Fuzzy Inference System Based Adaptive Modulation Scheme for Optical Wireless Communication

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Abstract

The modern era of indoor wireless optical communications is using the diffuse emissions in the infrared band for indoor communications. The optical wireless channel was limited by channel constraints such as the maximum allowable optical power and available bandwidth. Modulation schemes well suited to conventional channel were not necessarily perform well for the optical wireless channel. Bandwidth and power efficiency of various modulation schemes for wireless optical communication indoor applications are investigated. These schemes include On-Off Key (OOK), Pulse Amplitude Modulation (PAM), Differential Pulse Position Modulation (DPPM), and differential amplitude PPM (DAPPM). As a result, an adaptive modulation scheme named Adaptive Differential Amplitude Pulse-Position Modulation (DAPPM) is proposed because DAPPM was found to be the best modulation schemes in terms of power and bandwidth requirements under careful design. In addition, the fuzzy logic module is developed to assist the adaptation process of DAPPM. The Fuzzy logic control system can realise system adaptation by just applying the rules to fuzzy interference process. This showed a simple but yet powerful approach of Fuzzy logic method which can be provided for system design and used in which the decisions made by the system will be approaching to what would be decided by the user in the real world.

Keywords: Fuzzy inference system, Modulation scheme, Optical wireless communication

1. Introduction

The modern era of indoor wireless optical communications using the diffuse emissions in the infrared band for indoor communications (Gfeller and Bapst, 1979). Since that time, much work has been done in characterizing indoor channels, designing receiver and transmitter optics and electronics, developing novel channel topologies as well as in the area of communications system design.

An optical wireless communication system is an attractive alternative to radio, primarily because of a virtually unlimited, unregulated bandwidth. The optical spectrum is a universally available resource without frequency and wavelength regulations. An optical wireless communication system has the advantage of requiring low-cost and low power consumption components (Tanaka, 2002). On the other hand, the channel can be severely interfered by background noise: shot noise induced by the background ambient light and the interference induced by artificial light sources (Yu, 2010). In comparison, though, directed line-of-sight (LOS) IR systems had the potential to achieve a data rate of a few gigabits per second and higher.

Normally, an optical wireless communication system adopts a baseband modulation scheme such as On-Off Keying (OOK), Pulse Amplitude Modulation (PAM) or Differential Pulse Position Modulation (DPPM). To yield more efficiency in terms of optical power and bandwidth, Differential Amplitude Pulse-Position Modulation (DAPPM) has been proposed.

In this paper, mathematical model for the proposed modulation schemes has been derived in Section 2. Section 3 presents the numerical simulation and discussion in terms of optical power and bandwidth. In addition, the Fuzzy logic control module for DAPPM has been developed using Fuzzy Inference System (FIS). Furthermore, the output from the fuzzy control module such as amplitude level (A) and differential pulse-position change (L) has been determined in Section 4.

2. Mathematical Model

Selecting a modulation technique is one of the key technical decisions in the design of any communication system. The vital metrics against which a particular modulation technique is assessed are highlighted optical power efficiency and bandwidth efficiency in the order of importance from optical wireless communication stand point. In this paper, the expressed normalized power and bandwidth equation of OOK will be used only as a benchmark to obtain the normalized power and bandwidth requirement equations for OOK, PAM, DPPM and DAPPM.

2.1 On-Off Keying

The most reported modulation techniques for IM/DD in optical communication is the On-Off Key. OOK is the simplest technique to implement in wireless infrared transmission. Prior to transmission, the information is translated to a specific code such as Manchester, Return to Zero (RZ), or Non Return to Zero (NRZ) codes, to get a stream of pulses.

In OOK, a pulse is transmitted if the code bit is 'one' during a fixed time slot and a 'zero' is represented by the absence of the pulse during the time slot (Singh et al., 2002).

Normalized bandwidth requirements of On-Off Keying (OOK) schemes are as follows:

$$B_{OOK} = R_b = 1 \qquad (1)$$

Bit error rate (BER) of OOK

$$BER_{OOK} = Q\left(\frac{P_{ar-OOK}}{\sqrt{N_0 R_b}}\right) \qquad (2)$$

A normalized power requirement of OOK is given by:

$$P_{OOK} = \sqrt{N_0 R_b}\, Q^{-1} \cdot (BER_{OOK}) \qquad (3)$$

Where, N_0 = the power spectral density of the White Gaussian Noise

$Q(x)$ = the customary Q-function of digital telecommunication

2.2 Pulse Amplitude Modulation (PAM)

The Pulse Amplitude modulation technique belonged to pulse amplitude level modulation scheme is shown in Figure 1. L-level PAM (L-PAM) is one of L possible amplitude levels transmitted from the transmitter to represent a specific value (Yu, 2010).

Normalized bandwidth requirement of PAM is:

$$B_{PAM} = \frac{R_b}{\log_2 L} \qquad (4)$$

$$B_{PAM} = \frac{1}{\log_2 L} \cdot B_{OOK} \qquad (5)$$

$$\frac{B_{PAM}}{B_{OOK}} = \frac{1}{\log_2 L} \qquad (6)$$

Normalized power requirement of PAM as:

$$P_{PAM} = \frac{L-1}{\sqrt{\log_2 L}} \cdot \sqrt{N_0 R_b}\, Q^{-1} \cdot (BER_{PAM}) \qquad (7)$$

$$P_{PAM} = \frac{L-1}{\sqrt{\log_2 L}} \cdot P_{OOK} \qquad (8)$$

$$\frac{P_{PAM}}{P_{OOK}} = \frac{L-1}{\sqrt{\log_2 L}}$$

(9)

2.3 Differential Pulse Position Modulation (DPPM)

Differential Pulse-position modulation (DPPM) is a simple modification of PPM that can achieve improved power or bandwidth efficiency in applications where low cost dictates the use of hard-decision detection, and multipath ISI is minimal. The time waveform for DPPM is shown in Figure 2 (Singh, 2002).

Normalized bandwidth requirements of DPPM

$$B_{DPPM} = \frac{(L+1)R_b}{2\log_2 L}$$

(10)

$$B_{DPPM} = \frac{(L+1)}{2\log_2 L} \cdot B_{OOK}$$

(11)

$$\frac{B_{DPPM}}{B_{OOK}} = \frac{L+1}{2\log_2 L}$$

(12)

Normalized power requirements of DPPM

$$\frac{P_{DPPM}}{P_{OOK}} = \frac{2^M+1}{2}\left(\frac{2}{L\log_2 L}\right)$$

(13)

2.4 Differential Amplitude Pulse-Position Modulation (DAPPM)

The pulse modulation schemes named Differential Amplitude Pulse-Position Modulation (DAPPM) is a combination of the Differential Pulse Position Modulation (DPPM) and Pulse Amplitude Modulation (PAM) as shown in Figure 3 (Sethakaset and Gulliver, 2004).

Normalized bandwidth requirement of DAPPM is given by:

$$B_{DAPPM} = \frac{(L+1)R_b}{2\log_2 (L\times A)}$$

(14)

$$B_{DAPPM} = \frac{(L+1)}{2\log_2 (L\times A)} \cdot B_{OOK}$$

(15)

$$\frac{B_{DAPPM}}{B_{OOK}} = \frac{L+1}{2\log_2(L \times A)}$$

(16)

Normalized power requirement of DAPPM scheme as:

$$\frac{P_{DAPPM}}{P_{OOK}} = \frac{A(L+1)}{(A+1)} \cdot \frac{1}{2^M} \cdot \left(\frac{2}{L\log_2 L} \right)$$

(17)

Where, $M = Log_2(A \times L)$

$$\frac{P_{DAPPM}}{P_{OOK}} = \frac{A(L+1)}{(A+1)} \cdot \frac{1}{2^{(Log_2(A \times L))}} \cdot \left(\frac{2}{L\log_2 L} \right)$$

(18)

3. Normalized Optical Power and Bandwidth Requirement

An optical power efficient and bandwidth efficient modulation scheme is desirable in an indoor optical wireless system (Hranilovic and Kschischang, 2003). On-Off keying (OOK), Pulse Amplitude Modulation (PAM), Differential Pulse Position Modulation (DPPM), and Differential Pulse-Position Modulation (DAPPM) are four extremely popular modulation schemes for optical wireless channel. This paper considers these four modulation schemes in terms of their power and bandwidth requirement. A comparison among the different modulation schemes is done.

3.1 Pulse Amplitude Modulation (PAM)

Figure 4 present the optical bandwidth and power requirements of PAM. Each point for PAM represents that the maximum length L={2,3,4…32}. As one observes, increasing symbol length (L) for PAM results will decrease the bandwidth requirement B_{PAM}/B_{OOK} but increase the power requirement P_{PAM}/P_{OOK}.

The lowest bandwidth requirement for PAM, B_{PAM}/B_{OOK}= 0.20, is achieved at L = 32, and the largest one, B_{PAM}/B_{OOK} =1.00, at L = 2. Similarly, the lowest power requirement, P_{PAM}/P_{OOK} =0, is achieved at L = 2 and the largest one, P_{PAM}/P_{OOK}= 11.42, occurs at L = 32. Figure 4 also shows that PAM modulation was not preferred in terms of power efficiency but in term of bandwidth requirement is more efficient compare with other modulation schemes.

3.2 Differential Pulse-Position Modulation (DPPM)

Figure 5 shows that the optical bandwidth and power requirements of DPPM. As the result, the lowest bandwidth requirement for DPPM, B_{DPPM}/B_{OOK}=1.50, is achieved at L=2, and the largest one, B_{DPPM}/B_{OOK}=3.30, at L=32. Similarly, the lowest power requirement, P_{DPPM}/P_{OOK}=-6.10, is achieved at L=32 and the largest one, P_{DPPM}/P_{OOK}=2.00, occurs at L=2. Besides this, Figure 5 also shows that

DPPM always achieves higher power efficiency than other modulation schemes such as PAM and PPM.

3.3 Differential Amplitude Pulse-Position Modulation (DAPPM)

The pulse modulation schemes named, Differential Amplitude Pulse-Position Modulation (DAPPM) is a combination of the Differential Pulse Position Modulation (DPPM) and Pulse Amplitude Modulation (PAM). For the DAPPM scheme, the value for symbol length (L) and amplitude level (A) will effect the bandwidth and power requirements.

Results obtained in Figure 6 shows that the normalised power and bandwidth requirements of DAPPM. The bandwidth requirement increase with the symbol length (L) of the DAPPM scheme. However, this increment in bandwidth requirement for DAPPM (lower bandwidth efficiency and allowable bit rate) can be reduced by adopting a wide variety of the amplitude (A) for the operating optical pulses. This gives an advantage of combining PAM with DPPM. The lowest bandwidth requirement for DAPPM, B_{DAPPM}/B_{OOK}= 0.25, is achieved at A = 32, L = 2 and the largest one, B_{DAPPM}/B_{OOK} =2.75, at A = 2, L = 32. Similarly, the lowest power requirement, P_{DAPPM}/P_{OOK} = 0.003, is achieved at A = 32, L = 32 and the largest one, P_{DAPPM}/P_{OOK} = 0.5, occurs at A = 2, L = 2.

3.4 Comparison among different modulation schemes

Figure 7 presents the optical bandwidth and power requirements for OOK, PAM, DPPM, and DAPPM (A=2). Each point for PAM, DPPM, and DAPPM represents that the maximum length L={2,4,8,16,32}. The performance of modulation schemes for optical wireless communication channel analysis shows that, OOK is the simplest schemes, therefore it does not require symbol synchronization and the minimum bandwidth requirements, B_{OOK}=1 , but power utilization ratio is too low, P_{OOK}=0.

As one observes, increasing symbol length (L) for PAM results will decrease the bandwidth requirement B_{PAM}/B_{OOK}= 0.20, is achieved at L = 32. However, it will increase the power requirement P_{PAM}/P_{OOK}= 11.42, occurs at L = 32. Therefore, PAM modulation was not preferred in terms of power efficiency but in term of bandwidth requirement is more efficient compare with other modulation schemes such as OOK and PPM.

The lowest bandwidth requirement for DPPM, B_{DPPM}/B_{OOK}=1.50, is achieved at L=2, while lowest power requirement, P_{DPPM}/P_{OOK}=-6.10, is achieved at L=32. DPPM always achieves higher power efficiency than other modulation schemes such as PAM and PPM.

The analysis suggests that using DAPPM modulation techniques will provide more advantages over OOK, PAM, and DPPM. DAPPM will provide better bandwidth and power efficiency depending on the number of amplitude level (A) and the maximum length (L) of a symbol. The lowest bandwidth requirement for DAPPM, B_{DAPPM} /B_{OOK}= 0.75, is achieved at A = 2, L = 2 and the largest one, B_{DAPPM} /B_{OOK} =2.75, at A = 2, L = 32. Similarly, the lowest power requirement, P_{DAPPM} /P_{OOK} = 0.038, is achieved at A=2, L = 32 and the largest one, P_{DAPPM} /P_{OOK} = 0.5, occurs at A = 2, L = 2. In addition to this, DAPPM also provide lower average symbol length, higher transmission capacity and lower peak-to-average power ratio. The lowest and largest of normalized optical power and bandwidth required among PAM, DPPM and DAPPM modulation schemes is shown in Table 1.

4. Fuzzy Inference System for Adaptive DAPPM Modulation Scheme

The optical wireless channel was limited by channel constraints such as the maximum allowable optical power and available bandwidth. DAPPM schemes well suited to conventional channel. The optical wireless channel can be easily affected by modulation state; therefore a fuzzy inference system was set up to solve this problem and named Adaptive DAPPM System. BER level and rate are the input fuzzy sets, while Amplitude level (A) and differential pulse position change value (L) are the outputs of fuzzy sets as shown in Figure 8.

The Fuzzy Inference System (FIS) structure is the MATLAB object that contains all the fuzzy inference system information. This structure is stored inside each GUI tool. All the information for a given fuzzy inference system is contained in the FIS structure, including variable names, membership function definitions, and so on. This structure can itself be thought of as a hierarchy of structures.

Constructing the rules using the graphical Rule Editor interface is fairly self-evident. Based on the descriptions of the input and output variables defined with the FIS Editor, the Rule Editor for Adaptive DAPPM modulation technique was developed. Fuzzy logic incorporated a simple rule-based “If X and/or Y then Z” approach to solve control problems rather than attempting to model a system mathematically. The rules are flexible to add, delete or change using the rule editor. An example of five rules that are already sets is shown in Figure 9.

Figure 10 shows that the rules of fuzzy controller are used to change the system status and stabilize the BER. The first columns of plots show the membership functions referenced and the if-part of each rule for BER level. The second column of plots shows the membership functions referenced the “and” or “or” of each rule for variation rate. The third and four columns referenced by the consequent, or the then-part of each rule for amplitude level (A) and differential pulse position change (L). The six plot in the third and four column of plots represents the aggregate weighted decision for the given inference system. This decision will depend on the amplitude level (A) and differential pulse position change (L) values for the system. The defuzzified output is displayed as a bold vertical line on this plot. In this Figure, BER-level = 0.392 and Rate = 0.506 is chosen as sample inputs. The required amplitude level (A) is 0.611 and differential pulse position change (L) is 0.0488. Table 2 shows that the values of Amplitude level (A) based on the BER level and variation rate, while Table 3 shows that the values of differential pulse position change (L) based on the BER level and variation rate.

The surface of amplitude level (A) versus the BER level and change rate is shown in Figure 11(a), while the differential pulse position (L) versus the BER level and change rate is shown in Figure 11(b). The fuzzy control method was incorporated with the developed adaptive DAPPM as a viable control process for optical wireless communication channel. From the simulation result, fuzzy logics is able to provide powerful control functionality for BER, variation rate and modulation level. Incorporating Fuzzy control with DAPPM, communication systems can provide flexible and efficient adaptations for improving communication system.

5. Summary

In this paper, the optical power and bandwidth requirement for different modulation schemes were investigated. A detailed and general comparison between OOK, PAM, DPPM and DAPPM were done. As the obtain result shows, that DAPPM scheme is most power and bandwidth efficient. DAPPM is an asynchronous modulation technique which is a combination of PAM and DPPM. Therefore the symbol length (L) and the pulse amplitude (A) are varied to represent the information being transmitted. Furthermore, the fuzzy logic module has been developed to assist the adaptation process of DAPPM modulation scheme by using fuzzy inference system. The BER level and rate are the input fuzzy sets, while amplitude level (A) and differential pulse position change value (L) are the outputs fuzzy sets for adaptive DAPPM system. This proposed system shows that the fuzzy logic control module is very promising in controlling adaptive modulation scheme process for optical wireless communication channels.

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Appendix

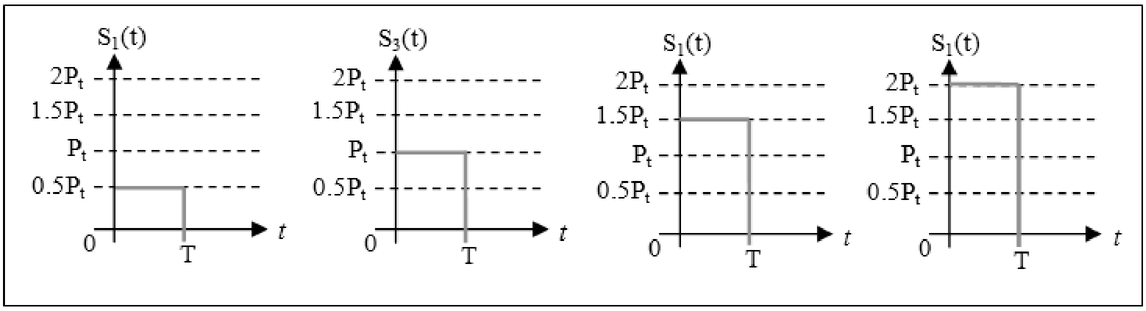

Figure 1. Time waveform of 4-PAM (Yu, 2010).

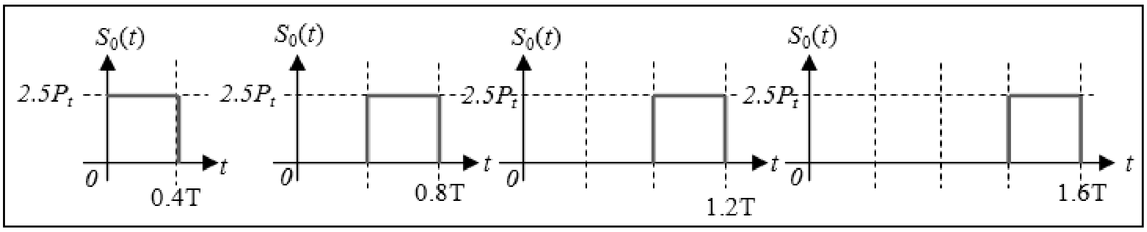

Figure 2. Time waveform of DPPM (Singh, 2002).

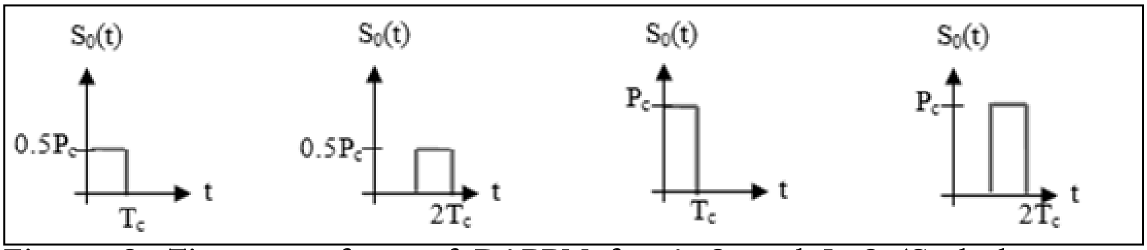

Figure 3. Time waveform of DAPPM for A=2 and L=2 (Sethakaset and Gulliver, 2004).

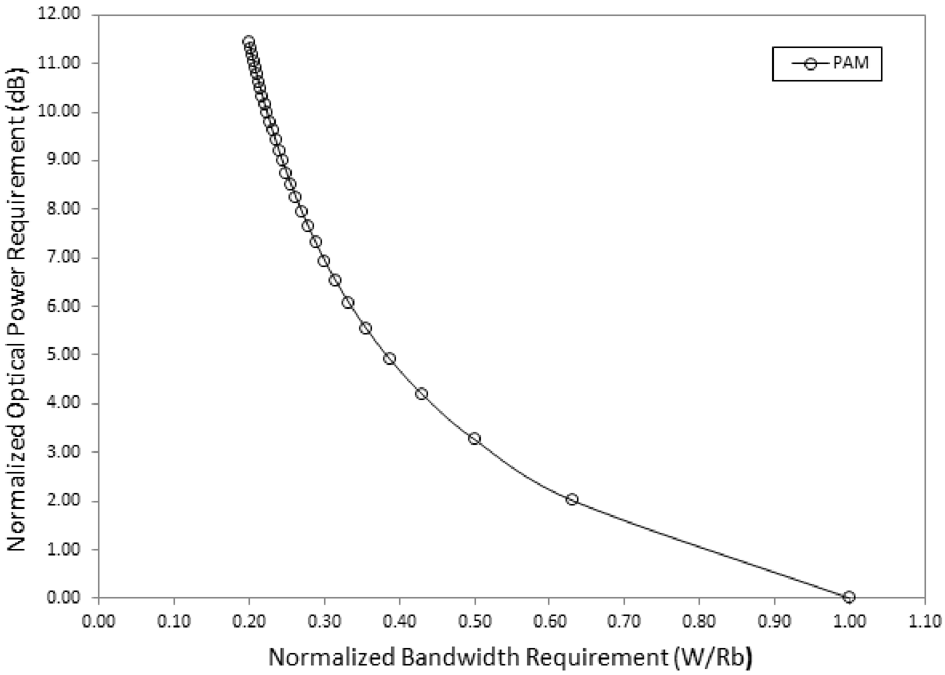

Figure 4. The normalized optical power and bandwidth required for PAM.

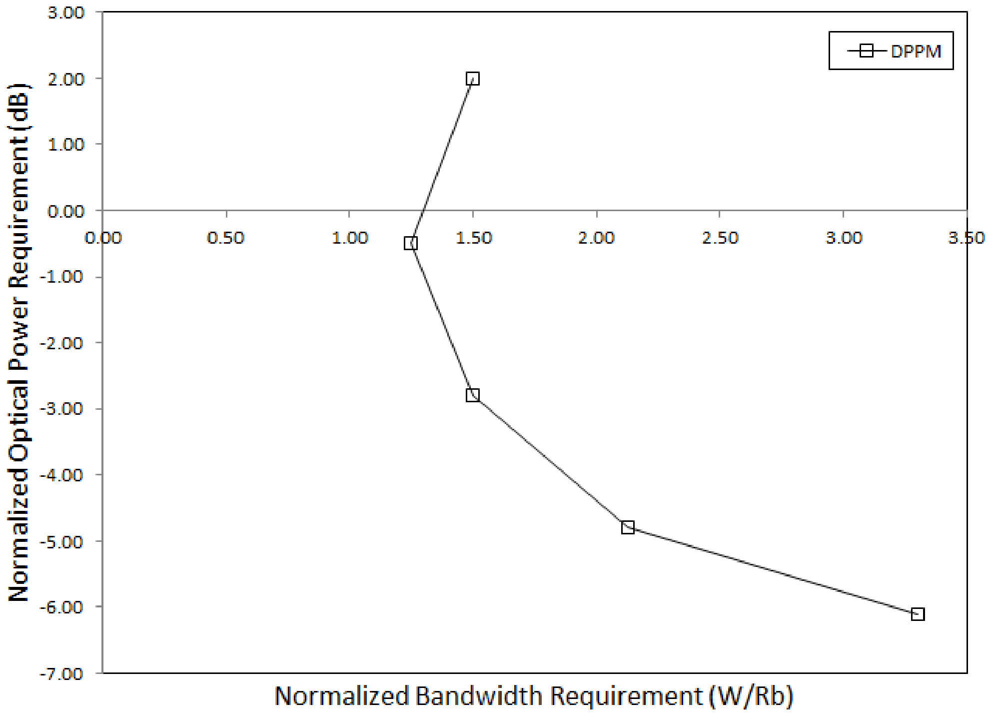

Figure 5. The normalized optical power and bandwidth required for DPPM.

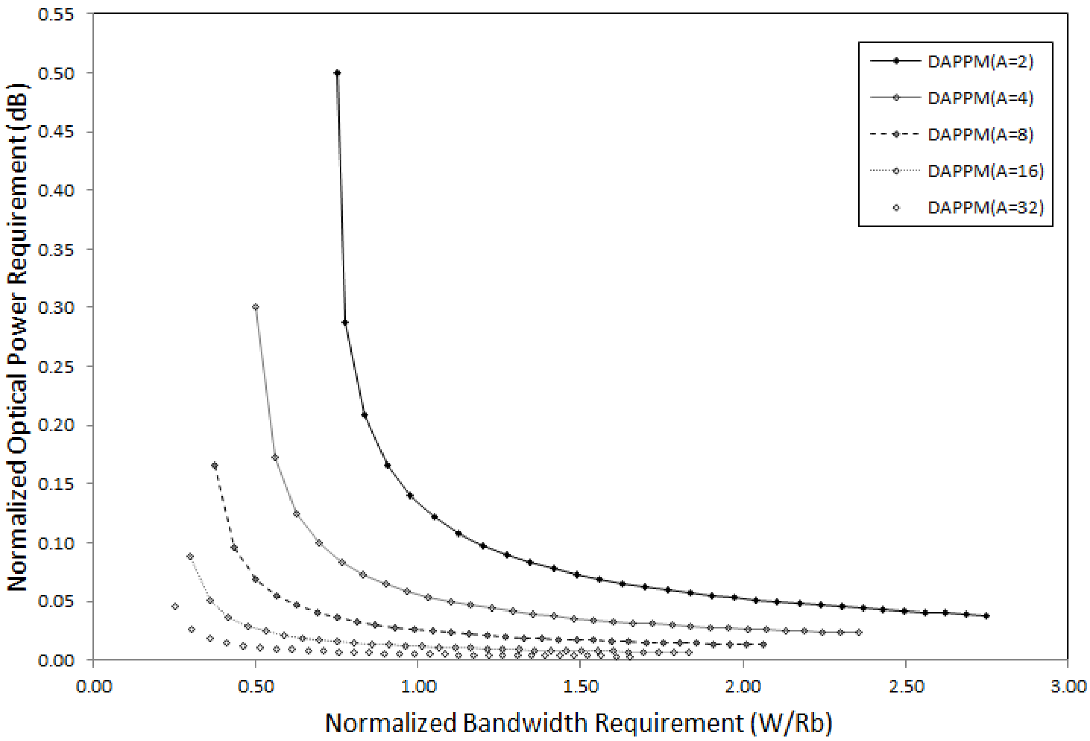

Figure 6. The normalized optical power and bandwidth required for DAPPM.

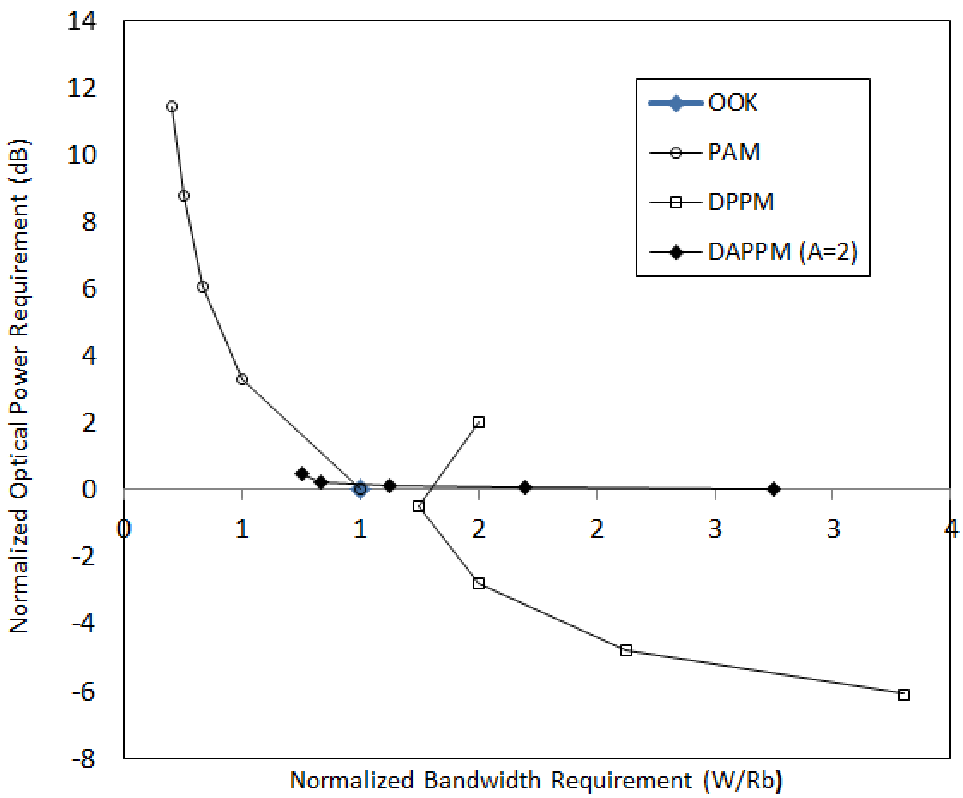

Figure 7. The normalized optical power and bandwidth required for OOK, PAM, PPM, M_N_PAPM and DAPPM.

Table 1. Comparison of normalized optical power and bandwidth required among different modulation schemes.

No.	Modulation schemes	Normalized optical bandwidth requirement		Normalized optical power requirement	
		Lowest	Largest	Lowest	Largest
1.	PAM	0.20	1.00	0	11.42
2.	DPPM	1.50	3.30	-6.10	2.00
3.	DAPPM(A=2)	0.75	2.75	0.038	0.50

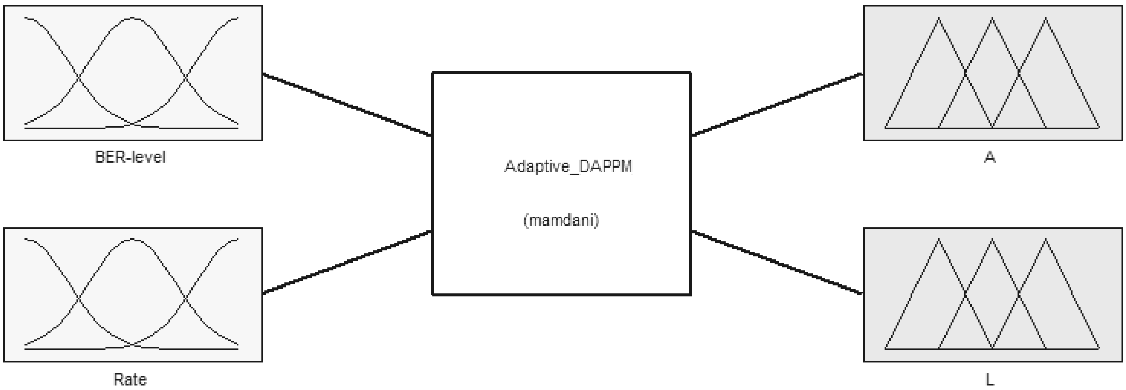

Figure 8. Block diagram of adaptive DAPPM system.

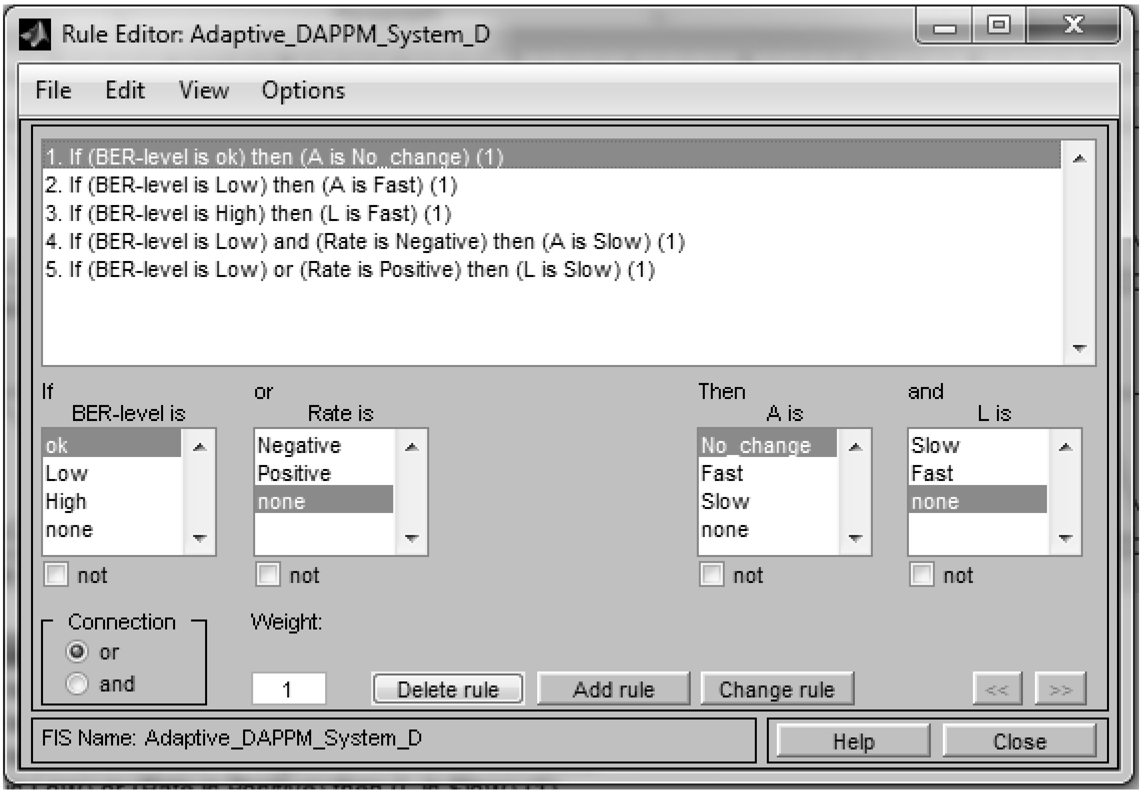

Figure 9. The rule editor for DAPPM system.

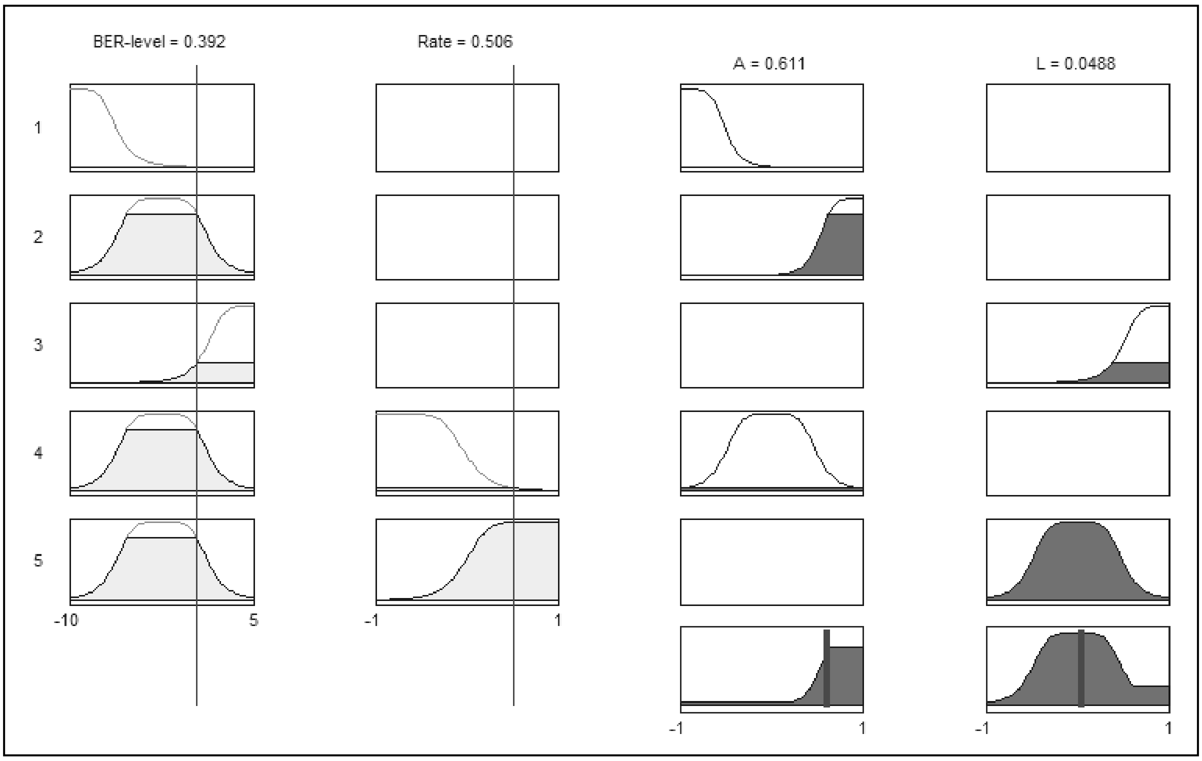

Figure 10. Rule view for DAPPM system

Table 2. The values of Amplitude level (A)based on the BER level and variation rate.

No.	Fuzzify Input				Fuzzify Output		Color
	BER-level		Variation Rate		Amplitude level		
1.	-10	OK	-1	NEGATIVE	-0.658	NO-CHANGE	Red
2.	-10	OK	1	POSITIVE	-0.664	NO-CHANGE	
3.	-8	OK	1	POSITIVE	-0.51	NO-CHANGE	Orange
4.	-8	OK	-1	NEGATIVE	-0.464	SLOW	
5.	-6	LOW	-1	NEGATIVE	0.0467	SLOW	Yellow
6.	-6	LOW	0.5	POSITIVE	0.0737	SLOW	
7.	-5.5	LOW	-1	NEGATIVE	0.126	SLOW	Pringgreen
8.	-5.5	LOW	0.0	POSITIVE	0.16	SLOW	
9.	-5.5	LOW	0.5	POSITIVE	0.253	SLOW	Lawngreen
10.	-5.5	LOW	1.0	POSITIVE	0.257	SLOW	
11.	-5	LOW	-1	NEGATIVE	0.169	SLOW	Cyan
12.	-5	LOW	0	POSITIVE	0.23	SLOW	
13.	-5	LOW	0.5	POSITIVE	0.39	SLOW	Blue
14.	-5	LOW	1	POSITIVE	0.396	SLOW	
15.	-4	LOW	0.5	POSITIVE	0.552	FAST	Purple
16.	-4	LOW	1	POSITIVE	0.561	FAST	
17.	0	LOW	0.6	POSITIVE	0.659	FAST	Deeppink
18.	0	LOW	1	POSITIVE	0.711	FAST	

Table 3. The values of Differential Pulse Position Change (L) based on the BER level and variation rate.

No.	Fuzzify Input				Fuzzify Output		Color
	BER-level		Variation Rate		Differential Pulse Position Change		
1.	-10	OK	-1	NEGATIVE	-0.646	NO-CHANGE	Red
2.	-9	OK	-0.5	NEGATIVE	-0.593	NO-CHANGE	
3.	-8	OK	-1	NEGATIVE	-0.498	SLOW	Orange
4.	-8	OK	-0.5	NEGATIVE	-0.464	SLOW	
5.	-7.5	OK	-1	NEGATIVE	-0.36	SLOW	Yellow
6.	-7.5	OK	-0.2	NEGATIVE	-0.208	SLOW	
7.	-6.0	LOW	-1	NEGATIVE	-0.132	SLOW	Lawngreen
8.	-6.0	LOW	1	POSITIVE	-0.0986	SLOW	
9.	-5	LOW	-1	NEGATIVE	-0.0352	SLOW	Pringgreen
10.	-5	LOW	-1	NEGATIVE	-0.0332	SLOW	
11.	-2	LOW	1	POSITIVE	0.0005	SLOW	Cyan
12.	0	LOW	-1	NEGATIVE	0.03	SLOW	
13.	2.5	HIGH	-1	NEGATIVE	0.421	SLOW	Blue
14.	2.5	HIGH	1	POSITIVE	0.194	SLOW	
15.	4	HIGH	-1	NEGATIVE	0.592	FAST	Purple
16.	4	HIGH	-0.5	NEGATIVE	0.592	FAST	
17.	5	HIGH	-1	NEGATIVE	0.646	FAST	Deeppink
18.	5	HIGH	-0.8	NEGATIVE	0.646	FAST	

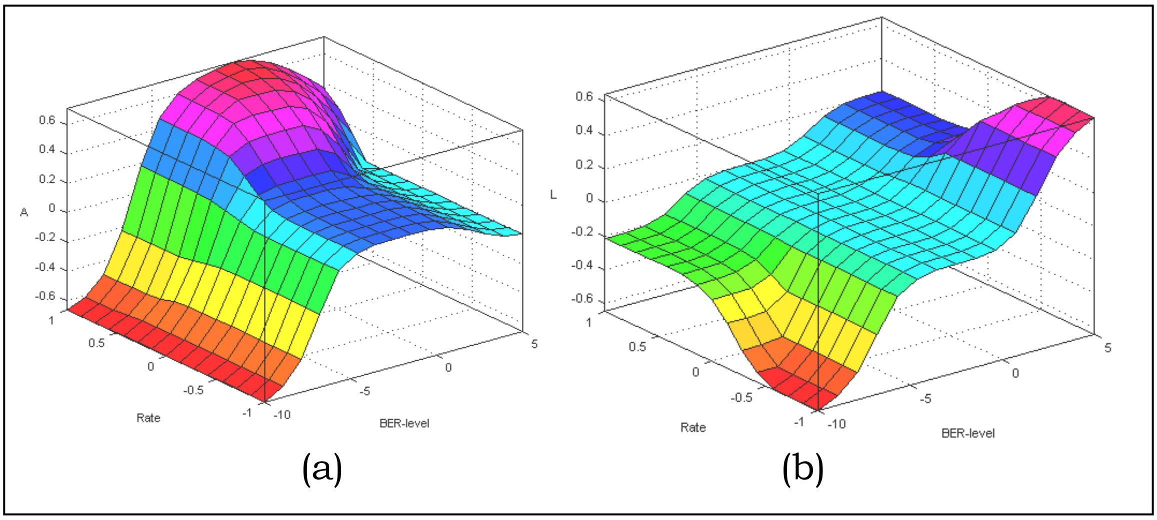

Figure 11. The surface of A and L versus the BER level and change rate.