Dynamic Range of Optically Amplified RF Optical Links

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***Abstract*—We investigated, theoretically and experimentally, the effect of optical amplification on the dynamic range performance of both externally modulated direct detection and coherent RF optical links. Our results show that, for low- to medium-loss links, a direct detection link with or without an optical amplifier, depending on the loss range, gives the best dynamic range. For high-loss links, the best link to use is a coherent link with the optical amplifier after the modulator. We also showed that the position of an amplifier is an important design parameter; it determines whether or not an optical amplifier improves the link's dynamic range.**

***Index Terms*—Analog systems, erbium, microwave technology, optical amplifier, optical communication, optical fiber amplifier, optical fiber communication, optical signal processing.**

I. Introduction

HIGH-PERFORMANCE analog optical links are needed for many broad-bandwidth microwave and millimeter- wave systems and applications. The use of optical amplifiers (OAs) in these links could improve their performance. OAs can be used as in-line amplifiers, boosters of transmitter power, preamplifiers at the receiver, and compensators of distribution losses.

Previous works on optically amplified RF optical links have concentrated on the use of OAs in digital systems and on subcarrier multiplexed (SCM) direct detection analog links only (please refer to [1] for a summary). In this paper, a unified investigation into the impact of OAs on the dynamic range of both direct detection and coherent analog optical links is presented. Can OAs improve the performance of direct detection and coherent links? Does the positioning of an OA affect the overall link performance? Under what conditions should one use a direct detection link or a coherent link? These are some of the issues that are investigated in this paper.

II. System Description

A. Direct and Coherent Detection Systems

The block diagrams of the direct detection and coherent RF analog optical links we constructed and investigated are shown in Fig. 1(a) and (b), respectively. The transmitters are identical in both cases but the receivers are different. The system parameters are given in Table I.

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The RF signal modulates the optical carrier via an $LiNbO_3$ Mach–Zehnder amplitude modulator. A polarization controller is used to align the polarization of the laser light to that allowed by the modulator. From the modulator, the optical signal travels through an optical attenuator used to vary the received optical power and link loss, several meters of optical fiber, and to the optical receiver. Angled optical connectors are used throughout the optical link to minimize reflections.

A complete description of the direct and coherent detector receivers shown in Fig. 1(a) and (b), respectively, including the component specifications and parameters, and the WIRNA receiver is given in [2].

B. Optical Amplifier

The two most popular types of OAs that have been developed to date are: 1) erbium-doped fiber amplifiers (EDFAs) and 2) semiconductor optical amplifiers (SOAs). Of the two, EDFAs have found the widest use since they give better link performance [3], [4]. Therefore, EDFAs rather than SOAs are used in our studies of the impact of using OAs in RF analog links.

As shown in Fig. 1(a) and (b), optical amplifiers (OAs) can be placed in the following positions in the direct detection and coherent AM links:

1) OA after the transmitter laser, to boost the signal power going into the electrooptic modulator (EOM);
2) OA after the EOM, to amplify the signal going out into the transmission fiber;
3) OA before the optical receiver as a preamplifier, to amplify the signal at the receiver.

The performance at positions 1) and 2) could differ significantly in certain systems wherein the EOM is in a remote location (see, e.g., [5]). For the coherent link, there is one additional position: 4) OA after the local oscillator (LO) laser, to amplify the optical output of the semiconductor LO laser. This position is especially relevant for coherent receivers using remotely located LO lasers.

The location of the OA is an important design parameter since it affects the amplified spontaneous emission (ASE) noise collected at the receiver and the received optical power. To maximize the signal-to-noise ratio (SNR), the amplifier should be positioned where the signal power is still much greater than the noise power of the amplifier, but not where the received signal power causes the breakdown of the photodetector or saturation of the components in the receiver. In addition, a strong input power to the optical amplifier would cause the amplifier to saturate, thus reducing its gain. Therefore, there is an optimum position for the optical amplifier.

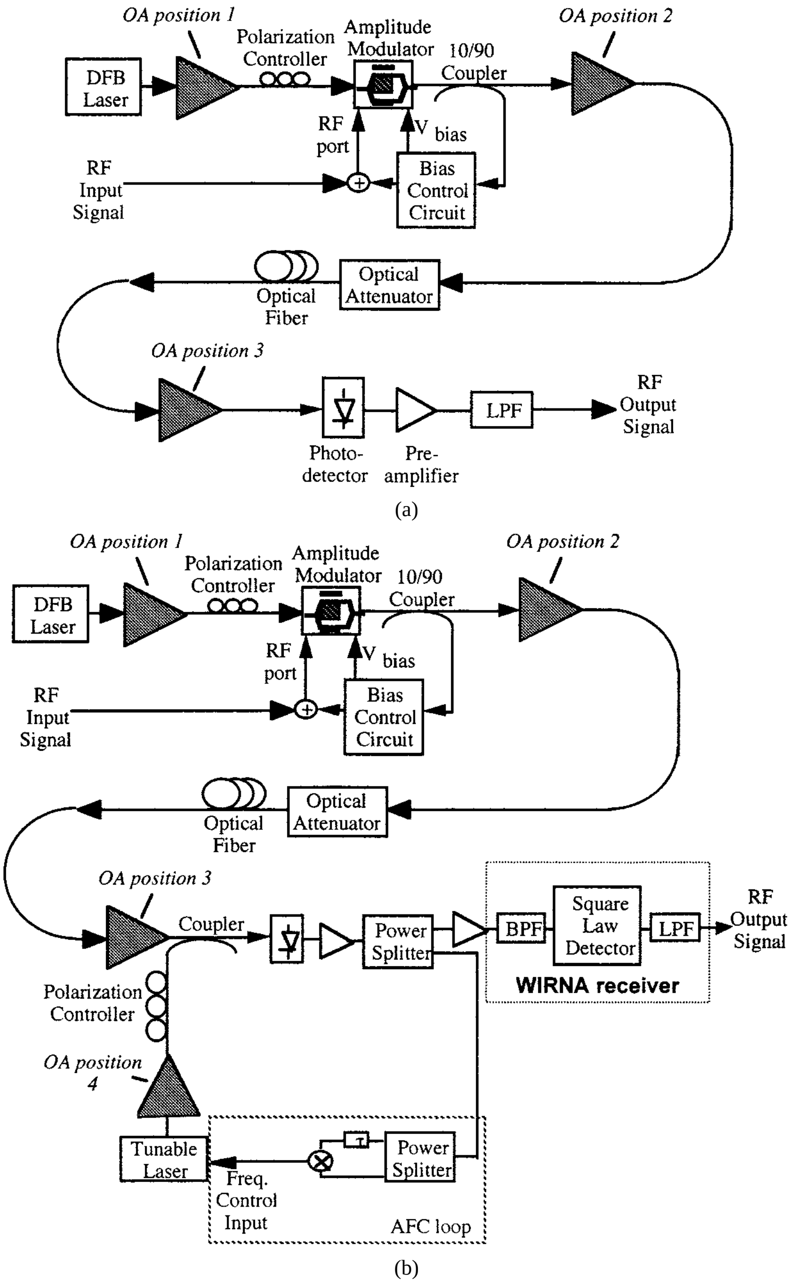

Fig. 1. (a) Block diagram of the experimental direct detection RF analog optical link constructed. (b) Block diagram of the experimental coherent AM-WIRNA RF analog optical link constructed.

III. Dynamic Range Analysis

In an RF analog optical link, the two main causes of performance degradation are system noises and link nonlinearities. Since noise and nonlinearities are inter-related, the spurious-free dynamic range (SFDR), a performance measure that considers both these effects, is considered the main measure of link performance. The SFDR is a measure of the variation in the RF signal level that can be carried by the link and is given by

$$\begin{aligned}\mathrm{SFDR} &\equiv \frac{\text{Maximum RF Power}}{\text{Minimum RF Power}} \\ &= \frac{\mathrm{RFPower}|_{\mathrm{IMD=noise}}}{\mathrm{RFPower}|_{\mathrm{signal=noise}}} \\ &= \frac{m^2|_{\mathrm{IMD=noise}}}{m^2|_{\mathrm{signal=noise}}}\end{aligned} \tag{1}$$

where m is the RF modulation index. For the links shown in Fig. 1(a) and (b), the maximum RF power is usually limited by the nonlinearity of the EOM [6]. SFDR is experimentally measured using the setup given in [2].

A. Dynamic Range of the Direct Detection Link

Following the analysis presented in [7], the SFDR for the direct detection link, i.e., SFDR_{dd}, employing a single OA is given by (see Table II for symbol definitions)

$$\mathrm{SFDR}_{dd} = 4\left[\frac{R^2 G_T^2 P_T^2 L^2}{\eta_{dd} B}\right]^{2/3} \tag{2}$$

where η_{dd} is the total power spectral density (PSD) of the additive noise at the output of the photodetector. η_{dd} is the sum of all the noise components in the direct detection link (in other words,

TABLE I
SYSTEM PARAMETERS FOR SFDR VERSUS LINK LOSS MEASUREMENTS FOR EDFA-BASED LINKS

Parameter	Value
RF signal frequencies	900 MHz, 1000 MHz
Transmitter laser power	2 mW
Transmitter laser linewidth	7.9 MHz
Transmitter laser RIN	-153 dB/Hz
EOM optical insertion loss	5 dB
EOM V_π	8V
EOM bandwidth	5 GHz
EOM optical return loss	> 50 dB
EOM waveguide ends	angled
LO laser power	500 µW
LO laser linewidth	20 kHz
LO laser RIN	-148 dB/Hz
EDFA pump configuration	Backward pumping
EDFA pump wavelength	1480 nm
EDFA output saturation power	14 mW
EDFA 3 dB optical bandwidth	35 nm
EDFA Gain	35 dB
EDFA noise figure	10 dB
PD max input optical power	10 mW
IF bandpass filter bandwidth	3 GHz
Lowpass filter bandwidth	1 GHz

$\eta_{dd} = \eta_{\text{sig, sh}} + \eta_{\text{sig, RIN}} + \eta_{\text{sig−ASE}} + \eta_{\text{ASE, sh}} + \eta_{\text{ASE−ASE}} + \eta_{\text{th}}$). These noise components are as follows.

1) Shot noise due to the signal laser:

$$\eta_{\text{sig, sh}} = 2qR(P_T G_T L). \tag{3}$$

2) Relative intensity noise (RIN) due to the signal laser:

$$\eta_{\text{sig, RIN}} = R^2(P_T G_T L)^2 t_{\text{RIN}}. \tag{4}$$

3) Beat noise between the signal field and the ASE noise:

$$\eta_{\text{sig−ASE}} = 4R^2(P_T G_T L) S_{\text{ASE, T}}. \tag{5}$$

4) Shot noise due to the ASE:

$$\eta_{ASE,\,sh} = 4qRS_{ASE,\,T} B_o. \tag{6}$$

5) Beat noise of the ASE:

$$\eta_{\text{ASE−ASE}} = 4R^2 S^2_{\text{ASE, T}} B_o. \tag{7}$$

6) Thermal noise:

$$\eta_{\text{th}} = \frac{4kTF}{r}. \tag{8}$$

In the foregoing expressions, $t_{\text{RIN}} = 10^{\text{RIN}/10}$ [8], $S_{\text{ASE, T}}$ is the PSD of the ASE noise of the OA in the transmitter path given by

$$S_{\text{ASE, T}} = (G_T - 1) n_{\text{sp, T}} h\upsilon. \tag{9}$$

B. Dynamic Range of the Coherent Link

The resulting SFDR for the coherent link is given by [7]

$$\text{SFDR}_{cd} = 4\left[\frac{4R^4 G_T^2 P_T^2 L^2 G_{\text{LO}}^2 P_{\text{LO}}^2}{32R^2 G_T P_T L G_{\text{LO}} P_{\text{LO}} \eta_{cd} B + 16\eta_{cd}^2 B(4B_{\text{IF}} - B)}\right]^{2/3} \tag{10}$$

where η_{cd} is the PSD of the additive noise at the output of the photodetector of the coherent optical receiver; η_{cd} is comprised of the following components [9].

1) Shot noise due to the LO laser:

$$\eta_{\text{LO, sh}} = 2qR(P_{\text{LO}} G_{\text{LO}}). \tag{11}$$

2) RIN due to the LO laser:

$$\eta_{\text{LO, RIN}} = \frac{1}{4} R^2 (P_{\text{LO}} G_{\text{LO}})^2 t_{\text{RIN}}. \tag{12}$$

3) Beat noise between the LO laser and the ASE noise:

$$\eta_{\text{LO−ASE}} = 4R^2(P_{\text{LO}} G_{\text{LO}}) \cdot (S_{\text{ASE, T}} + S_{\text{ASE, LO}}). \tag{13}$$

4) Beat RIN between the LO laser and the signal laser:

$$\eta_{\text{LO−sig, RIN}} = \frac{1}{2} R^2 (P_T G_T L)(P_{\text{LO}} G_{\text{LO}}) t_{\text{RIN}}. \tag{14}$$

5) Shot noise due to the signal laser:

$$\eta_{\text{sig, sh}} = 2qR(P_T G_T L). \tag{15}$$

6) RIN noise due to the signal laser:

$$\eta_{\text{sig, RIN}} = \frac{1}{4} R^2 (P_T G_T L)^2 t_{\text{RIN}}. \tag{16}$$

7) Beat noise between the signal laser and the ASE noise:

$$\eta_{\text{sig−ASE}} = 4R^2(P_T G_T L) \cdot (S_{\text{ASE, T}} + S_{\text{ASE, LO}}). \tag{17}$$

8) Shot noise due to the ASE:

$$\eta_{\text{ASE, sh}} = 4qR(S_{\text{ASE, T}} + S_{\text{ASE, LO}}) B_o. \tag{18}$$

9) Beat noise of the ASE:

$$\eta_{\text{ASE−ASE}} = 4R^2(S^2_{\text{ASE, T}} + S^2_{\text{ASE, LO}} + S_{\text{ASE, T}} S_{\text{ASE, LO}}) B_o. \tag{19}$$

10) thermal noise:

$$\eta_{\text{th}} = \frac{4kTF}{r} \tag{20}$$

where $t_{\text{RIN}} = 10^{\text{RIN}/10}$, $S_{\text{ASE, T}}$, and $S_{\text{ASE, LO}}$ are the PSD of the ASE noise of the OAs in the transmitter and

TABLE II
DEFINITIONS OF THE VARIABLES

NOTATION	NAME
R	Photodetector responsivity
P_T	Optical power of the transmitter laser
G_T	Gain of the optical amplifier in the transmitter laser path
L	Link loss in the transmitter laser or signal path
B	Signal bandwidth
q	Electron charge
RIN	Average RIN of the transmitter and LO lasers
B_o	Optical bandwidth
$n_{sp,T}$	Spontaneous emission factor of the OA in the transmitter laser path
h	Planck's constant
ν	Frequency of the signal
k	Boltzmann's constant
T	Temperature of the optical receiver
F	Noise figure of the electrical amplifier/amplifier chain following the optical receiver
r	Load resistance of the optical receiver
P_{LO}	Optical power of the local oscillator laser
G_{LO}	Gain of the optical amplifier in the LO laser path
B_{IF}	IF bandwidth
$n_{sp,LO}$	Spontaneous emission factor of the OA in the LO laser path

LO laser paths, respectively. The PSD $S_{\mathrm{ASE,\,T}}$ is given by (9); similarly, $S_{\mathrm{ASE,\,LO}}$ is expressed as

$$S_{\mathrm{ASE,\,LO}} = (G_{\mathrm{LO}} - 1) n_{\mathrm{sp,\,LO}} h\upsilon. \tag{21}$$

Since we are only considering the use of one optical amplifier at a time, $G_{\mathrm{LO}} = 1$ when the amplifier is in the transmitter path, and $G_T = 1$ when the amplifier is in the LO laser path.

The total additive noise density in a coherent receiver with an optical amplifier, η_{cd}, is the sum of all the noise terms given in (11)–(20):

$$\begin{aligned}\eta_{cd} = {} & \eta_{\mathrm{LO,\,sh}} + \eta_{\mathrm{LO,\,RIN}} + \eta_{\mathrm{LO-ASE}} + \eta_{\mathrm{LO-sig,\,RIN}} \\ & + \eta_{\mathrm{sig,\,sh}} + \eta_{\mathrm{sig,\,RIN}} + \eta_{\mathrm{sig-ASE}} + \eta_{\mathrm{ASE,\,sh}} \\ & + \eta_{\mathrm{ASE-ASE}} + \eta_{\mathrm{th}}.\end{aligned} \tag{22}$$

IV. DYNAMIC RANGE VERSUS LINK LOSS

A systems designer's problem can be formulated as follows: what is the best RF analog link in terms of the SFDR, given the transmission distance (for a point-to-point link) or the total number of subscribers (for a distribution system)? The answer to this question is discussed below by presenting measurements of the SFDR versus the link loss for optically amplified links. Link loss can easily be converted into the number of destinations or splits for distribution systems and into transmission distance for point-to-point links. So, if one wants to build a system with a prescribed number of splits or transmission distance, the plot of SFDR versus link loss shows the best configuration.

Fig. 2(a) and (b) shows the SFDR versus link loss measurements for the direct detection and coherent links, respectively; Table I enumerates the system parameters. The data in our experiments were collected for received optical powers up to 1 mW; at higher power levels, the photodetector used in our receiver saturates or is damaged. It is for this reason that some configurations do not have data for low link loss values. For both direct detection and coherent links, with an EDFA before or after the EOM, we increase the optical power going into the fiber; this enables the links to handle larger losses. Because of the loss in the modulator, the link with an EDFA after the EOM has a higher power into the fiber and can handle greater link loss than the links with the EDFA before the EOM.

The effect of the approximately 10-dB loss in the EOM is clearly seen in the direct detection case; the separation between the two curves, for the link with the EDFA before and after the EOM, is 10 dB. This phenomenon is not quite obvious in the coherent link, since the performance of the link is affected by other effects such as the RIN of the lasers and the much larger effect of the LO–ASE, signal–ASE, and ASE–ASE beat noises.

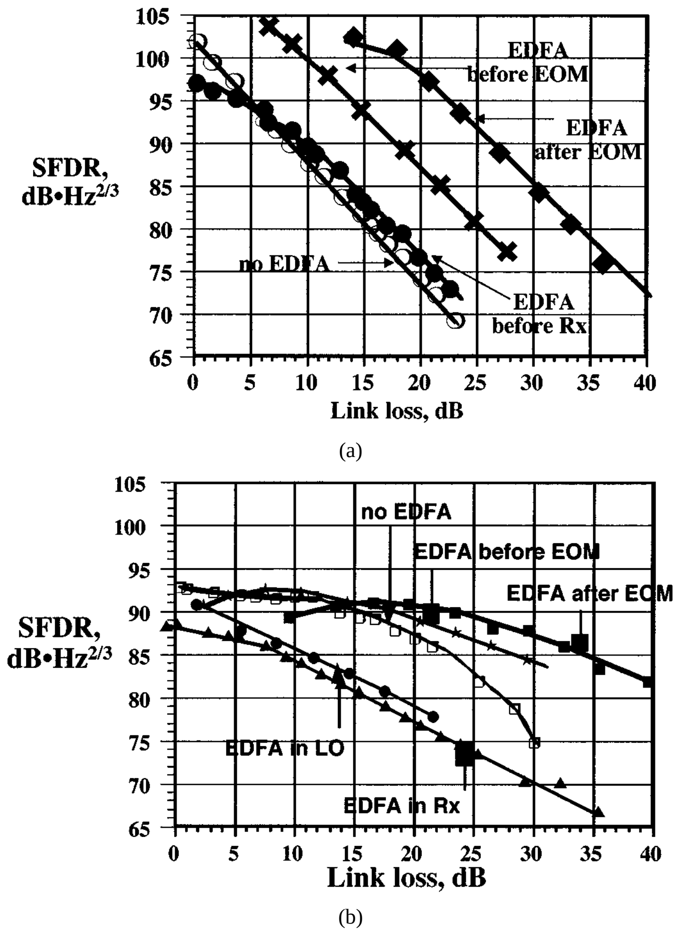

Fig. 2. (a) Spurious-free dynamic range versus the link loss for the direct detection link, with the OA at different positions. (b) Spurious-free dynamic range versus the link loss for the coherent AM link, with the OA at different positions.

The main difference between the direct detection and the coherent links is the flattening of the curves in the low-loss region for the coherent case because of the impact of RIN for the single photodetector receiver. Overall, an EDFA still extends the link-loss margin that can be handled by both direct detection and coherent links.

For both direct detection and coherent links, the EDFA in the receiver gives poor SFDR performance because of the LO–ASE, signal–ASE, and ASE–ASE noises. This is due to the fact that when the input power to the EDFA is smaller, the impact of the amplifier's ASE noise is stronger. Also, more ASE noise is collected at the receiver as compared to the cases when the EDFA is before and after the EOM, since for the latter cases the link loss attenuates the ASE noise while for the former all the ASE noise generated goes into the receiver.

Similar reasons explain the performance of the coherent AM link with the EDFA after the LO laser: the signal–ASE, LO–ASE, and ASE–ASE noises deteriorate the system performance significantly; all the ASE noise generated is collected by the photodetector since the EDFA is located at the receiver. The performance of the coherent link with the EDFA after the LO laser is slightly better than when the EDFA is in the receiver, since the input power to the EDFA is larger when the EDFA is after the LO laser.

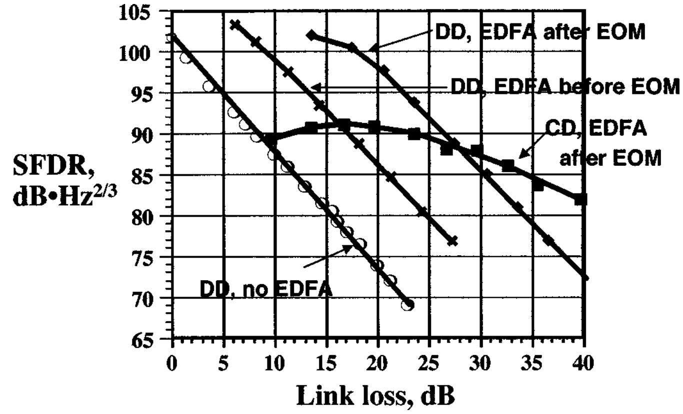

Fig. 3. Spurious-free dynamic range versus the link loss; comparison of the four best links.

TABLE III
SUMMARY OF THE BEST LINK DESIGNS IN TERMS OF SFDR

If the Link Loss, L, is:	The Best Link (in terms of SFDR) is:	Highest SFDR in Given Region
0 dB < L < 7 dB	Direct Detection, no EDFA	102 dB•Hz$^{2/3}$
7 dB < L < 13 dB	Direct Detection, EDFA before EOM	103 dB•Hz$^{2/3}$
13 dB < L < 28 dB	Direct Detection, EDFA after EOM	102 dB•Hz$^{2/3}$
L > 28 dB	Coherent Detection, EDFA after EOM	88 dB•Hz$^{2/3}$

To summarize the results presented in Fig. 2(a) and (b), let us compare the performance of the best four links for specific ranges of link loss. The results are replotted in Fig. 3 and stated in Table III. Due to the optical power limit that can be accepted by the photodetector, no data for link loss less than 7 dB, for a direct detection link with the OA before the EOM, was obtained. However, we can confidently say that for low-loss links (for link loss less than 7 dB), a direct detection link without any OAs gives the best performance. As the link loss decreases, the SFDR of links without OAs improve linearly, while the SFDR of links with OAs will saturate and worsen due to the following reasons:

1) ASE noise begins to dominate;
2) RF amplifiers and other RF components at the receiver may saturate resulting in increased nonlinearities;
3) breakdown of the photodetector;
4) regarding coherent links, the degradation caused by laser RIN.

For low to medium link loss (between 7–13 dB), a direct detection link with the OA before the optical modulator gives the best performance, while for medium to high link loss (from 13 to 28 dB), the best link to use is a direct detection link with an OA after the optical modulator. Once again, the choice is due to how much ASE noise and/or RIN is collected at the receiver. For large loss links (for link loss greater than 28 dB), the link with the best performance is the coherent AM–WIRNA link with an OA after the optical modulator. This is due to the better receiver sensitivity of coherent detection.

Note that the final link loss values depend on the component parameters. Theoretical analysis shows that the trend is similar to that shown in Fig. 3, with the results scaling and crossover values depending on the parameters given in Table I.

V. SUMMARY

We have constructed several experimental externally modulated direct detection and coherent RF analog optical links, and experimentally measured the spurious-free dynamic range of these links as a function of the total link loss. Our goal was to allow an RF analog optical systems designer to determine what configuration gives the best dynamic range performance given the prescribed number of splits or transmission distance.

The results of our investigation show that the location of the optical amplifier is an important design parameter: it affects both the ASE noise collected at the receiver and the received optical power. For both links, placing the amplifier at the receiver and the LO laser provides no improvement; doing so only results in collecting more ASE noise. In fact, for the coherent link, these conditions even result in up to a 10 dB performance penalty.

When the optical amplifier is placed before or after the EOM, the optical power going into the fiber is increased, enabling both links to handle higher losses. However, for the coherent link case, there is a flattening in the SFDR response in the low- and medium-loss region, indicating that the use of an optical amplifier does not benefit the coherent link for this range of link loss. This degradation at low to medium link loss is not observed in the direct detection link, where the use of an OA gives a uniform improvement in the link performance. Therefore, for low to medium link loss (0 to 28 dB), the direct detection link gives the best performance as summarized in Table III.

For the case of high link loss (link loss greater than 28 dB), an optically amplified coherent link gives better performance than an optically amplified direct detection link. This is because the presence of an LO laser in the coherent link allows it to have better receiver sensitivity.

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