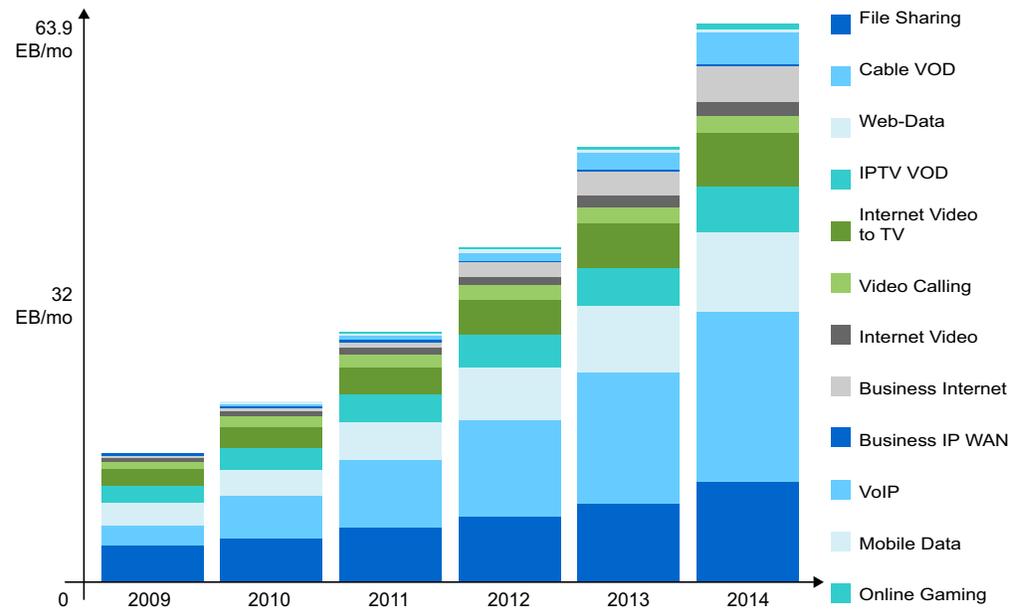Passive optical network (PON) technology is emerging as the key access technology, as it has a scalable and cost-effective architecture to satisfy the ever-growing bandwidth requirements generated by advanced applications such as high-definition television (HDTV). Standard bodies are finalizing next-generation PON requirements to further increase the bandwidth available, service diversity, reach distance, and split ratios. Changes are expected in these standards, and the timing of transition to next-generation PON systems is unclear.

FPGAs play a key role for early adopters of next-generation PON systems due to their flexibility to allow development of future proof designs and implementation of unique features to differentiate against competitors versus standard products. Altera® Stratix® V FPGAs' abundant resources, robust transceivers with native PON burst mode support, and fast external memory interfaces bring an unprecedented level of system integration. Altera further helps to lower system cost and power consumption via its seamless migration path from FPGAs to its HardCopy® series ASICs.

Introduction

With the development of many advanced multimedia applications, there is a massive increase in bandwidth demand. According to the June 2010 forecast of the Cisco Visual Networking Index *(1)*, total global Internet Protocol traffic will quadruple from 2009 to 2014, reaching 63.9 exabytes (EBs) per month, or 766.8 EBs per year (Figure 1).

Figure 1. Global Internet Protocol Traffic, 2009–2014

Source: Cisco VNI, 2010

101 Innovation Drive
San Jose, CA 95134
www.altera.com

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Internet video streaming and downloads already are starting to take up a greater share of the bandwidth and will grow to almost 60% of all consumer Internet traffic in 2014. In order to support this ever-increasing demand for higher broadband bandwidth, PON technology appears to be the best choice among various access technologies due to its ability to scale to a much higher speed (10 Gbps and beyond).

In addition, the cost-effective PON architecture with passive optical elements and shared fiber among multiple customers addresses both capital and operating expenditures for service providers. The active components within a fiber-to-the-home (FTTH) network only account for a small portion of the total cost. Since a single fiber can support multiple customers in a PON, it helps to keep the cost of the optical distribution network deployment low. Operators such as Verizon, NTT, China Telecom, and China Unicom prefer PON as their mainstream access technology.

PON Overview

PON technology provides a powerful point-to-multipoint solution to meet the ever-increasing bandwidth demand, and at the same time is able to provide low maintenance in the access part of the communication infrastructure. A PON consists of an optical line terminal (OLT) located at the central office and multiple units of optical network units (ONUs) at the customer sites, as illustrated in Figure 2.

Figure 2. Passive Optical Network
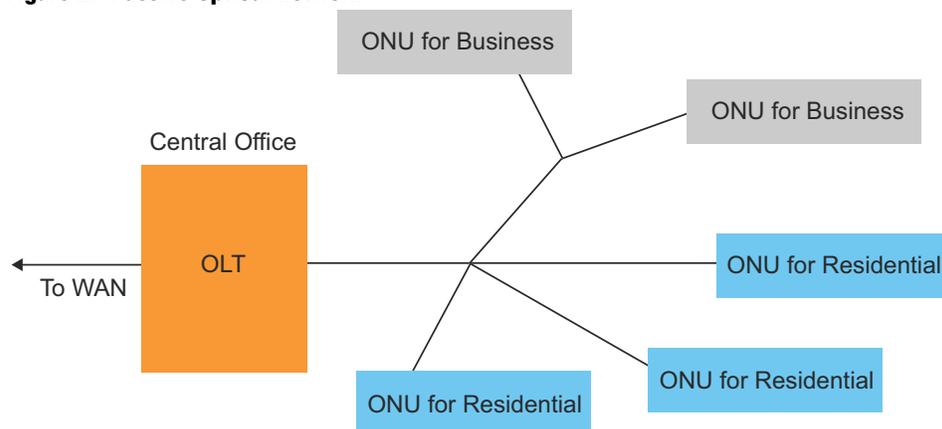
Different flavors of PON standards have been specified by two standard bodies, International Telecommunications Union (ITU) and Institute of Electrical and Electronics Engineers (IEEE). Within the ITU, the earliest version was the Asynchronous Transfer Mode (ATM) PON (APON) standard, which was mainly used for business applications. Then there was the Broadband PON (BPON) standard, which was based on the APON standard with improvements (ITU-T G.983) providing 622 Mbps of downstream bandwidth and 155 Mbps of upstream bandwidth. The BPON standard was mainly deployed by Verizon in the U.S. The next evolution was the ITU-T G.984 *(2)*, or so called Gigabit-capable PON (GPON) standard, ratified in March 2008. The GPON standard provides an additional performance boost in terms of both the total bandwidth and bandwidth efficiency, with 2.488 Gbps of downstream bandwidth and 1.244 Gbps of upstream bandwidth. The GPON standard is widely deployed in all geographical regions with the exception of Japan.

Now the next-generation GPON standard, NG-PON, is being worked on by the ITU and Full Service Access Network (FSAN) working group *(3)*. As illustrated in Figure 3, the next-generation GPON technologies will be rolled out in two phases: XG-PON1 and NG-PON2. XG-PON1 is an evolutionary growth of the existing GPON standard, and requires coexistence with GPON on the same fiber infrastructure. NG-PON2 will be a revolutionary change of the existing GPON standard that does not require coexistence with GPON on the same fiber infrastructure, and thus is intended for green-field applications. XG-PON1 provides users 10 Gbps of downstream bandwidth and 2.5 Gbps or 5 Gbps of upstream bandwidth. The XG-PON1 standard (ITU-T G.987) was approved in June 2010, and Verizon has performed some field trials with equipment vendors already. Which PON technology will be selected for NG-PON2 is still to be determined, and is the current focus of FSAN. NG-PON2 is not expected until 2015 or later.

Figure 3. Next-Generation PON Roadmap
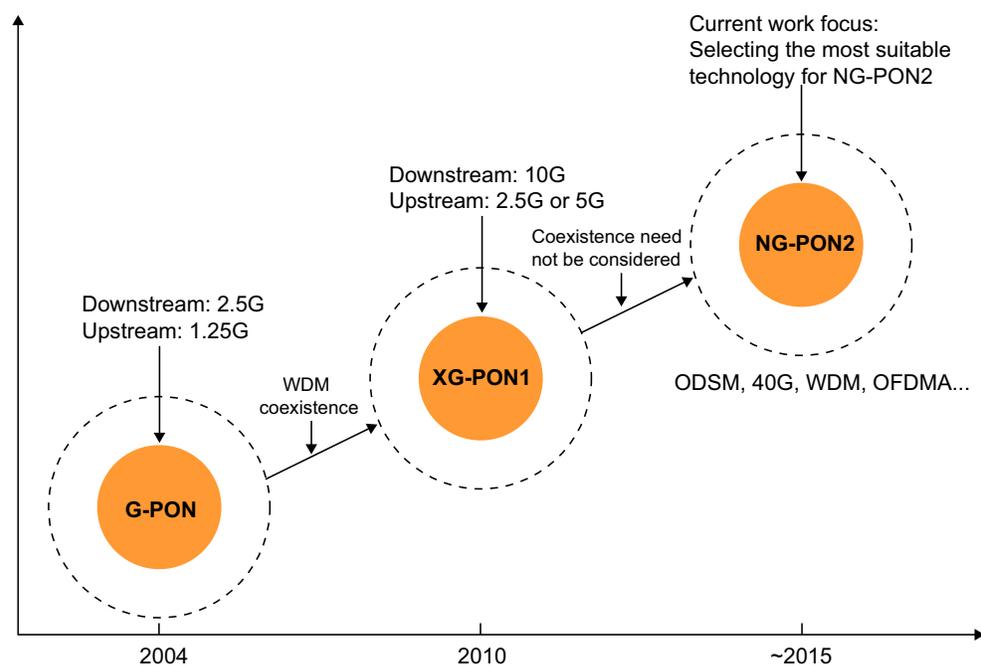
Source: FSAN

Within IEEE, the IEEE 802.3 Ethernet PON (EPON or GEPON) standard *(4)* was completed in 2004. It uses standard Ethernet frames with 1 Gbps bandwidth for both upstream and downstream. The EPON standard has mostly been adopted by operators in Japan and China. The next-generation standard, 10G-EPON, was ratified as IEEE 802.3av in September 2009. It can provide 10 Gbps of downstream bandwidth and 1 Gbps or 10 Gbps of upstream bandwidth, and it supports the coexistence of EPON on the same fiber infrastructure.

The main emphasis of the EPON standard was to preserve the architectural model of Ethernet. It preserves the Ethernet framing format that carries variable-length packets without fragmentation. The GPON standard is based on a fixed frame of 125 µs and uses the GPON encapsulation method (GEM) to perform packet fragmentation. Compared to GPON, EPON is a relatively simpler standard that requires looser hardware and is less focused on quality of service (QoS) assurance. Some of the key differences between the GPON and EPON standards are guard times, overheads, and other forms of parameter influencing bandwidth utilization.

Downstream traffic is broadcast from the OLT to each ONU with the use of optical splitters. Each ONU continuously listens to the broadcast traffic, and extracts the packets destined to one of its ports based on the packet address information. For security reasons, encryption and decryption capability is needed. Upstream traffic from each ONU is combined using time division multiple access (TDMA) technology and sent to the OLT via the same shared fiber. The OLT assigns each ONU a time slot during which it can transmit its upstream data. To avoid overlap of the upstream burst transmissions of data from different ONUs, a guard time is required between the burst transmissions. The XG-PON1 standard has very stringent requirements for the guard time and the clock data recovery (CDR) lock time, which challenge component vendors to have XG-PON1 burst mode-compliant receivers. The current-generation high-performance Stratix IV FPGAs' transceivers can meet this requirement using a proprietary oversampling scheme. The next-generation high-performance Stratix V FPGAs' transceivers have native burst mode support for XG-PON1 and 10G-EPON technology.

Next-Generation PON Applications

With higher bandwidth and higher QoS capability, in addition to supporting various services (both legacy, such as time-division multiplexing (TDM) T1/E1 lines and plain old telephone service (POTS), and emerging packet-based services, such as IPTV) for current residential subscribers and business customers, next-generation PON technology can support mobile backhaul applications as well. Figure 4 shows the different applications of next-generation PON technology.

**Figure 4. Next-Generation PON Applications**
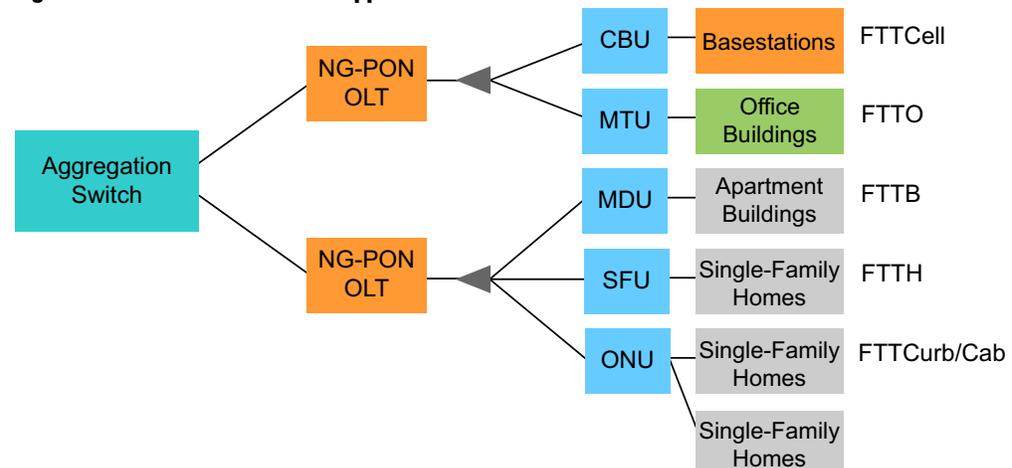
Next-generation PON technology will continue to support the current FTTH architecture in which each residential home has a dedicated single family unit (SFU), fiber to the building (FTTB) in which apartment units in a building share a multi-dwelling unit (MDU), fiber to the curb/cabinet (FTTC) in which multiple single family homes are connected to the ONU via copper cables, and fiber-to-the-office (FTTO) business applications via a multi-tenant unit (MTU). In addition, next-generation PON technology will support fiber-to-the-cell (FTTCell) backhaul applications via a cell-site backhaul unit (CBU) to the cellular base stations.

In order to support 3G/4G mobile backhaul, accurate frequency, phase, and time synchronization is required. The IEEE 1588 Precision Timing Protocol and ITU Synchronous Ethernet (SyncE) standards specify how to provide precise timing and synchronization over packet-based Ethernet networks. Both of the IEEE 1588 and SyncE solutions are offered by Altera's third-party intellectual property (IP) partners. The wide variety of existing and emerging services for multiple applications present a broad range of QoS characteristics, so more sophisticated traffic management mechanisms will be needed for next-generation PON systems.

PON Market Outlook

As illustrated in Figure 5, the PON equipment revenue outlook looks very promising for the next few years. PON revenue is forecasted to grow at a 22.5% CAGR from 2009 to 2014; however, the next-generation 10G-capable PON systems (especially 10G-capable GPON) will not ramp in volume until 2014. Changes in the next-generation PON specification are expected, so there are uncertainties in the 10G PON market timeframe and requirements. To minimize risk associated with these uncertainties, it is best to build a system with Altera's FPGAs that provide full flexibility to future-proof a product, especially for infrastructure OLT equipment that is produced in much lower volumes than ONU equipment. As the next-generation PON volume starts to ramp and the standard becomes more mature, HardCopy series ASICs provide a cost reduction path with a very quick turn-around time.

Figure 5. PON Equipment Total Revenue Outlook

Legend:
- BPON
- 1.25G/2.5G EPON
- 10G EPON
- WDM-PON
- 2.5G GPON
- 10G GPON
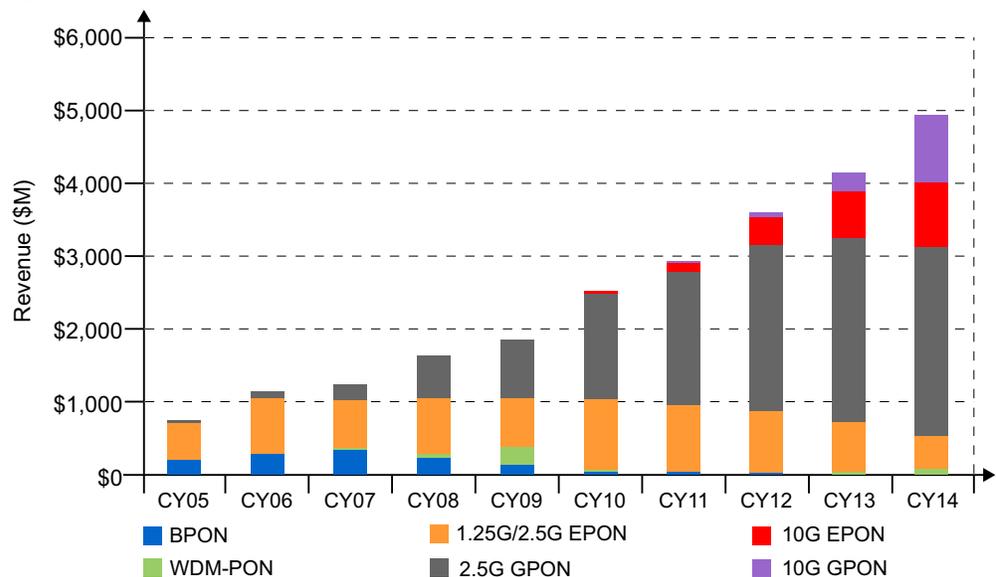
Source: Infonetics

Key Functions of PON OLT Line Card

The main functions on a PON OLT line card can be divided into four categories: physical layer, MAC layer, packet processing, and traffic management.

Physical Layer

The physical layer components include the optical transceivers and the burst mode CDR SERDES. The Stratix IV and Stratix V families of FPGAs have integrated the burst mode CDR SERDES that can support a variety of optical transceivers in the market. The Stratix IV GX variant has a maximum of 48 transceivers that can run up to 8.5 Gbps, while the Stratix IV GT variant has a maximum of 48 transceivers that can run up to 11.3 Gbps, and the Stratix V GX variant has a maximum of 66 transceivers that can run up to 12.5 Gbps. The integration of the burst mode CDR SERDES into the FPGA helps lower the bill of material (BOM) cost, board space, and power consumption. As an example, Table 1 shows some of the 10G-EPON characterization results for the Stratix IV GT variant. Stratix IV GT FPGAs meet the 10G-EPON burst mode CDR specification (<400 ns) with good margin across varying intergap time and run lengths.

Table 1. Stratix IV GT 10G-EPON Characterization Data

Intergap Burst	Code Word Run Length	AC Coupling Capacitor Value	CDR Lock Time	Number of Correct Bits
7.76 ns	1	1 nF	267.64 ns	$>10^{13}$
7.76 ns	80	1 nF	267.64 ns	$>10^{13}$
1 ms	1	1 nF	267.64 ns	$>10^{12}$
1 ms	80	1 nF	267.64 ns	$>10^{12}$
15,000 ns	PRBS31	1 nF	267.64 ns	$>10^{13}$
1500 ns	PRBS31	1 nF	267.64 ns	$>10^{12}$

Compared to the 10G-EPON standard, the XG-PON1 standard has much more stringent requirements on the guard time and CDR lock time. The Stratix IV GX and GT FPGAs' transceivers can support the XG-PON1 2.5-Gbps upstream burst mode requirements by using a proprietary oversampling reference design. In the next-generation high-performance Stratix V FPGA family, enhancements have been made to the receivers to support the XG-PON1 burst mode natively.

MAC Layer

The MAC layer functions mainly include framing, media access control, operations, administration and maintenance (OAM), dynamic bandwidth allocation (DBA), forward error correction (FEC), and security.

In terms of framing, EPON standards are based on Ethernet. In EPON, Ethernet frames are carried in their native format on the PON system. Services are all mapped over Ethernet (either directly or via Internet Protocol). On the other hand, GPON is based on a fixed GPON Transmission Convergence (GTC) frame of 125 µs. Frame fragmentation is used to divide the large TDM or Ethernet frames into smaller fragments which are reassembled at the receiver to help reduce delay variations of real-time traffic and TDM traffic in case of large data packets. Each frame fragment is then encapsulated in a GEM frame. And then the GEM frames are further encapsulated into GTC frames to be transported over the PON system.

For both EPON and GPON standards, media access is performed through the concept of TDMA via granting. For the EPON standards, the Multi-point Control Protocol (MPCP) is implemented at the EPON MAC layer to perform bandwidth allocation, the auto-discovery process, and ranging. Each ONU has a unique logical link identifier (LLID). Bandwidth grants are sent per LLID, and each grant specifies an upstream transmission opportunity for a given ONU. REPORT and GATE are the two control messages used for bandwidth allocation. For the GPON standards, the upstream bandwidth map (BWmap) field of the downstream frame header indicates the time at which each ONU may begin and end its upstream transmission, so only one ONU can access the medium at any time to avoid any contention.

OAM refers to the management tools and utilities to install, monitor, and troubleshoot a network to help operators run their networks more efficiently. The EPON protocol's OAM mechanism is specified as part of the IEEE 802.3ah standard. The GPON protocol has more sophisticated OAM capabilities. In GPON, there are three different types of control messages: physical layer OAM (PLOAM), embedded OAM, and ONU management and control interface (OMCI). PLOAM takes up a dedicated space in the GTC frame, and it handles ONU activation, encryption configuration, and alarm notification, etc. Embedded OAM utilizes the overhead fields defined in the downstream and upstream frames to communicate time-sensitive information such as bandwidth allocation, security exchange, DBA reporting, and link BER monitoring. OMCI messages are carried over GEM channels, and they are used to provision ONU service-defining layers above Layer 2.

Instead of using an external CPU to handle the control and management functions, Altera's Nios® II embedded soft processor can help lower system cost by integrating the datapath and control functions into a single FPGA while providing the performance needed (over 300 MIPS) and flexibility to create the exact set of CPUs, peripherals, and memory needed. In order to achieve higher efficiency of bandwidth utilization, DBA algorithms should be implemented. DBA algorithms can be implemented either in software with Nios II embedded soft processor or in hardware with Altera's high-performance FPGA fabric depending on the design's performance requirements.

FEC is needed for PON applications to help increase distance or split ratios that can be supported by the PON equipment since it enables a link to operate with a higher bit error rate at the receiver. FEC was optional in current-generation PON systems, but it is mandatory for next-generation PON systems as the bit rate increases. The Gigabit EPON protocol uses a frame-based Reed-Solomon RS(255, 239), and the 10G-EPON protocol uses a more powerful stream-based RS(255, 223). The GPON protocol uses a stream-based RS(255, 239), and the XG-PON1 protocol uses two different families of FEC codes, RS(25a, 22b, 32) and RS(25c, 23d, 16), depending on the transmission direction and power budget of the optical link. Therefore, it is best to have a flexible FEC implementation such as Altera's parameterizable Reed-Solomon FEC reference design that can be used for all these different PON standards.

Because the OLT broadcasts the downstream traffic to each ONU via the same fiber, the packets must be encrypted before transmission to prevent eavesdropping between ONUs. The encryption standard commonly used for PON is the Advanced Encryption Standard (AES 128-bit). Altera's AES reference design can support 10-Gbps encryption and 2.5-Gbps/10-Gbps decryption.

Packet Processing and Traffic Management

To process the aggregated end-user flows and provisioning per different QoS requirements from different operators in different applications, such as home, business, or backhaul, sophisticated packet processing and traffic management functions are implemented on each PON OLT line card. A combination of Altera's multi-threaded RISC-based soft datapath processor and hardware acceleration blocks implemented in FPGA fabric can be well suited to perform the Layer 2 to Layer 4 packet processing functions needed for access platforms such as classification, table look-up, policing, filtering, and packet forwarding.

As the service providers try to maximize end user experience by having the ability to differentiate services of each user and more and more users get aggregated onto the same pipe, it is very important to be able to enforce the service level agreement (SLA) per user to guarantee fair bandwidth allocation. Flexible traffic management capability is needed for both upstream and downstream traffic. Altera offers a complete 40-Gbps traffic management solution that consists of a 5-level scheduler/shaper with weighted fair queuing (WFQ) support, queue manager, congestion control block with weighted random early detection (WRED) support, and a highly efficient packet memory controller. With five levels of scheduling, the solution enables service providers to implement hierarchical QoS, and it also provides much flexibility for dynamic queue configuration and mapping.

Using Altera FPGAs to implement the next-generation PON OLT system provides the flexibility to build future-proof products and design unique features to differentiate against competitors while Altera provides the building block IPs needed to help accelerate the internal development effort.

Single-Chip Next-Generation PON OLT Solution

Most of the current PON OLT systems deployed in the network today utilize multiple components to achieve the needed functionality. As operators move to next-generation PON systems, they are not only looking for higher bandwidth and higher functionality but are also constantly driving for lower cost and power.

To address these challenges, the 28-nm Stratix V FPGA family enables an unprecedented level of system integration on one device. The combination of its abundant resources (up to one million logic elements (LEs) and up to 50 Mb of on-chip memory), its very robust 12.5-Gbps transceivers with built-in XG-PON1 and 10G-EPON burst mode and 10GBase-KR backplane support capability, and its high-performance external memory interfaces (up to 7 x 72 DDR3 memory interfaces at 800 MHz) provides a single-chip solution for next-generation PON OLT line cards. An external PHY device, a PON MAC device, a packet processing and traffic management engine, and a fabric interface chip can all be integrated into one Stratix V FPGA, as illustrated in Figure 6. These capabilities help save BOM cost, board space, and system power.

Figure 6. A One-Chip Solution for 10G PON OLT Enabled on a Stratix V FPGA
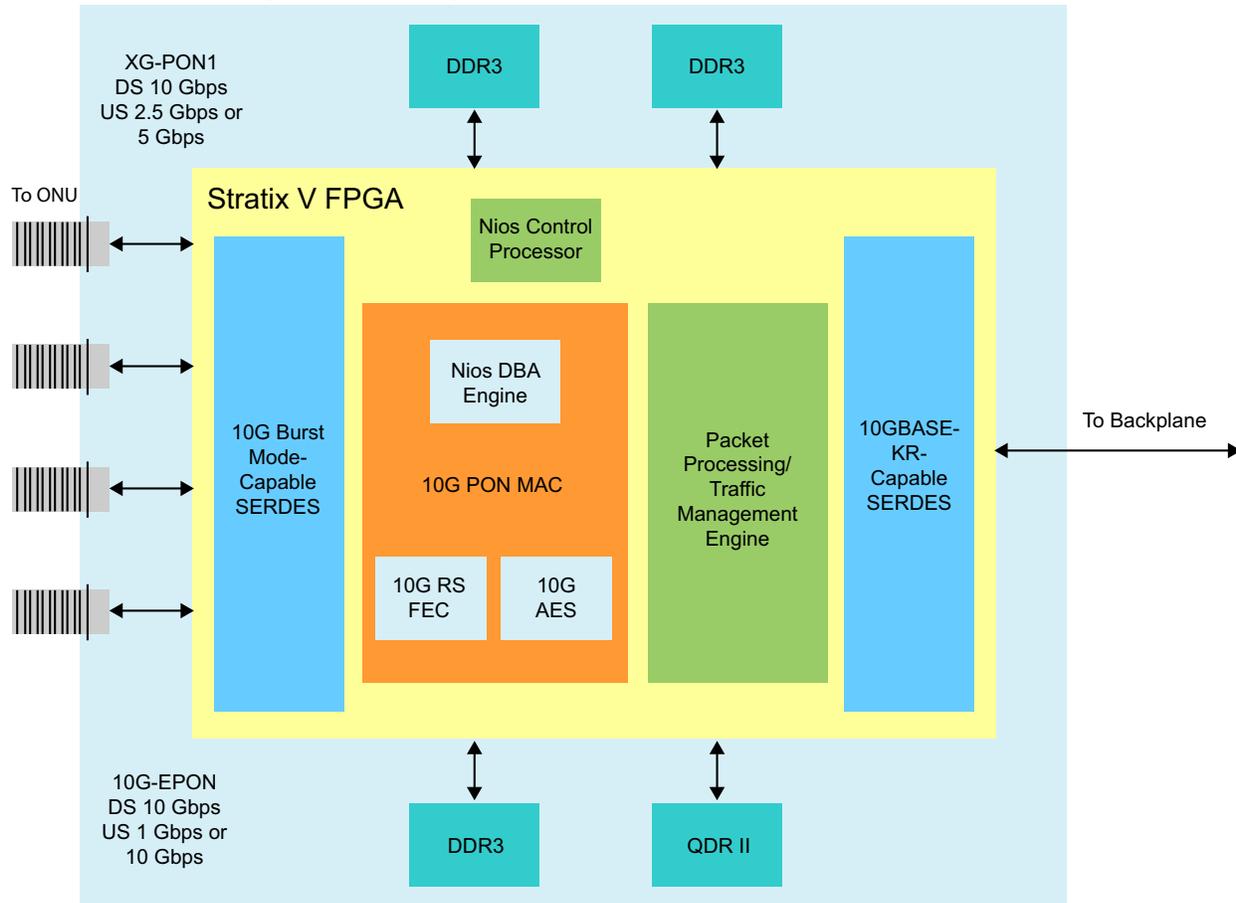
In terms of power savings, Stratix V FPGAs reduce total power by 30% compared to previous-generation devices through the following key process and architectural innovations:

- TSMC's high-performance, high-K metal gate 28-nm process technology optimized for lower power

- 0.85-V core supply voltage

- Programmable Power Technology to automatically reduce static power consumption in the design while maintaining high-performance for critical timing paths

- Clock gating technology to minimize dynamic power consumption

Another key innovation of Stratix V FPGAs is the easy-to-use partial reconfiguration feature. With this user-friendly fine-grain partial reconfiguration capability, the designer can easily change the core functionality of the design while other portions are still running. In essence, this enables a single programmable solution for current-generation and next-generation PON OLT systems, because the lower speed ports can be dynamically reconfigured to support higher speed real time as the subscribers transition to next-generation PON.

Conclusion

With the ever-increasing demand of higher broadband bandwidth, PON is becoming the mainstream access technology due to its ability to scale to higher speed and its cost effective architecture. One key success criteria for service providers is to adopt technology platforms that are scalable to support higher bandwidth and service density while being flexible to accommodate future enhancements driven by market competition or regulatory framework. Due to the uncertainty of the next-generation PON market with further changes likely needed for the standard, flexibility to change the design is a key design criterion.

The advantages of using a FPGA to implement the next-generation PON OLT design are that it enables adding unique features to differentiate against competitors, building future-proof products while the standard and market are still immature, and quickly making modifications to accommodate different operator requirements. Altera's 28-nm Stratix V FPGAs help designers achieve a higher level of system integration while lowering the overall BOM cost and power consumption. Once the next-generation PON design stabilizes and volume starts to ramp, migration to Altera's HardCopy series ASICs can help further reduce the cost and power with a quick turn-around time.

Further Information

1. Cisco Visual Networking Index:
   www.cisco.com

2. ITU-T G.984:
   www.itu.int

3. FSAN's Next-Generation PON Task Group:
   http://fsanweb.com

4. IEEE 802.3 and 802.3av:
   www.ieee802.org

5. "Next-Generation PON," IEEE Communications Magazine, Volume 47, Issue 11, November 2009:
   http://ieeexplore.ieee.org/

6. Stratix V FPGAs: Built for Bandwidth:
   www.altera.com/products/devices/stratix-fpgas/stratix-v/stxv-index.jsp

7. About HardCopy ASIC Series:
   www.altera.com/products/devices/hardcopy-asics/about/hrd-index.html

Acknowledgements

Document Revision History

Table 2 shows the revision history for this document.

Table 2. Document Revision History

Date	Version	Changes
May 2012	1.2	■ Minor text edits.
October 2010	1.1	■ Minor edits. ■ Updates to Figure 3 and Figure 6.
October 2010	1.0	Initial release.