Experimental Demonstration of Attenuation-Based All-Optical Time-To-Live Indicator

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Abstract: A novel attenuation-based Optical Time-To-Live indicator is demonstrated for DWDM All-Optical Packet Switches using a 1×2 SOA-based optical switch. Error-free operation is verified for packetized 4×10Gb/s pseudorandom payloads with three different Optical Time-To-Live limits.
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1. Introduction

The aggressive expansion in scale and density of High-Performance Computing (HPC) and Data Center (DC) systems has motivated the need for interconnection networks capable of providing high bandwidth and low latency to fully utilize the latest chip multiprocessors. Optical Packet Switched (OPS) networks have been proposed as a solution capable of meeting the requirements of current and future HPC and DC systems by leveraging the incredible bandwidth of optical fiber at time-of-flight latencies with potentially low power consumption. Among the OPS network options, non-deterministic OPS networks are promising for their ability to reduce the sender overhead through optical buffering mechanisms at the packet timescale. Examples of proposed non-deterministic OPS designs include the virtual-buffered Data Vortex [1,2] and scalable packet injection buffers [3]. As these optical packet switching designs become viable alternatives to electronic switches, there is an increasing interest in providing traditional electronic network capabilities in the OPS design. One such capability is Time-To-Live (TTL), which in practice represents the number of switches a packet is allowed to traverse in the network before a switch must drop the packet. Because the TTL is decremented at each switch from a maximum set by the sender, the TTL limits the maximum number of hops a packet can take from source to destination. As such, this capability is equally valuable in non-deterministic optical packet switched networks.

Optical Time-To-Live (OTTL) indicators reported in literature center on either optically encoding the TTL count in a low-speed MPLS-like label [4-6] or on direct measurement of Optical Signal to Noise Ratio (OSNR) with techniques for out-of-band [7] and in-band [8,9] measurement. The label-based approaches require each switch to be able to read and decrement the TTL count, which increases the latency and component cost per switch. The OSNR-based approaches have the drawback of deliberately degrading the OSNR to specify a particular OTTL limit per switch and per packet, in addition to power-averaging latency, BER measurement, receiver sensitivity, and component cost.

2. Attenuation-Based Optical Time-To-Live Indicator

The proposed attenuation-based OTTL indicator method is to intentionally attenuate a designated always-on wavelength (λ_{OTTL}) in each OPS, relative to the overall packet attenuation introduced by the OPS. Thus, as a packet travels through the OPS network, the accumulated attenuation of λ_{OTTL} is proportional to the number of switches traversed. The OPS can then make the decision to propagate or drop the packet by detecting the attenuation of λ_{OTTL}.

This attenuation-based approach requires three specific components in order to be implemented. The first is a single-wavelength attenuator (OTTL attenuator), implementable in the profile of a gain-flattening thin film filter. The second is a λ_{OTTL} detection and decision unit, implementable with a low-speed optical receiver followed by a Schmitt-trigger set to a decision threshold. The third is a means for the sender to adjust λ_{OTTL} power, implementable by direct modulation of the λ_{OTTL} laser. The number of hops before the packet is dropped can be engineered through careful selection of these three components (i.e. receiver threshold, relative attenuation, and λ_{OTTL} source).

OPS designs [10-12] that switch wavelength-striped packets provide a natural fit for this approach. First, the latency introduced by a wavelength-specific attenuator can be reduced (or negated) by placement in the fiber delay line of this OPS design. Second, λ_{OTTL} detection and decision can be performed in line with the packet control information processing, since both share the same receiver chains. Thus the added processing latency is negligible. Third, the SOA-based OPS benefit of providing ideally zero insertion loss (excluding the OTTL attenuator) allows for near-identical low-speed optical receiver sensitivity and threshold requirements for all switches in the network.

3. Experimental Setup

The attenuation-based OTTL demonstration is constructed as shown in Fig.1. Wavelength-striped optical packets are created (Fig. 1A) by first multiplexing the Frame (C27, 1555.75nm) and λ_{OTTL} (C53, 1535.04nm) with decorrelated 4×10Gb/s pseudorandom (2^{15}-1) payloads (C40, C41, C42, C43; 1545.32nm, 1544.53nm, 1543.73nm, 1542.94nm). A Kamelian OPB-10-15-N SOA is then used packetize the Frame, λ_{OTTL}, and payloads into individual packets.

The OTTL attenuator (Fig.1B) is implemented (Fig. 2) using an 3-port Optical Add-Drop Multiplexer (OADM) fixed to λ_{OTTL} (C53) to separate λ_{OTTL} from the rest of the packet. Next, λ_{OTTL} is attenuated with a screw-type Variable Optical Attenuator (VOA), followed by a 99:1 power splitter to measure the VOA attenuation with an optical power meter (OPM). Finally, λ_{OTTL} is recombined with the rest of the packet using a second OADM.

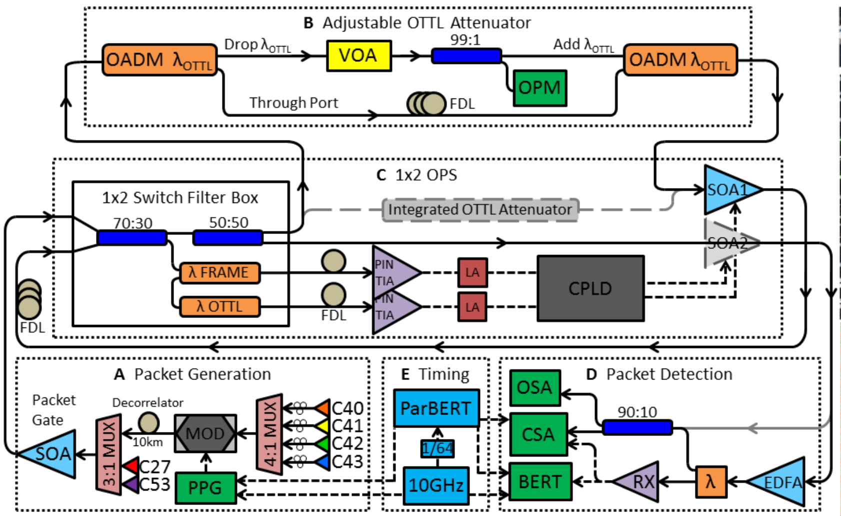

Fig. 1 Experimental Setup Diagram

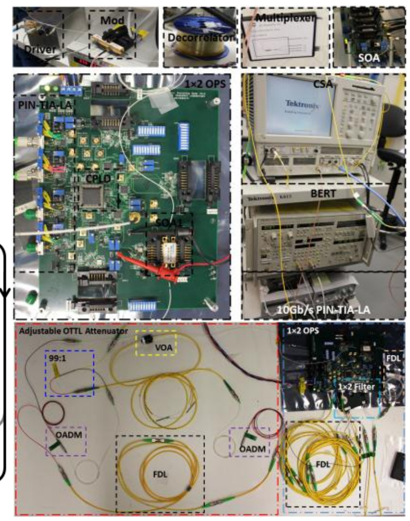

Fig. 2 Experimental Setup Photo

The OTTL attenuator is inserted in a custom 2-input 1×2 OPS (Fig.1C, Fig. 2) in place of the fiber delay line between the 2×2 switch filter box and SOA1. Both the Frame and λ_{OTTL} are detected by a 155Mb/s PIN-TIAs with automatic gain control, followed by a limiting amplifier. The Complex Programmable Logic Device (CPLD) is coded to enable SOA1 when both the Frame and λ_{OTTL} are detected as logic 1. The output of SOA1 is connected to the second filter box input to simulate a multi-hop network via iterations of this loop. Thus the expected behavior is for a packet to circulate in the loop until the accumulated attenuation is enough for the receiver to detect a logic 0 and drop the packet. SOA2 is bypassed to enable measurement of the packet with each hop.

Wavelength-striped optical packets are measured (Fig. 1D) in the optical domain using an Optical Spectrum Analyzer (OSA) and a Communications Signal Analyzer (CSA). A two-stage Erbium-Doped Fiber Amplifier (EDFA) and Programmable Optical Filter are used to select individual channels for measurement on the CSA and for Bit Error Rate (BER) verification using a 10Gb/s PIN-TIA-LA attached to a BER Tester (BERT).

Packet timing (Fig. 1E) outside the OPS is controlled by an Agilent ParBERT, which is configured to provide arbitrary sequences of 184 bits at 156.25Mhz, divided down from a 10GHz clock fed to a Pulse Pattern Generator (PPG) and the BERT. This is used to generate 44.8ns (7×6.4ns) optical packets with a repetition time of 588.4ns (92×6.4ns) by controlling the packet gating SOA in Fig. 1A, as well as a repetition-rate trigger for the CSA. The ParBERT is also used to generate a 25.6ns (4×6.4ns) gating signal for BER measurement. This signal is shifted in time relative to the packet generation signal to measure successive packets' BER.

4. Results

Through adjusting the attenuation of λ_{OTTL}, the ability to control the number of loops traversed before the packet is dropped is shown. Attenuation adjustment is shown to alter the OTTL limit between 1, 2, 3, 4, and 5 network hops before being dropped. The 4×10Gb/s payloads were each shown to 10^{-12} error-free for 1, 2, and 3 hops with a window of 25.6 ns. A 4^{th} hop is shown to a BER of 10^{-11} for the same 4×10Gb/s payloads with a 6.4ns window.

For each case, CSA screen-captures (Fig. 3) were taken of λ_{OTTL}, Frame, and payloads in the optical domain. Representative screen-captures of the low-speed PIN-TIA optical receiver output were also taken with an active probe. Due to the location used for packet measurement, the left-most packet is the injected packet before processing by the OPS, while the rightmost packet has been reduced to an OTTL limit of zero. Thus the rightmost packet is dropped by the OPS on the next loop and does not appear in the screen-capture. BER is measured for this rightmost packet because the rightmost packet is the last possible packet the OPS could choose to deliver to the destination.

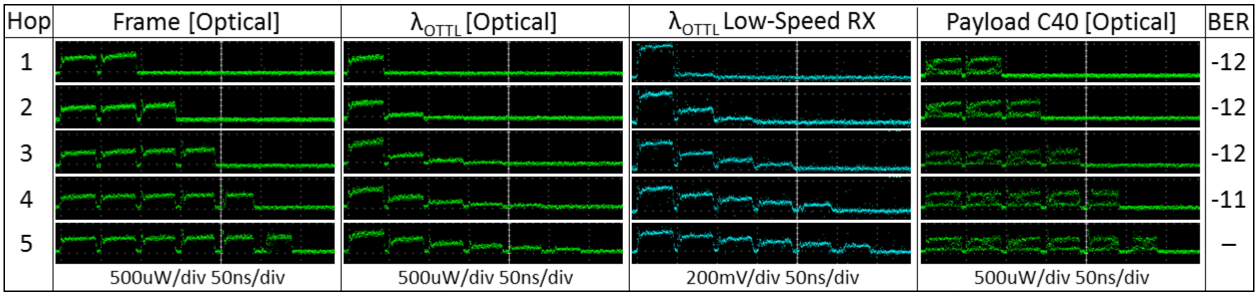

Fig. 3 CSA screen-capture of Frame, λ_{OTTL}, Low-Speed PIN-TIA, and Payload Channel for 1-5 Hops

The OTTL attenuation (Fig. 4) appears to follow an exponential decay as the desired OTTL limit is increased. Note that the larger red data point (1 hop) is the highest attenuation for which a 2-hop packet can be recovered error-free at 10^{-12} and not the lowest attenuation limit for the 1-hop packet.

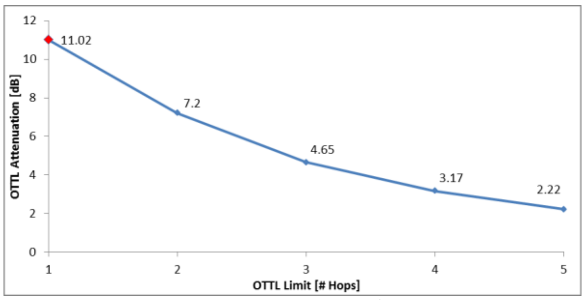

Fig. 4 OTTL Attenuation for 1-5 hops

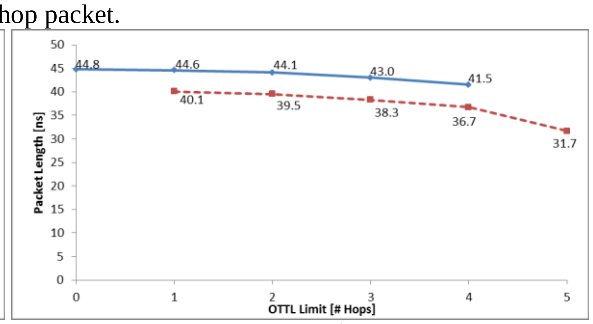

Fig. 5 Packet Length for 0-5 hops

Packet length measurement (Fig. 5) is complicated by the formation of a second rising edge (red, dashed) in addition to the original leading edge (blue, sold). This formation is due to accumulated optical gain ringing from the driver-to-SOA load mismatch causing the SOA gain to consistently dip a few ns after the start of the packet, and can be corrected [13]. The first edge packet length measurement indicates timing mismatches still present in the setup, while the second edge indicates the maximum available payload window for the experiment.

5. Conclusion

A novel method was shown to provide an Optical Time-To-Live capability for wavelength-striped optical packets based on cumulative attenuation of a selected wavelength. This method offers low latency and potentially low component investment verses other OTTL methods, and offers straight-forward integration into wavelength-striped OPS designs. This method can be engineered by the network operator for a specific maximum OTTL limit, while allowing the packet source to reduce this limit on the fly. This demonstration was achieved with little optimization of the setup, which suggests the maximum error-free OTTL limit can be increased in this setup. Lastly, as OPS components and designs approach the ideal switch behavior (e.g. wavelength-flattened low insertion loss, low noise, low optical switch ringing, Schmitt-triggered receivers) this method's capability as an OTTL indicator improves.

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6. References

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