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# Transmission Quality Measurement of Two Types of 60 GHz Millimeter-Wave Generation and Distribution Systems

Frédéric Lecoche, Eric Tanguy, Benoit Charbonnier, Hongwu Li, Frédéric van Dijk, Alain Enard, Fabrice Blache, Michel Goix, and Franck Mallécot

**Abstract**—In this paper, we demonstrate and compare experimentally two techniques achieving very high-data-rates ( $>1$  Gb/s) wireless transmission in the 60 GHz window using radio over fiber (RoF) for reach extension. The first RoF link is based on a 10 GHz vertical-cavity surface-emitting laser and uses a multimode fiber. The radio signal is transported on an intermediate frequency of 4.5 GHz and electrically upconverted to 60 GHz after the optical link. The second uses an optical frequency upconversion from 4.5 to 60 GHz by direct modulation of a mode-locked Fabry–Pérot laser whose self-pulsating frequency is 54.8 GHz before transmission over a single-mode fiber. For both techniques, two different types of modulation were tested. The first one was an ON–OFF keying at 1.5 Gb/s and the second one was an orthogonal frequency-division multiplexing-QPSK signal compliant to the IEEE 802.15.3.c prestandard (3.03 Gb/s). Radio propagation performance is also reported.

**Index Terms**—Home network, IEEE 802.15.3.c, OFDM, radio over fiber (RoF), wireless indoor transmissions.

## I. INTRODUCTION

**M**ULTIPLICATION of connected devices (computers, media center, etc.) of services available to the end user (videophony and videoconferencing, television over Internet protocol (TVoIP), etc.) [1], [2] and the increase in media storage necessary (and available) for various digital media lead to look for novel home network architectures and technologies to enable wireless coverage offering a data rate above 1 Gb/s (Fig. 1) [3]. We have proposed a home network architecture based on a wired backbone distributing local very high-speed wireless connectivity in the different rooms of the house/building [3]. Optical fiber seems to be a good solution for the network's backbone as its large bandwidth would ensure a long life span

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to this new wire [4]. Furthermore, the principle of using an optical fiber in the house is seen as a natural evolution of the optical access, and some studies [5], [6] consider about the convergence of different signals (Wi-Fi, WiMAX, 60 GHz) on this medium.

Even if the houses are well-wired, users have developed a strong taste for wireless connectivity (ease of use, flexibility, etc.), and will require that future connectivities evolve to higher data rates while staying wireless.

The only radio technology whose capacity approaches 1 Gb/s is ultra-wideband (UWB), described in present or upcoming standards such as ECMA-387 [7], IEEE802.15.3c [8], and more recently, the IEEE802.11ad [9]. From these standards, it becomes clear that the main features of emerging high-capacity radio interfaces are their large spectral bandwidth and short transmission distance ( $< 15$  m). Both requirements result from the use of an RF carrier in the 60 GHz window. The use of such carrier frequency is also pushed by recent advances in CMOS technology to provide low-cost transceiver [10], [11]. Due to the limited reach, it is necessary to deploy several radio access points to cover the whole house, as depicted in Fig. 1.

The radio home network will then become a multicellular network, where the cell interference and management issues are similar to those of larger scale mobile/radio networks [12]. In this context, the use of the optical infrastructure to link the different remote antennas and the potential offered by radio over fiber (RoF) to provide a cost-effective and flexible solution must be considered.

In this paper, we present and compare two different methods of 60 GHz radio signal generation and distribution for broadband wireless indoor transmission. The first one is based on direct modulation at 4.5 GHz of a vertical-cavity surface-emitting laser (VCSEL) before the transmission over fiber for distribution. The frequency upconversion to 60 GHz is made at the end of the fiber, after photodetection and amplification, with the help of a local oscillator (LO) at 54.5 GHz (cf., Fig. 2). This first technique uses low-cost components and silica multimode fiber (MMF). The second technique uses a frequency upconversion from 4.5 to 60 GHz by directly modulating a mode-locked Fabry–Pérot laser (ML-FPL) [13], [14] whose self-pulsating frequency is 54.8 GHz before transmission over fiber, realizing, at the same time, the distribution and upconversion (cf., Fig. 3). This second setup uses more advanced components (e.g., 70 GHz photodiode [16]) and single-mode fiber (SMF), but allows the remote access point to be free of complicated

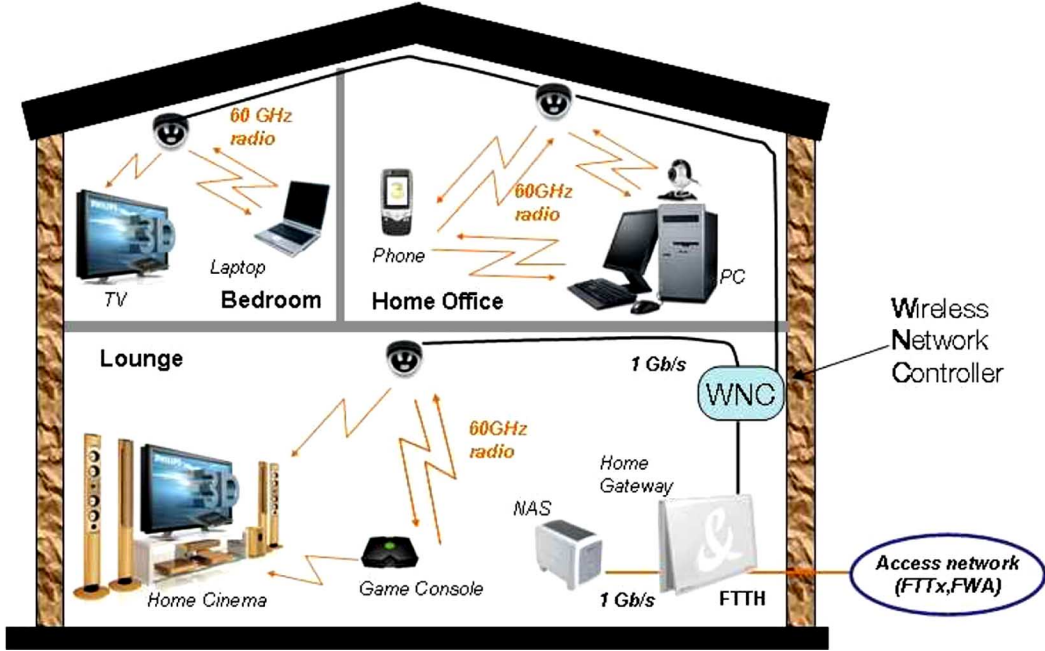


Fig. 1. Architecture and solution for next generation very high data rate wireless home network.

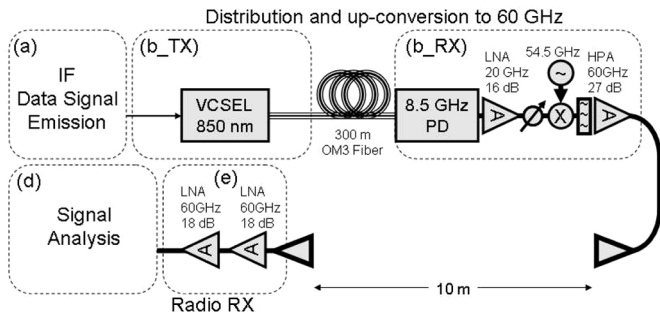


Fig. 2. Setup with distribution of IF signal before upconversion to 60 GHz.

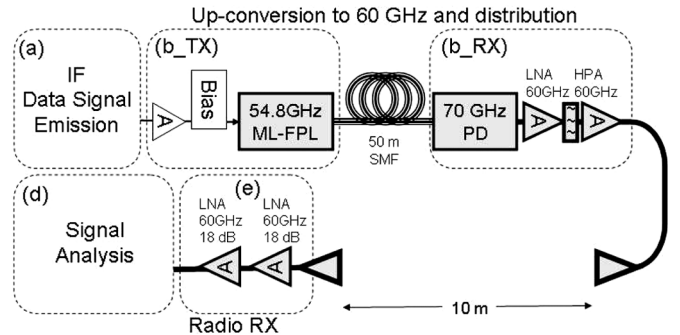


Fig. 3. Setup with IF signal upconversion to 60 GHz before distribution.

RF parts (no 60 GHz LO and mixer) as well; in this architecture, the base station does not contain any 60 GHz circuitry. For both techniques, two different types of modulations were tested. The first was an ON-OFFkeying (OOK) at 1.5 Gb/s and the second was an orthogonal frequency-division multiplexing (OFDM) signal compliant to the IEEE 802.15.3.c prestandard carrying 3.03 Gb/s. Air propagation results are also reported to reinforce the demonstration. Only the downlink experiments (i.e., when the optical distribution occurs prior to the air transmission) are reported here as similar results should be expected from the uplink tests [15].

## II. RF SETUPS

In this section, we show two setups that are used to generate and distribute a 60 GHz millimeter-wave radio signal. First, we assume that the radio signals are generated at an intermediate frequency (IF) of a few gigahertz, and we concentrate on the frequency upconversion and distribution functions. The generation of this IF radio signal will be detailed afterward.

### A. MMF Setup

The principle of this setup is depicted in Fig. 2. The data on IF directly modulate a VCSEL that converts the electrical signal into an optical one. This VCSEL is widely commercially available, and was originally designed for 10 Gb/s digital transmission over LANs. After transport over 300 m of MMF (OM3 with 4000 MHz.km), a 8.5 GHz bandwidth photodiode with integrated transimpedance amplifier converts the optical signal into an electrical one in order to be upconverted. After the signal has passed into a low-noise amplifier (LNA), the signal is mixed with a 54.5 GHz local oscillator (LO) to reach the 60 GHz RF window. Then the signal is filtered (59–63 GHz), amplified by a high power amplifier (HPA), and transmitted by a 20 dBi horn antenna. After a wireless transmission of 10 m, the signal is amplified by two identical 60 GHz LNA before it is analyzed.

### B. SMF Setup

In Fig. 3, we show the setup that upconverts the signal to 60 GHz before transmission over fiber by using a 54.8 GHz ML-FPL. The IF radio signal is amplified to modulate directly

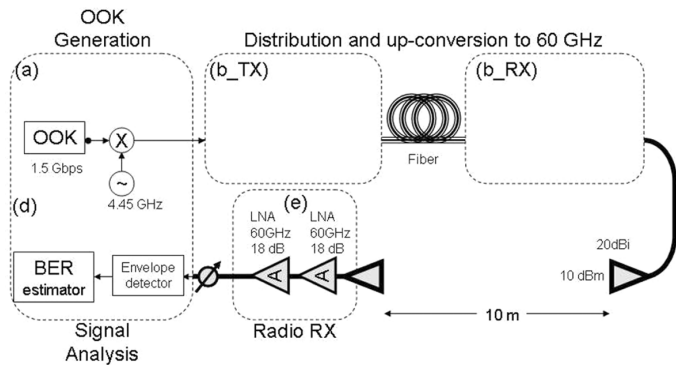


Fig. 4. OOK generator and associated signal analysis.

the ML-FPL (average bias current set to 260 mA). The optical output power of the ML-FPL is +6 dBm. The laser pulses with a repetition rate of 54.8 GHz. Its modulation produces a mixing between the pulsating frequency and the IF carrier, leading to an optical frequency upconversion of the original signal to 59.3 GHz. The optical radio signal is then transmitted through 50 m of SMF up to a commercial 70 GHz photodetector, which is followed by an LNA (LNA  $G = 18$  dB from 55 to 65 GHz), a bandpass filter (58–64 GHz), and an HPA (HPA  $G = 31$  dB from 58 to 63.5 GHz). The transmit antenna and the receiver radio front end are identical to those used in the MMF setup.

### III. SIGNAL GENERATION AND ANALYSIS

As aforementioned, both RF setups are compared using two different radio modulation schemes, which we now describe.

#### A. OOK Modulation (Fig. 4)

1) *Signal Generation [Fig. 4(a)]:* The OOK signal under test is generated from a pseudorandom bit sequence generator (ANRITSU MP1632C, sequence length  $2^{31} - 1$ ) with a peak-to-peak value of 600 mV. It is sent to a mixer to generate the radio signal on a 4.45 GHz carrier at 1.5 Gb/s. Then, it is sent to the VCSEL or ML-FPL, depending on the two different setups presented earlier.

2) *Performance Evaluation [Fig. 4(d)]:* The 60 GHz radio signal received from the experimental setup [radio front end Fig. 4(e)] is converted directly to baseband by an envelope detector. BER measurement is then performed.

#### B. OFDM Modulation (Fig. 5)

1) *Signal Generation [Fig. 5(a)]:* The OFDM signal under test is created on a PC using MATLAB following the specification of the IEEE802.15.3c group [8]. The fast Fourier transform (FFT) block size is 512 with 336 data subcarriers. Each subcarrier is modulated in QPSK. The baseband signal is sampled at 2.59 GHz. A total raw data rate of 3.03 Gb/s is achieved for a bandwidth of 1.87 GHz. The signal is generated by a 10 GS/s dual output arbitrary waveform generator (AWG Tektronix 7102), and both outputs (representing both  $I$ - and  $Q$ -OFDM components) are sent to an RF mixer to generate the radio signal on a 4.5 GHz carrier. At this point, the spectrum

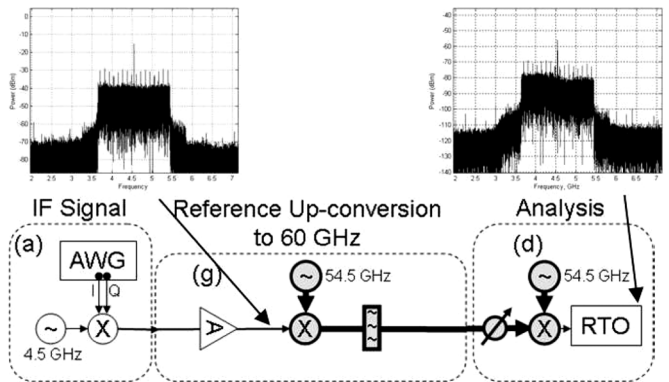


Fig. 5. OFDM reference test bed and electrical IF spectrums.

TABLE I  
EQUIVALENT DISTANCE AS A FUNCTION OF ATTENUATION  
BETWEEN ANTENNAS AND ASSOCIATED BER

Attenuation (dB)	Equivalent distance (m)	BER
63	18	Error-free
66	26	$4 \cdot 10^{-9}$
69	35	$7 \cdot 10^{-3}$

of the signal extends from 3.5 to 5.4 GHz and the available RF power is  $-15$  dBm.

2) *Performance Evaluation [Fig. 5(d)]:* To measure the quality of the 60 GHz radio signal out of the experimental setup [front end Fig. 5(d)], it is first attenuated to the optimal power level (around  $-22$  dBm), then down-converted using a conventional electrical mixer fed with a 54.5 GHz LO, and finally, it is captured by using a 40 GSa/s real-time oscilloscope (RTO Agilent DSO91304A). OFDM demodulation and error vector magnitude (EVM) [17] evaluation are then performed offline using MATLAB. Each capture records a total of 44 OFDM symbols over  $10 \mu\text{s}$ , representing 296 000 bits of data.

For baseline measurement, the signal from the block [Fig. 5(a)] is upconverted to 60 GHz, and then, analyzed and captured by the RTO, giving an EVM of 6%.

## IV. RESULTS AND DISCUSSION

#### A. OOK Modulation Results

Based on Fig. 4, the results obtained for both setups for the OOK modulation at 1.5 Gb/s are similar. For a distance of 10 m between the antennas, we have an error-free result (BER better than  $10^{-10}$ ) in both cases. In order to know the limit of our setups, we replaced the air radio transmission (including the two 20 dBi antennas) by a series of attenuators. Table I shows the BER, depending on the attenuation value and also the equivalent covered distance (assuming free-space propagation losses) with the used setup antennas. Distance in excess of 20 m without multipath interference can be attained. Results are common for both setups and confirm their similar behaviors.

#### B. OFDM QPSK Modulation

In this section, we show the results obtained for an OFDM modulation and for each setup.

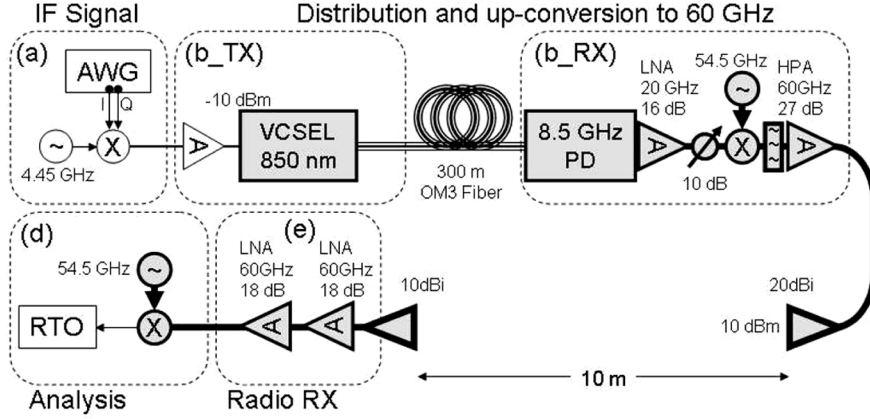


Fig. 6. VCSEL setup and OFDM QPSK modulation.

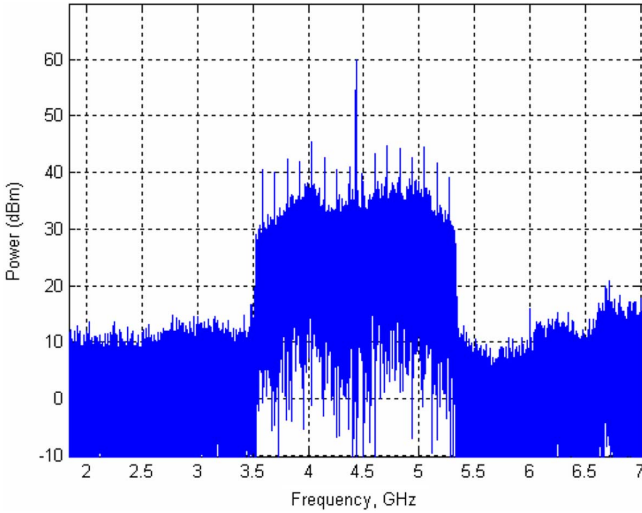


Fig. 7. OFDM signal spectrum received in the MMF setup.

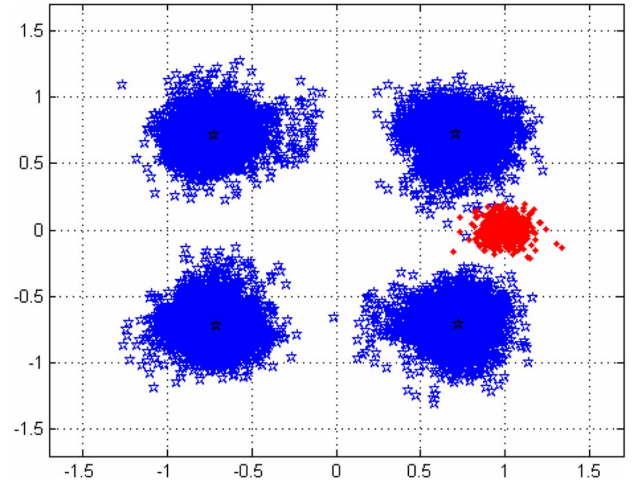


Fig. 8. MMF setup received OFDM constellation (dots around coordinates [1, 0] are the pilot tones used for equalization).

1) *MMF Setup*: The principle of this test bed is depicted in Fig. 6. The electrical power at the input of VCSEL is set to  $-10$  dBm and the power at the output of the 20 dBi horn antenna is around 10 dBm.

In Figs. 7 and 8, we present, respectively, the spectrum of the received OFDM signal and the associated constellation diagram obtained after demodulation. In spite of a strong disturbance of the spectrum, the computed EVM from the captured signal is 18.7% for an SNR of 23 dB. From the calculated EVM, a BER can be estimated around  $10^{-10}$  [17]. This measured SNR should provide a theoretical EVM of 7% [17]. The difference between the two values of EVM (measured and theoretical from the SNR) is attributed to the residual nonlinearities of our system as well as multipath interferences during radio transmission.

2) *SMF Setup*: Fig. 9 shows the complete setup used for the test. For comparison, the level of radiated power is similar to the previous setup at the output of the transmit horn antenna.

In Figs. 10 and 11, we exhibit the spectrum of the received signal and the QAM diagram constellation, respectively. The computed EVM is 19% for an SNR of 21.5 dB. The value of BER can be estimated at  $10^{-10}$  [17]. Again, the measured SNR

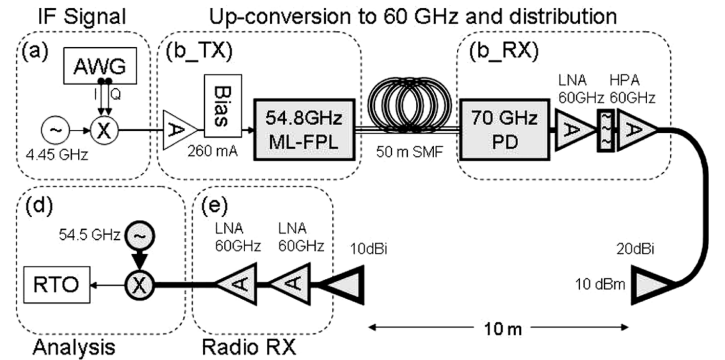


Fig. 9. ML-FPL setup and OFDM QPSK modulation.

should provide a theoretical EVM of 8.4% [17]. Strong distortions, multipath interferences, and nonlinearity still affect the calculated EVM, but results are still acceptable.

## V. CONCLUSION

In this paper, we presented two different techniques for very high data rate 60 GHz wireless transmission using RoF. The first one uses low-cost commercial components (VCSEL and

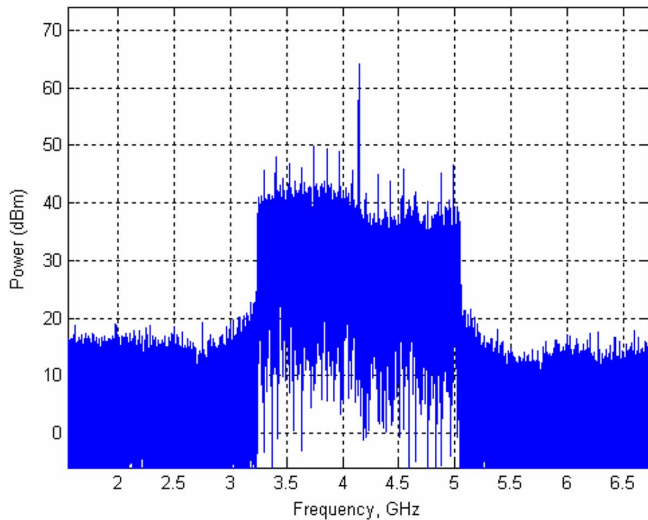


Fig. 10. OFDM signal spectrum received in the SMF setup.

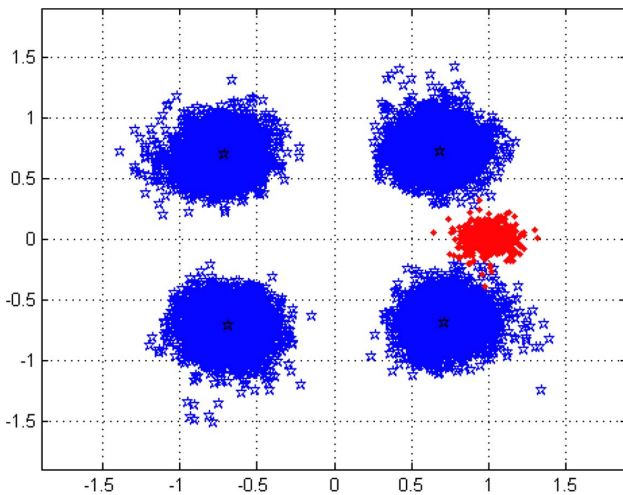


Fig. 11. SMF setup received OFDM constellation (dots around coordinates [1, 0] are the pilot tones used for equalization).

8.5 GHz photodiode) as well as MMF, and the upconversion to 60 GHz is performed at the remote antenna site after the signal optical distribution. The second one uses an ML-FPL at 54.8 GHz, which is able to upconvert directly the signal to 60 GHz before distribution over SMF. For both setups, we present the performance evaluations for two modulation formats (OOK and OFDM QPSK). At a wireless radio transmission of 10 m, we report an error-free result for the OOK modulation at 1.5 Gb/s for both setups. For the same wireless distance, in the case of OFDM QPSK modulation at 3.03 Gb/s, the computed EVM is 18.7% for the VCSEL setup and 19% for ML-FPL. These values should lead to a theoretical BER around  $10^{-10}$ . From these results, we can conclude that both setups have quite similar performances. The difference mainly lies on technological maturity for the components. On one hand, the MMF setup has proven commercial availability and allows a longer distribution distance, but requires a more complex

remote antenna. On the other hand, the SMF setup allows the remote antenna to be simplified but the components are not readily available.

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