Analysis of Optimum Avalanche Gain of Burst-Mode Receivers for PON Applications

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***Abstract*—We present optimum avalanche gains for burst-mode receivers (BMRx) for passive optical networks (PONs). The avalanche gain is optimized to maximize the geographical coverage of the PON, instead of the BMRx sensitivity. The optimization has been done with respect to differential reach [(DiR) the difference in distance between the longest and shortest optical path] for different splitting factors (SFs). Optimum avalanche gains are calculated for a 1.25-Gb/s BMRx, using both a theoretical model and measurements that take into account the tail occurring after a strong packet, limiting the BMRx dynamic range. The curves that quantify the tradeoff between SF and DiR can be used to select an avalanche gain for gigabit PONs.**

***Index Terms*—Avalanche photodiodes (APDs), bit-error rate (BER), burst-mode receivers (BMRx), optical access networks, optical receivers.**

I. Introduction

RECENT new standardization efforts prove that there is growing interest in increasing the bit rate of passive optical networks (PONs) toward 1.25 Gb/s and higher [1], [2]. Fig. 1 shows the typical configuration of a PON where the optical line termination (OLT) equipment and fiber feeder are shared among subscribers. The OLT broadcasts data in the downstream direction to all optical network units (ONUs). The upstream data from an ONU is sent to the OLT in a point-to-multipoint time-division multiple-access scheme. At the OLT, this results in a signal that consists of a succession of packets with different amplitudes, due to the different optical path losses between different ONUs. For a cost-effective PON, the primary concern is to maintain a high splitting factor [(SF) the number of subscribers connected to the OLT] and differential reach (DiR). The SF and DiR are typically limited by the sensitivity and dynamic range (DR) of the burst-mode receiver (BMRx) located in the OLT. A second concern is to keep the transmission efficiency high. In the upstream direction, this amounts to keeping the guard time separating successive packets and the preamble needed to extract the decision threshold and timing information as short as possible. This letter focuses on the performance of the BMRx intended for PONs where the guard time and preamble length is as short as a few tens of nanoseconds [1]. To maintain high BMRx sensitivity despite higher bandwidths needed to accommodate the higher bit rates, an avalanche photodiode (APD)

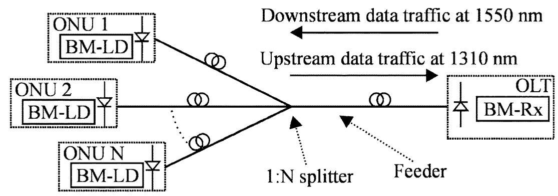

Fig. 1. PON configuration with bidirectional transmission over a single fiber. Only the components concerning the upstream transmission are shown. BM-LD: Burst-mode laser driver.

can be used in the upstream direction of the PON [3]–[5]. In conventional optical receivers, the avalanche gain G is optimized to reach highest sensitivity. If a large DR is required, G can be adapted depending upon the incoming optical power [3]. However, it is difficult to adapt G on a nanosecond scale, as would be required due to the short guard time [4], and it is, therefore, kept fixed. This implies that the maximum optical input power that the BMRx located in the OLT can handle is limited compared to conventional receivers. Therefore, G should not be used to optimize the sensitivity of the BMRx, but instead be used to optimize the geographical coverage of the PON, i.e., the number of subscribers that can be reached over a certain area. This results in a network with a high degree of freedom on ONU location. This letter presents such optimum G using the relationship between G on one hand and the sensitivity and DR on the other hand. In a first step, a previously developed BMRx model is used [4]. In a second step, measurements are used, taking into account the fact that the worst-case performance for the upstream transmission occurs when a weak packet follows a strong packet.

II. PON and Burst-Mode Receiver Model

A. PON Model

Upstream transmission at a wavelength of 1310 nm is considered, it is assumed that a single fiber is used for both upstream and downstream traffic. At either side of the PON, the upstream and downstream channels are separated using wavelength-selective [wavelength-division multiplexing (WDM)] filters. While the feeder length L_F is identical for each ONU, the length L_D of the dedicated fiber from the splitter toward the ONUs will vary from ONU to ONU. It is assumed that this length L_D varies from 0 to $L_{\rm DMAX}$. Given the sensitivity P_m (in decibel milliwatts, average optical power) and the minimum average launched power $P_{\rm Lm}$ of the ONU, the following inequality applies for the ONU located at a maximum distance $L_F + L_{\rm DMAX}$ from the OLT:

$$P_m + \Delta_{Sm} \leq P_{Lm} - A_F\,(L_F + L_{\rm DMAX}) - 10\log_{10}(N) - \Delta \quad (1)$$

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TABLE I
OPTICAL POWER BUDGET PARAMETERS

Parameter	Value
Attenuation per unit length fiber	0.4 dB/km
Maximum average launched power P_M	+2.0 dBm
Maximum average launched power P_m	-3.0dBm
Extinction ratio	10 dB
Accumulated insertion loss Δ	5 dB

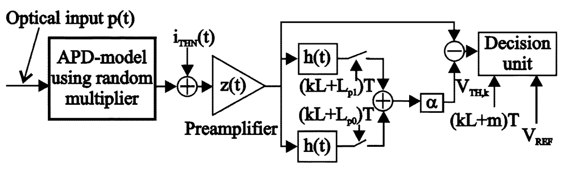

Fig. 2. Model of the BMRx. $(kL + L_{\mathrm{px}})T$, $x = 0, 1$ are the times where the decision threshold extraction unit samples its input response for a 1 and a 0, $(kL + m)T$ is the time where the decision unit samples its input for bit m of packet k.

where A_F is the attenuation per unit length of the fiber at 1310 nm. Δ accumulates the insertion loss from connectors, the WDM filter at the OLT side and excess loss of the $1:N$ splitter. Δ_{Sm} is a system margin on the sensitivity of the BMRx, necessary for robust operation of the PON. For the ONU located closest to the OLT, the following inequality must be fulfilled:

$$P_M - \Delta_{\mathrm{SM}} \geq P_{\mathrm{LM}} - A_F L_F - 10\log_{10}(N) - \Delta \quad (2)$$

where P_M is the maximum average optical input power that the BMRx can properly handle, Δ_{SM} a system margin on the maximum optical input power, and P_{LM} is the maximum average optical power launched by the ONU. Table I gives the values used in this letter. Although the results derived in this letter are calculated for the values of Table I, the conclusions will be valid for a wide range of parameters. The values for P_{Lm} and P_{LM} correspond to class B ONU transmitter operation [1]. From (2), one can see that a sufficient amount of attenuation should be present to ensure that the BMRx is not overloaded by the ONU located closest to the OLT. From (1), it can be seen that there exists a tradeoff between achievable SF on one hand and the DiR on the other hand.

B. BMRx Model

Fig. 2 gives a model of the BMRx taking into account the APD multiplication noise and the sensitivity penalty due to noise-corrupted threshold [4]. An explanation how this model works and its mathematical equations were given in [4]. The APD with gain G has an impulse response $h_{\mathrm{APD}}(t)$ that is assumed to exhibit a first-order gain-bandwidth product of 25 GHz. The preamplifier has a first-order resistance–capacitance (*RC*) (with 3-dB bandwidth $f_{3\ \mathrm{dB}}$) impulse response $z(t)$. The preamplifier noise $i_{\mathrm{THN}}(t)$ is assumed to be white and Gaussian. To simplify the analysis, it is assumed that the convolution of $z(t)$ with $h(t)$ is a first-order *RC*-filter with time constant τ. As explained in [4], this model can be used to calculate the bit-error rate (BER) for given optical power. The sensitivity of the BMRx is defined as the optical power needed to ensure a BER equal to 10^{-10}. Table II gives the parameters of the BMRx. These values correspond to measurement results

TABLE II
BURST-MODE RECEIVER PARAMETERS

Parameter	Value
Bit rate B = 1/T	1.25-Gbit/s
Ionization ratio k of electrons and holes of the APD	0.35
Responsivity of the avalanche photodiode	0.85 A/W
3-dB bandwidth of the preamplifier f_{3dB}	1 GHz
Transimpedance gain	1 kΩ
Maximum preamplifier input current	1 mA
Time constants of threshold extraction circuitry $\tau_0=\tau_1$	3 ns
Scaling factor α	0.5
Input referred noise of the preamplifier (A_{rms})	200 nA

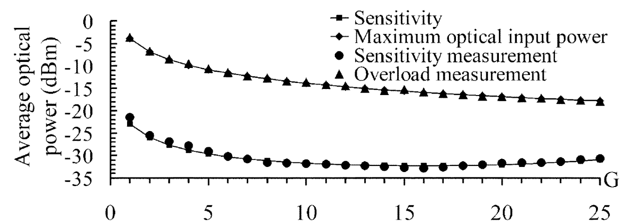

Fig. 3. Sensitivity and maximum allowed optical input power of the BMRx.

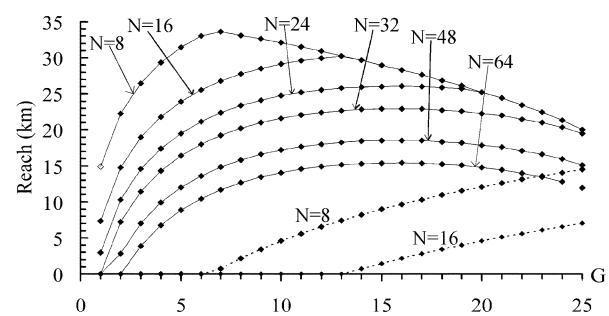

Fig. 4. Maximum allowed DiR (solid lines) and minimum required fiber feeder length L_F (dashed lines) as a function of avalanche gain for various SFs N.

reported in Section III and [5], where a preamble consisting of 12 1s and 12 0s was used. The maximum allowed input optical power P_M is limited by the maximum input current of the preamplifier that allows correct data recovery or the maximum allowed reverse current of the APD. Hence, P_M is inversely proportional to G. Fig. 3 displays both the calculated and measured sensitivity P_m and maximum allowed input optical power P_M of the BMRx as a function of G. G equal to 16 gives the best sensitivity.

III. OPTIMUM AVALANCHE GAIN

A. Using Theoretical BMRx Model

Fig. 4 shows the minimum required feeder length L_G needed to fulfill condition (2) and the maximum allowed DiR needed to fulfill condition (1) as a function of G. These curves are obtained using the parameters from Tables I and II and for system margins $\Delta_{Sm} = \Delta_{\mathrm{SM}} = 1$ dB. It can be seen that for SFs smaller than 16, a minimum L_F is needed to ensure sufficient attenuation for the ONUs located closest to the OLT, to avoid overloading the BMRx. It was found that for a SF > 28, there is sufficient attenuation in the PON to ensure that the BMRx never gets overloaded. From Fig. 4, one can clearly see that there exists an optimum G that maximizes the DiR. As long as there

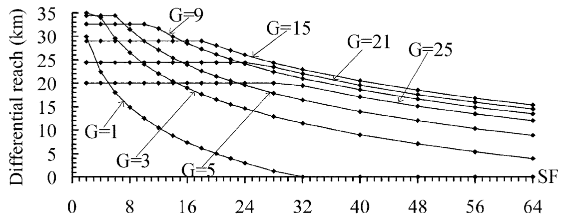

Fig. 5. Tradeoff between SF and DiR for various avalanche gains.

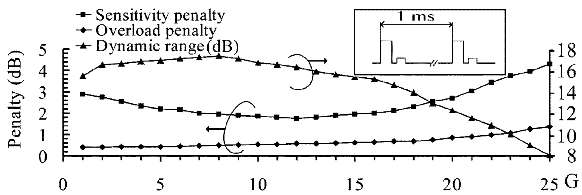

Fig. 6. Penalty due to strong packet as a function of avalanche gain.

is insufficient attenuation in the PON, one can see that the optimum G is significantly lower than G that optimizes only the sensitivity of the BMRx. This is true for the curves with SFs $N = 2$ to $N = 24$. For example, for $N = 16$ the optimum avalanche gain is 13. If the SF is greater than 28 (e.g., the curve with $N = 32$), then the optimum G equals the G for maximizing sensitivity, i.e., $G = 16$. Fig. 5 illustrates how the SF can be traded off against DiR, and that the exact tradeoff depends upon G. One can see that for a PIN-BMRx ($G = 1$), it is not possible to obtain an SF of 32, neither is it possible to obtain a DiR of 20 km. This proves that it is necessary to use an APD to meet the requirements put on the BMRx for gigabits per second PON operation with reasonable DiR and SF. Note how for high G and sufficiently low SFs, the achievable DiR saturates, due to the limitation on the maximum allowed optical input power of the BMRx. For G between 9 and 25, an SF of minimum 32 and a minimum DiR of 20 km is achieved.

B. Using Experimental Results

The theoretical model overlooks the fact that after every strong packet, a tail occurs that reduces the weakest packet that can be detected. To evaluate the influence of this tail, the sensitivity of the BMRx was measured on a weak packet that follows a strong packet (both with length 128 μs), both separated with a guard time of 25.6 ns (the minimum in [1]) and with the timing of the packets shown in Fig. 6. The shown timing is identified as the worst case for the BMRx. A penalty can be measured for both the sensitivity and the overload of this second packet, and is displayed in Fig. 6 (where the resulting DR is also shown). Both penalties were measured with the power of the strong packet set at the overload value displayed in Fig. 3. For low G, a high sensitivity penalty can be observed due to a tail that is attributed to the APD. An explanation for this tail at low G can be found in [6]. For high G, the penalty increases again, attributed to the finite APD gain-bandwidth. The penalty on the overload is attributed to an incomplete removal of the decision threshold of the strong packet [5]. Fig. 7 shows that the influence of this tail is significant. Indeed, for an SF of 16, the achievable DiR is 6.3 km less than in the case of the experimental results. Also shown in Fig. 7 is the improvement in DiR that can be achieved by selecting the G that maximizes the DiR, instead of maximizing BMRx sensitivity. For an SF of 16, this improves the DiR by 5 km, a significant distance for an access network. The optimum G is 8. For an SF of 32 the improvement is 1.4 km, the optimum G is 13. It is important to note that the maximum achievable DiR for an SF of 32 is 17 km, which is less than the 20 km required in [1]. This demonstrates the importance of the power leveling mechanism proposed in the ITU-T Recommendation G.984.2 [1], where the launched ONU power can be adjusted according to requests by the OLT. In this way, the effective optical power budget can be increased, and in this way, the requirement of an SF of 32 and a DiR of 20 km can be met [7]. This scheme was also recognized to enhance reliability for Ethernet PONs [8].

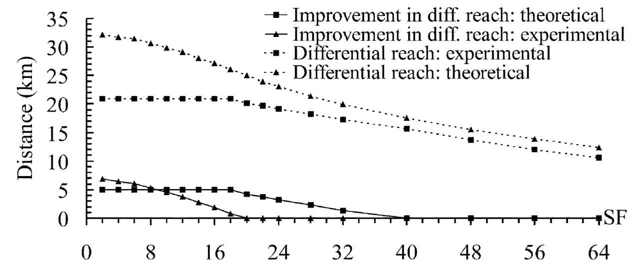

Fig. 7. Improvement in DiR and maximum achievable DiR versus SF.

IV. Conclusion

Avalanche gains for the BMRx that maximize the geographical coverage of a PON have been presented. It is shown that if there is insufficient attenuation in the optical path from the ONU closest to the OLT toward the OLT, the optimum gain is significantly lower than the gain that optimizes BMRx sensitivity. The tradeoff between SF and DiR is quantified. Using experimental results, it is shown that the DiR is severely limited by the tail after a strong packet.

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