ISSN 2278-3091

Volume 8, No.1.4, 2019

International Journal of Advanced Trends in Computer Science and Engineering

Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse5481.42019.pdf

https://doi.org/10.30534/ijatcse/2019/5481.42019

CNDS-Rules and Pattern Based Signal Recovery for Multi-level Signal Decision Making

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ABSTRACT

This paper focuses on the pattern based decision making over a multilevel symbol coding, Duty-cycle Division Multiplexing (DCDM). The pattern based decision making is used to increase the bit generation reliability at the receiver. It is used in conjunction with the existing rules-based decision making, which leads to better Bit Error Rate (BER). In this study, a reference pattern is first established from a combination of signals of multiple users' data. Subsequently, a new signal is generated according to the established patterns. This signal is then transmitted over the optical medium. At the receiver, signal validation and bit generation are then taking place based on the DCDM regeneration rules. Due to the signal impairments, the received signal will be corrupted. The impairments may cause the signal patterns to differ from the transmitted patterns. These non-conforming patterns are classified as invalid patterns, which are then subjected to the error evaluation and pattern re-mapping. In this paper for the first time we have used a new pattern based decision making in order to increase the reliability of bit sequence generation at the receiver, which leads to better BER.

Key words : DCDM, Optical receivers, Optical modulation, Optical signal detection, Signal to noise **ratio.**

1. INTRODUCTION

The decision making process at the receiver plays an important role in deciding the received bits sequence. A set of rules are normally used, associated with the received signal's amplitude level. In a binary system, the received signal is organized in high and low levels namely *marks* and *spaces* [1]. Based on these two values, a marginal level is chosen at the right sampling time, normally at the middle of bit duration, as a threshold (fixed or dynamic) [2; 3]. Based on the threshold value, the rules are used in order to decide the received bits. If the received signal level is less than the threshold value, it normally will be evaluated as '0', otherwise it will be assessed as '1'.

Meanwhile, in a more complex system such as M-ary [4; 5] , more levels and threshold values are involved. Although it has the advantage of increased baud rate or number of symbols transmitted per second [6], the decision making process becomes more complicated. In multi-slot multi-level system e.g. DCDM and AP-DCDM data recovery will be even more challenging as the slot duration is smaller in comparison to conventional multilevel systems.[7; 8]. Thus the decision making based on re-generation rules may not be sufficient. Therefore in this case, for the purpose of generating a reliable bits sequence over multi-level and multi-slot symbols, we combined the decision making rules and a further signal evaluation process using pattern based approach. We introduce the patterns set which enables the classification of patterns into valid and invalid ones. The invalid patterns are then subjected to a remapping process in order to convert them to the closest valid pattern. By doing so, the probability of error reduced significantly.

In this paper, the re-mapping process involves recursive decision making based on the probability of its occurrence. It is derived from the established patterns resulting from the multiplexing of multiple signals using DCDM technique. This approach makes it different from the study in [9]. The complexity of this algorithm is manageable since the number of hypotheses, M is small (e.g. 4, 8 or 16) [10]. M is associated with the number of level in M-ary signaling alphabet. The proposed approach involves only 12 inference rules.

This paper organized as follow: Section II discusses the methodology and simulation setup, Section III covers the coefficient index and Section IV, discusses the calculated results.

2. METHODOLOGY

The block diagram of the simulation of the Duty-cycle Division Multiplexing (DCDM) is shown in Figure 1. It comprises of three main components namely a transmitter, communication medium as well as a receiver. At the transmitter, the individual non-return to zero (NRZ) users' signal is converted to return to zero (RZ) format. These signals are then modulated using a constant wave (CW) laser diode with the wavelength of 1550 nm and power of 0 dBm.

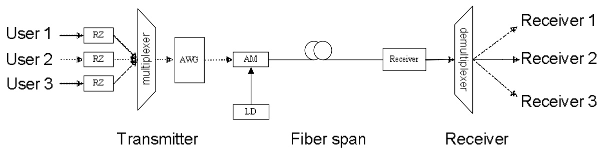

Figure 1. The DCDM system Setup

Prior to that, the specified pattern is established to represent certain combination of user's data. These symbol patterns are characterized by the use of different duty-cycles and power levels associated with each user. It is then divided into four different slots within a symbol period. As a result, the DCDM symbols mimicking "stair case" are established as illustrated by Figure 2.

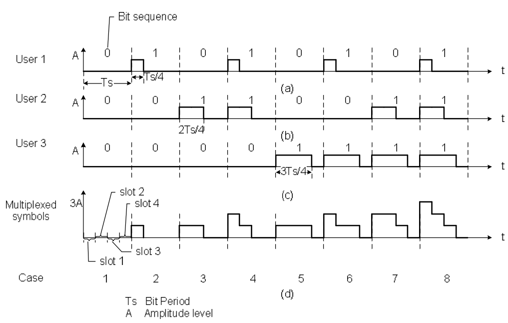

Figure 2. (a) the possible pattern for User 1 (U1), (b) the possible pattern for User 2 (U2) (c) the possible pattern for User 3(U3), (d) the multiplexed signal for U1, U2 and U3 (valid patterns)

The number of slots within the period Ts is associated with the number of users, *n* following *n+1* rule. These slots are due to the RZ duty-cycles of original users' symbol duration. Meanwhile the amplitude level of the signals are actually contributed by the combination of the original user's signal amplitude level, *A*. The relation with the users' data and signal properties are based on these two parameters, slots and amplitude levels. For instance, if User 1(U1), User 2(U2) and User 3(U3), carrying bit '0's – initial amplitude level for these users are 0, thus when it is multiplexed, the original levels are maintained and thus the DCDM signal pattern can be seen as in Case 1 of Figure 2. The same strategy is used for Case 2-Case 8, where each user's amplitude levels are added to form the stair case signal patterns.

Table 1: A Decision Making Rules

No	User	Rule	Decision	Case (see Figure 2)
1	U1	if (S1 < th1)&(S2 < th1)	0	1
2	U1	if (th1 ≤ S1 < th2)&(th1 ≤ S2 < th2)	0	3, 5
3	U1	if (th2 ≤ S1 < th3)&(S2 ≥ th2)	0	7
4	U1	if (th1 ≤ S1 < th2)&(S2 < th1)	1	2
5	U1	if (th2 ≤ S1 < th3)&(th1 ≤ S2 < th2)	1	4, 6
6	U1	if (S1 ≥ th3)&(S2 ≥ th2)	1	8
7	U2	if (S2 < th1)&(S3 < th1)	0	1, 2
8	U2	if (th1 ≤ S2 < th2)&(S3 ≥ th1)	0	5, 6
9	U2	if (thr1 ≤ S2 < th2)&(S3 < th1)	1	3, 4
10	U2	if (S2 ≥ th2)&(S3 ≥ th1)	1	7, 8
11	U3	if (S3 < th1)	0	1, 2, 3, 4
12	U3	if (S3 ≥ thr1)	1	5, 6, 7, 8

At the receiver's end, the signal detection and bit regeneration is supposed to take place. In the process to determine the transmitted signals data, the inference rules in Table 1 are used. The decision is based on the fixed three threshold values associated with each level. The threshold values are th1, th2 and th3, respectively. Based on rule no 1 of T, for instance, the received signal at slot 1 and slot 2 are both less than th1 and th2, thus the bit '0' will be generated. This "bit is assumed to represent the received data for receiver 1 or R1. This scenario is best described by Case 1 in Figure **2** (d). In the meantime, the decision making process is shown in Figure 3(a).

Table 2 : Signals Validation Classification Based on the DCDM Original Patterns

Case (as shown in Figure 2)	Slot 1	Slot 2	Slot 3	validity
1	0	0	0	valid
-	0	0	1	invalid
-	0	1	0	invalid
-	0	1	1	invalid
-	0	2	0	invalid
-	0	2	1	invalid
2	1	0	0	valid
-	1	0	1	invalid
3	1	1	0	valid
4	1	1	1	valid
-	1	2	0	invalid
-	1	2	1	invalid
-	2	0	0	invalid
-	2	0	1	invalid
5	2	1	0	valid
6	2	1	1	valid
-	2	2	0	invalid
7	2	2	1	valid
-	3	0	0	invalid
-	3	0	1	invalid
-	3	1	0	invalid
-	3	1	1	invalid
-	3	2	0	invalid
8	3	2	1	valid

In reality, the received signal experienced some imperfection (e.g attenuation and dispersion) as it travels through the transmission medium, which cause a huge problem in the decision making perspective. It is leads to inherit wrong message interpretation. Based on this patterns analysis, there are more than 66% or 2/3 of the received patterns can be invalid. The details of the study are based on the slots level and patterns validity with regards to the received signals as shown in T. According to Table II number of invalid patterns is significantly more than the valid ones. Thus, a mapping process (from invalid patterns to the corresponding valid ones) is required in order to recover the original bits as much as possible, which will lead to better data recovery and smaller BER. In our implementation, the mapping function is done if and only if the signal does not follow exactly the pre-established pattern in Figure 2. This is considered as “out of rules” and mapping process will follow pattern based signal recovery process as shown in Figure 3.

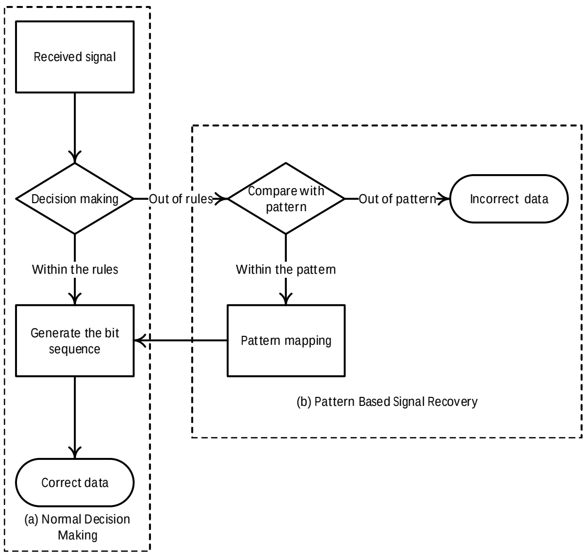

Figure 3. Flow chart of signal generation at the receiver with (a) existing decision making process and (b)pattern based implementation

For the purpose of increasing the reliability of the decision making process at the receiver, we introduce a Figure of Merit (FoM) based on the received symbol pattern. This will then be used to map the eroded signals or invalid patterns to the valid ones. The mapping process will consider the probability of which invalid signal is best to be assigned to a valid pattern. The evaluation is based on the uniqueness of DCDM signal pattern properties namely power level and slot. At the end of the generation process, those patterns can be re-evaluated as a normal decision making depicted in Figure 3(a).

3. COOFICIENT INDEX

The decision in distinguishing between ’*0*’s and ’*1*’s are based on samples from $(n + 1)$ slots over *Ts* seconds. In previous techniques such as [8; 11], it is done based on a set of rules. Whereby the amplitudes associated with each slot will be used to decide the bits transmitted of each different user. For example, amplitudes of Slot 1 and Slot 2 are used to determine the bit from U1, while the amplitudes of Slot 2 and Slot 3 are used for U2. The details can be found in the references [8; 12]. In enhancement to the previous technique [8], we further classify the signals into valid and invalid patterns. The classifications are based on the total number of possible patterns, $(n + 1)!$, where n is the number of users. Thus the number of valid patterns, 2^n, and the number of invalid patterns is $((n + 1)! - 2^n)$. Hence, in our case where $n = 3$; the total number of patterns is *24*, the number of valid pattern is *8* and the number of invalid patterns is *16*. The valid patterns are received as they are (although the patterns may be erroneous) while the invalid patterns are further evaluated for mapping purposes. Meanwhile, the invalid signals are further evaluated using a new coefficient index as evaluated by a function:

$$f(FoM) = AS\delta \,/ P\_d \quad (1)$$

here A denotes a total amplitude of signal changes, S, number of slot change, δ, distance factor between slots and P_d, the probability of amplitude at particular slots being ’0’, ’1’ ,’2’ or ’3’. The probability of amplitude, P_d for each associated slots are shown Table 3.

Table 3: Probability of received amplitude signal at each slot

Amplitude (A)	Probability of amplitude(P_d)		
	Slot 1	Slot 2	Slot 3
0	0.125	0.25	0.50
1	0.375	0.50	0.50
2	0.375	0.25	-
3	0.125	-	-

This probability is used as a metric to map the incorrect signal into a valid one. It is slightly different with the conventional metrics such as Hamming distance and Euclidean distance. This mapping is due to the different level of received and the transmitted signal [13]. Precisely, it refers to the probabilities of the received signal level corresponds to the established pattern’s level for each slot.

Meanwhile, we established the distance factor, δ to indicate the effort that needed to map the received signal to any possible received pattern. This can be represented with a new index/factor as shown in Table 4. The higher the values indicate that more effort is needed to change the level into the possible value.

Table 4: Index of effort, Δ in order to change to the possible slot level

Slot 1	Slot 2	Slot 3	δ
-	-	Δ	1
-	Δ	-	1
Δ	-	-	1
Δ	Δ	-	2
-	Δ	Δ	2
Δ	-	Δ	3
Δ	Δ	Δ	5

Note: Δ the slot require changes in its amplitude

With that, the new mapping function can be accomplished by using this index. For an instance, suppose that the receiver is received an amplitude level of

'0, 0, 1'. According to T, this received pattern is invalid. In this technique, based on the FoM technique the received signal's amplitude which was '0, 0, 1' will be evaluated as '0, 0, 0' since the index of change is the lowest, (index of change 1.1 as shown in Table V). It is indicated that the lowest effort is to be undertaken in order to convert to the closest valid patterns. The rest of the mapping received signal waveform amplitude to the possible transmitted signal waveform is shown in Table 5.

Table 5: Index of change: the lowest index is selected as the lowest effort to change the level

Possible Transmitted			Probability of amplitude at each slot			Amplitude changes needed for each slot			Total amplitude	Number of slot changes	δ	Index of change
U1	U2	U3	S1	S2	S3	S1	S2	S3				
0	0	0	0.1	0.3	0.5	0	0	1	1	1	1	1.1
1	0	0	0.4	0.3	0.5	1	0	1	2	2	3	11
1	1	0	0.4	0.5	0.5	1	1	1	3	3	5	33
1	1	1	0.4	0.5	0.5	1	1	0	2	2	2	5.8
2	1	0	0.4	0.5	0.5	2	1	1	4	3	5	44
2	1	1	0.4	0.5	0.5	2	1	0	3	2	2	8.7
2	2	1	0.4	0.3	0.5	2	2	0	4	2	2	14
3	2	1	0.1	0.3	0.5	3	2	0	5	2	5	57

In reference to (1), the function is actually a representation of the lightest effort to be taken in order to transform the incorrect signal patterns into the valid one (i.e the closest pair). This pattern based approach can be also considered as a signal error detection and correction scheme. Opposed to the conventional error correction schemes [14; 15; 16], the proposed method focuses on the signal remapping process prior to the data generation. It is considered as enhanced features utilising inheritance DCDM signal properties. By utilising (1), the mapping of the invalid patterns can be established as in Table 6.

Table 6: Mapping from invalid to valid patterns

Invalid level			Valid level		
Slot 1	Slot 2	Slot 3	Slot 1	Slot 2	Slot 3
0	0	1	0	0	0
0	1	0	1	1	0
0	1	1	1	1	1
0	2	0	0	0	0
0	2	1	2	2	1
1	0	1	1	1	1
1	2	0	1	1	0
1	2	1	1	1	1
2	0	0	2	1	0
2	0	1	2	1	1
2	2	0	2	1	0
3	0	0	1	0	0
3	0	1	2	1	1
3	1	0	2	1	0
3	1	1	2	1	1
3	2	0	3	2	1

4. Results and discussions

The simulation setup contains three channels; with an aggregated bitrate of 30 Gb/s (3 x 10 Gb/s) . The individual signals from different channels are then multiplexed to form a three-level multiplexed signal. Initial transmitted signal is shown in

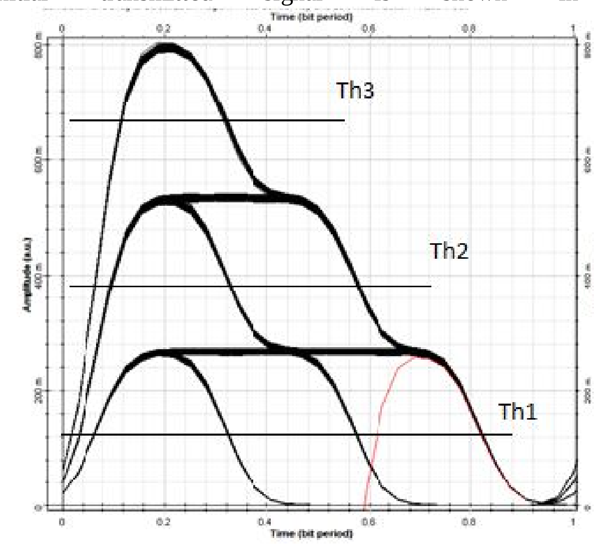

Figure . Meanwhile the received signal in the form of eye diagram can be seen in

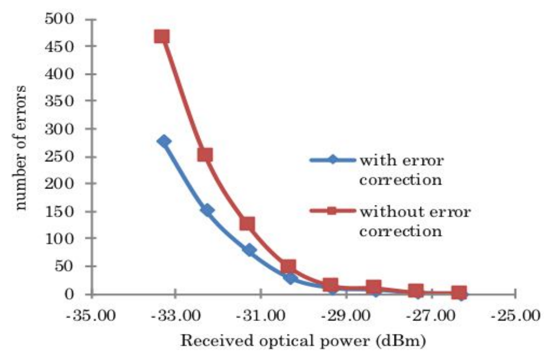

Figure . Threshold values (*Th1-Th3*) with regards to the different receiving levels are also illustrated in

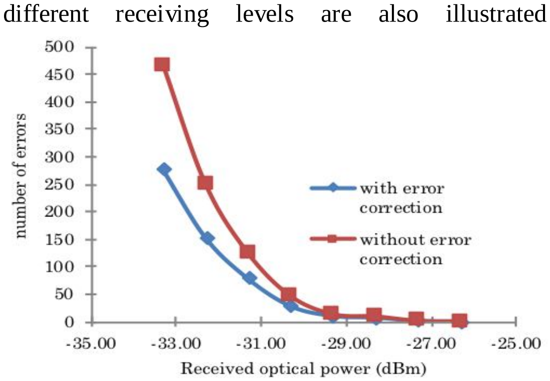

Figure .

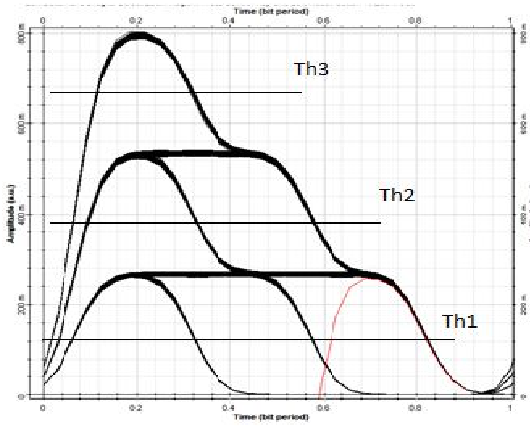

Figure 5. Transmitted signals of three users

The results in

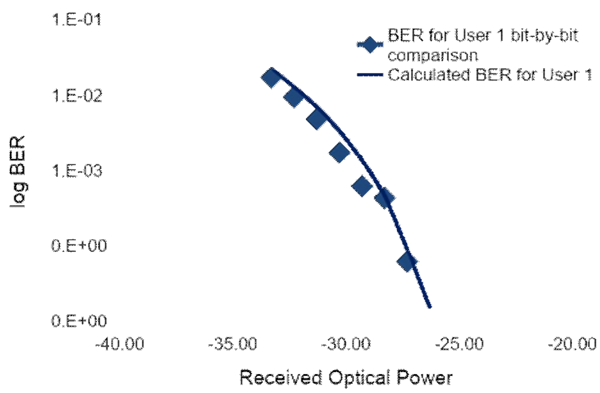

Figure shows the number of errors for the worst user scenario (U1) based on the bit-to-bit comparison. This is due to the U1 is having three level associated with their own threshold value in order to decide which signal received. At a low power (-33dBm), the new validation method shows an improvement by almost 50%. It is expected to be even higher when the received power is smaller than -33 dBm. This is due to the better eye opening of each received signal is hard to achieve at this level, thus most of the signals are expected to be laid under the invalid patterns. Thus the mapping plays an important role for the decision making.

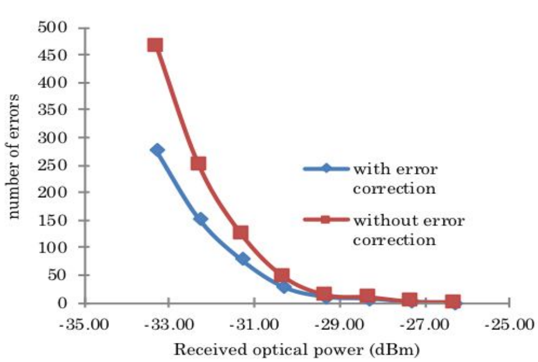

Figure 6: Eye diagram of received signal

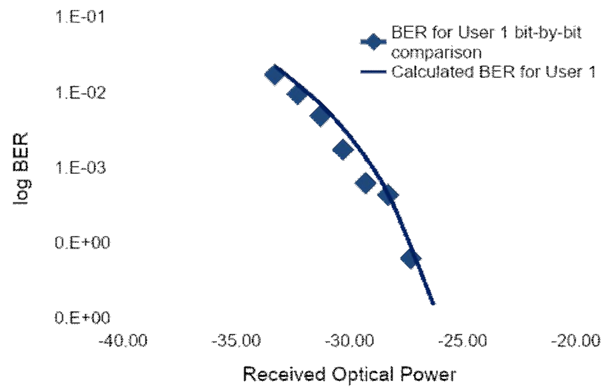

Figure 7: Number of errors in bit-by-bit comparison over received optical power for U1 (worst case user scenario)

As can be seen from Figure 7, the BER is compared with bit-by-bit comparisons at the receiver (with the data from transmitter) and proposed method. Both methods show almost the same trend with small numerical difference (less than 1dB at the same BER level). This comparison is important to show that the proposed method is valid. As the number of transmitted bit increases, the BER estimation based on the calculation should be used instead of bit-to-bit comparison technique. This is due to the limitation and complexity of the bit-to-bit in real application environment.

Meanwhile, the results in Figure 8, show the relation between the SNR and the log BER for U1. At the same SNR level, ranging from 3dB to 14dB the proposed method outperforms as compared to the previous method. It is more significant when the SNR is less than 10dB. At this point, the receiver is still able to map the invalid signal to the valid one, besides the use of the existing rules. Thus, the number of the eroded signal over SNR level that can be corrected using proposed approach is shown in Figure 10.

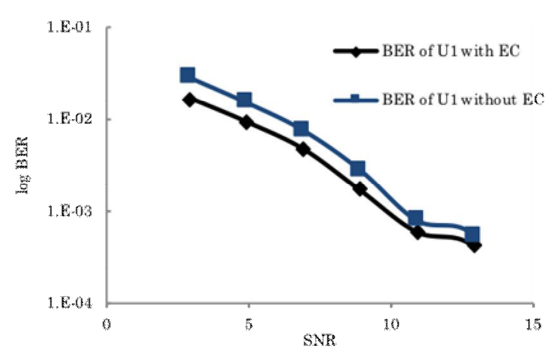

Fig.ure 8: log BER over SNR for U1 of the proposed enhanced rules-pattern based decision making with the post-amplifier (as in [17])

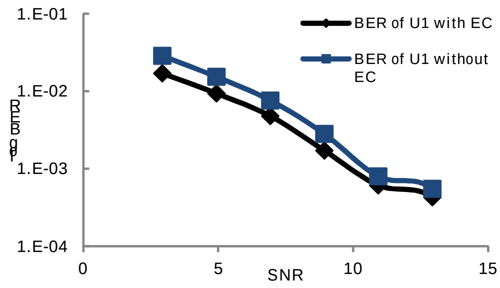

Figure 9. log BER over SNR for U1 of the proposed enhanced rules-pattern based decision making with the post-amplifier (as in [17])

As illustrated in Figure 10, when the SNR level is low, more received signals are out of established patterns. The invalid patterns can be corrected by the mapping technique based on the proposed method using criterion defined in (1). Meanwhile, at low received power, normal data recovery is no longer effective and should be combined with the proposed error correction technique. This is in order to re-map those un-decided signals. As far as it is concern based on the proposed technique, the received signal is still can be further evaluated to the right decision making at lower communication layer or physical layer without the need for retransmitting.

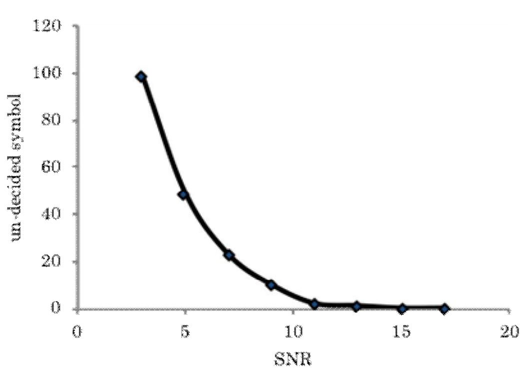

Figure 10. Number of un-decided received symbols that can be corrected using the mapping function

5. CONCLUSION

Pattern based decision making is used to assist the inference rules in the process to increase the reliability of bit sequence generation at the receiver. It results in increasing the reliability and reducing the BER as compared to conventional data recovery rules for DCDM technique. On the other hand, the enhanced decision rules also allow the DCDM receiver for the generic implementation as it does only involve in the physical layer, thus it is not inherited with complex computing power. The proposed approach is fruitful to improve the decision making reliability particularly in a power limited system.

ACKNOWLEDGMENT

The authors wish to acknowledge the ministry of Higher Education Malaysia of giving the scholarship for this study. Not to forget, the gratitude also given to Significant Technologies (M) Sdn Bhd for assisting this study.

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