Experimental assessment of WLAN performance supported in a fiber-radio network

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Abstract: In this paper we experimentally evaluate the performance of a fiber supported radio application, namely WiFi IEEE802.11n, using a low power consumption base-station based on a reflective electro absorption modulator and commercial transceivers. We conclude that the proposed setup is suitable to achieve a transmission of 20 Mbit/s over a 4 m wireless channel. A theoretical signal to noise ratio analysis is also carried out, based on experimental results. Finally, we evaluate the possibility of employing the proposed setup in a passive optical network, concluding that this solution may not be cost effective.

Keywords: Radio-over-fiber, Electro-absorption modulator, Wi-Fi, Passive Optical Network

1. Introduction

The concept of radio-over-fiber (RoF) involves the transmission of RF signals through an optical fiber between a control station (CS) and a number of base stations (BSs). The end users are commonly considered as mobile stations (MSs) connected to BSs through a wireless link. The integration of both optical and wireless broadband infrastructures into the same backhaul network leads to a significant simplification and cost reduction of BSs since all routing, switching and processing are performed at the CS. This centralization of signal processing functions enables equipment sharing, dynamic allocation of resources and simplified system operation/maintenance. Ideally, RoF systems can be completely transparent to all signals transmitted in the optical channel. It has been experimentally shown that RoF networks are well suited to simultaneously transport several wireless standards like wideband code division multiple access (WCDMA), IEEE 802.11 wireless local area network (WLAN) [1], global system for mobile communications (GSM) [2], WiMAX [3] and ultra-wide band (UWB) [4]. Moreover, RoF systems are attractive for future avionics communication networks since they are lightweight and immune to electromagnetic interference and satisfy the requirements for future RF communications between the aircraft and earth stations. Furthermore they facilitate the provision of wireless services to passengers addressing the growing need by end users for ubiquitous connectivity and network services. Indeed, commercial aircraft operators are currently looking for ways to attract more customers by increasing the value of their service offerings to passengers [5].

In a RoF system, an optically modulated electrical signal can suffer several impairments

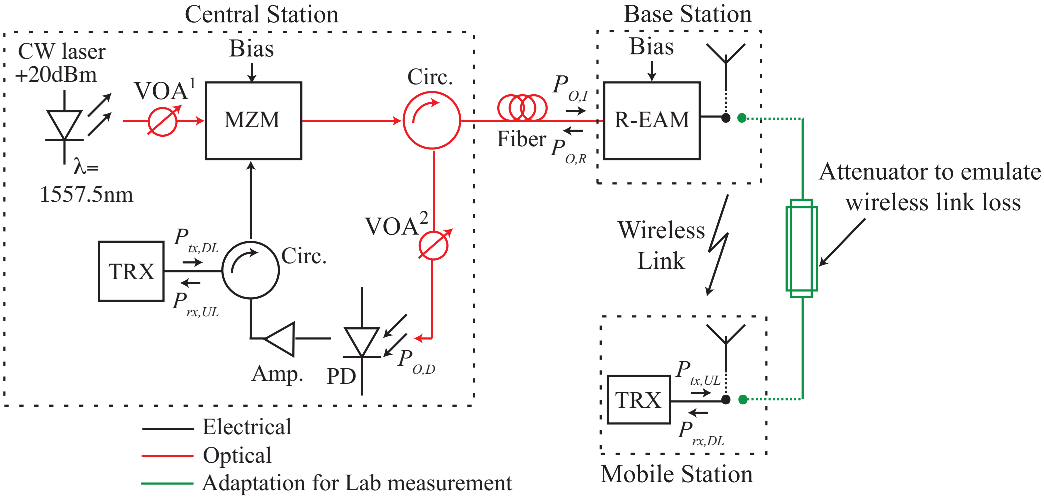
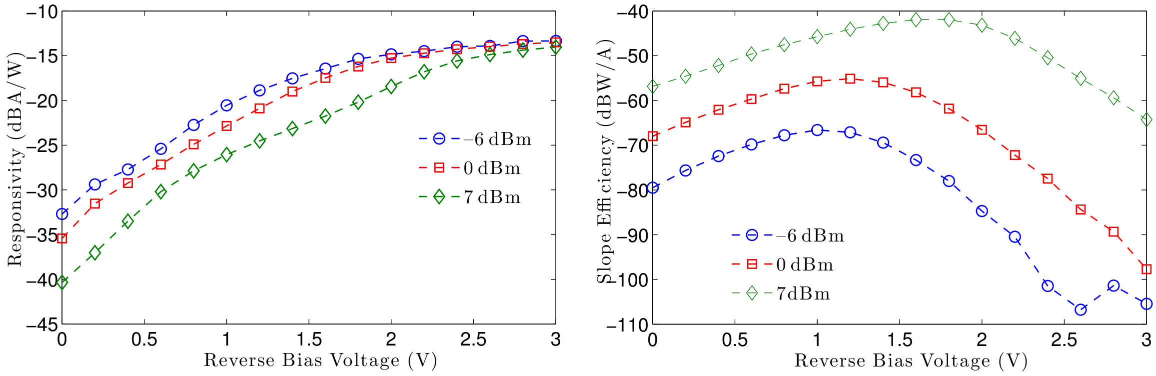


Figure 1: RoF system configuration

namely nonlinear distortion and power penalty from the electro-optical conversion process, chromatic dispersion and attenuation from the optical fiber. Moreover, optical sources with narrow line-widths are required at the base station to minimize laser phase noise degradation, hence, very stable and expensive lasers are required [6]. For the downlink signal transmission an ultra-stable and common optical source can be used. Yet, in the uplink, it is not attractive in terms of complexity, size, power consumption and cost to have an optical source for each BS. Furthermore, by eliminating the need of an optical source at each BS, the wavelength assignment can be performed at the CS, turning all BSs to be colorless.

In this paper we study the performance of a reflective electro - absorption modulator (R-EAM) transceiver in a RoF network, and experimentally evaluate the *wireless fidelity* (Wi-Fi) standard IEEE 802.11n supported by that network. The concept under study avoids the usage of amplification in the BS, the EAM simply requiring a small reverse voltage bias, which consumes only approximately 2 mW. Additionally, this concept is adequate for a high user density scenario such as the aircraft cabin, given the low radiated power of the amplifier-less base station. A pico-cell infrastructure concept for in-flight communications has already been proposed in [7], using UWB at 60 GHz. However, it is also pertinent to provide an analysis on the RoF distribution of well proven and mature standards, such as Wi-Fi, while considering the usage of simple devices in the base-station, namely the EAM. In section 2, the EAM is described and its role as a transceiver in RoF systems is discussed. We also analyze the R-EAM Slope Efficiency (SE) and responsivity for different optical powers and bias points. In section 3, a case study of Wi-Fi signal transmission is addressed, where its performance is evaluated as a function of the EAM injected optical power and reverse bias voltage. We also evaluate the possibility of employing the R-EAM transceivers in a passive optical network. Finally, conclusions are given in section 4.



(a) O/E

(b) E/O

Figure 2: Measured electrical to optical (a) and optical to electrical (b) conversion efficiency of the EAM, for different inject optical powers at EAM input.

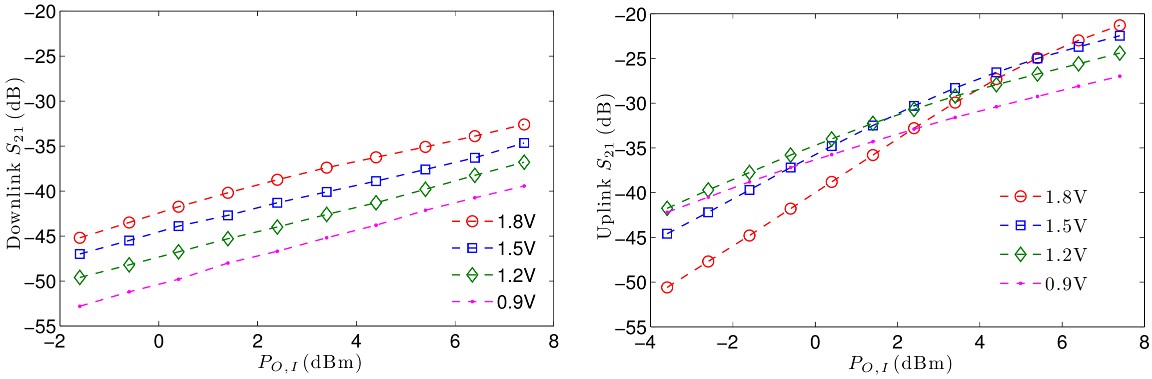
2. Electro-absorption transceiver based RoF systems

The simplification of remote BSs can be achieved by avoiding the need for an optical source. Source free RoF systems can be based in two different schemes, either by providing the optical carrier remotely from the CS and using special configurations to allow its re-usage in the uplink [8], or by using a single electro - absorption waveguide device. This is a single component, where the rear facet is coated with high reflection layer, acting as a modulator for the uplink and as photo-receiver for the downlink [9]. Therefore, this transceiver device is a very attractive solution for a full-duplex RoF transmission.

Fig. 1 shows the RoF system under consideration in this paper. The CS is based on a Mach-Zhender Modulator (MZM), which modulates the transmitted electrical signal into an optical carrier. At the CS, an optical circulator separates the downlink direction (from CS to the end user) and uplink direction (from end user to CS) optical paths. An electrical circulator separates the downlink/uplink electrical paths. The received optical signal is detected by means of a photodiode, which typically includes amplification (electrical and possibly optical). Finally, the remote BS is based on the colorless EAM transceiver.

In this work the EAM used is the model '60G-R-EAM-1550", from CIP. The measured electro-optical (EO) and optical to electrical (OE) responses of the EAM, corresponding respectively to the slope efficiency (SE) and responsivity, are shown in Fig. 2, as a function of the reverse bias voltage, for different average optical input powers, $P_{O,I}$. We assume the decibel units for these variables to be obtained by 20log10($\cdot$), as defined in the measurements of the laboratory equipment, an Agilent lightwave component analyzer 8703B.

In the electro-optical response, it is apparent that the optimum bias voltage increases with the optical input power. Furthermore, it is easily seen that SE at the optimum bias voltage increases with $P_{O,I}$. Concerning the optical to electrical response, the results also show that the responsivity increases monotonically with the reverse bias voltage, and slightly decreases with $P_{O,I}$. The fact that the RoF transmission system is comprised by several components apart from the EAM suggests a careful analysis of the total link gain in both downlink and uplink directions. In this way, it is relevant to



(a) Downlink

(b) Uplink

Figure 3: Measured (a) Downlink and (b) Uplink total gain (S_{21} parameter).

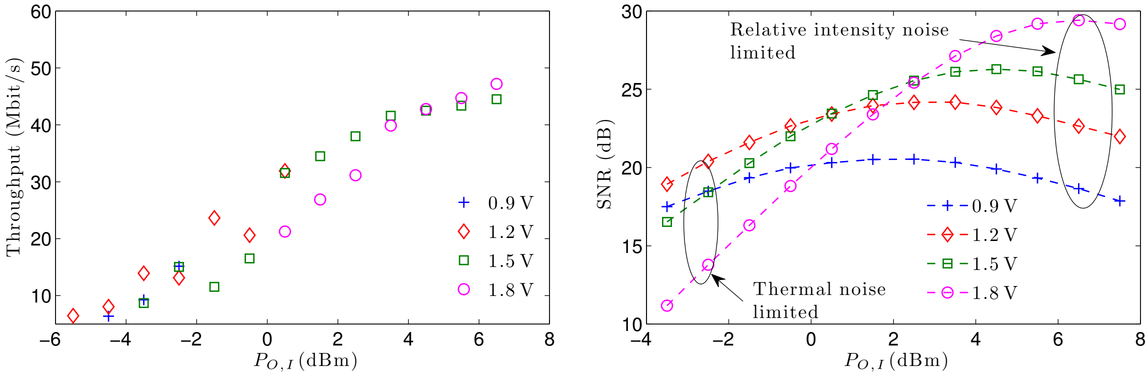
determine the total gain affecting the signal, between the CS and the MS transceivers, in both directions, which is plotted in Fig. 3. To obtain these values the wireless channel attenuation has been neglected. The total downlink gain (Fig. 3a) is essentially the result of the EO conversion efficiency of the MZM and the OE conversion efficiency of the EAM, added to the comparatively small contribution of other components, such as circulators, connectors and cables. The MZM conversion efficiency increases with its input optical power, and therefore, for an injected optical power of -1.5 dBm referred to the EAM input (corresponding to the first value in the x axis), the MZM conversion efficiency is approximately -30 dBW/A, and increases up to -12 dBW/A, at $P_{O,I} = +7.5$ dBm. Conversely, the total uplink gain (shown in Fig. 3b) is the result of the EO conversion efficiency of the EAM and OE conversion efficiency of the photodetector plus amplifier, which is approximately equal to 18 dBA/W. In this way, it is straightforward to verify that although the EAM conversion efficiency is poorer in the uplink direction, the combined total gain is lower in the downlink direction, provided the applied reverse bias voltage is 1.5 V or less.

3. Case study: MIMO-OFDM Wireless LAN [IEEE802.11n]

Multiple-Input Multiple Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) technology is used for the wireless LAN systems (IEEE802.11n), typically referred as WiFi. The WiFi receiver sensitivity of -61 dBm at 300 Mbit/s specified in the standard [10], is not applicable for an optical front-end. Instead, a minimum SNR of 33 dB is required, considering the typical noise level of a WiFi receiver at -94 dBm in a 40 MHz bandwidth, and the minimum sensitivity specified in the IEEE802.11n standard of -61 dBm, in the 2.4 GHz band. In the present study, IEEE802.11n commercial WiFi transceivers were used, with an experimentally measured sensitivity of approximately -64 dBm, for the maximum data-rate, which indicates that a minimum SNR around 30 dB would be required to maintain the maximum data-rate.

The experimental setup used to perform throughput measurements is based on the diagram shown in Fig. 1. The optical power injected into the EAM was adjusted using a variable optical attenuator (VOA[1]). Finally, the attenuation of the wireless link was simulated using different RF attenuations.

Fig. 4 shows the experimentally measured throughput (4a) and calculated SNR (4b)



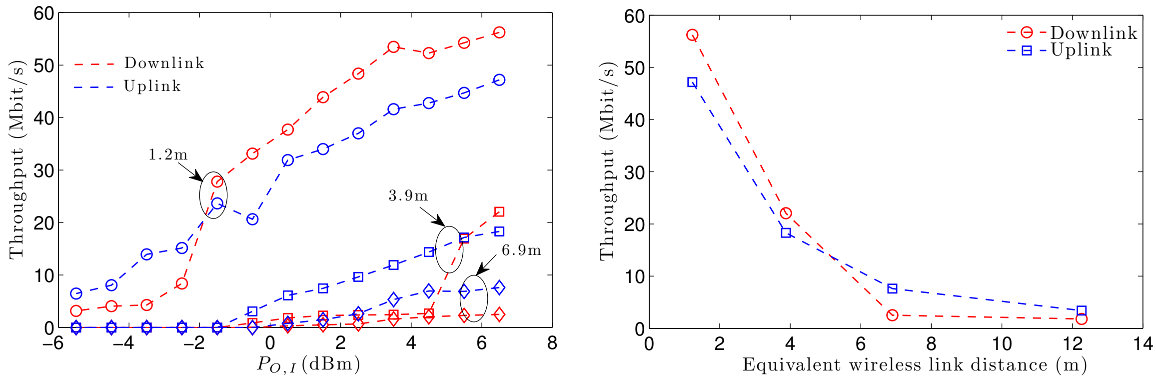
(a) Measured Throughtput

(b) Calculated SNR

Figure 4: (a) Measured throughput and (b) calculated SNR as a function of injected optical power at EAM input, in the uplink, using a wireless channel equivalent attenuation of 30 dB.

as a function of the injected optical power at the EAM input, in the uplink direction, for different reverse bias voltages and considering a wireless channel equivalent attenuation of 30 dB (corresponding to approximately 1.2 m length with typical 6 dBi gain antennas). The throughput parameter reflects the measured average transfer rate (in Mbit/s) of a large file between the two transceivers using the Transmission Control Protocol (TCP) and Internet Protocol (IP), using a benchmarking software tool called "Test TCP". In this way, the transmission is performed simultaneously in the uplink and downlink directions, due to the requirements of the higher layer TCP. The observed pattern indicates that the optimum performance depends on the reverse bias voltage, in agreement with the conversion efficiency dependence shown in Fig. 3b. The calculated SNR was obtained using the measured EAM slope efficiency, as well as the noise terms that we have previously derived in [11]. The noise terms include the thermal noise, stemming from the equivalent input resistance of the electrical amplifier following the photodetector, added to the the amplifier noise figure (estimated to be around 6 dB). The noise terms also include the shot noise and relative intensity noise (RIN), proportional to the received optical power and its squared value, respectively. The RIN parameter was set at the value of -150 dB/Hz. The received optical power at the photodetector ($P_{O,D}$) was measured for different bias voltages and injected EAM input powers, and subsequently used in the calculations. The relationship between throughput and SNR is not obvious, since the throughput depends on the receiver specific configurations, including higher layer network parameters (TCP/IP level) as well as on the efficiency of error correcting codes, channel estimation and equalization. Additionally, nonlinearities from the MZM and EAM can also contribute to limit the performance. Although the SNR is a reasonable performance indicator, the effective throughput is the ultimate benchmark. Still, the calculated SNR gives an insight on the limiting performance degradation noise factors. In fact, as shown in Fig. 4b, for lower injected optical powers, the SNR is limited by thermal noise, whereas for higher injected optical powers the estimated SNR becomes limited by the relative intensity noise.

Fig. 5 plots the throughput for both uplink and downlink directions, for different equivalent wireless channel attenuations, using the optimum reverse bias voltage for the best uplink throughput. If a target throughput of 20 Mbit/s is specified, approx-



(a) Input power dependence

(b) Link length dependence

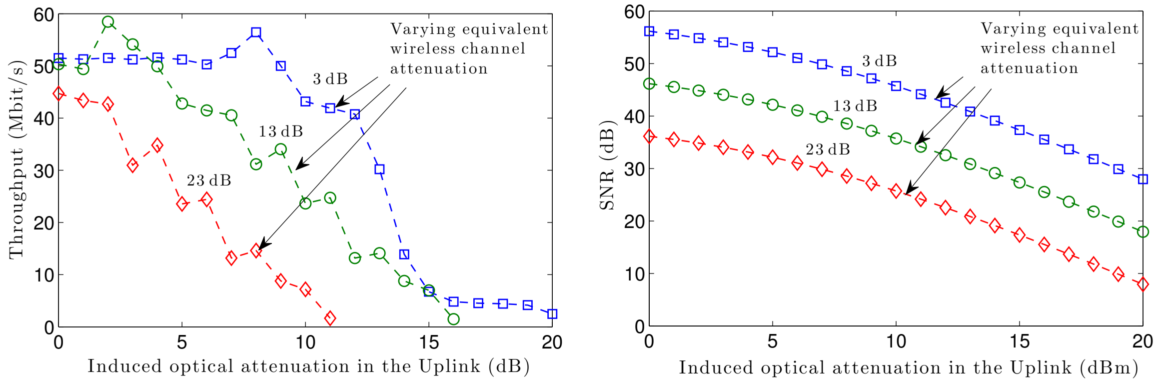
Figure 5: (a) Measured throughput as a function of the injected optical power at EAM input, and (b) equivalent wireless channel length, at the maximum $P_{O,I}$, for different equivalent wireless link lengths.

imately 4 m of wireless channel length could be achieved, which seems reasonable for the distribution of wireless signals inside future aircrafts. These results also show that the uplink throughput, compared to the downlink, is poorer for stronger signals, although being higher for weaker signals. Indeed, for stronger signals, the same result was found by directly connecting the two transceivers (without optical channel), which is likely explained with manufacture differences between the two transceivers. As for the weaker signals, as seen previously in Fig. 3, the uplink total gain is higher than that of the downlink, as long as the bias voltage is set for the best uplink performance, which translates into a SNR difference, and likely into the throughput observed difference.

3.1 Distribution of IEEE802.11n over a PON

Passive Optical Networks (PONs) are suitable both for the delivery of digital infotainment in aircrafts and for providing wireless communication services, due to their high bandwidth and absence of electromagnetic interference, avoiding the deployment of separate optical infrastructures for these services. However, using electro-absorption modulators at the optical network terminals can be problematic. Firstly, while in a digital PON each network node transmits in its own time slot (time division multiplexing), the uplink in a PON equiped with analogue EAM based nodes employs simultaneous transmission of signals modulated on a common light source, which causes optical beat interference (OBI) [12], and significant performance degradation. The OBI problem can not be avoided when using the reflective EAMs architecture since it relies on modulating a common source of light. Nevertheless, an interesting scenario could be the employment of a single analog node in one of the 1×16 PON branches, so that a single pico-cell could distribute wireless services to this group of 16 users. However, both the significant uplink and downlink PON attenuations can limit the wireless services distribution performance. While the downlink attenuation could be easily compensated by increasing the CS laser source power, the uplink attenuation can only be compensated by including an EDFA in the CS uplink path.

In order to determine the implications of the large PON uplink attenuation, we experimentally introduced a variable optical attenuator (VOA[2]) in the uplink CS path (instead of the EDFA in Fig. 1). Three different electrical attenuations have been used,



(a) Measured Throughtput (b) Calculated SNR

Figure 6: (a) Measured throughput and (b) calculated SNR as a function of induced optical attenuation in the uplink, for three different equivalent wireless channel attenuations.

equivalent to wireless channel attenuations of 3, 13 and 23 dB (all corresponding to less than 1 meter). The results are shown in Fig. 6a. For a target throughput of 20 Mbit/s, optical attenuations of approximately 7, 12 and 14 dB would be acceptable, respectively for 23, 13 and 3 dB of equivalent wireless channel attenuation. Therefore, although a 14 dB optical attenuation is a reasonable value for a 1×16 PON, the tolerable wireless channel attenuation is too small. Additionally, Fig. 6b, shows the calculated SNR, corresponding to the experimental conditions. This result is in agreement with those of Fig. 6a and supports the poor performance of the uplink transmission with induced optical attenuation in the uplink. Therefore, these results show that the uplink loss would have to be compensated by including an EDFA for distributing wireless services over a 1×16 PON, which may not be a cost effective solution.

4. Conclusions

In this work we experimentally evaluated the performance of WiFi IEEE802.11n supported over fiber, using an almost powerless BS based on a reflective EAM and commercial transceivers. We concluded that the proposed setup is suitable to achieve a transmission of 20 Mbit/s over a 4 m wireless channel. A theoretical signal to noise ratio analysis was also carried out, supported in experimentally obtained values, which was in agreement with the measured throughput experimental results. The possibility of employing the proposed setup in a passive optical network was also evaluated, which might not be cost effective. An improved performance could be achieved using a more efficient photodiode at the CS, providing a higher conversion efficiency and lower noise. Additionally, a MZM with lower nonlinearity could be employed, although its conversion efficiency would be always limited by the maximum injected optical power tolerated by the EAM. Alternatively, using a directly modulated laser would allow for an higher conversion efficiency.

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References

[1] J. Mitchell, “Performance of OFDM at 5.8 GHz using radio over fibre link,” *Electronics Letters*, vol. 40, no. 21, pp. 1353–1354, 2004.

[2] P. K. Tang, L. C. Ong, A. Alphones, B. Luo, and M. Fujise, “PER and EVM measurements of a radio-over-fiber network for cellular and WLAN system applications,” *Lightwave Technology, Journal of*, vol. 22, pp. 2370 – 2376, nov. 2004.

[3] N. Gomes, M. Morant, A. Alphones, B. Cabon, J. Mitchell, C. Lethien, M. Csörnyei, A. Stöhr, and S. Iezekiel, “Radio-over-fiber transport for the support of wireless broadband services [invited],” *Journal of Optical Networking*, vol. 8, no. 2, pp. 156–178, 2009.

[4] M. Jazayerifar, B. Cabon, and J. Salehi, “Transmission of multi-band OFDM and impulse radio ultra-wideband signals over single mode fiber,” *Journal of Lightwave Technology*, vol. 26, no. 15, pp. 2594–2603, 2008.

[5] D. Coelho, L. Pessoa, J. Oliveira, H. Salgado, and J. Castro, “Performance Analysis of WDM-PON Architecture for Wireless Services Distribution in Aircraft Networks,” in *Proceedings of CETEC 2011*, Lisbon, 2011.

[6] C. Lim, A. Nirmalathas, M. Bakaul, P. Gamage, K. Lee, Y. Yang, D. Novak, and R. Waterhouse, “Fiber-wireless networks and subsystem technologies,” *Lightwave Technology, Journal of*, vol. 28, no. 4, pp. 390–405, 2010.

[7] M. Beltrán, R. Llorente, R. Sambaraju, and J. Martí, “60 GHz UWB-over-fiber system for in-flight communications,” in *Microwave Symposium Digest, 2009. MTT’09. IEEE MTT-S International*, pp. 5–8, IEEE, 2009.

[8] Z. Jia, J. Yu, and G. Chang, “A full-duplex radio-over-fiber system based on optical carrier suppression and reuse,” *Photonics Technology Letters, IEEE*, vol. 18, no. 16, pp. 1726–1728, 2006.

[9] A. Stohr, K. Kitayama, and D. Jager, “Full-duplex fiber-optic RF subcarrier transmission using a dual-function modulator/photodetector,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 47, no. 7, pp. 1338–1341, 1999.

[10] IEEE, “IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements Part 11,” *IEEE Std 802.11n-2009*, pp. c1 –502, 29 2009.

[11] L. Pessoa, D. Coelho, J. Oliveira, J. Castro, and H. Salgado, “Assessment of noise impact on UWB signals in R-EAM based optical links,” in *Avionics, Fiber-Optics and Photonics Technology Conference (AVFOP), 2011 IEEE*, pp. 59–60, IEEE, 2011.

[12] H. Le Bras and M. Moignard, “Distribution of 3G base stations on passive optical network architecture,” in *Microwave Photonics, 2006. MWP’06. International Topical Meeting on*, pp. 1–4, IEEE, 2006.

