Performance Analysis of WDM-PON Architecture for UWB Distribution in Aircraft Networks

D. Coelho, J.M.B. Oliveira, L.M. Pessoa, H.M Salgado, J.C.S. Castro

***Abstract*— In this paper, we analyze the performance of WDM-PON architecture within aircraft applications. In this scenario, a WDM-PON is used to provide wireless services such as in-flight entertainment for passengers. We have considered the transmission of UWB signals through direct modulation of a VCSEL. A performance analysis in terms of signal-to-noise ratio (SNR) and spurious free dynamic range (SFDR) is conducted.**

***Index Terms*— WDM-PON, UWB, signal-to-noise ratio, spurious free dynamic range.**

I. Introduction

One application domain in which wireless networks can obtain greater practical use is aviation, since planes are scattered all over the world and there is the necessity, by the users, for connectivity and network services "every time" and "everywhere". Another important factor is that commercial aircraft operators are currently looking for ways to attract more customers by increasing the value of their services offerings to passengers [1].

PON networks are suitable for the delivery of infotainment in aircrafts. Simultaneously it can be used to provide wireless communication services in these networks due to its high bandwidth and without electromagnetic interference. In contrast to terrestrial access networks the total distance from the optical line terminator (OLT) to the optical network units (ONUs) is less than 100 meters.

Ultra Wide Band (UWB) signals are characterized by their huge bandwidth occupation, data rates up to 480 Mbit/s, and very low power density levels (-41.3 dBm/MHz), which gives them a noise-like signal characteristic and provides both interference mitigation and very low device power consumption. The available spectrum (3.1-10.6 GHz) is divided into 14 sub-bands, each with 528MHz bandwidth. The standard also defines that these bands are grouped into four groups of three bands, allowing for frequency hopping and multiple user communication in a picocell network [2]. Additionally, its coverage is limited to a few meters, due to its low power level, making it a good candidate for deployment in future aircraft in-flight entertainment networks, where the high user density benefits from a reduction of the sharing factor between wireless cells.

Here, we analyze the uplink performance of WDM-PON for delivery signals such as UWB. The system is analyzed in terms of signal-to-noise ratio and spurious free dynamic range for several values of optical modulation index.

II. WDM-PON

A WDM-PON scheme representation is depicted in Fig. 1. In this architecture, each ONT is assigned with a pair of downstream and upstream wavelengths.

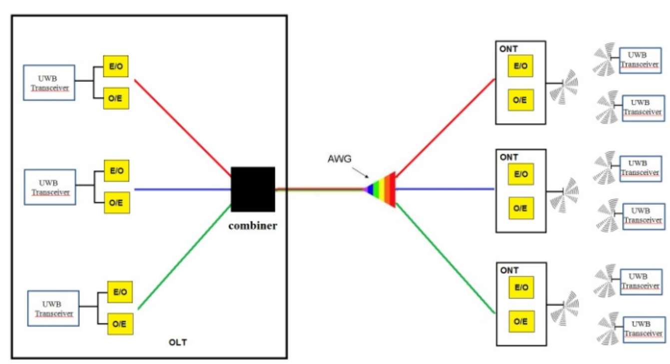

Fig. 1. WDM-PON scheme.

The use of array waveguide (AWG) to mux/demux the upstream and downstream wavelengths, respectively, for each subscriber provides a dedicated point-to-point optical channel to the OLT. Nevertheless, they are sharing a common point-to multipoint physical architecture [3]. Consequently, the SNR is essentially independent of the number of ONTs, allowing efficient scaling and flexibility for a WDM-PON architecture.

III. Architecture Analysis

As previously stated, the maximum fiber length of an optical network to be deployed inside an aircraft is considered to be 100 meters. So, it is reasonable to neglect both the

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attenuation and dispersion for RF signals with frequencies up to 10 GHz [4].

Let us consider a WDM-PON architecture with M optical channels as it is shown in Fig.1. All the ONTs work with direct modulation. The laser parameters can be represented in the Fig. 2, where I_0 is the bias current and I_{th} the threshold current of the laser.

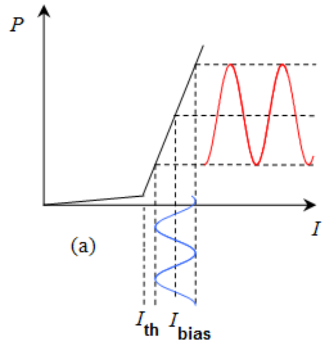

Fig. 2. Laser parameters.

The SNR for the uplink path (worst case) can be given by (1)

$$SNR_{WDM\_uplink} = \frac{\langle I_{Rx}^2 \rangle}{\langle I_{RIN}^2 \rangle + \langle I_{SN}^2 \rangle + \langle I_{th}^2 \rangle + \langle I_{dist}^2 \rangle} \quad (1)$$

where the four noise current terms are: the RIN noise current, the shot noise current, the thermal noise current from the equivalent resistance of the photodetector (PD) load and amplifier (R_{eq}) a and the current due to the third order intermodulation distortions, respectively. The source thermal noise can be neglected. Each noise term in Eq. 1 can be expressed as [5]

$$\langle I_{Rx}^2 \rangle = \frac{1}{2}\left(r_d\, m \langle P_o \rangle\right)^2 \quad (2)$$

$$\langle I_{RIN}^2 \rangle = r_d^2 \langle P_o^2 \rangle 10^{\frac{RIN}{10}} \Delta f \quad (3)$$

$$\langle I_{SN}^2 \rangle = 2 q r_d \langle P_o \rangle \Delta f \quad (4)$$

$$\langle I_{th}^2 \rangle = {4kTF\Delta f}/{R_{eq}} \quad (5)$$

$$\langle I_{dist}^2 \rangle = \frac{1}{2}\left(r_d \langle P_o \rangle\right)^2 m^6 D_{111} N^2 \quad (6)$$

The r_d parameter is the photodetector responsivity, P_o is the average optical power detected by the PD, Δf is the electrical bandwidth of the receiver, q is the electronic charge ($1.6\text{x}10^{-19}$ Coulomb), m is the optical modulation depth, L is the wireless channel attenuation, k is Boltzmann's constant, T=290K, F_n is the noise factor of the amplifier following to the PD and D_{111} is third-order distortion coefficient, which depends of the laser.

The optical modulation index can be expressed by (7), where I_s represents the current signal amplitude at the laser.

$$m = \frac{I_S}{I_0 - I_{th}} \quad (7)$$

The Spurious Free Dynamic Range (SFDR) is illustrated in Fig. 3. The red curve represents the variation in output power as function of input power for three fundamental input signals and the blue curve depicts the behavior of the output power of the third order intermodulation product as a function of the fundamental input power. The intersection of the two extended lines is the 3rd Order Intercept Point (IP3) [5].

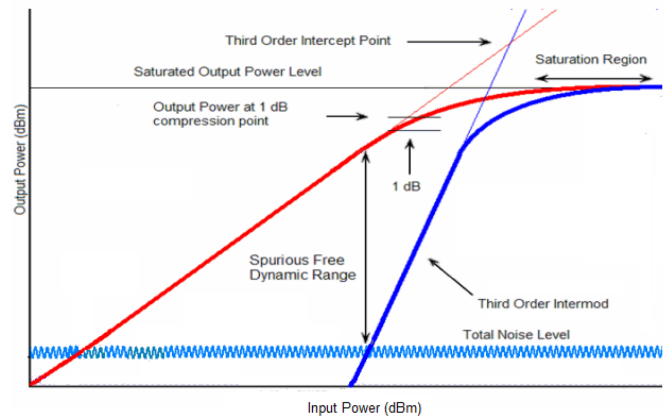

Fig. 3. SFDR representation.

The spurious free dynamic range is a parameter used usually to evaluate the distortion performance of a microwave device. It can be related to the noise floor and the third order intercept point (IP3). The IP3 corresponds to the intersection of the RF output power (PRF) of the extrapolated fundamental, with the extrapolated output power of the third order intermodulation distortion [5].

$$SFDR = \left(\frac{IP3}{P_{noise}}\right)^{2/3} \quad (8)$$

IV. Results

The presented analysis considers the usage of commercial UWB transceivers (Wisair DVK9110) that operates in band group 1 (from 3.168 GHz to 4.752 GHz) and has maximum Effective Isotropic Radiated Power (EIRP) of -41.3dBm/MHz, according to the ECMA 368 standard [2]. Here we have assumed that the UWB directly modulates a VCSEL.

The point-to-point transmission scheme is represented in the Fig. 4. The RF uplink signal is generated by the Mobile

Station and reaches to the ONT through the wireless channel, which has a signal loss of $0 < L < 1$. The weak RF uplink signal can be amplified electrically (G) before being converted from the electrical to the optical domain by a VCSEL. The attenuation and dispersion generated by the optical fiber can be neglected due to the short length optical path. In the OLT, the optical signal is detected by a PIN photodetector with r_d responsivity, being converted from the optical to the electrical domain and reaching to the UWB receiver (UWB Rx). The RF signal detected will suffer the impact of noise generated in the optical path, such as RIN noise, shot noise, photodetector thermal noise and third order intermodulation distortion as well.

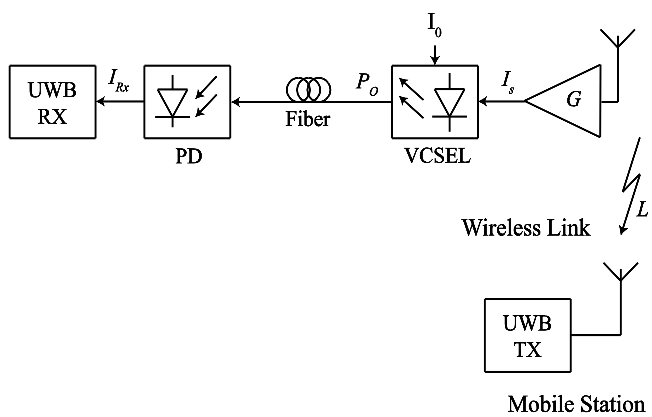

Fig. 4. Point-to-point transmission scheme.

Considering the allocation of subcarriers between 3.168 GHz to 4.752 GHz, the third-order distortion coefficient D_{111} varies between 0.01 and 0.03 depending on the bias current [6]. These lasers are characterized by low threshold current (a few mA), high bandwidth (several GHz) and low cost [7].

We have considered a VCSEL laser with slope efficiency of 0.3 W/A, a threshold current of 1.1 mA, a RIN level of -140 dB/Hz and a third order intermodulation distortion coefficient (D_{111}) equal to 0.03. Note that this relatively high IMD coefficient corresponds to the worst subcarrier frequency component. The laser is working out of the saturation region with 7.5mA of bias.

The PIN photodetector is considered to have a responsivity of 0.9 A/W. It is also considered that the receiver has a bandwidth from 3.168 GHz to 4.752 GHz.

In order to analyze the performance of the scheme represented in Fig 4, we have obtained results for the transmission of three different signal scenarios, namely sub-band 1, sub-bands 1+2 and sub-bands 1+2+3, simultaneously.

Fig. 5 shows the relationship between the optical modulation index (OMI) per subcarrier with the SNR. Results for SNR were obtained for a UWB signal transmission considering sub-bands 1, 2 and 3. The SNR limit of 10.5 dBm for a bitrate of 480 Mb/s is also represented. Note that the results are for the central subcarrier, where the most number of IMPs fall, representing the worst case. The results also show that there is an optimum modulation index for a maximum SNR allowed by the system. For 1 sub-band the modulation index per subcarrier, for an SNR above the 10.5 dB limit, ranges between 1.89% and 11.13% with an optimum at 5.65%, for a maximum SNR of 18.09 dB. For 2 sub-bands the allowed OMI per subcarrier ranges between 1.89% and 7.98% with an optimum at 4.47%, for a maximum SNR of 16.11dB. Similarly, for 3 sub-bands the allowed OMI ranges between 1.89% and 6.47% with an optimum OMI of 3.92% for a maximum SNR of 14.94dB.

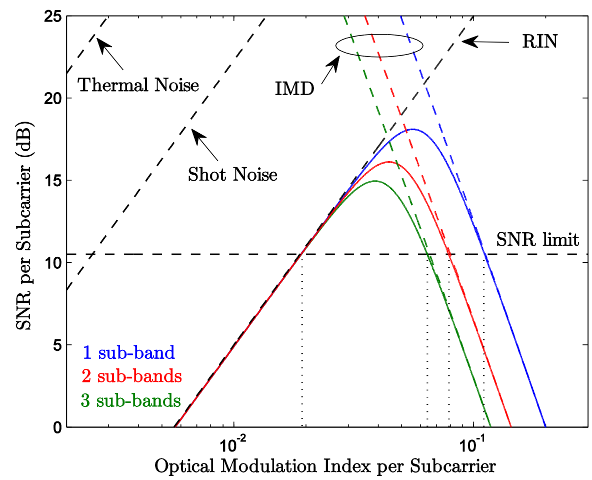

Fig. 5. SNR variation with the OMI per subcarrier.

We can see a decrease of the OMI range allowed with the increase of the number of sub-bands used in the system. The OMI range for a fixed bias current in the VCSEL will allow a signal current amplitude of I_S at the laser input. This current amplitude can be controlled by the amplifier that precedes the VCSEL and provides gain in order to compensate the attenuation of the wireless channel. The relationship between gain and attenuation can be expressed as

$$G = \frac{\left[m\left(I_0 - I_{th}\right)\right]^2 R_{laser}\, L}{2\times 10^{\left(\frac{-41.3-30+10\log_{10}\Delta f}{10}\right)}} \qquad (9)$$

where R_{laser} is the laser resistance and L is the wireless channel attenuation.

For a transmission with SNR > 10.5 dBm, the OMI has to be between two values ($m_{min} < m < m_{max}$), which will match a range of the amplifier gain ($G_{min} < G < G_{max}$). By (9), the range of the amplifier gain for a 1 meter of wireless channel is 19.33dB to 39.5dB for 1 sub-band, 19.33dB to 33.60 dB for 2 sub-bands and 19.33 dB to 30.02 dB for 3 sub-bands. The gain range decreases with the number of sub-bands used in the transmission. This occurs due to the decrease of the OMI range allowed.

Fig. 6 shows the fundamental and the third order intermodulation distortion powers as a function of the optical modulation index per subcarrier. Similarly we have obtained SFDR results for the setup considering the transmission of UWB signals with 1, 2 and 3 sub-bands. The SFDR for sub-band 1 was 41.97 dB.Hz$^{2/3}$, for the sub-band 1+2 was 40.23 dB.Hz$^{2/3}$ and for the sub-band 1+2+3 was 38.79 dB.Hz$^{2/3}$,

which is low due the great number of subcarriers used in the UWB signal.

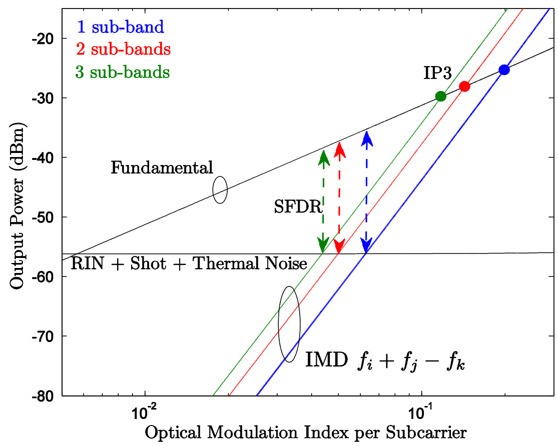

Fig. 6. Fundamental and IMD power with the OMI.

V. Conclusion

We have analyzed WDM-PON architecture for wireless services distribution inside aircrafts. Moreover, a case study on UWB signals was also performed. Results for SNR and SFDR for the worst subcarrier and for the uplink were obtained.

In WDM-PON, each ONT has a dedicated point-to-point optical channel to the OLT which represents a better solution for distribution of wireless services.

For a transmission with SNR > 10.5 dBm, the OMI has to be between two values ($m_{min} < m < m_{max}$), which will match a range of the amplifier gain ($G_{min} < G < G_{max}$).

The transmission of only one sub-band allows a higher optical modulation index range, which allows a higher gain margin for the amplifier. Results also show that the optimum OMI per subcarrier is around 5%. When considering 3 sub-bands there is a penalty of 6.35 dB in the optimum SNR in reference to the one using only 1 sub-band.

Results indicate that the gain range decreases with the number of sub-bands used in the transmission due to the decrease of the OMI range allowed.

The results were always obtained for the worst case, which is the subcarrier located in the center of the transmission bandwidth.

The SFDR low results were obtained due the great number of subcarriers used in the UWB signal. There is a necessity for optical devices with low nonlinear parameters for maximum performance.

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