Half-Duplex Transmission Avoiding Rayleigh Backscattering Crosstalk in UDWDM-PON with Coherent Receivers

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ABSTRACT

Ultra Dense Wavelength Division Multiplexing (UDWDM) is a promising technique for access PON, introducing the wavelength-to-the-user concept. The key enabling technology will be a new cost-effective coherent detection scheme, providing high splitting ratios and long-reach extension. This also will allow implementing low-cost, yet effective, coherent terminals suitable for mass deployment. Employing a unique laser diode as transmitter and receiver local oscillator at the ONU to realize a cheap terminal implies to use the same wavelength for both up and down directions; therefore, in Full-Duplex (FD) transmission mode the Rayleigh Backscattering (RB) crosstalk will drastically perturb the reception. We propose and study a Half-Duplex (HD) solution to avoid the RB disturbance and analyze the different scenarios of reach and splitting ratios.

Keywords: Half-Duplex (HD) transmission, Rayleigh Backscattering (RB), Ultra Dense Wavelength Division Multiplexing-Passive Optical Network (UDWDM-PON), coherent receivers.

1. INTRODUCTION

Presently, PON based FTTH networks are being upgraded to deliver more capacity and bandwidth per user by increasing the bit rate at the OLT and ONU optical transceivers according to the usual TDM method [1]-[2]. This needs complex medium requirements running up to 10G per user with increased power consumption, providing low economic effectiveness and bandwidth inefficiency of only 1% when using 100 Mb/s per owner. On the other hand, exploiting the wavelength domain in the PON can allow implementing a wavelength-to-the user approach, giving each user a single wavelength [3]. The significant technology to be developed is a low-cost coherent detection scheme with excellent wavelength selectivity and high sensitivity [4], enabling high speed connections to end users while deploying high splitting ratios and long-reach extension in the Optical Distribution Network (ODN). Furthermore, the most bandwidth efficient solution is the Ultra Dense Wavelength Division Multiplexing (UDWDM) [5]-[6], spacing channels ultra-densely at a few GHz and using bit rates from 100 Mb/s to 10G, thus adding a high aggregate capacity to the deployed PON.

In order to minimize the cost of ownership, only one laser diode can be employed shared for both transmitter and coherent receiver at the ONU with a unique wavelength for down and up transmission. This makes the activation process of a new ONU very simple, because this ONU just listens to its natural wavelength to be free and then transmits on it; if it is not free or there is no answer from the OLT, then the ONU retunes its laser diode until an answer is received. Using the same wavelength for up and down in Full-Duplex (FD) transmission mode origins a Rayleigh Backscattering (RB) crosstalk, which is a fraction of the light backscattered towards the transmitter [7]. RB cannot be eliminated due its random nature, but can be mitigated reducing the overlap between upstream and downstream signals. Hence, we propose and study a Half-Duplex (HD) transmission mode solution to avoid the RB disturbance and analyze the different scenarios of reach and splitting ratios.

When using the same local oscillator as transmitter and receiver in a HD mode, particularly in DPSK, the transceiver architecture can be with external modulation [5] (Fig. 1, left) or direct modulation [8] (Fig. 1, right). In the direct modulation case the up and down signals cannot overlap because the generated modulated signal cannot be used as local receiver oscillator, but in the external modulation situation both up and down signals can overlap and the local oscillator works in transmitter and receiver configurations simultaneously.

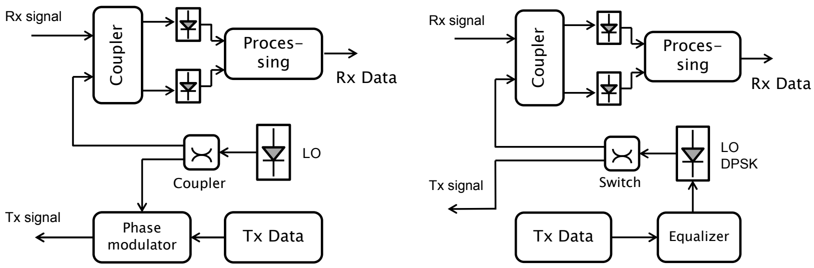

Figure 1. Coherent transceiver: left, transmitter external modulation; right, transmitter direct modulation.

This article is organized in the following sections: Section 2 describes the power budget and distance reach under RB disturbance, Section 3 analyses time diagram, transmission efficiencies and delays under HD, Section 4 shows experimental results of RB measurements, and, finally, at Section 5 the conclusions are discussed.

2. POWER BUDGET AND REACH

RB is a diffuse reflection of waves due to scattering back to the direction in which they propagate. Light propagation through a fiber optic cable attenuates exponentially due to Rayleigh scattering, but at the same time part of the wavelength is gradually returned scattered back to the original source. The RB acts as a noise and is however unavoidable [7]. First we will develop the total RB noise power in the uplink direction due to the downstream signal, which is given by [9]-[10]:

$$P_{RBu} = P_S B\left(1-e^{-2\alpha l}\right)$$

Where P_S (dBm) is the injected signal power into the fiber, l (km) is the fiber length, α [km^{-1}] is the attenuation coefficient and $B = S\alpha_s/2\alpha$; with α_s [km^{-1}] the fiber scattering coefficient and S (dimensionless) the fiber recapture coefficient. For fiber distances longer than 20 km, the term $\xi = B(1\text{-}e^{-2\alpha l})$ converges to a constant value B = -34 dB [10]-[11]. Measurements of RB powers with power source P_S < 7 dBm for different Single Mode Fiber (SMF) lengths, ranging from 25 km to 125 km at 1550 nm, show that B can be taken to be -34 dB [12].

In a PON with an ODN based on splitters the RB noise power in the downlink direction due to the upstream signal, taking into account that the splitters are very much closed to the ONU, is mainly caused by the final drop fiber, which is very short and in the order of a hundred meters, and then is mostly $P_{RBdD} = P_S B(1-e^{-2\alpha D})$. Where P_S is the applied signal power to the fiber at the ONU with the same value as that of the OLT side, D is the final drop fiber length, F the feeder fiber length and L the total fiber length, with $D << L = F + D$.

But another RB contribution factor to downlink direction to be considered is due to the rest of the feeder fiber: $P_{RBdF} = P_S B\, e^{-2\alpha D}\,(1-e^{-2\alpha F})/(EN)^2$. Where the splitting ratio is $N = 2^k$, with k the number of splits by factor 2, and additionally, an excess loss E_2 of 0.5 dB must be included in each partition by 2, giving a total of $E = kE_2$ (dB) excess losses. The attenuation coefficient α is taken to be 0.2 dB/km and the launched power P_s = 0 dBm at both sides OLT and ONU. The received signal power at both sides OLT and ONU is $P_R = P_S e^{-\alpha\, L/EN}$.

The optical coherent receiver sensibility is supposed to be -45dBm, then we need P_R > -45dBm. The received power expressed in dBm is P_R (dBm) = P_S (dBm) – αL (dB) – E (dB) – 10log$N$ (dB). Distances up to 85 km can be reached with a split of N = 256 and even 120 km with a split of N = 64.

The thermal noise plus the shot noise at the optical receptor is supposed to be a fixed value of P_N = -60 dBm. Then, the Optical Signal to Noise Ratio (OSNR), including all noises (thermal, shot and backscattering), can be calculated. In the reception at the OLT the $(OSNR)_{up}$ is:

$$OSNR_{up} = \left(P_R/P_{RBu}\right) = \frac{P_S e^{-\alpha L}/\left(EN\right)}{P_N + P_S B\left(1-e^{-2\alpha F)}\right) + P_S B e^{-2\alpha F}\left(1-e^{-2\alpha D)}\right)/\left(EN\right)^2}$$

Similarly, in the reception at the ONU the optical signal noise ratio $(OSNR)_{down}$ is:

$$OSNR_{down} = \left(P_R/P_{RBd}\right) = \frac{P_S e^{-\alpha L}/\left(EN\right)}{P_N + P_S B\left(1-e^{-2\alpha D}\right) + P_S B e^{-2\alpha D}\left(1-e^{-2\alpha F)}\right)/\left(EN\right)^2}$$

When $OSNR$ > 20 dBs, the Bit Error Rate (BER) obtained is very good in the order of 10^{-9}; if $OSNR$ > 15 dBs only, then the BER achieved is in the order of 10^{-3} and a Forward Error Correction (FEC) coding is needed to recover the correct signal [13].

After very few kilometers the RB effect at the OLT side is important, therefore degrading the $OSNR_{up}$. Up and down OSNRs are calculated, including the total effects of feeder and drop fiber paths. Figure 2 (left) shows the $OSNR_{up}$ against the fiber length L and splitting ratio, with a final drop of D = 100 m. For example, with a typical split of 64, uplink OSNRs of 20 dBs and 15 dBs are achieved in 2 km and 6 km, respectively; in these short fiber length cases a FD mode transmission is still available.

At the ONU side, considering that the splitters are closed to the ONU, the $OSNR_{down}$ is much better, as illustrated in Fig. 2 (right) for a final drop length of D = 100 m. With a typical split of 64, downlink OSNRs of 20 dBs and 15 dBs are achieved in 60 km and 86 km, respectively. Hence, at the ONU side RB noise is not important even for long-reach.

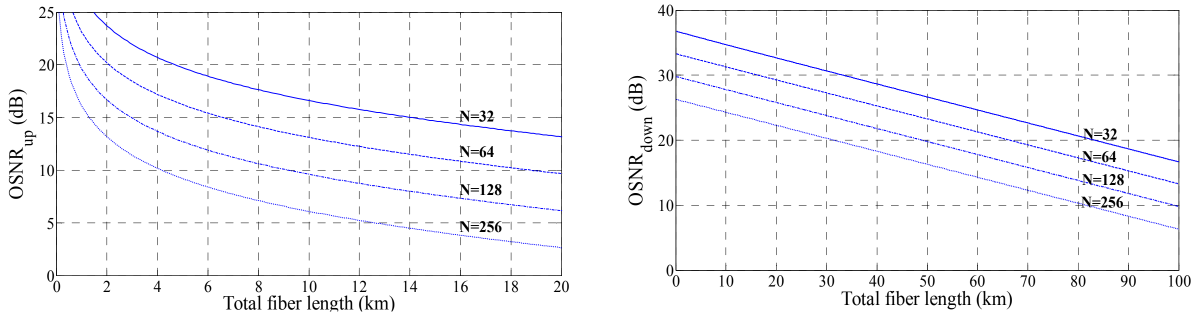

Figure 2. $OSNR_{up}$ at the OLT side (left) and $OSNR_{down}$ at the ONU side (right) against the fiber length and the splitting ratio.

3. TIME DIAGRAM, TRANSMISSION EFFICIENCIES AND DELAYS

To avoid the RB disturbance, a HD transmission mode in bursts without down/up or up/down signals overlap at both OLT and ONU sides is presented, as depicted in Fig. 3 time diagram:

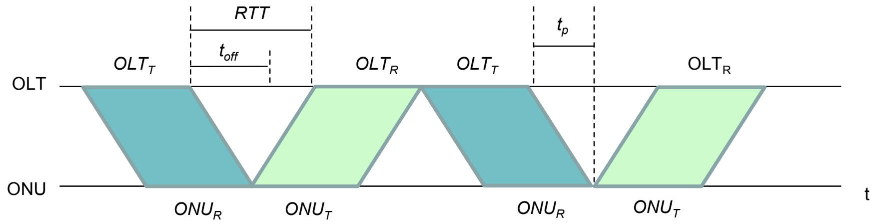

Figure 3. Time diagram without reception/transmission overlap and with symmetric traffic.

Where t_p is the propagation time OLT-ONU; and the Round Trip Time is $RTT = 2t_p$. OLT_T and ONU_T are the OLT and ONU transmission burst times, respectively; besides OLT_R and ONU_R are the OLT and ONU reception times, respectively. It is obvious that $OLT_T = ONU_R$, $ONU_T = OLT_R$. Nevertheless, when transmission begins RB exhibits a transient response and, until a RB power threshold is not reached, reception and transmission could overlap at the OLT and ONU sides during a short rise time t_{on} if external modulation transceiver is used. Moreover, when transmission ends, the RB power disturbance continues during a fall time t_{off}. Instantaneous time evolution of $OSNR_{up}$ was calculated and t_{on} and t_{off} providing an $OSNR_{up} > 15$ dB were derived: t_{on} was found to be in the order of some microseconds and hence it is negligible and t_{off} reached up to hundreds of microseconds, but $t_{off} < RTT$ in all distance cases (Fig. 4), therefore not affecting the HD transmission mode.

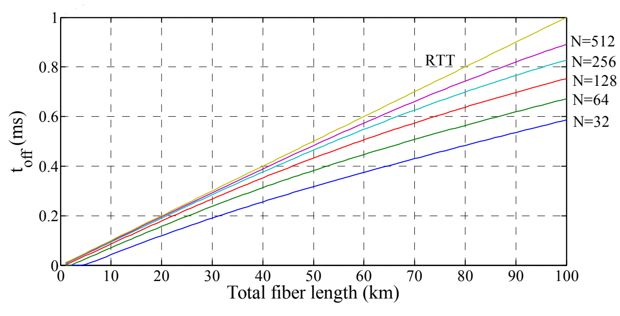

Figure 4. Fall time t_{off} in a RB transient response to a burst of 1 ms reaching $OSNR_{up} = 15$ dB.

Without overlap, a low cost direct modulation transceiver can be used. In order to evaluate the system, we define the OLT transmission efficiency as the ratio of the OLT used data time $t_{OLTdata}$ over an OLT cycle time $t_{OLTcycle}$, which includes transmission, reception and RTT:

$$\eta_{OLT} = t_{OLTdata} / t_{OLTcycle} = OLT_T / (OLT_T + OLT_R + RTT) = 1 / (1 + (OLT_R + RTT)/OLT_T)$$

In the same way, the ONU transmission efficiency is defined:

$$\eta_{ONU} = t_{ONUdata} / t_{ONUcycle} = ONU_T / (ONU_T + ONU_R + RTT) = 1 / (1 + (ONU_R + RTT)/ONU_T)$$

With symmetric traffic we have also the relations $OLT_T = ONU_T$, and OLT and ONU efficiencies are equal: $\eta_{OLT} = \eta_{ONU} = 1/(2+RTT/OLT_T)$. We will consider only the delay due to the HD mode, which is supposed to be much greater than the average waiting time W_q when transmission is available. Therefore, the maximum down-delay which suffers a packet at the OLT until is received at the ONU is $D_{dm} = RTT + OLT_R + t_p = OLT_R + 3t_p$.

Similarly, the maximum up-delay which suffers a packet at the ONU until is received at the OLT is $D_{um} = RTT + ONU_R + t_p = OLT_T + 3t_p$. Hence, with down/up symmetric traffic, the maximum admitted delay is then $D_m = D_{dm} = D_{um} = RTT + OLT_T + t_p = OLT_T + 3t_p$. And the HD latency, which is the average delay, now including W_q, is $D_{lat} = OLT_T/2 + 2t_p + W_q$. Therefore, in the symmetric traffic case, the maximum transmission burst time OLT_{Tm} which suffers D_m is $OLT_{Tm} = ONU_{Tm} = D_m - 3t_p$. Next Fig. 5 (left) shows this maximum OLT_{Tm} and Fig. 5 (right) the OLT efficiency as a function of the distance L OLT-ONU and the maximum admitted delay D_m:

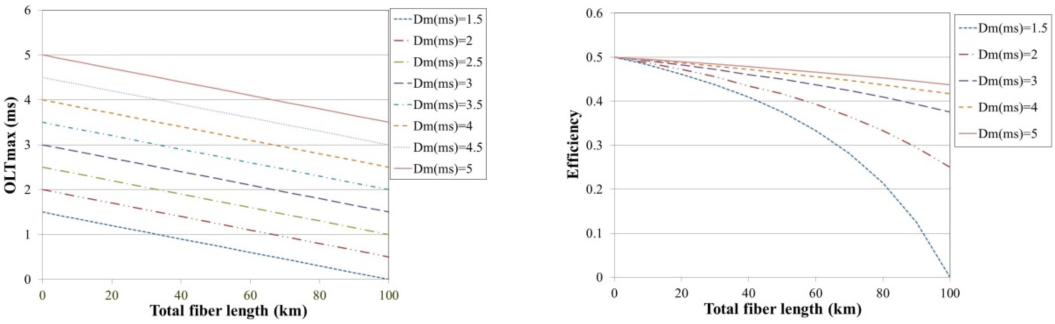

Figure 5. Maximum OLT_{Tm} time (left) and transmission efficiency (right) with symmetric traffic.

For distances up to 60 km and $D_m > 2$ ms the efficiencies are greater than 39%. In an asymmetric traffic scenario, which models a typical residential user behavior, with $OLT_T > ONU_T$, $\eta_{OLT} > \eta_{ONU}$ and $\eta_{OLT} + \eta_{ONU} < 1$.

As an example, with $N = 64$ and $L = 60$ km ($RTT = 600$ µs), $t_{on} = 15$ µs and $t_{off} = 320$ µs and taking $D_m = 2$ ms, $OLT_T = ONU_T = 1.1$ ms, then $\eta_{OLT} = \eta_{ONU} = 39\%$. Employing a line rate of 1 Gb/s, this corresponds to a symmetrical distribution of 390 Mb/s down/up bit rate.

4. EXPERIMENTAL VERIFICATION

To verify the theoretical assumptions experimentally and quantify the influence of RB disturbance, power and time measurements of RB signals were performed implementing the network setup detailed in Fig. 6 (left).

A 1550 nm laser was directly modulated in Intensity Modulation (IM). The laser average output power was 6 dBm, with a very high extinction ratio and a peak power of 9 dBm. The modulation frequency was only of about 1 kHz to observe the transient response of the RB effects in the time domain.

A 25 km SFM spool was used as the access trunk and a circulator was employed to separate the signal injected to the fiber spool and the RB noise returning back. The measured RB power was found of -28 dBm, with a peak power of -25 dBm; thus, providing a difference of 34 dB with respect to the transmitted power, which corresponds to the value of the previous assumed B factor. The received RB disturbance was detected by an Avalanche Photodiode-Transimpedance Amplifier (APD-TIA), and then electrically amplified, to furnish enough level of signal to be visualized at the oscilloscope. The electrical amplifier includes a low-pass filter to eliminate high frequency noise. Both laser and RB signals were plotted at the oscilloscope (Fig. 6, center and right). The measured rise and fall times are about 100 µs, and the transients last up to 250 µs, which corresponds to the RTT of a 25 km fiber length.

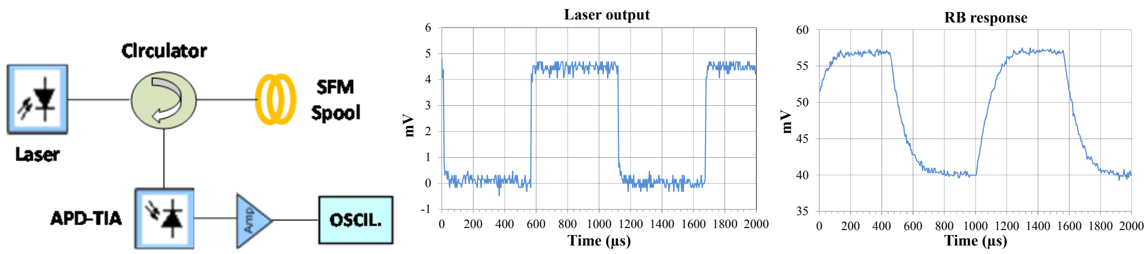

Figure 6. Left, experimental setup for RB characterization. Center, laser output pulse. Right, fiber optic RB transient response to the pulse.

5. CONCLUSIONS

A novel Half-Duplex (HD) transmission mode for UDWDM-PON has been proposed to avoid Rayleigh Backscattering (RB), while suiting coherent transceivers with a unique laser diode, which serves as transmitter and receiver local oscillator. Without signal overlap at both OLT and ONU sides, a cost-effective ONU transceiver can be implemented. The OLT and ONU transmission achieved efficiencies with symmetric traffic are greater than 39% for distances up to 60 km and the delay due to the HD method can be limited to 2 ms. Employing a line bit rate of 1 Gb/s, 390 Mb/s down/up bit rates are furnished.

RB measurements are performed to validate the theoretical assumptions. They show a transient response: the rise time admitting overlap is in the order of ten microseconds, which can be negligible; but the fall time of the transient response, where overlap is forbidden, is in the order of hundred microseconds, which is important and has to be considered to avoid RB disturbance. However, this RB trouble does not affect the reception because its fall time is inferior to the RTT, which is the guard time between transmission and reception.

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