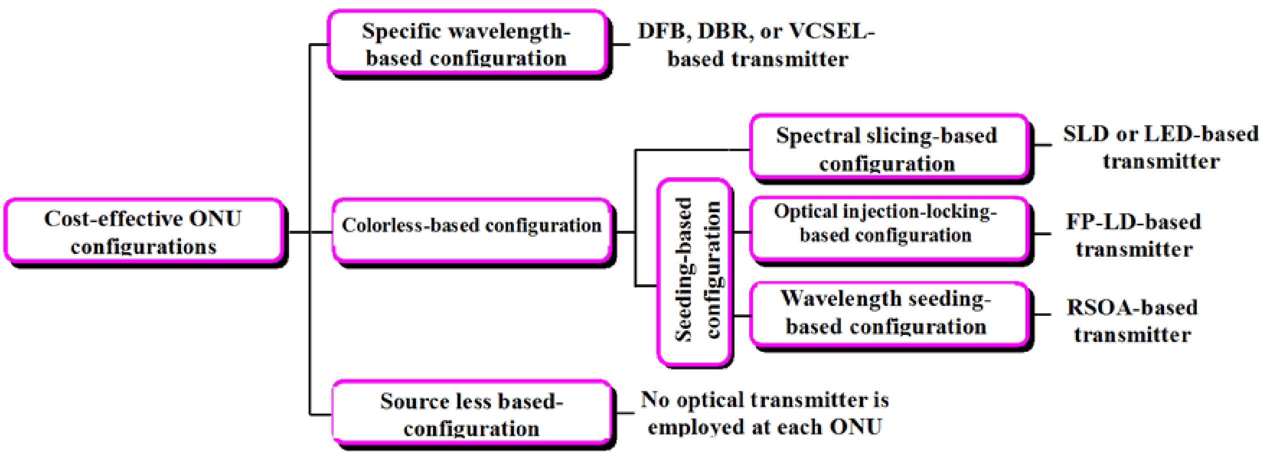

FIGURE 3. Cost-effective ONU configurations

COST EFFECTIVE ONU CONFIGURATIONS

Many proposals can be found in the literature aiming to develop a cost-effective ONU. Each of which was based on different configuration (Carvalho & Cartaxo 2015; Yu Yin et al. 2017; Bingchang Hua et al. 2018; Haitao Yao et al. 2017; Vesna Erzen et al. 2015; H. Hu et al. 2016).

These configurations can be categorized as follows: (a) single and shared wavelength-based ONUs, (b) spectrum slicing-based ONUs, (c) source less-based ONUs, (d) wavelength seeding-based ONUs, and (e) injection looking-based ONUs. Figure 3 shows a diagrammatic representation of these categories. A review of theses state-of-the-art configurations is provided below.

SINGLE AND SHARED WAVELENGTH-BASED ONUS

In the single and shared wavelength-based ONUs, unified design ONUs can be realized by assigning identical wavelength in each ONU that is intended for usage in the upstream direction. I.e. identical optical source is employed in each ONU in the WDM-PON system as a transmitter. Although this configuration can enable the use of identical ONUs (unified design ONUs) which leads to achieve the desirable goal of reducing the cost, it imposes the involvement of the time-division multiple access TDMA technique to control the access to the shared medium (i.e. ensures fair access to the shared medium) (A. Banerjee et al. 2005). Figure 4 shows schematic diagram of this configuration.

In this configuration, identical wavelengths can be produced by using a number of single-mode optical sources, such as distributed feedback (DFB) lasers, or distributed bragg reflector (DBR) lasers due to their high-speed direct modulation property and excellent single-mode behavior (around 1 MHz spectral width) (U. Troppenz et al. 2006). However, employment of such optical sources in the WDM systems requires the use of active temperature control and wavelength feedback monitoring to ensure stable and strict wavelength emission (within the WDM grid). This is due to their relatively high temperature coefficients (around 0.1 nm/^{o}C), which leads to increase the power consumption, level of complexity, and the cost. Identical wavelengths can also be produced by using the single-mode vertical-cavity surface-emitting laser (VCSEL) (C. Chang-Hasnain. 2003).

The VCSEL has a fundamental advantage over the DFB and DBR lasers in that it exhibits low-threshold currents and thus consumes less power. Additionally, it has low manufacturing and packaging cost. Moreover, it has a surface-emitted and circular beam, which leads to high coupling efficiency into single-mode fibers. Various proposals based on this configuration can be found in (W. Hofmann et al. 2006; E. Wong et al. 2006; L. Chrostowski et al. 2003; L. Chrostowski et al. 2006; W.S. Jang et al. 2004; E. Wong et al. 2006; W. Yuen et al. 2001).

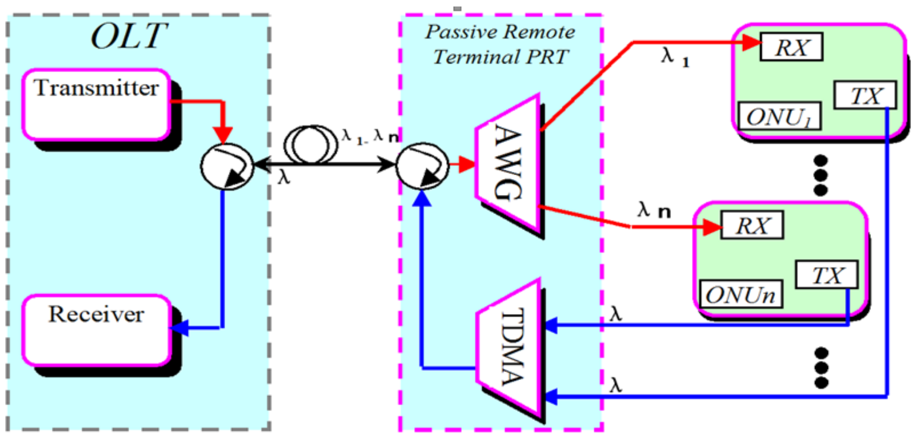

FIGURE 4. Schematic Diagram of single and shared wavelength-based ONUs

SOURCE LESS-BASED ONUS

In the source less-based configuration, the carrier wavelength used for the downstream transmission (the wavelength comes from the OLT side) is actually reused for the upstream transmission. I.e. no optical source is really employed at the ONU side. Various options were adopted in the literature to enable this configuration. In the first options, a tunable laser is employed as a central transmitter at the OLT side to emit a range of wavelengths. Each peace of wavelength within this range is oriented to a specific ONU. The innovative solution in this configuration is based on creating a compound packet at each peace of wavelength, i.e. Each peace of wavelength is carrying a packet that is divided evenly by a mean of time-division multiplexing where the first half of the packet time is used to carry the upstream data, while the second half of the packet time is a pure continuous wavelength (CW). A 1 x 2 optical power splitter is employed at each ONU to separate the received power evenly by a mean of time-division de-multiplexing such that each peace of a separated power is directed to a different path. One path is devoted for downstream data detection and the other is used for modulating the received CW by the upstream data using an external modulator. This option was first implemented experimentally in 1994 in the RITE-net architecture (N.J. Frigo et al. 1994). Figure 5 shows the schematic diagram of this option. In the second options, a number of N lasers is employed at the OLT side to emit a range of wavelengths. Each peace of wavelength within this range is oriented to a specific ONU. The innovative idea in this configuration is to modulate the downstream carrier by the downstream data using a modulation technique that is able to produce a carrier with a constant optical intensity (constant envelope), such as the frequency shift keying (FSK), which allows the re-modulation of the upstream carrier by the upstream data using a modulation technique that is able to produce a carrier with a variable intensity (variable envelope), such as the so-called amplitude shift keying (ASK) technique (also referred to as intensity modulation). A 1 x 2 optical power splitter is employed at each ONU to separate the received power evenly such that each peace of a separated power is directed to a different path, i.e., one for detecting the FSK signal and the other is for re-modulating the received carrier by the upstream data using an external intensity modulator.

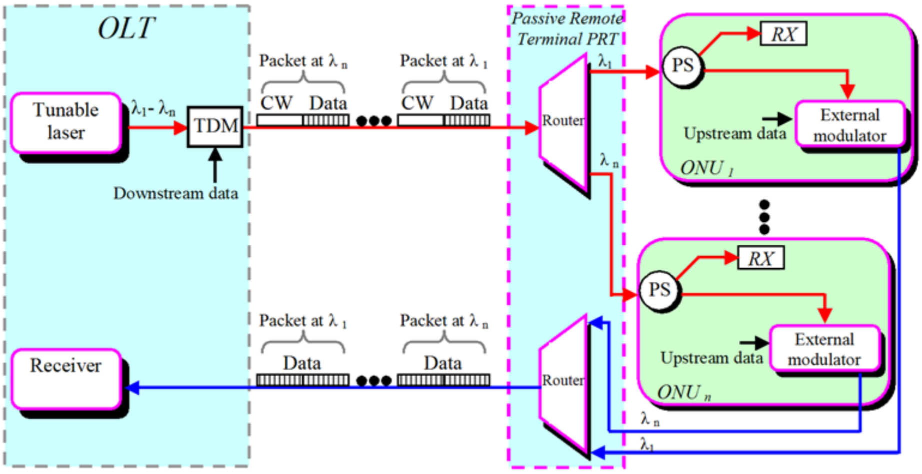

FIGURE 5. Source less-based ONUs: A tunable laser is employed as a central transmitter at the OLT

Figure 6 shows the schematic diagram of this option. Another option in which the downstream carrier is modulated by the downstream data using ASK technique at an adequate low optical extinction ratio (ER) (W.R. Lee et al. 2005; J.J. Koponen & M.J. Soderlund. 2004; J. Prat et al. 2006). A reflective semiconductor optical amplifier that is driven into saturation region is employed at each ONU to re-modulate the received carrier by the upstream data using ASK technique at a higher optical ER. This option has an advantage over the aforementioned options in that it has an implicit amplification feature that is resulted by the RSOA, which would lead to compensate for the loss imposed during the downstream transmission and thus increases the distance. Two optical amplifiers can be added in the OLT side in each of the fore mentioned source less-based ONU options to further extend the reach (i.e. one boost amplifier in the downstream direction and one pre-amplifier in the upstream direction). Although source less-based configuration allows the usage of unified design ONUs, which simplifies the WDM-PON design and thus leads to reduce the cost, it necessitates using dual fiber configuration rather than single fiber configuration to realize bidirectional operation as the same wavelength is assigned for transmission in both directions (downstream and upstream directions). Various proposals based on this configuration can be found in (Yu-Siang Huang et al. 2010; Christian Ruprecht et al. 2015; Yu-Siang Huang et al. 2010; Kwanil Lee et al. 2007).

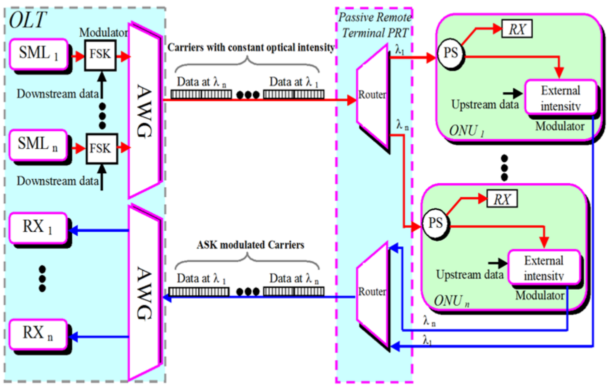

FIGURE 6. Source less-based ONUs: A number of N lasers are employed at the OLT

COLORLESS-BASED ONUS

In the colorless-based configuration, the wavelength used in the upstream direction is nonspecific, i.e., it can be selectively determined by an external factor, such as the filtering characteristic of an optical component located at the remote node (e.g. AWG), or the wavelength of an external light that is seeded into the ONU.

This flexibility allows the usage of identical ONUs (unified design ONUs), which simplifies the WDM-PON design and thus leads to reduce the cost. Colorless-based ONU configurations can be classified into two main categories, spectrum slicing-based ONU configuration and seeding-based ONU configuration. In the spectrum slicing-based configuration, either a super luminescence diode (SLD) or a light-emitting diode (LED) is used as a broadband optical source in each ONU transmitter. (M. Zirngibl et al. 1995; K.-Y. Liou et al. 1997; S.S. Wagner & T.E. Chapuran. 1990). The broadband lightwave, emitted from such an optical source is first modulated by the upstream data, sliced at a remote node using an AWG, and finally transmitted to the OLT over the feeder fiber. Each peace of sliced light is centered to a different wavelength according to the AWG grid. Although the spectrum slicing-based configuration allows the usage of unified design ONUs, which simplifies the WDM-PON design and thus leads to reduce the cost, it has a limited power budget due to the low coupling efficiency of LEDs and SLDs into single-mode fibers. A circulator can be used at the OLT side to realize bidirectional operation over a single fiber. Figure 7 shows the schematic diagram of this configuration. Various proposals based on this configuration can be found in (W.T. Holloway et al. 1997; S.L. Woodward et al. 1998; Bo Zhang et al. 2006; A. Banerjee et al. 2005). In addition to the limited power budget of the spectral-slicing-based configuration mentioned above, the modulation speed (transmission bit-rate) is also limited due to the high spectral-slicing loss. On other word, only a narrow band out of the entire broadband lightwave is effectively utilized for data transmission as a result of the slicing process performed at the remote node.

Although the slicing loss can be reduced by increasing the pass-band used at the remote node (using a wider AWG grid), an increase in the pass-band could worsen the dispersion problem. The latter can be mitigated by adopting the so-called seeding-based configuration where an only one stable mode (alternative to wavelength) can be produced and used for high speed modulation. Two options were adopted in the literature to enable this configuration (the injection looking-based and wavelength seeding-based options). In the injection looking-based option, a fabry-perot laser diode (FP-LD) is used as a multimode optical source in each ONU transmitter.

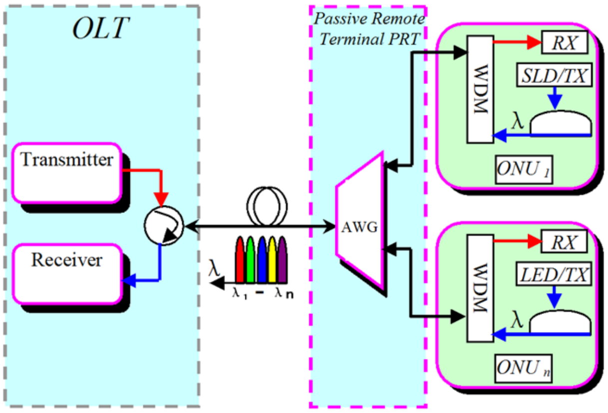

FIGURE 7. Schematic Diagram of a spectrum sliced-based ONU

An external optical light is injected into the FP-LD. This process stimulates the FP-LD to emit a one stable mode (alternative to wavelength) according to that wavelength injected into it, while suppressing the rest of modes (H. Sanjoh et al. 1997). In the wavelength seeding-based option, a reflective semi-conductor optical amplifier (RSOA) that is driven to the saturation region is used as a transmitter in each ONU. An external light is injected (seeded) into that saturated RSOA (S.-B. Park et al. 2006; P. Healey et al. 2001).

Compared to the SOA, a reflective SOA has one front facet, coated with a very low-reflectivity antireflection coating, and a rear facet, coated with high reflectivity coating rather than two low-reflection facets, which allows an efficient entering, reflection, and exiting of light. Thus, the seeding process into the RSOA would stimulate it to emit a stable wavelength that follows the wavelength of the seeded light (S.-B. Park et al. 2006). The wavelength-seeded RSOA has an advantage over the injection-locked FP-LD in that it has high output power, which makes it the better choice for high speed transmission over longer distances. Additionally, a RSOA that operates in the saturation region has an inherent amplitude-squeezing property that omits the so-called excess intensity noise imposed by the seeding light (H.C. Shin et al. 2004). A reflective electro- absorption modulator (REAM) can also be used in each ONU transmitter as an alternative to the RSOA. Most of the proposed WDM-PONs based on this approach makes use of a centralized broadband optical source, such as superluminescent light emitting diode SLED or a multi-frequency laser (MFL) with its broadband output spectrum being spectrally sliced at the remote node to establish several master injection/seeding lights. These lights are injected/seeded into an equivalent number of FP-LDs, RSOAs, or REAMs that are located at the ONU side, which leads to stimulate each FP-LD, RSOA, or REAM to produce an only one stable wavelength. Similar to the source less-based ONUs option, the seeding-based approach can exploit the advantage of adding two optical amplifiers in the OLT side to further extend the reach (i.e. one boost amplifier in the downstream direction and one pre-amplifier in the upstream direction). Various proposals based on this configuration can be found in (S.H. Shin et al. 2006; H.D. Kim et al. 2000; D.J. Shin et al. 2003; D.J. Shin et al. 2006; Soo-Jin Park et al. 2004; F. Payoux et al. 2005; Ting Su et al. 2012; Ting Su ET al. 2013; Qi Guo & An V. Tran. 2013; Jie Hyun Lee et al. 2010; X. Q. Jin et al. 2013). Figure 8 shows the schematic diagram of this approach.

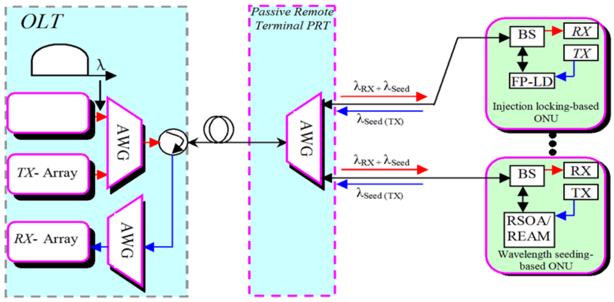

FIGURE 8. Schematic diagram of seeding-based ONUs

TABLE 1. Comparison among the proposed cost-effective ONU configurations

Options for unified ONU design	Category	Transmitter used	Challenges
Identical optical source is used in each ONU	Single and shared wavelength-based configuration	DFB, DBR, or VCSEL-based Transmitter	- TDMA is needed to control the access to the shared medium
Each ONU can use a purely continuous wavelength embedded in the received packet for upstream transmission	Source Less-based configuration	No optical source is employed at the ONU	- TDMA is needed to separate the received packet
The received wavelength that carries the downstream date is re-modulated again by the upstream data	Source Less-based configuration	No optical source is employed at the ONU	- Two different modulation techniques are needed for downstream and upstream transmission - Dual fiber configuration is needed to realize bidirectional operation on the same wavelength
A broadband optical source is used in each ONU transmitter	Colorless-based configuration	SLD or LED-based Transmitter	
Each ONU is stimulated to produce a stable wavelength based on the received wavelength	Colorless-based configuration	FP-LD, RSOA, or REAM-based Transmitter	- Limited power budget due to low coupling efficiency of LEDs and SLDs into single-mode fibers

A comparison among the aforementioned configurations, based on key specifications and challenges is provided in Table 1.

CONCLUSIONS

The tremendous number of wavelength-specific-based ONU used in the WDM-PON technology would increase the cost and thus leads to limit its commercial spread. This motivated many researchers to spend their efforts for proposing a cost-effective ONU. In this paper, the author provided a review of different state-of-the-art cost effective ONU configurations to open the door for future research plans.

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