Monte-Carlo Simulation for PDC-Based Optical CDMA System

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ABSTRACT

This paper presents the Monte-Carlo simulation of Optical CDMA (Code Division Multiple Access) systems, and analyse its performance in terms of the BER (Bit Error Rate). The spreading sequence chosen for CDMA is Perfect Difference Codes. Furthermore, this paper derives the expressions of noise variances from first principles to calibrate the noise for both bipolar (electrical domain) and unipolar (optical domain) signalling required for Monte-Carlo simulation. The simulated results conform to the theory and show that the receiver gain mismatch and splitter loss at the transceiver degrades the system performance.

Key Words: **Monte-Carlo, Optical CDMA, Noise Calibration.**

1. INTRODUCTION

The ever hungry consumers of current and potential future access networks are making OCDMA systems more and more attractive in the field of all optical communications as it promises to enable the end users to access the network asynchronously and simultaneously with high level of transmission security [1-7]. Designing an OCDMA system, however, imposes few challenges such as to minimize the influence of MAI (Multiple Access Interference). SAC (Spectral Amplitude Coding) techniques are one of the techniques widely considered to address this issue as the MAI can be cancelled theoretically when code sequences with fixed in-phase cross-correlation (such as perfect difference codes or Hadamard code) are used [3-5].

In the most research on OCDMA systems [3,4], the evaluation of error probability is based on the ideal assumptions such as the gains of APDs (Avalanche Photo-Diodes) used in information extracting and MAI cancelling branches of OCDMA systems receiver are matched or the multiplexers used at transmitter and receiver uniformly split the input and received power. The APDs are assumed to be similar in both their electrical and optical characteristics, specifically gain, temperature etc. Such approximations in practice may be an overestimate or underestimate of the actual probability of error. In this paper, the Monte-Carlo simulation technique is utilized to gauge the impact of APD mismatch [4, 5] and splitter's uniformity loss [5] in the OCDMA systems based on the PDC (Perfect Difference Codes). Conventional optical systems differ from electrical domain systems due to the fact that the former adopts unipolar signaling technique, while the later uses bipolar signaling techniques. Keeping the unique nature of optical domain communication systems into consideration, the noise variance is derived from first principles to calibrate noise in the optical communication channel.

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Remainder of the paper is organized as follows. In section 2, the structure of the transmitter and receiver for the OCDMA system under study is described. Section 3 introduces the perfect difference codes and discusses its correlation properties. Section 4 presents the framework adopted to carry out Monte-Carlo simulation and derives the expressions for noise variances in binary baseband and CDMA based baseband systems. Finally section 5 discusses the results and section 6 gives the concluding remarks.

2. SYSTEM MODEL

In [4], an asynchronous OCDMA system is proposed based on PDCs as shown in Fig. 1. However, in [4], the analysis is carried out in ideal conditions and is based on some serious assumptions such as the gain of APDs used in receiver of proposed systems are perfectly matched and that the power is splitted uniformly in the splitters used at transmitter and receiver side. In what follows, the system proposed in [4] is analyzed considering practical environment and the authors attempt to critically analyze the obtained results and also propose some ways to minimize or overcome the losses.

Each subscriber is assigned a unique code. Each active user transmits a signature sequence of laser pulses (representing the destination address), over a time frame to send a mark, i.e. "logic 1". However, to send a space, i.e. "logic 0", no pulses are transmitted during the time frame. The system presented in [4] proposes the use of PDC to overcome the limitation of codeword synchronization and power loss incurred in the SAC-OCDMA Systems.

2.1 Transmitter

The arrayed waveguide grating vxv wavelength multiplexer (AWG MUX) proposed in [6] is used as encoder and decoder since both, the wavelength multiplexer and PDC have a cyclic-shift property. It is assumed that a broadband optical pulse entering one of the input ports of the AWG MUX is split into v number of spectral components. Each spectral component follows a unique route through the AWG MUX in accordance with its particular wavelength. OOK (On-Off-Keying) is selected as modulation scheme.

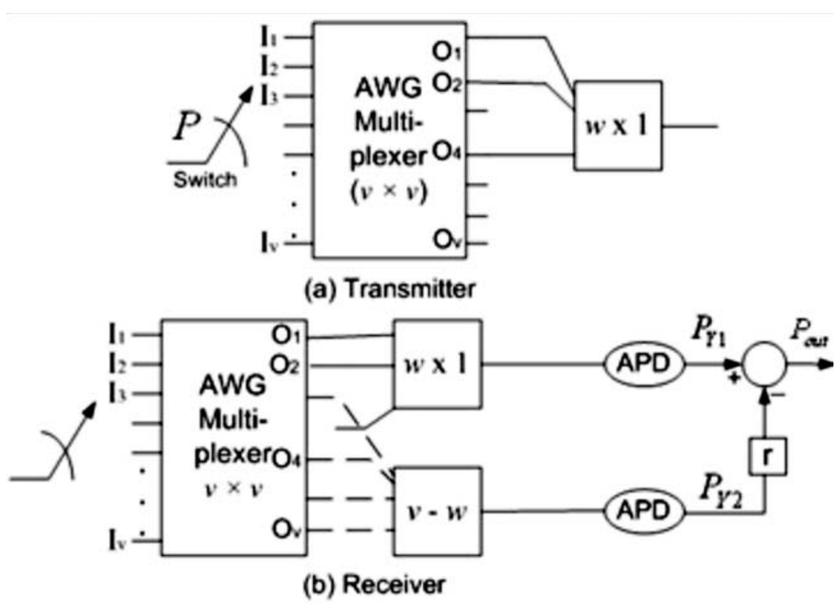

FIG. 1. SAC-OCDMA SYSTEM BASED ON PERFECT DIFFERENCE CODES [5]

The transmitter shown in Fig. 1 comprises a switch, a νxν AWG MUX and a wx1 coupler. In accordance with the employed PDC, output ports are selected in advance. When data bit '1' is to be sent, a broadband optical pulse is transmitted to one of the ν input ports of the multiplexer. The choice of input port is determined by the switch in accordance with the signature sequence of the destined user. The optical broadband pulse entering the multiplexer is split into ν spectral components. These components exit the multiplexer through the predetermined output ports and are then combined into a single pulse by the x1 coupler and transmitted to the destined user. To send bit '1' to a different user, the transmitter uses the switch in front of the AWG MUX to change the input port of the broadband optical pulse in accordance with the codeword sequence of the new user. Consequently, a different group of spectral components exits from the predetermined output ports. When a '0' data bit is to be sent, nothing is actually transmitted.

2.2 Receiver

The front of the receiver is implemented by adding a (ν-w)x1 coupler to the transmitter structure as shown in Fig. 1(b). In accordance with the code of the destined user, the received optical pulse is directed to the corresponding input port by the switch in front of the AWG MUX. As described above, the optical pulse is then split into several spectral components and each component follows its own particular route through the AWG MUX. The spectral components, exiting from the predetermined output ports, are collected by the wx1 coupler and combined into a single optical pulse. This pulse is transmitted to an APD, which responds by outputting the corresponding photoelectron count. Meanwhile, the (ν-w)x1 coupler collects the spectral components which exit through all of the output ports of the AWG MUX other than the predetermined ports. The output of the (ν-w)x1 coupler, referred to as the filtered MAI, is photodetected by a second APD, which outputs the photoelectron count. The filtered MAI signal is employed to remove the MAI from the spectral components coupled by the wx1 coupler, i.e. the residual MAI.

3. PERFECT DIFFERENCE CODES

Perfect difference codes are the special type of cyclic difference set with (ν,w,γ=1), where ν is the length, w is the weight and γ is the correlation constraint. The detailed information about the perfect difference codes can be found in [3,7,8]. For the purpose of this thesis we are interested in the following two properties of PDCs:

(i) The cross correlation between the two PDCs is unity. This property is exploited to design the decoder to efficiently recover data by suppressing MAI effect.

(ii) PDCs are shifted cyclically. The cyclic nature of PDCs is combined with the cyclic nature of Arrayed-waveguide multiplexers to construct compact and efficient encoders.

From the property of cyclic difference sets, let $C_k(i)$ denote the ith element of the k^{th} PDC. The code properties can be written as:

$$\sum_{i=1}^{\nu} c_k(i)\, c_l(i) = \begin{cases} w & k = l \\ 1 & k \neq l \end{cases} \qquad (1)$$

The example of PDC for w=3 and ν=7 are shown in Table 1.

4. MONTE-CARLO SIMULATION FOR OPTICAL CDMA

The framework to simulate Monte Carlo algorithms used in this work consists of the following steps:

- PDC are generated and assigned to each user at random.

- Data for each user is generated at random. Since the transmitters are chip synchronized, instead of bit synchronized, the code chips transmitted by several transmitters may overlap with each other during a subsequent bit period. The generated data pattern for each user is then positively summed to simulate the MAI effect.
- For channel, the noise is generated using Gaussian distribution according to the expression derived in section 4.3.
- At the target receiver, the superposition of the transmitted signal is detected.
- At the target receiver, a decision rule is applied as to whether bit "1" or bit "0" was sent.
- At the end of each bit period, the decision made by the target receiver is compared with the transmitted bit to determine whether a bit error was made.

4.1 Noise Calibration for Baseband Binary (Bipolar)

In digital communications, the SNR (Signal to Noise Ratio) is more often used as a figure of merit in terms of bit energy and noise variance. Therefore, we can write

$$\frac{S}{N} = \frac{E_S / T_S}{\sigma_n^2} \tag{2}$$

where, S is the signal power, N is the noise power, E_s is the symbol energy, T_s is the symbol period, and σ_n^2 is the noise variance with two-sided power spectral density equal to a constant $N_0/2$ as shown in Fig. 2. Being binary symbol energy is equal to bit energy and symbol period is equal to bit period.

Referring to Fig. 2, the PSD (Power Spectral Density) of noise variance can be given as:

TABLE 1. EXAMPLE OF PERFECT DIFFERENCE CODE

Perfect Difference Set for w=3 and v=7						
1	1	0	1	0	0	0
0	1	1	0	1	0	0
0	0	1	1	0	1	0
0	1	0	1	1	0	1
1	0	1	0	1	1	0
0	1	0	1	0	1	1
1	0	1	0	1	0	1

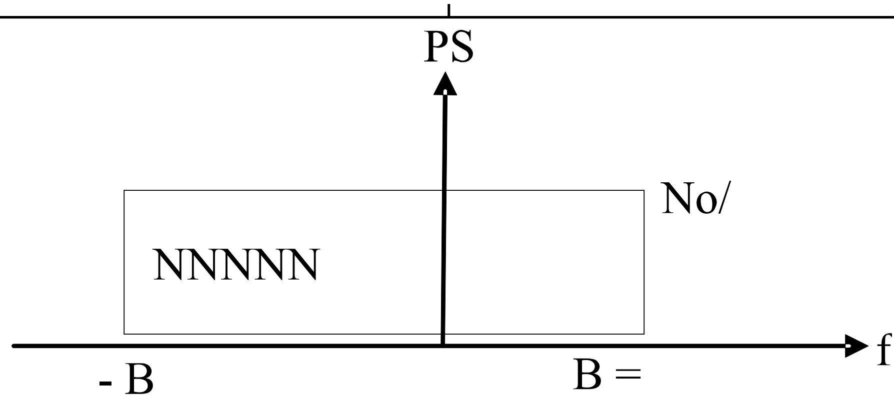

FIG. 2. POWER SPECTRAL DENSITY FOR NOISE IN BASEBAND COMMUNICATION SYSTEM

$$\sigma_n^2 = 2B \times \frac{N_0}{2} = BN_0 \Rightarrow N_0 \frac{1}{2T_s} = \frac{N_0}{2T} \tag{3}$$

Substituting this Equation (2), we get:

$$\frac{S}{N} = \frac{E_b / T}{N_0 / 2T} \Rightarrow \frac{2E_b}{N_0} \tag{4}$$

Rearranging the Equation (2) gives:

$$N = \frac{S}{2E_b / N_0} \tag{5}$$

or

$$\sigma = \sqrt{\frac{S}{2E_b / N_0}} \tag{6}$$

4.2 Noise Calibration for DSSS Baseband Binary (Bipolar)

In DSSS (Direct Sequence Spread Spectrum) commonly known as CDMA systems, we have a unique spreading code assigned to each user which expands its data in the time domain by direct multiplication. Hence, the bandwidth of spread signal becomes B_c and consequently, the noise variance becomes:

$$\sigma_n^2 = 2B_c \times \frac{N_0}{2} = \frac{N_0}{2T_c} \tag{7}$$

We know that:

$$\frac{S}{N} = \frac{E_b / T}{N_0 / 2T_c} \Rightarrow \frac{2T_c}{T} \times \frac{E_b}{N_0} \tag{8}$$

But the ratio of T and T_c is equal to the processing gain or the length of the spreading code ν, which means:

$$\frac{S}{N} = \frac{2}{v} \times \frac{E_b}{N_0} \tag{9}$$

Rearranging Equation (9) results in:

$$\sigma = \sqrt{\frac{vS}{2E_b / N_0}} \tag{10}$$

4.3 Noise Calibration for DSSS Baseband (Unipolar)

Assuming OOK, whereby data bit 1 is transmitted with spreading code and data bit 0 is represented by no signal as shown in Fig. 3.

The energy E and the signal power S for the data bit 1 and 0 can be given as:

$$E_1 = \int_0^T (P(t))^2 \qquad E_0 = 0$$
$$S_1 = \frac{1}{T}\int_0^T (P(t))^2 \qquad S_0 = 0 \tag{11}$$

$$S_1 = \frac{1}{T}\left[A^2 T_c w\right] = \frac{wA^2}{v} \tag{12}$$

where w is the number of chips in spreading sequences and A is the amplitude.

On average,

$$S_1 = \frac{wA^2}{2v} \tag{13}$$

FIG. 3. ON-OFF KEYING IN OPTICAL CDMA

Assuming that the amplitude is 1 and substituting in the Equation (13), we get:

$$\sigma = \sqrt{\frac{v}{\quad} \times \frac{w}{\quad}} = \sqrt{\frac{w}{\quad}} \tag{14}$$

Equation (14) is used to calibrate noise for the PDC based Optical CDMA systems.

5. SIMULATION RESULTS

The BER performance of the optical CDMA system utilizing spectral amplitude technique based on perfect difference codes is analyzed with the aid of Monte-Carlo Simulations. The simulation framework is already explained in Section 4. Perfect difference codes with weight, w=14 and length v=183 is assumed. For the purpose of our experiments, the gain difference between the two branches of the receiver shown in Figure 1b is varied in steps of 5 and 10%, while the split loss is taken to be 0.5 or 1.0dB [9].

Fig. 4 plot the BER versus normalized SNR for the system under study assuming ideal conditions with additive white Gaussian noise channel. The theoretical and simulated results match very well, and the BER performance improves as the SNR is increased.

Fig. 5 shows the impact of APD gain mismatch on the system performance assuming uniform split power at the transmitter and receiver side. Using PDC with same parameters of w=14 and T_c=0.1 ns, the results reveal that even the slight difference of 5% between the branches of receiver (Fig. 1(b)) can cause serious degradation in the probability of error performance. As the difference is increased to 10%, the performance further deteriorates. Fig. 6 depicts the results obtained after assuming perfectly matched APDs at the transmitter side but non-uniform split power at both transmitter and receiver. The split loss considered is 0.5 and 1.0dB. It is obvious to note that though, the split loss does negatively impact the BER performance of the system but its impact is not as severe as it is in the case of APD gain mismatch.

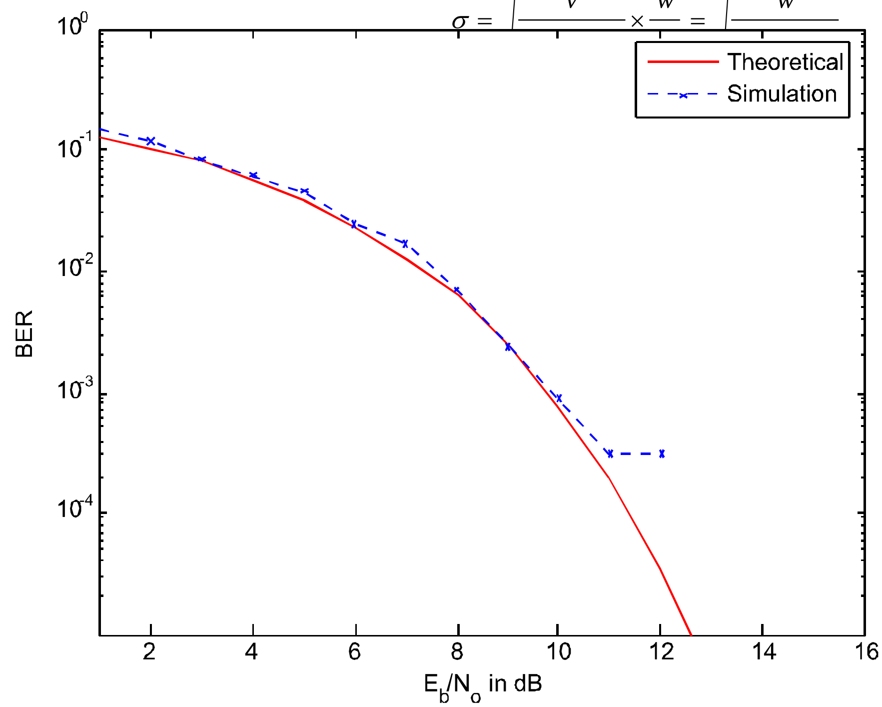

FIG. 4. BER VERSUS E_b/N_0 FOR PDC-BASED OCDMA SYSTEM, w=14, T_c=0.1 NS

Fig. 7 combines the losses incurred by APD gain mismatch and splitter and plots the BER versus SNR curves. Confirming the previous results, the results show that the performance is worsened

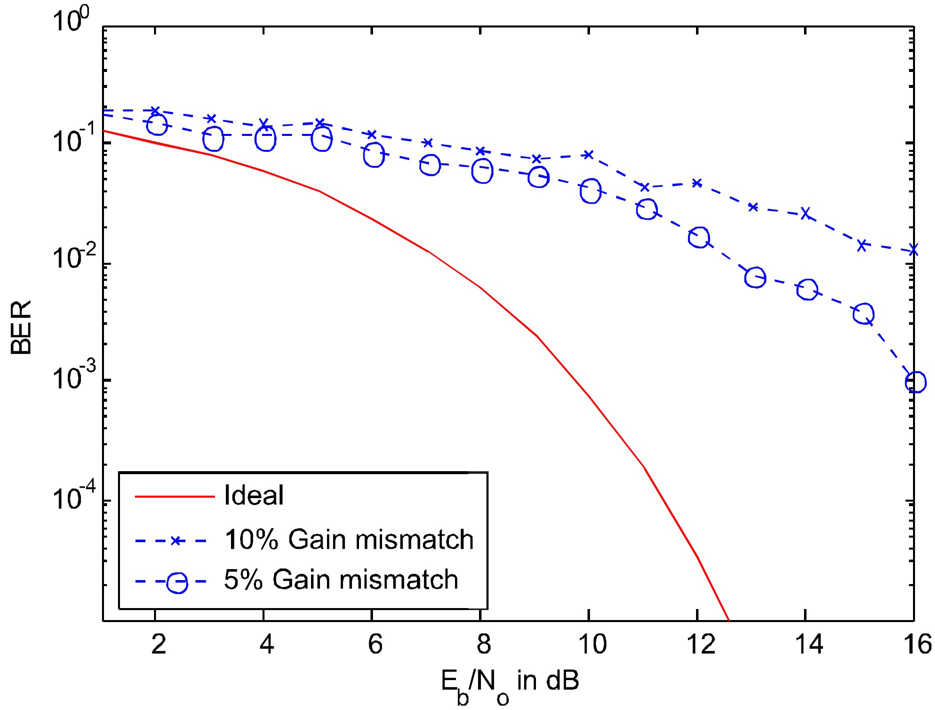

FIG. 5. BERVERSUS E_b/N_0 FOR PDC-BASED OCDMA SYSTEM WITH GAIN MISMATCH ONLY.

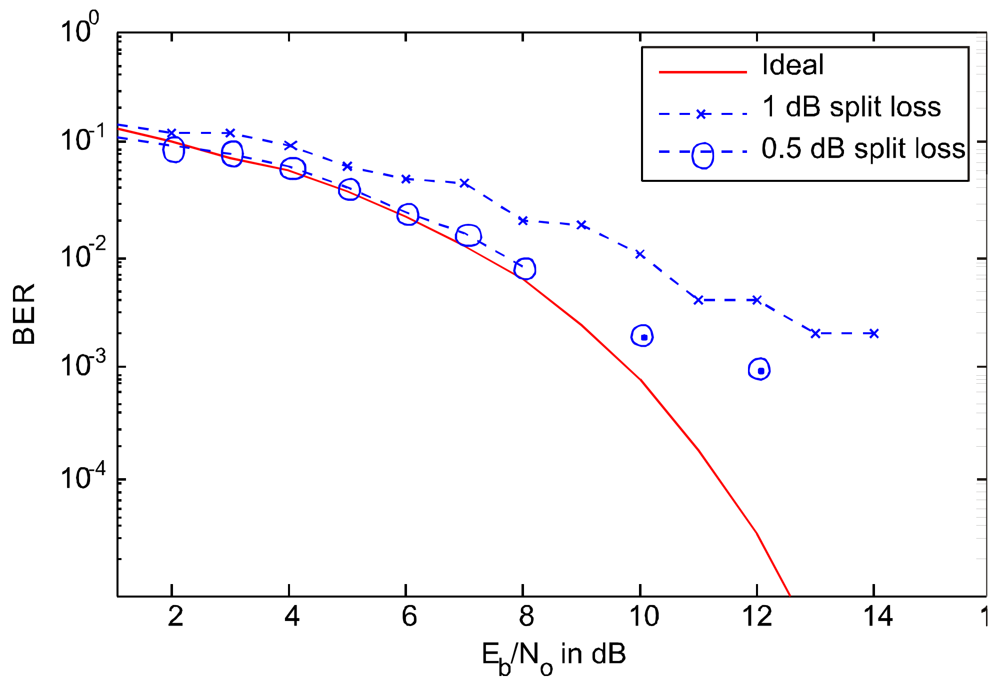

FIG. 6. BER VERSUS E_b/N_O FOR PDC-BASED OCDMA SYSTEM WITH SPLIT LOSS ONLY.

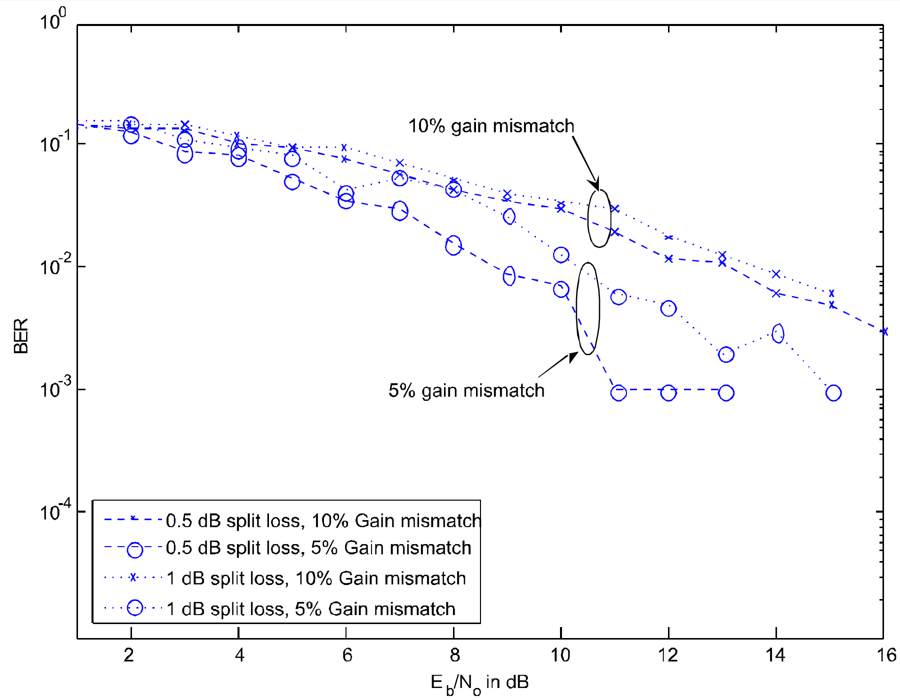

FIG. 7. BER VERSUS E_b/N_0 FOR PDC-BASED OCDMA SYSTEM WITH BOTH APD GAIN MISMATCH AND SPLIT LOSS

6. CONCLUSIONS

The Monte-Carlo simulations of optical CDMA based system utilizing SAC and perfect difference codes as spreading sequences is analyzed. Only slight mismatch in the gain of the receiver can severely degrade the system performance. Therefore, satisfactory system performance requires using efficient gain controllers. The results reveal that the split loss in its own is not as severe as gain mismatch, but when combined with later the effects are negative on the system performance.

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