Improved Polling Strategies for Efficient Flow Control for Buffer Reduction in PON/xDSL Hybrid Access Networks

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***Abstract*—Hybrid PON/xDSL access networks offer a cost effective alternative to passive optical networks (PONs). However, the drop-point device that bridges the fiber and copper portions of this network requires a power source potentially limiting where it can be deployed. To lift deployment restrictions, remote powering from a subscriber's power source can be utilized but available power will be limited. We explore polling strategies that provide flow control to limit the amount of buffering that occurs at the drop point device. The objective is to enable the use of a small memory capacity at the drop-point to reduce its energy consumption.**

I. Introduction

Access networks connect private networks inside a home or business to the networks of telecom service providers that provide access to the public Internet. Economic constraints apply to these access networks since the costs of individual links are amortized by one or only a few paying subscribers. Therefore, both deployment and operational costs must be kept low. For increased bandwidth and resilience against noise, fiber optic transmission technologies can be used in the access network. However, dedicated fiber optic transmission media between the telecom service provider point-of-presence (PoP) and subscriber customer premises equipment (CPE) incurs relatively high deployment and operational costs. Passive optical networks (PONs) utilize shared fiber optic transmission media to lower both deployment and operational costs for optical access networks.

In a PON, an Optical Line Terminal (OLT) inside a telecom service provider PoP connects to multiple Optical Network Units (ONUs) at subscriber premises through a shared fiber optic transmission media. That fiber optic transmission media is shared utilizing an optical splitter/combiner that splits the optical transmission power from a feeder fiber optic cable across several distribution fiber optic cables that connect to individual subscribers. Figure 1 provides an illustration of a PON. The PON architecture reduces the amount of fiber optic cabling deployed compared to a network that contains dedicated fiber optic cables connecting every subscriber to the PoP. However, there is still a requirement that fiber optic cable is deployed to each subscriber premise (i.e., the distribution fiber).

Already deployed copper transmission media can be utilized to shorten the length of the distribution fibers; thereby reducing deployment costs. These copper transmission media can include twisted-pair copper deployed for voice telephony and coaxial copper deployed for broadcast video services. The latest digital subscriber line (DSL) transmission technologies (e.g., VDSL2 [1]) for twisted-pair copper can provide bit rates on the order of 100s of Mbps over short distances. A hybrid fiber/copper access network can be created that lowers deployment costs while maintaining high bit rates utilizing a PON in tandem with a twisted-pair copper network that utilizes DSL transmission technologies. In this PON/xDSL hybrid access network, the PON is terminated at a fiber drop-point whereby twisted-pair copper is utilized to reach subscriber premises from that point. A device at the drop-point, referred to as a *drop-point device*, contains a PON ONU in tandem with a DSL access multiplexer (DLSAM) that connects to several subscribers. Figure 2 illustrates this hybrid access network.

The drop-point device, like the optical splitter/combiner in the PON, is deployed between the telecom service provider's PoP and the subscriber premises. However, unlike the optical splitter/combiner the drop-point device requires a power source thereby placing constraints on where it can be deployed. Remote powering can be utilized to lift these drop-point device deployment constraints. With remote powering the drop-point device draws its electrical power from subscriber locations over the twisted-pair copper. With a limited power supply available, the drop-point device must be designed in an energy sensitive manner. Two strategies, among many, can be followed to reduce the energy consumption of the drop-point device: 1) reduce the logic, and 2) reduce memory capacity. We focus on reducing the memory capacity without

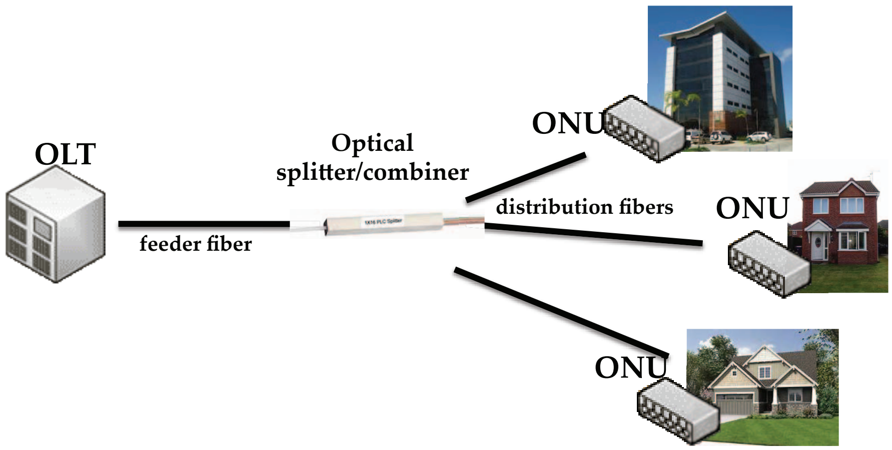


Fig. 1. A passive optical network (PON). An Optical Line Terminal (OLT) connects to multiple Optical Network Units (ONUs) via feeder fiber optic cable that is in close proximity to a set of subscribers and several distribution fiber optic cables. The optical transmission power on the feeder fiber is split for transmission on several distribution fibers that are connected to individual ONUs.

incurring significant packet loss thereby necessitating the need for careful flow control at the drop-point device.

A. Related Work

Although there is significant literature on the integration of PONs with wireless transmission media (e.g., WOBAN [2] and FiWi [3]) there is very limited literature on the integration of PONs with copper transmission media.

In [4], [5] an early PON standard called ITU-T 983.1 Broadband PON (BPON) was coupled with VDSL to reach subscribers in a cost-effective manner. Specifically, an architecture for a combined ONU/VDSL line card (drop-point) device that bridged a single VDSL line onto the PON was described in [4]. The BPON standard uses the ATM protocol at the link layer so their line card design consisted of ATM logic blocks and two 512-cell buffers (one to buffer ATM cells flowing upstream, and one to buffer ATM cells flowing downstream).

In [6], a mathematical model of the number of VDSL subscribers that can be serviced by a single ONU as a function of a few VDSL parameters (e.g., symmetric operation and bit rates) was presented. This model can help service providers design their PON/xDSL networks to support the desired number of subscribers. In a study on QoS-aware intra-ONU scheduling for PONs [7], hybrid PON/xDSL access networks were noted as a promising candidate for cost-effective broadband access. This early work on hybrid PON/xDSL access networks demonstrated its feasibility and provided some analysis for capacity planning. However, this work ignored specific design attributes of the drop-point device.

In contrast, we focus on an energy sensitive drop-point device design that reduces energy consumption by containing a small memory capacity. To reduce the drop-point device buffer requirements to fit the small memory capacity we utilize flow control mechanisms. We define a flow control mechanism in which DSL CPEs are strategically polled, despite the point-to-point nature of the twisted-pair copper, to control the flow of upstream data that accumulates at the drop-point device. The polling media access control (MAC) protocol used on the PON is thereby extended to a second stage of polling of the DSL CPEs. This flow control mechanism is referred to as GATED flow control. We conduct a performance analysis focused on maximum buffer occupancy at the drop-point device to compare this flow control mechanism to the absence of flow control and the use of standard Ethernet PAUSE frame flow control.

B. Outline

In Section II we describe our polling strategies for flow control. In Section III we compare the performance of the various polling strategies under various conditions. In Section IV we summarize our findings.

II. Polling Strategies for Flow Control

We now discuss the use of flow control mechanisms in the hybrid PON/xDSL network with the objective of avoiding packet loss at the limited buffer inside each drop-point device. We discuss standardized Ethernet PAUSE frame flow control followed by our GATED flow control.

A. Ethernet PAUSE frame flow control

As part of the Ethernet standard (see Annex 31B), PAUSE control frames are defined for the purpose of flow control. When the receiver of an Ethernet station is overwhelmed by data received as indicated by a high occupancy receive buffer, that Ethernet station will transmit a PAUSE control frame toward the sender(s) that specifies the amount of time the sender(s) should cease transmission. We will refer to that time as the *pause time*.

When the drop-point device buffer reaches a certain threshold, PAUSE control frames can be transmitted toward the DSL CPEs with the pause time interval they should cease transmission.

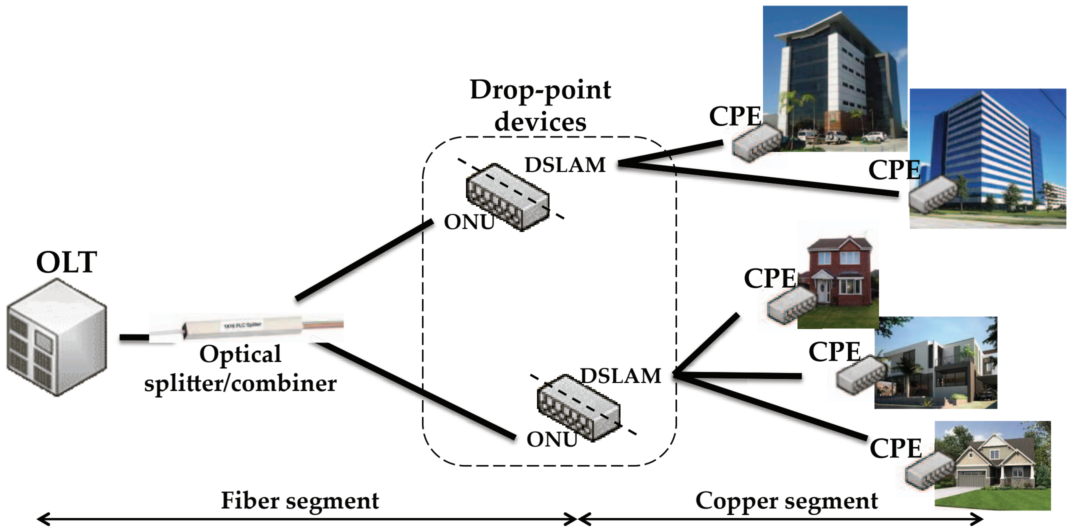


Fig. 2. Hybrid PON/xDSL access network. The device that bridges the fiber and copper portions of the network is a combined ONU and DSL access multiplexer (DSLAM) called a drop-point device.

B. GATED flow control

We define a two-stage polling strategy in which the PON OLT polls DSL CPEs to grant upstream transmission windows in addition to granting upstream transmission windows to PON ONUs. Although the twisted-pair copper used with DSL is not shared and therefore does not require a MAC protocol, the DSL CPEs are strategically polled to control the rate at which they transmit data upstream. We refer to this upstream polling strategy as GATED flow control because each DSL CPE's upstream transmission is gated by the PON OLT. Ideally, the polling of DSL CPEs will result in a cut-through at the drop-point device whereby no data is buffered. However, given the rate mismatch between the PON and DSL as well as some data framing differences this ideal scenario is not achievable. Figure 3 illustrates this two-stage polling mechanism that we call GATED flow control.

The polling of the DSL CPEs can be designed to keep CPE data separated in the upstream PON grant to the drop-point device. In this case, each DSL CPE is gated for transmission such that they transmit at times where their data arrives in distinct intervals at the drop point. Figure 4 illustrates this **segregated** version of GATED flow control.

Alternatively, the polling of the DSL CPEs can be designed such that the CPE data is multiplexed in the upstream grant to the drop-point device. In this case, each DSL CPE is gated for transmission such that their data arrives in time to be multiplexed together for transmission upstream on the PON. Figure 4 illustrates this **multiplexed** version of GATED flow control.

III. Performance Analysis

We conducted a set of simulation experiments to uncover the maximum buffer occupancy characteristics of GATED flow control compared to the absence of flow control and the use of standard Ethernet PAUSE frame flow control.

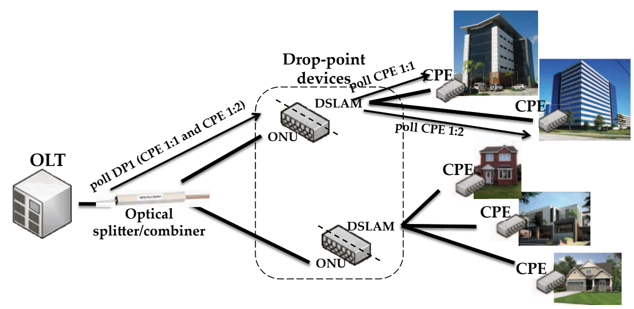
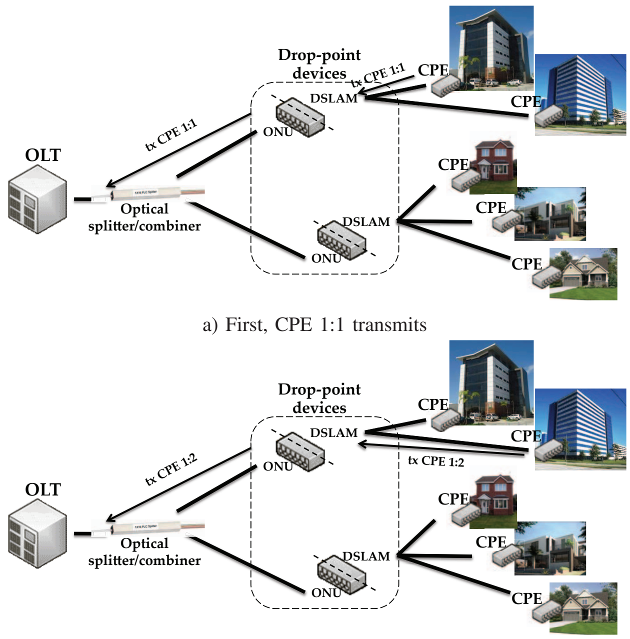


Fig. 3. The OLT polls a drop-point device (DP1) to grant upstream transmission access. Included in the polling message are polling messages for the DSL CPEs attached to DP1, CPE 1:1 and CPE 1:2. These CPE polling messages indicate when and for how long each DSL CPE should transmit.

A PON/xDSL hybrid access network simulator that we developed using the CSIM discrete event simulation library was utilized for all of the experiments. The simulator uses the XGPON [8] protocol for the PON segment and the VDSL2 [1] protocol for the DSL segment. The XGPON upstream bit rate was set to 2.488 Gbps and the guard time was set to 30 ns. The network contained 32 drop-point devices each with a single ONU to connect to the PON as well as a DSLAM serving 8 attached VDSL lines. At each drop-point there were 1MB buffers for each of the 8 attached VDSL lines; we refer to these as CPE buffers. Therefore, the PON/xDSL network contains a total of 256 CPEs. The upstream bit rate for each VDSL line was set to 77 Mbps to achieve a realistic over-subscription rate of 8x. The OLT to ONU one-way propagation delays were continuously distributed between 2.5 μs (i.e., 500 m) and 100 μs (i.e., 20 km). The ONU to CPE propagation delays are considered negligible.



a) First, CPE 1:1 transmits

b) and then CPE 1:2 transmits.

Fig. 4. In the segregated strategy, the DSL CPEs attached to the same drop-point device transmit one at a time.

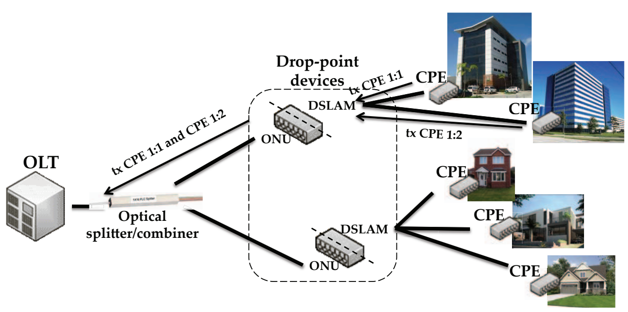


Fig. 5. In the multiplexed strategy, the DSL CPEs attached to the same drop-point device transmit at the same time. Their data subsequently appears multiplexed on the PON segment.

Each CPE independently generates data packets according to a quad mode packet size distribution with 60 % 64 Byte packets, 4 % 300 Byte packets, 11 % 580 Byte packets, and 25 % 1518 Byte packets. Unless otherwise specified each CPE generated data packets using a self-similar traffic generator with the Hurst parameter set to 0.8. The (Online, Limited) DBA algorithm was used to distribute PON upstream bandwidth each polling cycle. We set the maximum polling cycle length to 3 ms.

For PAUSE flow control we used a buffer threshold of 35 % occupancy to trigger the transmission of PAUSE frames. Each PAUSE frame specified a pause time of 2 ms. We conducted a wide set of experiments to determine that those two parameter values provided the best performance.

Figure 6 shows the maximum buffer occupancy for each CPE buffer (plot **a**) and the maximum aggregate buffer occupancy for a drop-point device (plot **b**) as we increase the load on the network. When either no flow control or PAUSE frame flow control are used the maximum buffer occupancy remains relatively static until the network load exceeds 60% of the capacity of the PON. At this point, due to the bursty traffic sources, the maximum buffer occupancy grows exponentially until it saturates either at the buffer capacity of 1MB for no flow control or slightly below that value for PAUSE frame flow control. At this point, packet losses occur. The reason for this behavior is that as the presented load increases, congestion increases, and subsequently the buffer occupancy increases until the buffer capacity is reached and packets are dropped. PAUSE frame flow control seems to mitigate this behavior a bit.

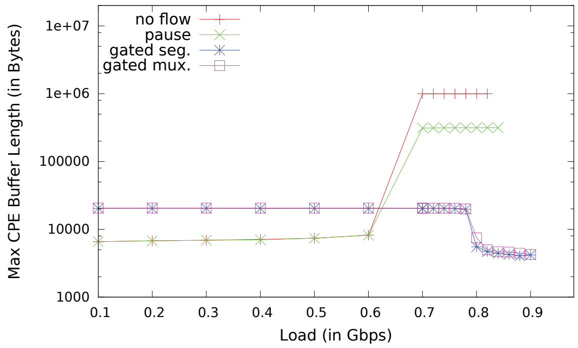
In contrast, when either of the two GATED flow control mechanism is used, the maximum buffer occupancy is mostly insensitive to the presented load on the network. The reason is that the traffic arriving at the drop-point from each CPE is accounted for in the upstream PON grant and therefore will depart shortly after arriving. As a result, no extended congestion occurs at the drop point and the maximum buffer occupancy does not increase with increasing load on the network. In lieu of accumulating at the drop point, the data accumulates inside each DSL CPE. We can see the effect of this by looking at the packet delays on the DSL segment and the PON segment, Figure 7 shows the average packet delay (plot **a** shows DSL segment delay and plot **b** shows PON segment delay). We can see that the GATED flow control mechanisms have increased DSL segment packet delay and reduced PON segment packet delay compared to no flow control or PAUSE frame flow control.

Lastly, to understand the factors that influence the maximum buffer occupancy value when using GATED flow control we varied the traffic burstiness using the Hurst parameter. We tried a Hurst parameter of 0.5 in addition to the 0.8 we used in the experiments above. Figure 8 compares the maximum buffer occupancy between the two Hurst parameter values for GATED flow control. We see that the smaller Hurst parameter (less bursty traffic) results in a much smaller maximum buffer occupancy value. So, clearly the traffic burstiness is a factor that influences the maximum buffer occupancy when using GATED flow control. Future work will uncover other factors that influence the maximum buffer occupancy.

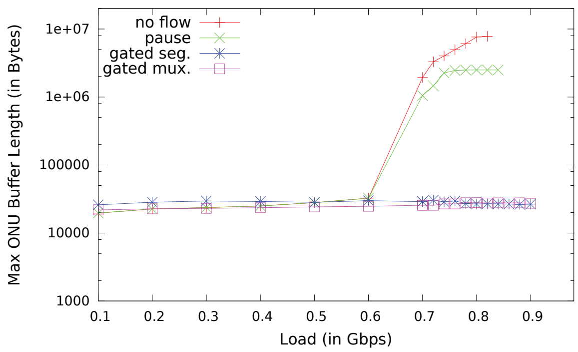
IV. Conclusion

We defined and evaluated two polling strategies that provide flow control for hybrid PON/xDSL access networks. We refer to these as GATED flow control. These GATED flow control mechanisms avoid packet losses at the drop-point device that bridges the fiber and copper segments of the hybrid access network. With effective flow control, a small memory capacity can be utilized in the drop-point device thereby reducing its power consumption.

We find that our GATED flow control mechanisms were able to maintain a consistent maximum buffer occupancy. We



a) CPE buffer occupancy

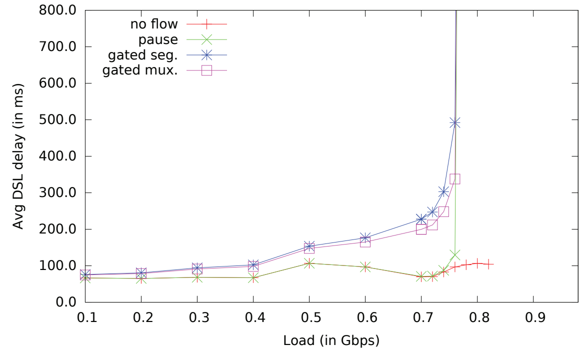


b) ONU aggregate buffer occupancy

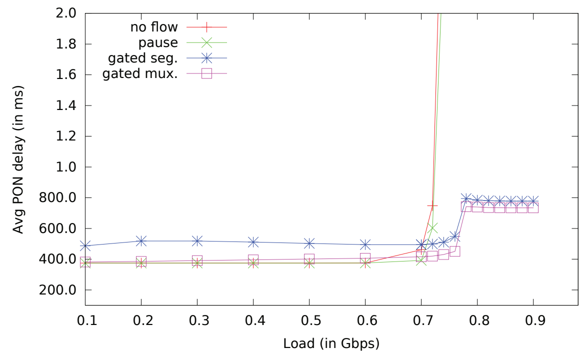
Fig. 6. Maximum drop-point buffer occupancy.

also found no statistically significant difference among the two different GATED flow control mechanisms.

Future work should seek to uncover all of the factors that influence the precise maximum buffer occupancy achieved with the GATED flow control mechanisms.



a) packet delay on DSL segment



b) packet delay on PON segment

Fig. 7. Average packet delays.

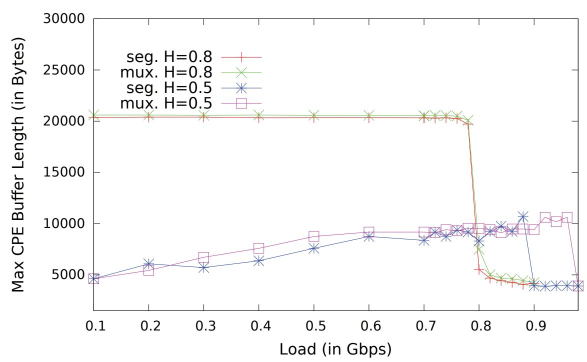


Fig. 8. Maximum CPE buffer occupancy for two different traffic burstiness settings.

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