Optically-Powered Remote Units for Radio over Fiber Systems

David Wake, *Member, IEEE*, Anthony Nkansah, Nathan J. Gomes, *Senior Member, IEEE*, Christophe Lethien, Cathy Sion and Jean-Pierre Vilcot

***Abstract*— Optically-powered radio over fiber remote units have been designed and constructed for distributed antenna system applications using separate fibers for power and signal transmission. The feasibility of this approach has been investigated through a series of transmission measurements, based on the IEEE 802.11g wireless local area networking standard at a frequency of 2.5 GHz using 64QAM OFDM modulation at 54 Mb/s. These measurements show that high quality multi-level signal transmission is possible with modest levels of optical power at the central unit. For example, an EVM of around 3 % has been achieved for an RF output power of 0 dBm using a central unit optical power of 250 mW over a link length of 300 m.**

***Index Terms*—Distributed antenna systems, power over fiber, radio over fiber, wireless local area networks.**

I. Introduction

Optical powering of remote electronic equipment, also known as power over fiber, is a technique that uses a high power laser at a central location, a photovoltaic converter at a remote location and an optical fiber linking the two sites as a transmission medium for the optical power. Power over fiber provides excellent electrical isolation, is impervious to RF and magnetic fields, is interference-free and is safe in applications where sparking may be dangerous. This technique can be used for applications that require a relatively low level of electrical power and where the provision of a conventional electrical power supply is either impractical, expensive or hazardous. It is used, for example, for data transmission links in high voltage environments in electricity sub-stations.

Power over fiber has also been considered for powering telecommunications equipment in fiber in the loop installations [1]. The main conclusion from this work was that optical powering was not economically viable for fiber in the loop at that time, partly because the high power lasers were expensive and partly because the power consumption of the remote equipment was relatively high. However the recent commercial availability of photovoltaic converters designed for fiber input and the reductions in the cost per Watt of high power lasers means that this technique may now be more attractive.

Radio over fiber is an analog optical transmission technology in which radio signals are delivered to remote locations from a central unit containing wireless access points or radio base stations. The advantages of radio over fiber are compelling; remote units are greatly simplified since most of the expensive, heavy and power consuming equipment is now located centrally and centralization of the wireless access points or radio base stations means that fewer radio resources are required to provide a given level of service. These advantages give network operators significant capital and operational cost savings and are the reasons why radio over fiber has been used extensively in distributed antenna systems around the world, especially for in-building applications [2, 3].

In-building distributed antenna systems require relatively low power consumption at their remote units, which means that it may be viable to power them optically [4]. The purpose of this paper is to investigate the feasibility of using power over fiber for this application more fully than was achieved in [4], using a greater range of transmission measurements including OFDM modulation. Section II describes the design options for optically-powered radio over fiber transmission links and Section III describes an experimental remote unit constructed from one of these designs. Section IV gives the results of the transmission measurements which were conducted in order to verify that the performance of the radio over fiber link was acceptable for the intended application. Finally, conclusions from this work are presented in Section V.

II. Design of Remote Units

A. Radio over Fiber Link Parameters

The design of the optically-powered remote units in this work is based on the wireless local area networking standard IEEE 802.11g [5], which operates in the 2.4 GHz band with raw data rates up to 54 Mb/s using 64-level quadrature

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D. Wake, A. Nkansah and N. J. Gomes are with the Broadband and Wireless Communications Group, Department of Electronics, University of Kent, Canterbury, CT2 7NT, UK (e-mail: d.wake@kent.ac.uk).

C. Lethien, C. Sion and J-P. Vilcot are with the Institut d'Electronique, de Microélectronique et de Nanotechnologie (IEMN), UMR CNRS 8520, Université des Sciences et Technologies de Lille, 59652 Villeneuve d'Ascq, France, and also with the Research Federation IRCICA, 59652 Villeneuve d'Ascq, France (e-mail: jean-pierre.vilcot@iemn.univ-lille1.fr).

amplitude modulation (64-QAM). The designs described here are based on this transmission rate and modulation format, and it is assumed that a minimum carrier to noise ratio of 24 dB is required for good quality signal transmission. The standard specifies other important design parameters, such as the maximum power level that the receive antenna must be able to accommodate (-20 dBm) and the maximum spurious emissions from the transmit antenna (-30 dBm in a 1 MHz bandwidth). These parameters determine the maximum and minimum signal and noise power levels that must be supported or generated by the radio over fiber links.

Fig. 1 shows the generic design of a bidirectional radio over fiber link. The remote unit contains a laser, a photodiode and amplifier chains for the downlink (transmission direction from central unit to remote unit) and uplink (transmission direction from remote unit to central unit). The performance of a radio over fiber link depends on the efficiency, noise and linearity of the laser and photodiode as well as the gain, noise and linearity of the RF amplifiers. High performance radio over fiber links will require relatively high electrical power consumption because their components need to be operated at elevated bias levels while maintaining adequate linearity. There is therefore a trade-off between power consumption and performance (radio range) that must be considered when designing optically-powered remote units.

B. Radio over Fiber Link Types

Three link types are considered for this work, classified as short, medium and long range. For each link type, the laser type, fiber type and amplifier gain must be optimized for performance and power consumption. The design assumptions for each link type are summarized in Table I. The short range link uses a vertical cavity surface emitting laser (VCSEL), which has low power consumption but relatively poor performance (high noise and low maximum RF input power). The medium range link uses a Fabry-Perot laser (FP), which has medium power consumption and medium performance. The long range link uses a distributed feedback laser (DFB), which has relatively high power consumption but has low noise and high maximum RF input power.

The relative intensity noise values given in Table I were based on typical data sheet values. The maximum RF input power was calculated from the maximum acceptable optical modulation depth (in this case 0.4, based on previous measurements) and bias current above threshold (9, 25 and 35 mA for VCSEL, FP and DFB lasers respectively). The short range link type uses 300 m of OM3 multimode fiber (MMF) which has been optimized for high bandwidth using VCSEL sources and typically has a bandwidth-distance product of 2 GHz.km. The medium and long range links use 1 km of single mode fiber (SMF).

C. Radio over Fiber Link Design Results

The link design process starts with the uplink, which is the direction that normally determines the maximum radio range for a balanced link. The uplink amplifier gain is set by the difference (in dB) between the maximum RF input power to the laser and the maximum power level that the receive antenna must be able to handle in the IEEE 802.11g standard. For example, in the short range link, this is 16 dB (-4 dBm - -20 dBm). The uplink radio range can be calculated from the gain and noise of the optical link, the receiver sensitivity of the access point (-75 dBm), the required carrier to noise ratio (24 dB), the transmit power of the mobile device (15 dBm) and the path loss over the air interface. The propagation model used in this work was the linear path loss method developed by Keenan and Motley for radio propagation within buildings using an attenuation coefficient of 0.47 [6].

The downlink radio range was set to the same value as the uplink radio range because we assumed a balanced link. The downlink transmit power to achieve this radio range was then calculated from the mobile receiver sensitivity and the path loss. The downlink amplifier gain was then calculated by a simple power cascade analysis. A check on the transmitted noise power was then made to make sure that the spurious emissions requirement specified in the standard was not violated. Results of this analysis are given in Table II.

D. Amplifier Design

Table 2 provides values for the amplifier gains and output powers required for the three link types. The downlink power amplifiers must be designed to provide sufficient output power with acceptable distortion and spurious emissions. Typically, the 1 dB saturation power (P1dB) of a power amplifier must be at least 6 dB higher than its maximum output power for 64-QAM OFDM modulation to achieve an EVM of less than 3 % [7]. This means that downlink power amplifiers having P1dB of +2, +10 and +18 dBm must be used for the short, medium and long range link types respectively.

The amplifier parameters used in the remote unit designs were taken from the Avago Technologies ATF-551M4 transistor datasheet [8], apart from those for the downlink power amplifier for the long range link, which were taken from the Avago Technologies ATF-54143 transistor datasheet [9]. Both of these devices are low noise enhancement mode pseudomorphic HEMTs with a frequency range of up to 6 GHz. Minimum power consumption was ensured for each link type by designing the amplifiers with minimum bias conditions to give the required P1dB power. From the ATF-551M4 transistor datasheet, a P1dB of +12 dBm can be achieved with a bias voltage of 2.2 V and a current of 10 mA (22 mW power consumption). This bias point was used for all amplifiers apart from the downlink power amplifier for the long range link, which was designed to operate at a bias voltage of 3.3 V and a current of 20 mA (66 mW power consumption). This bias point gives a P1dB of more than +18 dBm according to the ATF-54143 datasheet. It should be noted that the current values given here are quiescent levels and that actual current will be much higher when P1dB is reached. However, the maximum input RF power is limited to

6 dB below P1dB in this analysis, therefore the actual current will be very close to quiescent levels.

All amplifiers have a gain of approximately 16 dB at 2.5 GHz. Therefore the short range remote unit requires a total of three amplifiers, one for the uplink and two for the downlink, to achieve the required gains. The medium and long range remote units use four amplifiers each, two for the uplink and two for the downlink. Attenuators were inserted between amplifiers when the required gain was less than 32 dB.

E. Radio over Fiber System Design

The layout of the power over fiber system is shown in Fig. 2. Although higher optical power levels can be generated and transmitted if lasers with broad stripe widths and fibers with large core diameters are used, a compromise was made in this design so that standard data communications OM1 fiber could be used. This has a core diameter of 62.5 μm. Most high power lasers with output powers in excess of 1W have stripe widths of at least 100 μm, but the design of this system was based on a high brightness laser from JDSU, which has an output power of up to 2W into 60 μm core diameter fiber at a wavelength of 830 nm [10]. The photovoltaic converter used in this design was the PPC-4E from JDSU, which is optimized for this wavelength and is compatible with 62.5 μm core diameter fiber [11]. This device provides an output voltage of up to 4 V and an efficiency of around 50 %. The attenuation of OM1 fiber at the design wavelength of 830 nm is around 2.5 dB/km.

The output of the photovoltaic converter is regulated to +3.3 V and then converted to +2.2 V for the amplifiers (apart from the downlink power amplifier for the long range link, which operates directly from the +3.3 V output from the regulator). The output of the voltage regulator is also doubled and inverted to give -6.6 V for the photodiode. Finally, the output of the regulator feeds a current source circuit to provide a current supply of 10 – 45 mA for the laser.

F. Optical Power Requirements

The power consumption of each of the remote unit types is shown in Table 3. For example, the short range unit contains a VCSEL (2.2 V, 10 mA) a photodiode (-6.6 V, 1.5 mA) and three amplifiers (2.2 V, 10 mA each), which gives a combined power consumption of 98 mW. The remote power supply is assumed to have an efficiency of 95% based on the datasheets of the regulator, converter, current source and inverter/doubler circuits. The electrical power required at the output of the photovoltaic converter can be calculated from this efficiency figure and the results are also shown in Table 3. For example, the electrical power required for the short range link is 103 mW. If the photovoltaic converter has an efficiency of 50 %, then the optical power required at the short range remote unit is 206 mW. This and the corresponding powers for the other links are also shown in Table 3. The optical power required at the central unit can be calculated from the attenuation and length of the power fiber. These values are also given in Table 3 for the three link types. For example, the short range link requires a central optical power of 245 mW. Since the high power laser has an output power of up to 2 W, this means that around eight short range remote units can be powered from a single laser in this instance. Fig. 3 shows how the required optical power at the central unit varies as a function of fiber length and link type.

III. EXPERIMENTAL REMOTE UNIT

A. Remote Unit Layout and Power Consumption

An optically-powered remote unit was constructed based on the short range design variant described in Section II, in order to verify the performance and power consumption calculations. The experimental remote unit was designed to operate at 2.5 GHz and the layout is shown in Fig. 4. The laser is a ULM Photonics multimode VCSEL which operates at a wavelength of 850 nm. This device has a bandwidth of 3 GHz, a fiber-coupled efficiency of 0.4 W/A and a relative intensity noise of -145 dB/Hz at a bias current of 10 mA. The photodiode is an Appointech GaAs PIN device with an efficiency of 0.4 A/W. The bias tees were Minicircuits ZFBT-6G models with a frequency response up to 6 GHz. The amplifiers were all constructed using Avago Technologies ATF-55143 transistors, which are very similar to the ATF-551M4 discussed in the design section, but have a surface mount package which was more convenient to use. The amplifiers were designed to operate at 2.2 V and a frequency of 2.5GHz. They had an operating current of 9 mA, a gain of 15 dB and a P1dB of +7 dBm. A 3 dB attenuator was placed between the two downlink amplifiers to provide an overall gain of 27 dB.

The VCSEL was powered directly from the 2.2 V output of the voltage converter, rather than from the current source, to conserve power. This bias method provided stable performance within the scope of the measurements undertaken here. The combined power consumption of the laser, photodiode and amplifiers in the remote unit was 92 mW. The VCSEL consumed 22 mW (2.2 V, 10 mA), the photodiode consumed 10 mW (-6.6 V, 1.5 mA) and each of the three amplifiers consumed 20 mW (2.2 V, 9 mA). The efficiency of the power supply circuits (regulator, doubler/inverter and step-down converter) was 82%, which was mainly due to the choice of voltage regulator. Higher power supply efficiency can be obtained in future versions simply by choosing a regulated voltage closer to the output voltage of the photovoltaic converter (4 V in this case). An electrical power of 112 mW was required from the photovoltaic converter (4 V, 28 mA) to supply the remote unit components. The photovoltaic converter had an efficiency of 0.14 mA/mW and therefore required an input optical power of 200 mW.

B. Experimental System Configurations

All measurements on the remote unit were performed using the optical power supply. The high power laser was from JDSU, had a maximum output power of 2 W into a 62.5 μm core diameter fiber and a wavelength of 834 nm. The power transmission fiber had a core diameter of 62.5 μm, a length of 300 m and an optical loss of 1 dB. The output of the high power laser was adjusted to 250mW to provide sufficient power to the remote unit.

Dynamic range, error vector magnitude (EVM) and spectrum mask measurements were performed using a loop-back configuration in which a 300 m OM3 multimode fiber reel was connected between laser and photodiode. This fiber had a core diameter of 50 μm, an optical loss of 1 dB and a relative response of -0.5 dB at 2.5 GHz. The loop-back optical link (without amplifiers) consisting of the laser and photodiode from the remote unit and the 300 m OM3 fiber reel had a gain (G) of -25 dB and an output noise (N_{out}) of -154 dBm/Hz at a frequency of 2.5 GHz. Two-tone measurements at this frequency were performed which gave an input third-order intercept point (IIP3) of +11 dBm. The spur-free dynamic range (SFDR) was calculated from the relation SFDR = 2/3 (IIP3 – G – N_{out}) to be 93.3 dB.Hz $^{2/3}$.

EVM measurements were performed for both uplink and downlink directions. For the downlink measurements, the uplink amplifier was removed from the signal path such that the configuration consisted of laser, fiber, photodiode and post-amplifier. For the uplink measurements, the downlink amplifier was removed from the signal path such that the configuration consisted of pre-amplifier, laser, fiber and photodiode. All amplifiers, whether in the signal path or not, were connected to the power supply. The downlink configuration had an overall gain of +2 dB and the uplink configuration had an overall gain of -10 dB. Measurements were also made on the optical link without any electrical amplifiers in the signal path. The signal generator and signal analyzer used for these measurements (and also the spectrum mask measurements) were the Agilent E4438C and the Agilent E8408A mainframe with 89605B module respectively.

Throughput measurements using an IEEE802.11g access point were performed using the system configuration shown in Fig. 5. The central unit laser and photodiode were the same types as those used in the remote unit and the fibers linking the central and remote units for the uplink and downlink was a duplex reel with 50 μm core diameter and a length of 300 m. The access point in the central unit was a Netgear WG102 model with a detachable antenna. The connection from this access point was split into uplink and downlink directions using a circulator and the downlink signal power was attenuated (by 20 dB) before being applied to the central unit laser. The antennas and remote unit components were fixed to the upper surface of a ceiling tile which was suspended a few centimeters from the ceiling in our laboratory. The central unit was located in another laboratory and care was taken that direct signals radiating from the access point or central unit did not interfere with the measurements. Throughput measurements were performed by transferring a large video file between the desktop and laptop PCs.

IV. TRANSMISSION MEASUREMENT RESULTS

A. Error Vector Magnitude Measurements

Error vector magnitude is an important metric for multilevel transmission systems. All measurements were made at a frequency of 2.5 GHz using 64-QAM modulation and a data rate of 54Mb/s. Measurements were made with and without orthogonal frequency division multiplexing (OFDM) modulation. This was not done in an effort to compare the two types of modulation, but because we had access to different measurement equipment at different times. Measurements made without OFDM used a root raised cosine filter with α = 0.25; those made with OFDM used a Gaussian filter with α = 0.5.

Figs 6 and 7 show the results of the EVM measurements without OFDM. Fig. 6 gives the EVM variation with output power for both the full downlink configuration and for the standalone downlink power amplifier. Fig. 7 gives the EVM variation with input power for the downlink configuration, for the uplink configuration (input power normalized for amplifier gain) and for the optical link without amplifiers. These figures show that EVM is low (less than 2 %) at the design power levels (input and output powers in the range -5 to 0 dBm) and that high EVM is caused simultaneously by two effects; too high an input power to the VCSEL (around +3 dBm for 3 % EVM) and too high an output power from the power amplifier (around +5 dBm for 3 % EVM). These two effects occur at the same operating conditions, which is a result of the optimal design approach used in this work (laser and amplifier performance is only just good enough in order to conserve electrical power).

Figs 8, 9 and 10 show the results of the EVM measurements with OFDM. Fig. 8 gives the EVM variation with output power for both the full downlink configuration and for the standalone downlink power amplifier. Fig. 9 gives the EVM variation with input power for the downlink configuration, for the uplink configuration (input power normalized for amplifier gain) and for the optical link without amplifiers. Fig. 10 gives the EVM variation with input power for the optical link without amplifiers, both with and without the 300 m fiber reel. The first observation to make from these figures is that the EVM values for the downlink configuration are higher than those obtained without OFDM. EVM is around 3 % at the design conditions (input and output powers in the range -5 to 0 dBm) of the link compared to around 1.5 % without OFDM. A second observation is that high EVM is caused as a result of distortion in the VCSEL and in the power amplifier, as was the case in the previous measurements without OFDM, but at slightly lower power levels. An EVM of 5 % is now obtained for a VCSEL input power of only +1 dBm and a power amplifier output power of only +2 dBm. These observations are to be expected because OFDM modulated signals have a very high peak to average power ratio and are therefore less tolerant of any transmission system nonlinearities [12].

A third observation, from Fig. 10, is that the 300 m fiber reel is causing additional EVM. This becomes more apparent at low input power levels; for example, at an input power of -10 dBm, the optical link with fiber reel gives an EVM of around 3 % while the optical link without fiber reel (a 1 m patchcord replaces the fiber reel) gives an EVM of only 1.5 %. It is likely therefore that the fiber reel is introducing additional distortion to the transmission system. Distortion is known to occur as a result of the interaction of laser chirp and fiber dispersion [13]. Further investigation is required to fully resolve this issue but this is outside the scope of the present paper. However, in spite of this penalty, the EVM is well below the 5.6 % limit defined in the IEEE802.11g specification for 54 Mb/s transmission [5].

B. Spectrum Mask Measurements

Another important metric for radio systems is the spectrum mask. Compliance with the spectrum mask ensures that the emissions from a radio transmitter do not cause significant interference with other radio systems that are nearby. Figure 11 shows the output spectrum from the downlink configuration at an output power of +6 dBm. Note that at this level of output power the EVM of the link is extremely high and would therefore be unusable. Also shown on this figure is the spectrum mask for IEEE802.11g and it is clear that the output spectrum fits well within the mask. The output spectrum is therefore not a limiting factor in this design.

C. Throughput Measurements

Throughput measurements were also performed using an IEEE802.11g access point and a bidirectional radio over fiber system with a wireless path as described in the previous section. Throughput measurements as a function of antenna separation were taken for both uplink and downlink as a large video file was transferred backwards and forwards between desktop and laptop computers. Figure 12 shows the results of this measurement. For each measurement point, the laptop was moved along a line in the laboratory that gave the highest possible antenna separation. Throughput was measured at each location when the data transfer reached a steady state. Close observation of the transfer rate showed a greater variability as the separation increased, which is due to an increase in multipath effects within the cluttered environment of the laboratory. However, the results shown in the figure give the maximum steady-state transfer rate in order to avoid arbitrary effects from the particular shape and clutter of the laboratory. It can be observed that the radio range of the system is much greater than the size of the laboratory. Measurements were also performed where the optical links were replaced by a relatively short coaxial cable, using attenuators to ensure that the transmitted power level was equivalent to that of the radio over fiber system. Throughput levels were the same, so it is clear that the optical links do not have a negative effect on throughput.

V. CONCLUSION

Optically-powered radio over fiber remote units have been designed and constructed for distributed antenna system applications. The feasibility of this approach has been investigated through a series of transmission measurements, based on the IEEE 802.11g wireless local area networking standard at a frequency of 2.5 GHz using 64QAM OFDM modulation at 54 Mb/s. These measurements (error vector magnitude, spectrum mask and throughput) show that high quality multi-level signal transmission is possible with modest levels of optical power at the central unit. For example, an EVM of around 3 % has been achieved for an RF output power of 0 dBm, using a central unit optical power of 250 mW over a link length of 300 m. This means that up to eight low range remote units can be powered from a single 2 W laser. This type of laser is commercially available at reasonable cost. The combination of power over fibre and radio over fiber techniques is therefore likely to be economically viable for many distributed antenna applications.

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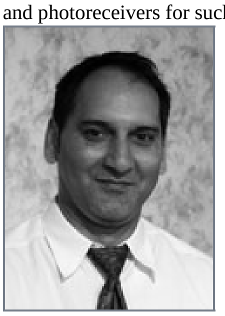
David Wake (M'02) received the B.Sc. degree in applied physics from the University of Wales, Cardiff, U.K., in 1979, and the Ph.D. degree from the University of Surrey, Surrey, U.K., in 1987. He is currently a Senior Research Fellow with the University of Kent, Canterbury, U.K.

From May 2003 to February 2005, he was Director of Research and Development and Chief Scientist with Microwave Photonics Inc., a startup company based in Los Angeles, CA, which was formed to develop a product set for the mobile communications industry based on novel radio-over-fiber technology. In 2002, he cofounded Zinwave Ltd., a startup company aimed at exploiting innovative radio-over-fiber technology for the mobile communications industry. He has been involved in the radio-over-fiber research topic for approximately 17 years, initially with BT Laboratories, where he was the Program Manager for the microwave photonics research domain and then with University College London as a Senior Research Fellow.

Anthony Nkansah received the B.Eng. (with honors) degree in electronic engineering, the M.Sc. degree in broadband and mobile communication networks and Ph.D degree in electronic engineering from the University of Kent, Canterbury, U.K., in 2000, 2001 and 2007, respectively. His research interests include low-cost microwave and millimeter-wave radio-over-fiber networks and their deployment within premises.

Nathan J. Gomes (M'92 - SM'06) received the BSc degree from the University of Sussex, UK, in 1984 and the PhD degree from University College London in 1988, both in electronic engineering.

From 1988 to 1989 he held a Royal Society European Exchange Fellowship at ENST, Paris. Since late 1989, he has been a Lecturer, and since 1999, a Senior Lecturer, in the Electronics department at the University of Kent. His present research interests include radio over fiber systems and networks, the photonic generation and transport of millimeter-wave signals, and photoreceivers for such applications.



Christophe Lethien was born in France, on May 3, 1978. He obtained a B.Sc degree in Physics at the University of Lens (France) in 2000. He received the M.Sc degree in Microwave and Microelectronics at the University of Sciences and Technologies (USTL) from Lille (France) in 2001 and its PhD degree in Optoelectronics in October 2004 at the USTL. From November 2004 to June 2007, he was a civil researcher at the *Royal Military Academy* from Brussels (Belgium) in the **C**ommunication **I**nformation **S**ystems and **S**ensors department (CISS) and he works on polymer based fibre optic link. Now, he is an associate professor at *the « Institut d'Electronique, de Microelectronique et de Nanotechnologie »* IEMN (UMR CNRS 8520, USTL, Avenue Poincaré, BP 60069, 59652 Villeneuve d'Ascq - France) and in the Research Federation *« Institut de Recherche sur les Composants logiciels et matériels pour l'Information et la Communication Avancée »* IRCICA (FR 3024, Parc Scientifique de La Haute Borne, 50 avenue Haley, 59652 Villeneuve d'Ascq - France). He works on wireless sensors networks and optical fibre based wired networks.

Cathy Sion was born in Lille, France in 1972. She received the Ph.D. degree in Electronics from the "Universite des Sciences et Technologies de Lille", Villeneuve d'Ascq, France in 1999. Her Ph.D. research deals with the study of the temperature sensitivity of aluminous-phosphorous multi-quantum well laser structure on InP substrate.

Since 1999, she is Assistant Professor at Ecole Centrale Lille (engineering school). Her research activities are with the Optoelectronic research group in the "Institut d'Electronique, de Microélectronique et de Nanotechnologie (IEMN)" in Villeneuve d'Ascq. Her main research topics concern microwave and photonics components characterization and radio over fiber systems.

Jean-Pierre Vilcot was born in Lens, France in 1958. He received the Ph.D. degree in Electronics from the "Universite des Sciences et Technologies de Lille", Villeneuve d'Ascq, France in 1984. His Ph.D. research focused on the design, fabrication and characterization of GaAs integrated photoreceivers.

From 1984 to 1986, he worked as a microwave engineer in a private company. His job was mainly dealing with the design and fabrication of X-band terrestrial and satellite transceivers. In 1986, he joined the "Centre National de la Recherche Scientifique (CNRS)" and since that time he is appointed to "Institut d'Electronique, de Microélectronique et de Nanotechnologie (IEMN)" in Villeneuve d'Ascq where he is working within the Optoelectronic research group. Since 2001, he is CNRS Research Professor: his main research activities deal with microwave-photonics systems and nanophotonics.

FIGURES

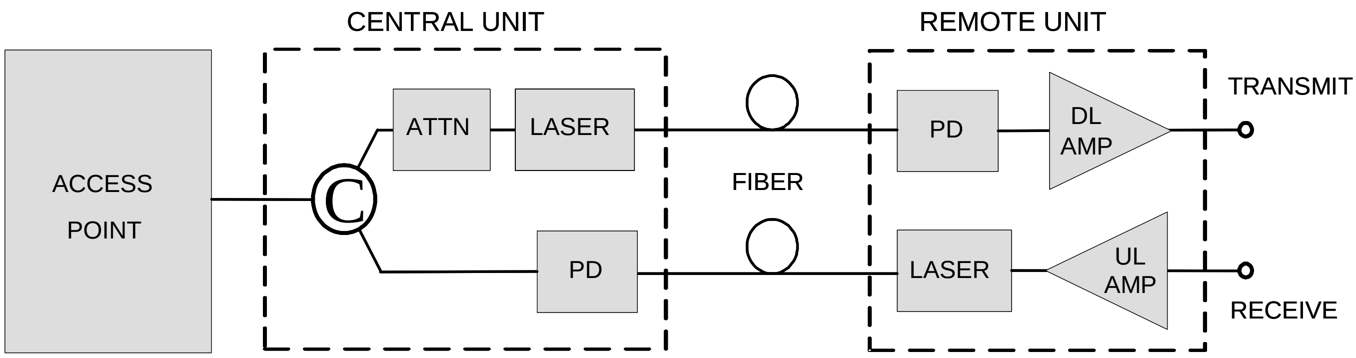


Fig. 1 Generic layout of a radio over fiber link.

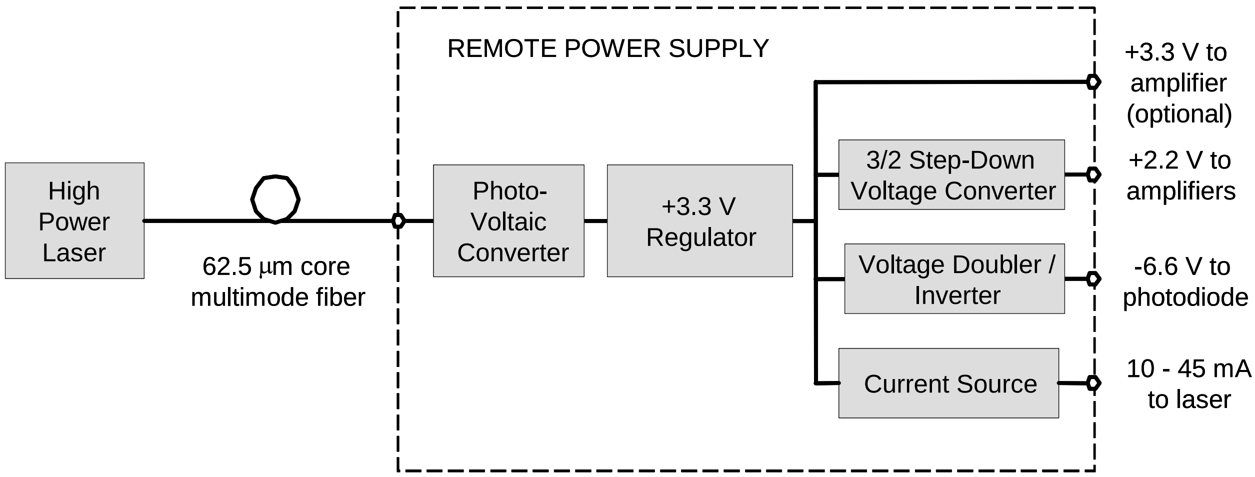


Fig. 2 Layout of power over fiber system.

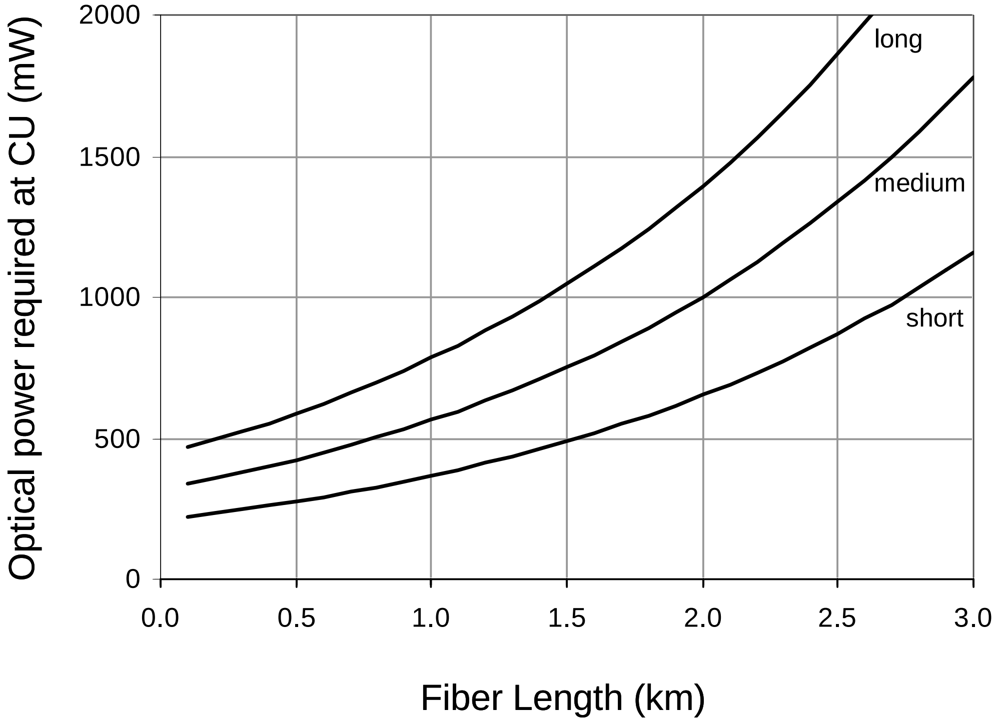


Fig. 3 Required optical power at the central unit as a function of fiber length and link type.

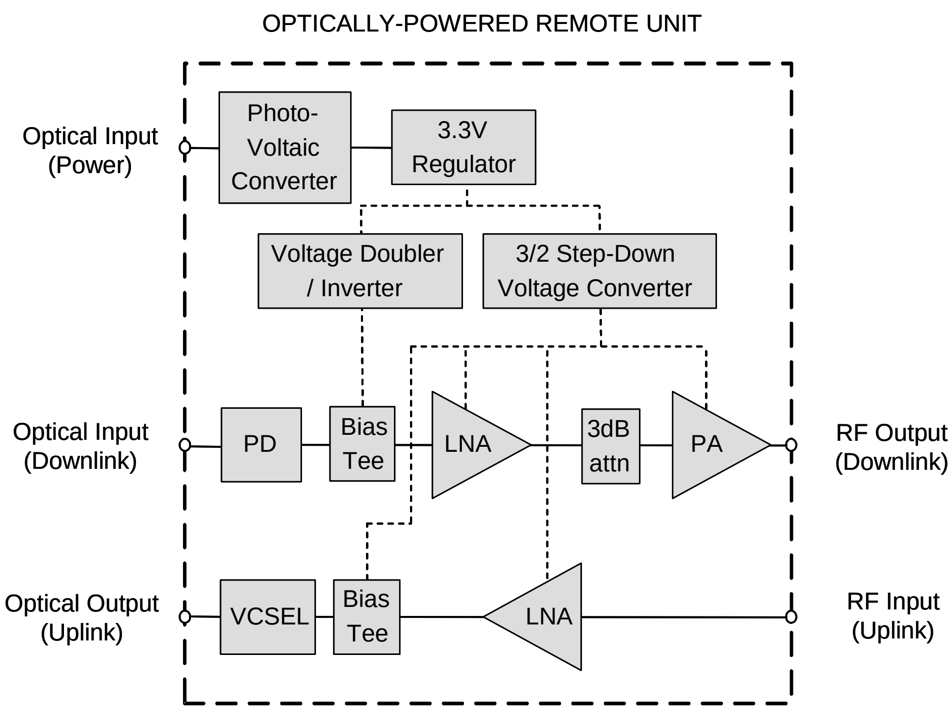


Fig. 4 Layout of experimental remote unit.

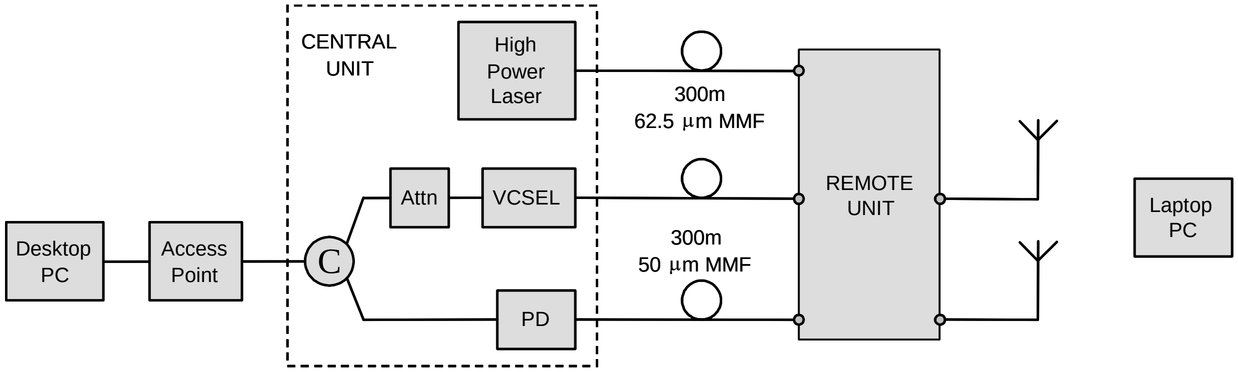


Fig. 5 Experimental system layout for throughput measurements.

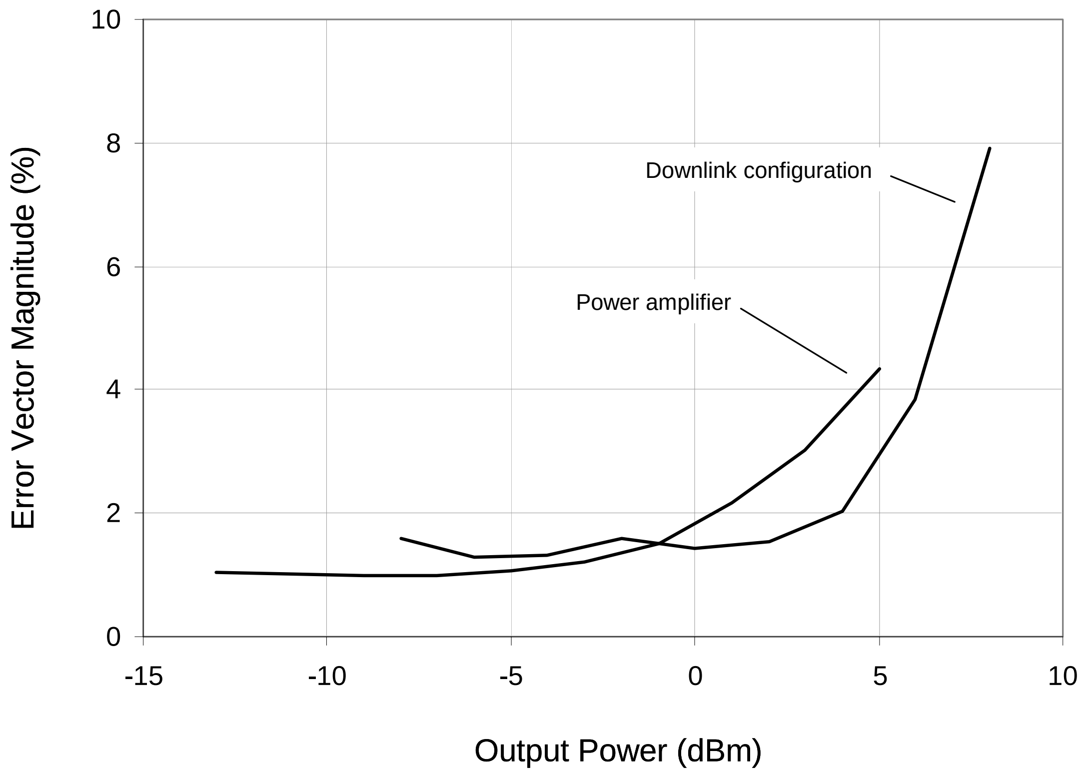


Fig. 6 Error vector magnitude (2.5 GHz, 64-QAM, 9 Ms/s) as a function of RF output power for downlink configuration and for downlink power amplifier.

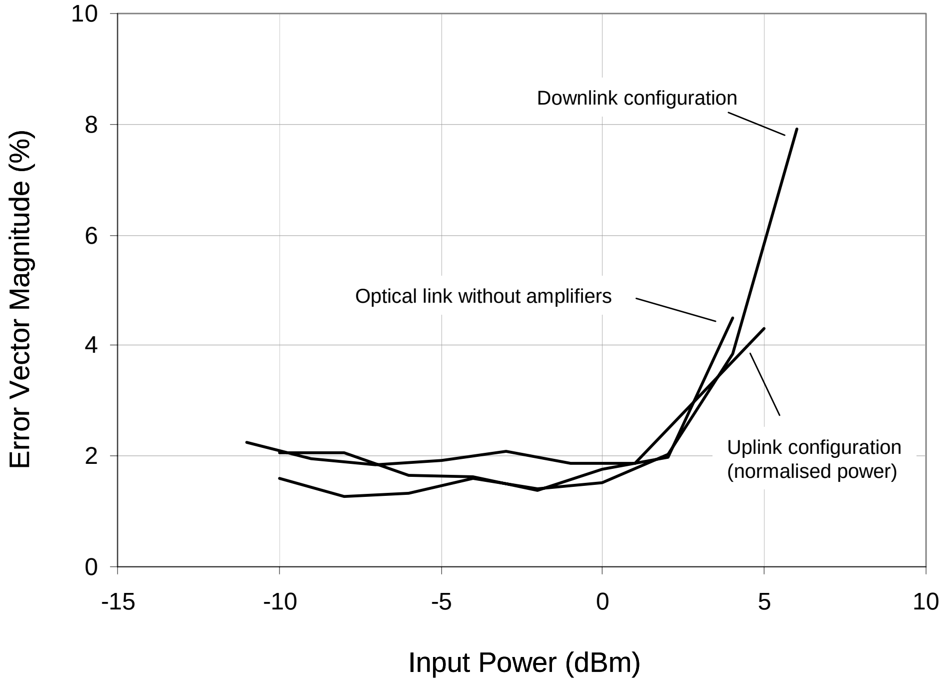


Fig. 7 Error vector magnitude (2.5 GHz, 64-QAM, 9 Ms/s) as a function of RF input power for downlink configuration, uplink configuration (normalized power) and for optical link without electrical amplifiers.

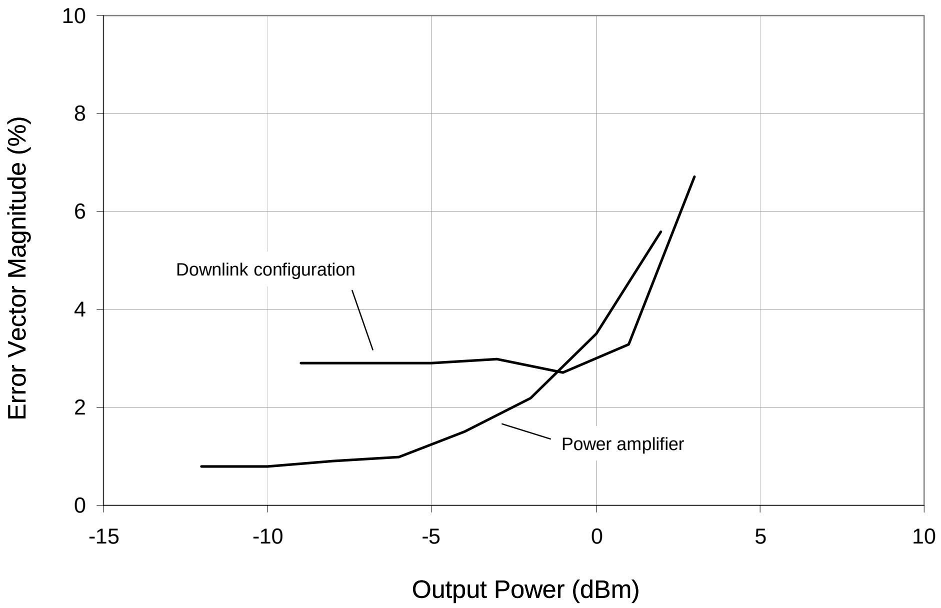


Fig. 8 Error vector magnitude (2.5 GHz, 64-QAM, OFDM, 9 Ms/s) as a function of RF output power for downlink configuration and for downlink power amplifier.

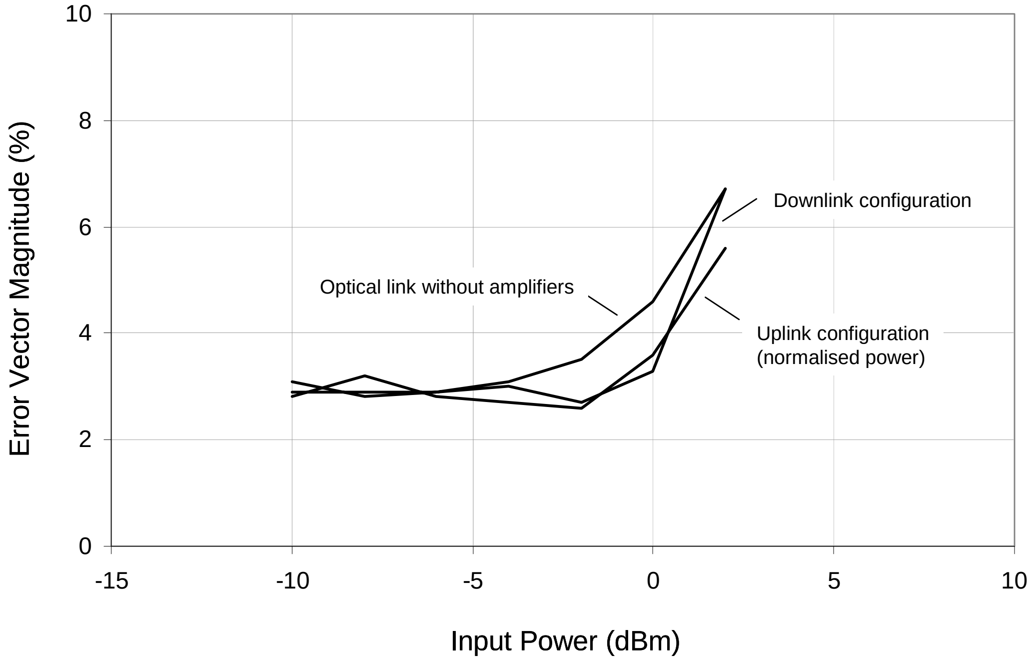


Fig. 9 Error vector magnitude (2.5 GHz, 64-QAM, OFDM, 9 Ms/s) as a function of RF input power for downlink configuration, uplink configuration (normalized power) and for optical link without electrical amplifiers.

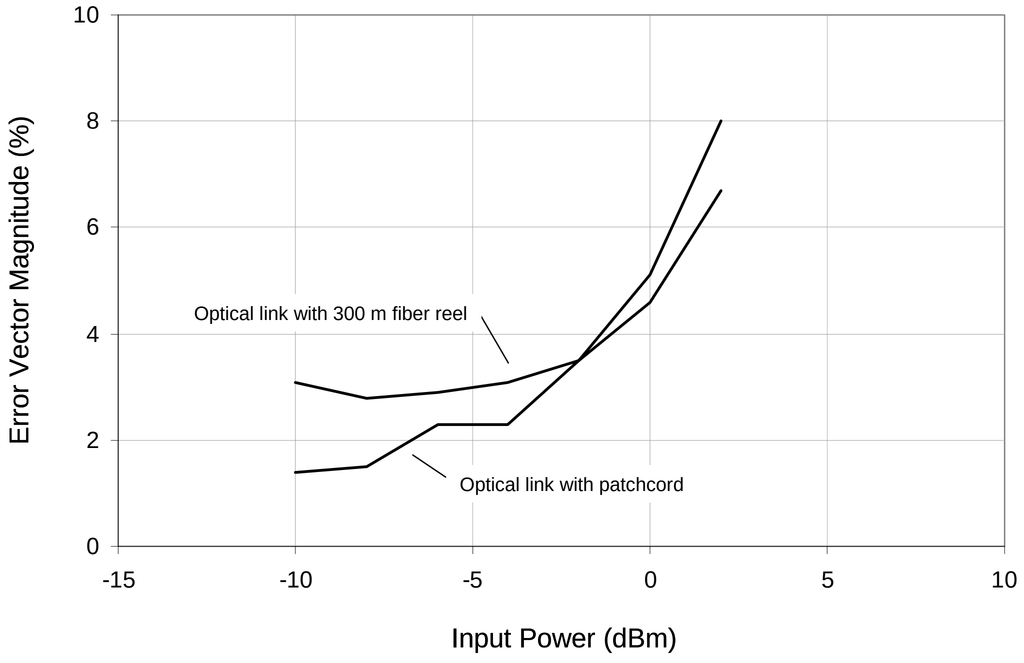


Fig. 10 Error vector magnitude (2.5 GHz, 64-QAM, OFDM, 9 Ms/s) as a function of RF input power for optical link without electrical amplifiers (with and without fiber reel).

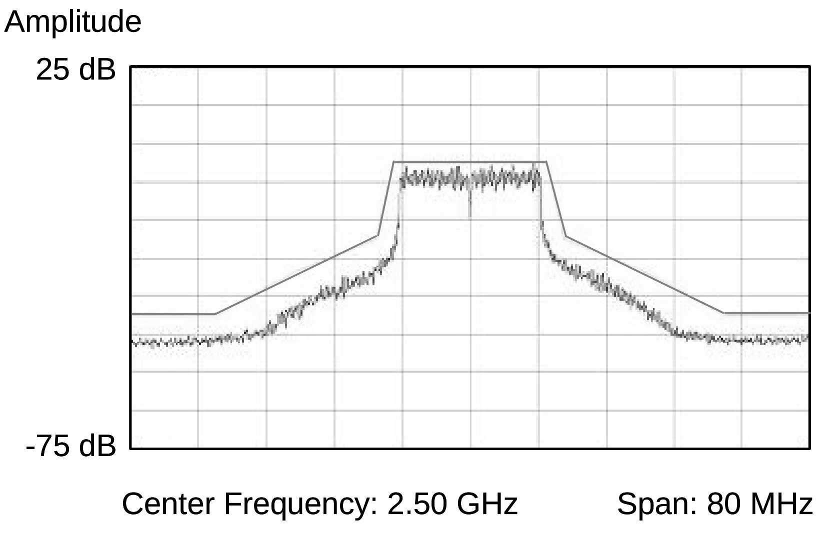


Fig. 11 Spectrum mask measurement on downlink configuration at an RF output power of +6 dBm.

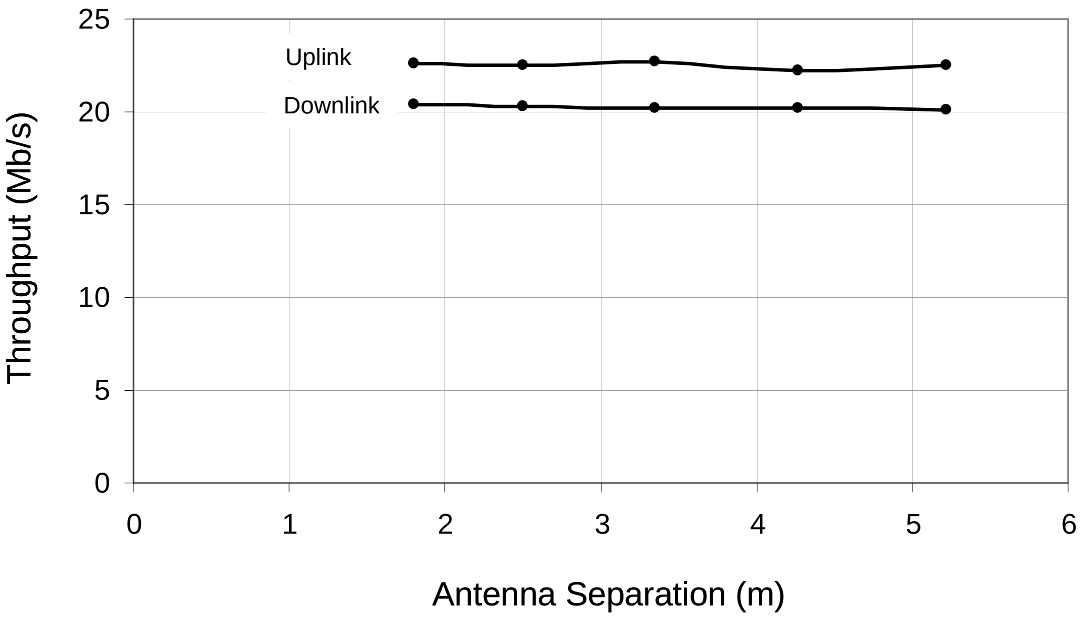


Fig. 12 Throughput as a function of antenna separation for uplink and downlink directions.

TABLES

TABLE I
DESIGN ASSUMPTIONS

Link Type	Laser Type	Laser RIN (dB/Hz)	RFin max (dBm)	Fiber
Short	VCSEL	-140	-5	300 m MMF
Medium	FP	-150	+4	1 km SMF
Long	DFB	-160	+7	1 km SMF

TABLE II
DESIGN RESULTS

Link Type	Transmit Power (dBm)	Amplifier P1dB (dBm)	Amplifier gain (DL / UL) (dB)	Range (m)
Short	-4	+2	26 / 16	14
Medium	+4	+10	30 / 25	24
Long	+12	+18	35 / 30	33

TABLE III
POWER CONSUMPTION AND POWER REQUIREMENTS

Remote Unit Type	Power Consumption (mW)	Required Electrical Power (mW)	Required Optical Power Remote Unit / Central Unit (mW)
Short	98	103	206 / 245
Medium	150	158	316 / 562
Long	210	221	442 / 786