Development and Evaluation of a Robust Full-Duplex ROF System

D. H. Thomas, G. Vilela de Faria and J. P. von der Weid

Abstract— **We developed a robust full-duplex radio-over-fibre (ROF) system with heterodyne carrier generation through two laser sources with efficient laser frequency stability control and a fully powered-over-fibre remote antenna unit. The ROF system was submitted to a long term performance evaluation, under IEEE 802.11 standards, resulting in an Availability of better than 99% at 156 Mbps during 150 hours evaluation time. This high performance was confirmed during a successful transmission for ASI/SDI-coded digital TV at 270 Mb/s.**

Index Terms— **Digital transmission, full-duplex transmission, microwave heterodyne generation, radio-over-fiber systems.**

I. Introdução

ROF systems are of great interest for radio links used in access networks. They have many advantages over conventional radiofrequency systems, such as lower attenuation with distance, interference immunity, wide bandwidth available, lower power consumption, enhanced microcellular coverage and easier installation. Moreover, the possibility of using optically powered remote ROF antenna strongly pushes towards their use when immunity to lightning discharges is considered. However, as every technology used in access networks, cost is of utmost importance, so that the development of low cost systems deserves attention of research projects.

The microwave signal can be obtained directly from a radiofrequency generator/oscillator located at the central station [1] or can be obtained from the beating of two optical signals at the photodetector located at the remote antenna unit (RAU), a technique called heterodyne generation [2].

Because the optical spectra of the beating sources are transferred to the RF range, the quality of the laser sources will affect the RF signal, mainly its phase stability. Different methods have been used to generate good quality RF signals, like self heterodyne generation [3] and injection locking with phase-lock loop forming an optical injection phase-lock loop (OIPLL) [4,5]. Brillouin [6] and frequency multiplication methods [7] are other examples of optical sources proposed for high frequency ROF generation.

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D. H. Thomas (thomas@opto.cetuc.puc-rio.br), G. Vilela de Faria (gian@opto.cetuc.puc-rio.br) and J. P. von der Weid (vdweid@opto.cetuc.puc-rio.br) are with Centro de Estudos em Telecomunicações – CETUC/PUC-Rio. R. Marquês de São Vicente, 225, Gávea – Rio de Janeiro – RJ – 22451-900.

Moreover, in order to improve reliability and low-cost of ROF systems, several efforts have been done. Among these efforts, we cite the impact evaluation of the chosen optical sources over the RF signal quality [2,8,9], the study of chromatic dispersion effects over ROF systems [7], the optimization of the optical power budget [10], how to use the optical fibre to power remote stations without the need of electrical power cables and sockets [11]. Furthermore, evaluations of similar systems under a set of standards were also investigated [8].

Although good results were obtained on most cases, practical implementations are still far from the field due to cost and power consumption problems. Nevertheless, when intensity modulated detection is used, phase noise impact is considerably smaller then in other detection techniques. Hence, a simple and low cost solution to the problem of optical sources is the use of intensity modulation and detection of the optical beat signal of two laser sources. We will analyse the impact of the laser linewidth on the quality of the transmitted signal and show that good quality IM detected transmission can be achieved, as well as phase modulated signal transmission can be used, provided that an intensity modulated FI tone is used as subcarrier.

Wavelength reuse for uplink transmission [10] is a very promising solution because laser sources at the remote antenna are eliminated. However electro-optical modulators are either polarization dependent or require high power drivers, which impact the electrical power budget of the power-over-fibre (POF) supply. In principle, polarization insensitive RSOA (reflected semiconductor optical amplifier) cascaded with an EAT (Electro-absorption transceiver) could be used to realize E/O conversion [12], but even though these devices are commercial, we consider these as an expensive solution either from the economical or electrical power budget point of view.

Electrical powering is an important feature in remote antenna units. They are normally placed in posts and/or high places and powering them is a problem, especially when high voltages or lightning problems are considered. POF is an interesting solution to these situations. Indeed POF was successfully used for current measurements in high-voltage electrical networks [13]. POF was also used in a simplex ROF transmission demonstration at 2.5 GHz [11].

Although technical progress and increase of signal quality have been reported, to the best of our knowledge no one reported a practical long-term availability evaluation of ROF systems. Availability is a property that is impaired by many factors, from the stability of the carrier generation method to the quality of the power supply.

We present a fully POF low cost and robust solution for ROF transmission using a simple and efficient laser frequency stability control, capable to lock the heterodyne generated microwave signal to the desired RF frequency, and wavelength reuse for the uplink transmission. Since low cost and low V_π modulators are now commercially available, their use became very attractive provided that polarization sensitivity could be eliminated. This can be easily achieved with depolarized light, and since two lasers are already being used for downlink transmission, we use part of their optical power in orthogonal polarizations to produce depolarized light. Considering that the distinct performance of the proposed ROF system was certified through a 150 hours-performance test, we allow automatic operation and enlarge the reliability of the whole ROF system, ensuring the high quality communication with high availability, as well as the several advantages of power-over-fibre supply [11]. The standard 802.11n was used as a parameter to guide the system availability evaluation.

II. Experimental setup

Fig. 1 shows the experimental setup of the central station and the RAU of our ROF system. As usual for this kind of system, we call the data flow from the central station to the RAU as downlink transmission and data flow in the opposite direction as uplink transmission. The units were designed to operate in matched pairs, one transmitting/receiving at 18.2/19.2 GHz and vice-versa for the other. A 12-fibres optical cable (6 MM + 6 SM) connected the central station to the RAU, providing signal and power to it. The total number of fibres in use is actually half the available fibres in the cable, so that there is one spare fibre for each fibre in use.

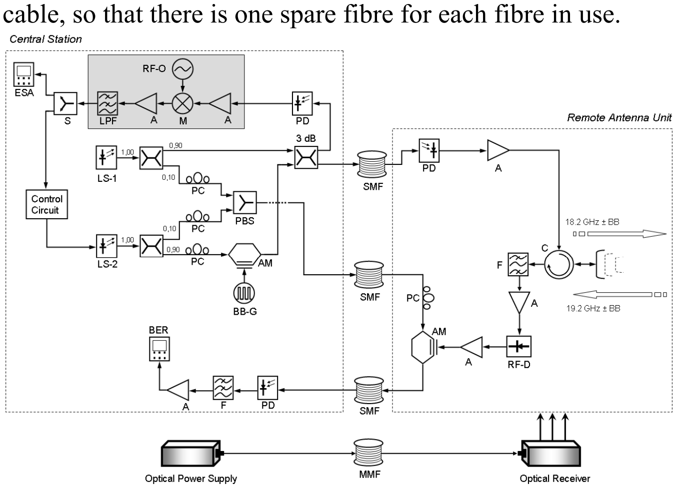


Fig. 1. Set-up of the central station and RAU; LS-1: Laser source 1, LS-2: Laser source 2, PC: Polarization controller, PBS: Polarization beam splitter, BB-G: Baseband generator, AM: Lithium-Niobate amplitude modulator, SMF: Standard single-mode fibre, PD: Photodetector, A: Amplifier, C: Circulator, F: Filter, RF-D: Radiofrequency detector, BB: Baseband, BER: Bit-error rate, RF-O: RF oscillator; M: Mixer; LPF: Low-pass filter; S: Splitter.

In the central station, two optical sources were used for all the ROF system. 90 % of the output signal of each laser was launched on a 2x2 coupler. Half of the coupled power was then used for downlink transmission whereas the other half was used as the feedback signal to control the laser stability.

The optical feedback signal was photodetected and the obtained RF beat tone, with frequency around 18.2 GHz, was used to generate the error signal. The block responsible for that is highlighted in Fig. 1. The beat tone was amplified and mixed with a reference signal from a RF oscillator at 18.2 GHz. At the output of the mixer, a tone corresponding to the difference between the frequencies of the mixed signals was obtained, amplified and filtered to produce the error signal. A sample of the error signal is showed on the Fig. 2. Of course, the laser phase noise is present in the feedback signal, but it is clean enough to allow good frequency stabilization of one laser relative to the other.

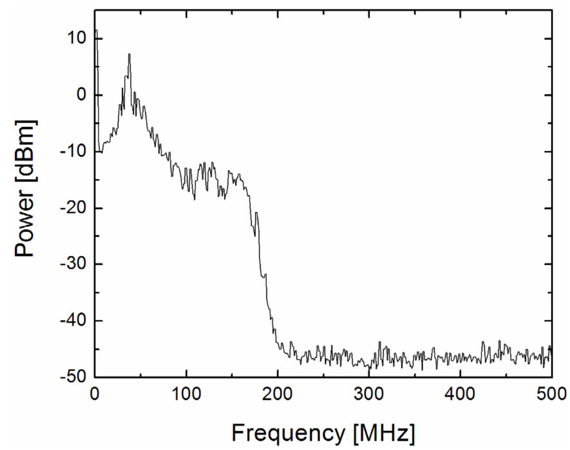


Fig. 2. Error signal obtained through the mixing between the reference signal and the beat tone.

As the laser frequency drifts the beat product moves away from the reference signal so that the low frequency beat signal increases. The error signal is then obtained from the total power of this low frequency beat signal after passing through a low pass filter, the higher the power the closer the difference between the laser frequencies to the required RF frequency.

The error signal, constantly monitored at an electrical spectrum analyzer (ESA), was coupled to the control circuit. The control circuit is based on a 14-bit microcontroller which works to keep the error signal into a 30 MHz range. If the frequency of the error signal moves out this range, the control circuit modifies the driver current of the laser 2 in order to change its wavelength and move the error signal back to the desired range. Laser 1 was operated with constant driver current and its optical frequency remains roughly constant.

It is important to note that the proposed control technique is quite different from the OPLL scheme. When an OPLL is used, the control circuit is sensible to the phase difference between the beat note and the RF reference and it acts to reduce the phase fluctuations between the two lasers and lock the phase of the beat note to the RF reference [14]. In our case, the control circuit reacts to the frequency difference between the beat tone and that of the RF oscillator. The proposed control works to keep the frequency difference between the two laser sources constant and equal to the desired RF carrier. A certain phase noise in the generated RF carrier is tolerated, not introducing serious limitations on the system performance as far as on-off keying modulation format is used.

The remaining 10% of the output signal of each laser in the central station was employed to generate depolarized light to overcome signal fading due to polarization fluctuations at the uplink modulator, located at the RAU. Different laser sources were used for comparison and in all cases the output power of each laser source was adjusted to +2.3 dBm. Considering the 90/10 proportion for downlink and uplink transmissions, the downlink radiofrequency carrier was generated from a total optical power of +4.8 dBm, while the total optical power available to perform the uplink transmission was -4.7 dBm, or -7.7 dBm for each laser source. The uplink optical carrier is directly modulated with the baseband signal, enabling a higher gain-bandwidth product at the detection and, consequently, high sensitivity detection for data recovery. Polarization controllers adjust the lasers in parallel polarizations for downlink and orthogonal polarizations for uplink.

To evaluate the influence of the laser linewidth over the quality of the radiofrequency signal generated, laser sources with linewidths of 200 KHz, 800 KHz and 10 MHz, approximately, were combined in pairs. Besides the linewidth difference, the wavelength stability of the wide laser was worse than that of the narrow laser source. First of all, it was necessary to adjust the optical frequency difference between the two laser sources to be equal to the desired microwave frequency, in our case 18.2 GHz, which corresponds to approximately 0.146 nm.

At the RAU, after the propagation through the 100-meters SMF optical cable, the downlink optical signal was detected and the microwave signal at 18.2 GHz, which is the result of the beating signal of the two laser sources at the photodetector, was amplified before transmitted to a 30 cm diameter RF antenna. An electrical circulator was used to perform full-duplex transmission. Low bias and low current amplifiers and drivers were used in this station. Three POF modules were used to provide the electrical power to drive the RAU. The electrical power was divided to independently feed the downlink with one module and uplink circuitry with two modules. Each module provides 300 mW electrical power at the RAU, included the fibre loss.

In order to test the full-duplex transmission we used a repeater station to loop back the downlink signal to the RAU. This station enabled us to realize the full-duplex transmission test of the ROF system without the need of a second central station and RAU: the 18.2 GHz radiofrequency signal was filtered, its power detected and the same base-band signal of the downlink light was used to perform uplink communication. Fig. 3 shows the repeater station, where a generator was used to provide the 19.2 GHz uplink RF carrier, which was mixed with the baseband signal, amplified and transmitted back to the RAU through an electrical circulator.

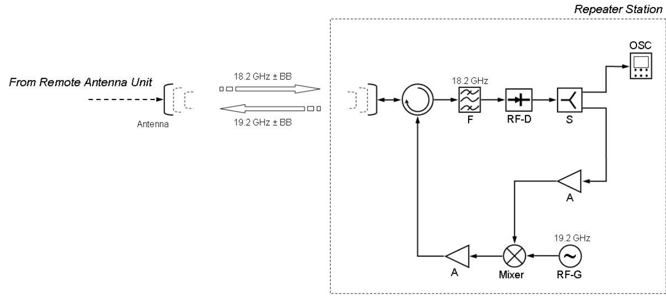


Fig. 3. Set-up of the repeater station; F: Filter, RF-D: RF detector, S: Splitter, OSC: Oscilloscope, A: Amplifier, RF-G: RF generator.

It is important to perceive that there is no optical component in the repeater station, it is necessary just to plug it in the power and it is ready for uplink transmission.

Back to the RAU, the 19.2 GHz uplink signal from the repeater was received and detected. The detected baseband signal was used to feed the uplink low V_π Lithium-Niobate modulator, after filtering to eliminate any high-frequency noise and further amplification.

The repeater station was six meters far from the RAU with line of sight (LOS), while the BER meter located at the central station was set to 155Mbps PRBS no frame data stream. Even that the system was tested in an indoor environment, its power budget enables an outdoor application with a wireless link length of about 400 meters.

The uplink optical signal was transmitted until the central station through another fibre of the 100-meters optical cable. Bit-error rate (BER) measurements of the detected uplink data at central station enable the communication quality evaluation of the whole ROF system.

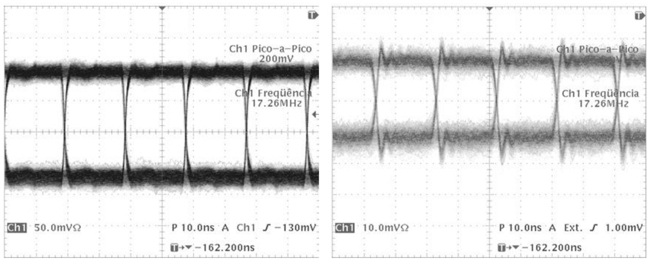
III. Results and Discussion

A. Influence of the quality of optical sources over ROF system performance and PCS application

To obtain the results showed in this session, the control of the laser frequency stability was turned off, since no long-term evaluation was carried on this time.

Fig. 4 allows a first evaluation of the transmission quality because it shows downlink and uplink eye diagrams of the transmitted 52 Mbps PRBS baseband signal. A PRBS (pseudo-random bit sequence) generator features the baseband signal. Despite of the amplitude difference, which reflects the different power budgets for downlink and uplink transmissions, both eye diagrams are clean and enabled error-free measurements, attesting a good quality transmission in the both directions. In this case, the radiofrequency for the downlink transmission was generated through the beating of the laser sources with 200 KHz and 800 KHz linewidths and maximum output powers of 2.3 dBm.

To test efficiency of the uplink polarization independent modulation scheme, polarization variations were induced by varying a polarization controller placed before the uplink modulator. The polarization variation introduced with the controller emulate those arising from temperature fluctuations and wind over installed aerial cables. Good performance was observed, enabling to completely eliminate signal fading due to polarization fluctuations at the RAU uplink modulator.

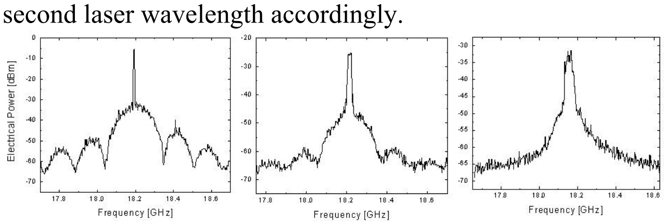


(a) (b)

Fig. 4. (a) Downlink and (b) uplink eye diagrams of the transmitted 52 Mbps PRBS baseband signal.

The influence of the linewidth of the beating lasers over the quality of the generated radiofrequency was evaluated by changing the laser sources. Two different tuneable lasers were used, with 200 kHz and 800 kHz linewidths, as well as two standard telecom DFB lasers with 10 MHz linewidth each. Fig. 5 shows the spectrum of the 18.2 GHz radiofrequency carrier used to transmit 156 Mbps downlink baseband signals for all the possible combinations between the three lasers available. It is clear that the linewidth of the beating lasers directly affect the linewidth and quality of the generated RF signal. Surprisingly, clear open eyes could be obtained even in the worst case RF spectrum, where the characteristic notch structure of the PRBS spectrum is almost smeared out.

Good quality baseband signal could be obtained even with a very bad quality RF spectrum. This intriguing feature may be explained by the fact that the measured RF spectra are actually mean spectra of a fluctuating RF central frequency. Because of the characteristics of the DFB laser temperature controls, their wavelength is fluctuating around a mean value, so that the beat signal frequency fluctuates in a time scale much slower than the baseband signal time scale. We confirmed this by turning off the DFB temperature control and temporarily running it at high temperature, tuning the second laser wavelength accordingly.



(a) (b) (c)

Fig. 5. Spectrum of the 18.2 GHz RF carrier modulated with 156 Mbps and generated from lasers with linewidths of: (a) 800 KHz and 200 KHz, (b) 800 KHz and 10 MHz and (c) two with 10 MHz.

Fig. 6 shows the measured power penalties for all possible combinations between the three lasers available, measured with data rates 156 Mbps. We note that the wider the laser linewidth the greater the power penalty and the curves present a BER floor tendency, even if error free transmission could be obtained. This is a further indication that the quality of the RF signal is the responsible for the power penalty when lasers with wider linewidths are employed.

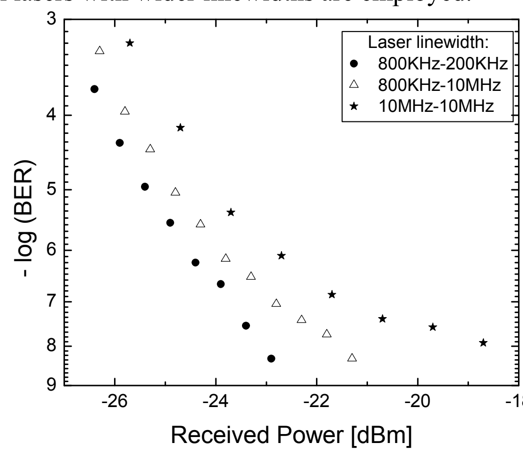


Fig. 6. BER measurements for all possible combinations between the three lasers available, with data rate 156 Mbps.

Considering the possible use of the ROF technology in personal communication systems (PCS's), an accurate evaluation of the RF signal quality is necessary, even when lasers with narrow linewidths generate it. In microcellular or wide coverage mobile PCS's systems, the quality of the optical-link which generates the RF signal is quantified by spurious-free dynamic range (SFDR) measurements.

SFDR is defined as the ratio between the power in the fundamentals and the third-order intermodulation (IMD3) at the input power where IMD3 reaches the noise level. The SFDR of our ROF system was quantified using conventional two-tone measurements [15], for laser sources with 200 KHz and 800 KHZ linewidths. The tone stability and purity was independent of the laser linewidths in all cases, allowing the transmission of phase modulated signals over the FI tone. SFDR measurements were performed replacing the PRBS baseband generator by the combined signals of two generators with equal amplitude and frequencies of 300 and 301 MHz, respectively. Figs. 7 and 8 show the SFDR of our optical-link, before the RF signal feeds the downlink RF transmission antenna and after reception over the microwave link.

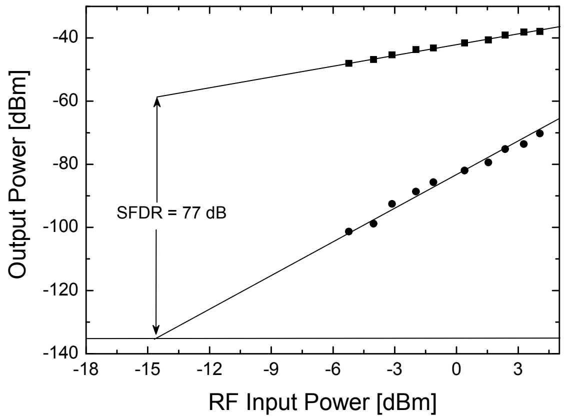


Fig. 7. SFDR measurement of the optical-link, before launching the RF signal to the downlink transmission antenna.

The 77 dB dynamic range is a good value, especially when the quality of the lasers is considered. Furthermore, simulation results in previous works, where the goal was to accurately quantify the relationship between optical-link quality and PCS [16] or Advanced Mobile Phone System (AMPS) [17] quality of service, indicate that representative SFDR requirements for fibre infrastructures in such systems are in the 72-83 dB · Hz2/3 range. These results confirm that the 77-dB SFDR of our optical-link satisfy these requirements and that it is suitable for use in wireless networks as PCS and AMPS.

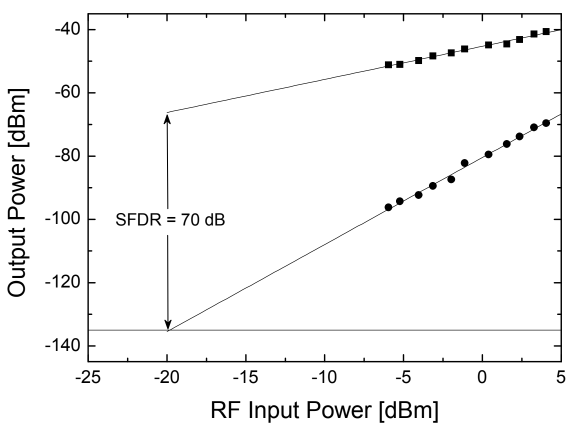


Fig. 8. SFDR measurement of the whole ROF link.

The whole ROF link also fulfils the SFDR requirements of the wireless networks, as shows the measured SFDR of the detected RF carrier at the repeater station, i.e., just after the RF link. As Fig. 8 shows, a degradation of 7 dB was observed after the RF link. We assign this degradation to the noise figure of the RF amplifier. Consequently, it is reasonable to point that the replacement of this device by another one with smaller noise figure will ensure that our whole ROF system is fully inside the range needed for use in wireless networks.

B. Laser frequency stability control and digital TV transmission

Even though a good full-duplex RF quality transmission was demonstrated, it is not sufficient for modern applications of ROF systems, like digital video transmission. In this scenario, more than transmission quality, reliability becomes the most important feature of such systems.

Consequently, in modern ROF systems which employ heterodyne generation to obtain the microwave signal, it is crucial to have a control system capable to keep constant the optical frequency difference between the two laser sources, ideally equal to the desired RF (in our case, 18.2 GHz), avoiding the divergence of the RF carrier from the desired value, the RF power fading and the communication loss.

To test the efficiency of our frequency stability control, we took a 9-hours average of the error signal with the control turned on.

The average spectrum presented in Fig. 9 is very similar to a smoothed version of the instantaneous spectrum of Fig.2. This means that the probability density function (PDF) of the tone produced by the mixing process is very sharp. The upper limit of 500 MHz can be considered a good approximation to infinity because the lower power level at high frequencies. Consequently, Fig. 9 clearly shows that a tone with frequency close to 20 MHz is more probable. This result confirms the efficiency of the control system, as the tone frequency remains in the 50 MHz frequency range during the most of the time, i.e., the downlink carrier remains stable and close to 18.2 GHz. The shape of the curve in Fig. 9 for frequencies higher than 100 MHz, reflect the shape of the characteristic curve of the low-pass filter used.

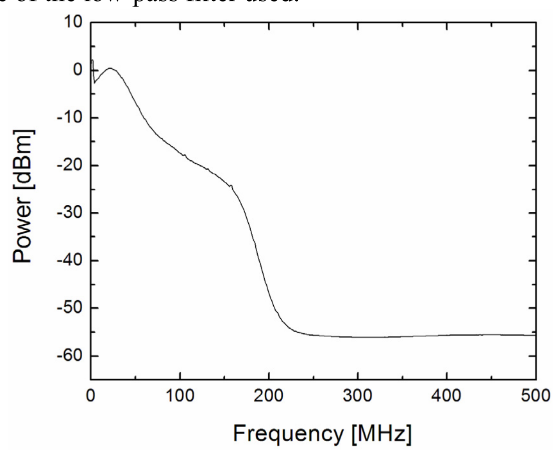
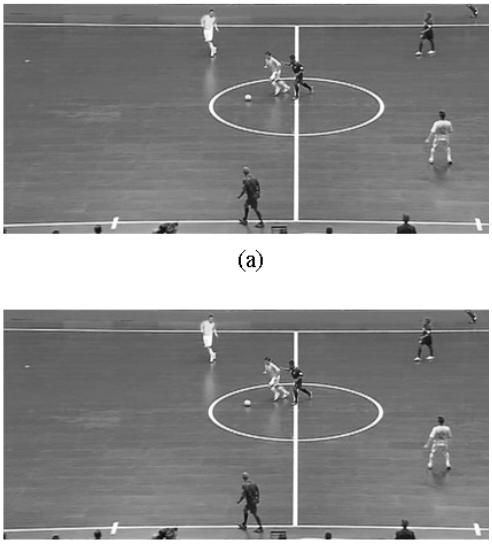


Fig. 9. 9-hours average of the error signal with the control turned on.

Therefore, confirming the efficiency of our frequency stability control, we employed our ROF system for a digital full-duplex TV transmission; the results, images of a soccer game, are displayed on Fig. 10.



(a)

(b)

Fig. 10. Transmission of a digital image; (a) Back-to-back and (b) Through our ROF system.

Fig. 10 (a) shows the image received in a back-to-back transmission, i.e., with the direct connection of the digital encoder and decoder, while in Fig. 10 (b) it can be observed the image received after our ROF system was introduced between them.

A subjective comparison between the images on Fig. 10 confirms their similarity, i.e., no significant differences between their appearance can be pointed out. Moreover, even that the original bit rate of the digital image transmitted is close to 18 Mbps (like in modern digital video transmission), the digital ASI/SDI encoder up-scales the bit rate to 270 Mbps for transmission. So, the success obtained not only certificates our ROF system for digital transmission, but confirms that error-free measurements can be reached with it for bit rates up to 270 Mbps.

C. *Long-term performance evaluation*

Considering the possible use of such a ROF technology in wireless local area networks, an accurate evaluation of the availability is necessary under the 802.11n parameter goals. To find out the long-term availability of the system, an uninterrupted 150 hours-measurement was performed at 156 Mbps, where bit-error-rate tester equipment performed averaged (BERT) measurements at each 3 elapsed minutes.

However, the performance requirements for wireless networks under the IEEE 802.11 standard are specified in terms of packet-error-rate (PER). Consequently, it was necessary to extract the PER from BER data in order to analyse the system according to the 802.11 standard.

To accomplish this we use the approximation given by $PER = 1 - [1\text{-}BER]^n$ where n is the packet size [18]. Another important parameter commonly used to evaluate current wireless networks is the throughput, which can be related to PER as Throughput = Rate x (1-PER) [19]. Therefore, anyone can find that Throughput = Rate x $(1 - BER)^n$.

According to the IEEE 802.11 standard, "the PER shall be less than 10% for a PSDU length of 4096 octets", i.e., 32768 bits. Taking into account this technical statement, we evaluated our system under the worst scenario, i.e., using the maximum packet size given by 802.11n or n equal to 32768 bits.

Under this environment, the achieved results are displayed on Fig. 11.

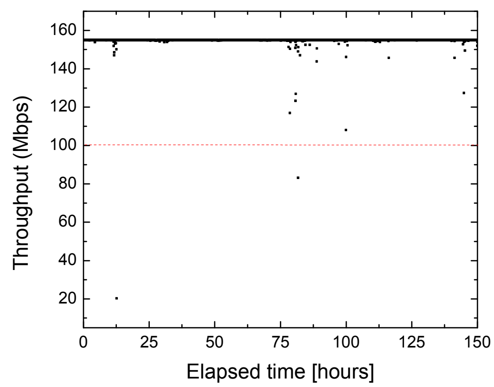


Fig. 11. Calculated throughput.

We can observe that for all the elapsed time (150 hours) the throughput was below 100 Mbps during only 6 minutes. Under a statistic approach, this behaviour corresponds to 2 points in a space of 3000 samples, which means that a throughput above 100 Mbps is available in more than 99.99% of the time.

Moreover, in Fig. 12 the cumulative probability of PER for 156Mbps confirms that the availability of our system is higher than 99%, fulfilling the 802.11n standard goals and allowing it to be used in wireless networks with high performance requirements.

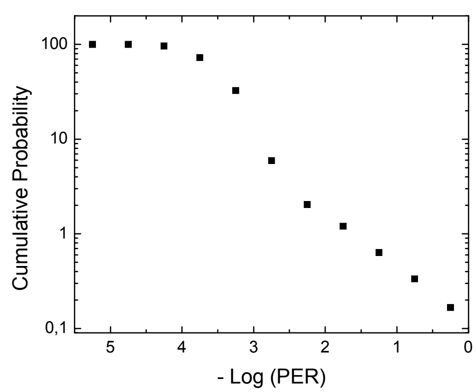


Fig. 12. Cumulative probability for PER under 156Mbps.

IV. Conclusions

It was shown a full-duplex ROF system with an efficient laser frequency stability control, capable to lock the microwave signal resultant from the heterodyne generation to the desired RF carrier.

The results of the SFDR measurements confirm that our ROF link is suitable for use in wireless networks as PCS and

AMPS.

The control system described here is very simple and robust, allowing automatic operation and increasing the reliability of the whole ROF system, ensuring high quality communication, confirmed with a successful digital transmission.

Therefore, to confirm the reliability of the proposed system, we have shown a long term performance evaluation of a robust ROF system. The results confirm that our system satisfy the requirements of the IEEE 802.11 standard, once an availability higher than 99% at 156 Mbps was achieved during uninterrupted 150 hours evaluation time (the cumulative probability of PER < 10% was 0.4%, approximately), enabling it for use in nowadays and future wireless local area networks.

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Djeisson Hoffmann Thomas was born in Alecrim, Rio Grande do Sul, Brazil, in March, 21, 1978. Graduated in Electrical Engineering from the Federal University of Santa Maria (Rio Grande do Sul, Brazil) in 2002. Obtained his Masters and PhD in Electrical Engineering from PUC-Rio in 2003 and 2007, respectively.
Currently he is a researcher at the Optoelectronics and Instrumentation Group at CETUC/PUC-Rio and his main research interests are Optoelectronics, Instrumentation, radio-over-fiber systems and the study of the properties of non-metallic and unpolarized materials through imaging in the terahertz frequency range.

Giancarlo Vilela de Faria was born in Barra Mansa, Rio de Janeiro, Brazil, in July, 5, 1973. Graduated in Electrical Engineering from the Pontifical Catholic University of Rio de Janeiro in 2002. Obtained his Masters and PhD in Electrical Engineering from PUC-Rio in 2004 and 2008, respectively. Currently he is a researcher at the Optoelectronics and Instrumentation Group at CETUC/PUC-Rio and his main research interests are optical communications, optoelectronics, instrumentation, and optical imaging techniques applied to NDE as optical coherence tomography among others.

Jean Pierre von der Weid was born in Rio de Janeiro, Brazil, in August 1, 1948. He obtained his PhD in physics from the Physics Department of the Pontifical Catholic University in 1976. He is currently full professor at the Center for Telecommunications Studies in the same university, where he heads the Optoelectronics and Instrumentation Group. His current research areas are optics, optoelectronics, optical communications and instrumentation.