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A Fuzzy Rule Base Assisted Adaptive Coding and Modulation Scheme for OFDM Systems

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ABSTRACT

Adaptive communication is one of the key technologies used to enhance the capabilities of future communication systems. Many adaptive bit and power loading techniques have been investigated in the literature for enhancement of transmission rate in combination with Orthogonal Frequency Division Multiplexing (OFDM). In these systems mainly either modulation or coding scheme was adaptive but not both. That is, one of the two aspects was fixed while other was adaptive e.g., adaptive modulation with fixed channel code or adaptive coding with a fixed modulation alphabet. In this paper, we propose a new scheme to adapt both code rate and modulation size by solving a non-convex optimization problem using a Fuzzy Rule Base System (FRBS) to enhance the achievable data rate in an OFDM system with a fixed target bit error rate and fixed transmit power for each subcarrier.

Keywords: OFDM; FRBS; Adaptive Modulation and Coding; Modulation Code Pair.

I. INTRODUCTION

Adaptive Orthogonal Frequency Division Multiplexing is one of the successful candidates for many 3rd and 4th Generation Systems. In this technique a single very high data stream is divided into several low data rate streams. Then these streams are modulated over different orthogonal subcarriers. Concept of adaptive communication is though not new, however, it was confined to adaptive modulation only in past decade. Combining practical channel coding is quite obvious but mostly neglected due to analytical limitations. Adaptive modulation for OFDM was proposed by Kelet [1] as early as 1989. Later same idea was examined for Gaussian slowly varying dispersive fixed links by Chow et al. [2] and for wideband radio channels by Cyzlwic [3] in 1996. Several researchers take adaptive modulation as an optimization problem and propose efficient solution for encoded systems, like [4]. Fuzzy system based adaptive modulation scheme for OFDM system was proposed by [5] in 2009.

Turbo coded adaptive modulation was investigated by Hanzo et al [6] and also different adaptation schemes were analyzed [7]. For single antenna OFDM systems, coded bit and power loading problem was addressed by Li et al. using LDPC codes[8] originally motivated by [9]. Many bit interleaved coded modulation (BICM) systems have been proposed like [9, 10, 11]. Adaptive communication using turbo codes was also investigated in [12].

In many of the above schemes decision for the next transmission rate was based on SNR thresholds. And in most of the above coded systems code rate was fixed and modulation was adaptive. Similarly, in his doctoral dissertation, Al-Askary [13] has proposed an adaptive OFDM system where modulation for fixed for all subcarriers and code rates were varying over subcarriers using concatenated codes. An adaptive coding and modulation scheme is proposed by Bockelmann et al in which a bisection method is used to adapt the transmit rate [14]. This bisection method was originally used by Krongold et al [15] to adapt power, modulation and code rate for a fixed channel.

In this paper we proposed a Fuzzy Rule Base System to adapt the code rate and modulation scheme according to varying channel conditions based upon set of rules that are derived from AWGN simulation results of various code rates (convolutional codes) and modulation schemes (QAM family). This technique is compared to other coded and encoded adaptive loading systems to show significance of Fuzzy Rule Base System over others.

The remainder of this paper is organized as follows. In section 2, system model is introduced. Performance of different codes in conjunction with different modulations is presented in section 3. The results of section 3 are used in section 4 to obtain a constrained optimization problem. In section 5 a brief introduction to Fuzzy Rule Base is given that is used to solve the optimization problem formulated in previous section. Section 6 contains the performance comparison of this scheme with various other famous adaptive schemes while section 7 concludes the paper.

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II. SYSTEM MODEL

The system model considered is OFDM equivalent baseband model with N number of subcarriers. It is assumed that complete channel state information (CSI) is known at both transmitter and receiver. The frequency domain representation of system is given by

$$r_n = h_n . \sqrt{p_n} . x_n + z_n ; \; n = 1,2,......,N \qquad (1)$$

where r_n , h_n , $\sqrt{p_n}$, x_n and z_n denote received signal, channel coefficient, transmit amplitude, transmit symbol and the Gaussian noise of subcarrier $n = 1,2,......,N$, respectively. The overall transmit power of the system is $P_T = \sum_{n=1}^{N} p_n = Np$ since power is same for all subcarriers, and the noise distribution is complex Gaussian with zero mean and unit variance.

It is assumed that signal transmitted on the *k*th subcarrier is propagated over an independent non-dispersive single-path Rayleigh Fading channel and where each subcarrier faces a different amount of fading independent of each other. Hence, the channel coefficient of *k*th subcarrier can be expressed as:

$$h_n = \alpha_n e^{j\theta_n} ; n = 1,2,......,N \qquad (2)$$

where α_n is Rayleigh distributed random variable of *n*th subcarrier, and the phase θ_n is uniformly distributed over $\left[0, 2\pi\right]$.

A. Coding Schemes

The codes used in this paper are non-recursive convolutional codes with code rates taken from the set $\mathrm{C} = \{1/4, 1/3, 1/2, 2/3, 3/4\}$ with constraint length 3. For decoding, standard soft output Viterbi decoder is used. For convenience, message bits length is taken equal to the number of subcarriers and standard OFDM interleaver/de-interleaver are used in simulations.

B. Modulation Schemes

In this paper we have utilized the symbols taken from Quadrature Amplitude Modulation (QAM), with rectangular constellation. The modulation symbols are taken from the set $\mathrm{M} = \{2,4,8,16,32,64,128\}$

III. CODED MODULATION

For experimentation the sequence of operations is carried out in same way as given in the figure1. The transmitted signal is first encoded using standard feed-forward convolutional encoder having code rate from the set C and then the encoded signal is modulated using the elements of QAM from the set M.

All codes used belong to set C with constraint length 3 each and modulation symbols from set M with symbols from rectangular QAM constellation. In this way we have following pairs of coding and modulation by cross product of sets C and M, which yields,

$$P = C\mathrm{x}M \; = \; \{(c_i , m_j); \forall c_i \in C , \forall m_j \in M\} \qquad (3)$$

Then graph for each pair is obtained over an Additive White Gaussian Noise (AWGN) channel. The selection of this channel is suitable in a sense that it reflects the proper relationship between signal to noise ratio (SNR) and data rate achievable under a specific target bit error rate (BER). Also other channel characteristics like fading types etc can be compensated easily. Graphs are depicted in the figures 1, 2, 3, 4 and 5 with rate 1/4, 1/3, 1/2, 2/3 and 3/5 respectively. All of the modulation schemes are investigated with each code rate.

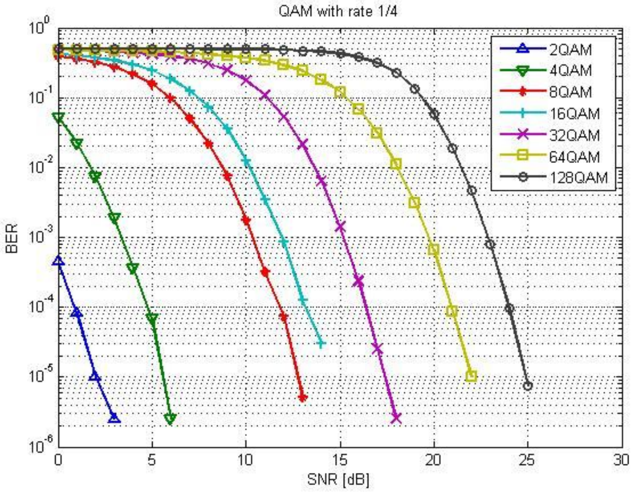


Figure 1. BER comparison of different QAM modulations using rate 1/4 convolutional codes

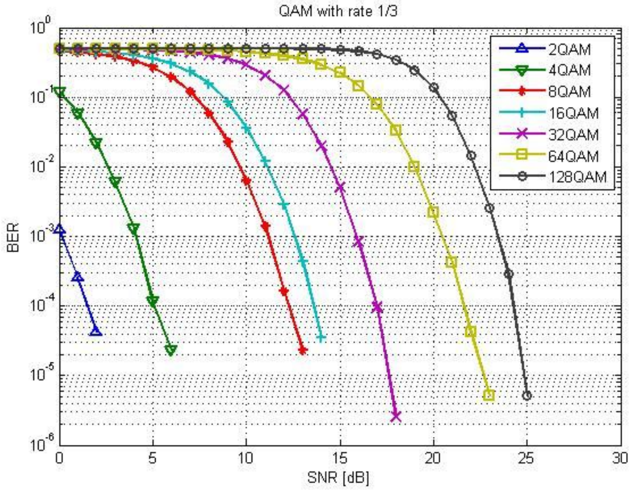


Figure 2. BER comparison of different QAM modulations using rate 1/3 convolutional code

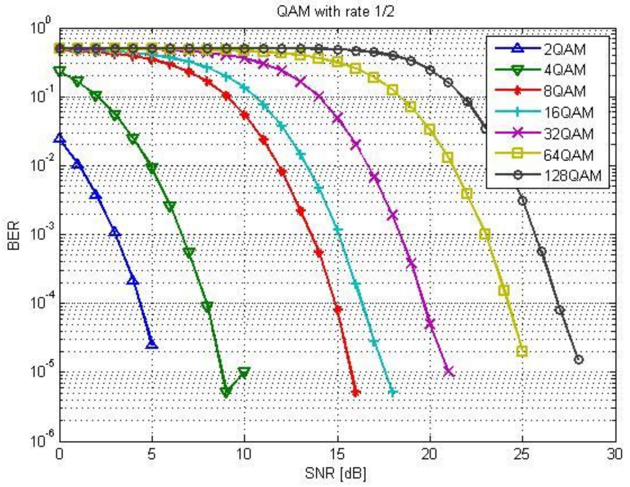


Figure 3. BER comparison of different QAM modulations using rate 1/2 convolutional code

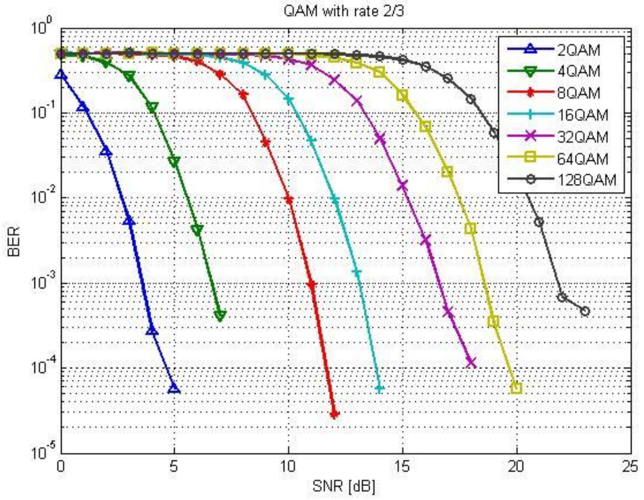


Figure 4. BER comparison of different QAM modulations using rate 2/3 convolutional code

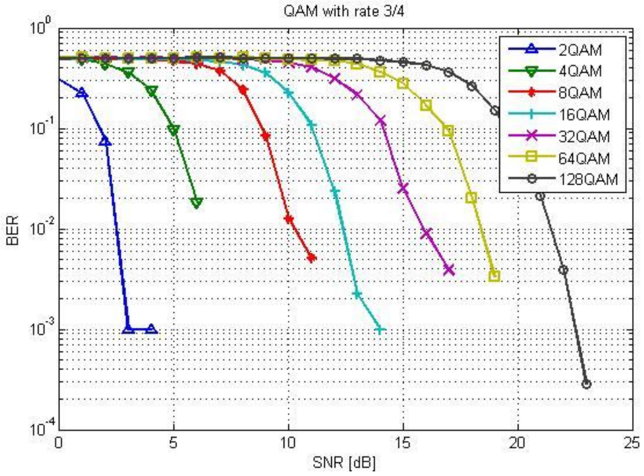


Figure 5. BER comparison of different QAM modulations using rate 3/4 convolutional code

Adaptive system will make use of these facts and it will use appropriate modulation code pair (MCP) for each subcarrier depending upon channel condition at that subcarrier. That is over a subcarrier with good channel condition a high code rate with a high QAM can be used. If channel condition is poor then low code rate with low QAM can be used. Similarly the blend of different MCP can be used to cope up with entire spectrum of channel variations.

As far as our demonstration is concerned, all of the modulation-code pairs are investigated, but obviously not all pairs will be used. Only a subset of these pairs will be considered due to the fact that two or more pairs may provide same throughput (modulation code product) but with different SNR demands. So, among them, we will choose the pair with least SNR demand. For example, 16QAM with rate 1/4 and 4QAM with rate 1/2 yields same throughput i.e. 1bit/sec/Hz but with different SNR requirements. So 4QAM with rate half will be chosen due to less SNR demanded. Now the performance of the system will be characterized in subsequent sections by using the above results.

IV. RATE OPTIMIZATION

In order to maximize the rate for OFDM following constrained optimization problem will be considered.

$$\begin{aligned} &\max \quad R_{Total} = \frac{1}{N}\sum_{n=1}^{N} r_n \\ &\text{s.t,} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (4) \\ &BER_n \le BER_{QoS_n} \quad and \quad \sum_{n=1}^{N} p_n < P_T \end{aligned}$$

Where $r_n = (\log_2(M))_n R_{C,n}$ is bit rate of *n*th subcarrier, which is product of code rate and modulation order used, P_T is the available transmit power and BER_{QoS_n} is target BER that depends upon a specific quality of service (QoS) request or application requirement over *n*th subcarrier, while N is number of subcarriers in OFDM system. The power distribution is considered as equal for all the subcarriers.

From the results obtained in section-III, those code-modulation pairs that fulfill different BER demands depending upon different quality of services i.e. $BER_T = 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}$ etc are obtained. These are obtained by drawing straight lines on the graphs shown in figures 1 to 5, on certain BER points (Quality of Service) like $10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}$. Then the points of intersection of these lines and the curves (representing a code and a modulation) are noted that gives the appropriate SNR value. So the information obtained can be expressed as "for a given SNR and specific QoS which modulation code pair can be used". In order to obtain more granularity BER points are even quantized. In this way there are about 500 pairs are obtained from the graphs. Few of these pairs so called input/output pairs (I/O pairs), are enlisted in table 1.

TABLE I. I/O PAIRS OBTAINED FROM SIMULATION

SNR	BER	MCP	SNR	BER	MCP
1.72	10e-2	[4,1/4]	1.529	10e-4	[2,1/3]
8.732	10e-2	[8,1/4]	5.093	10e-4	[4,1/3]
10.18	10e-2	[16,1/4]	12.25	10e-4	[8,1/3]
13.63	10e-2	[32,1/4]	13.59	10e-4	[16,1/3]
18.08	10e-2	[64,1/4]	16.98	10e-4	[32,1/3]
21.45	10e-2	[128,1/4]	21.63	10e-4	[64,1/3]
0.143	10e-2	[2,1/3]	24.27	10e-4	[128,1/3]
4.109	10e-3	[4,1/3]	17.62	10e-5	[32,1/3]
11.16	10e-3	[8,1/3]	22.68	10e-5	[64,1/3]
12.56	10e-3	[16,1/3]	24.83	10e-5	[128,1/3]

This table after completion is used as a starting point for generation of look-up table for the fuzzy rule base system. Without loss of generality we can say that this table represents a function (mapping) in which the throughput can be expressed in terms of BER and SNR.

$$R = MCP = f\,(SNR, BER) \qquad (5)$$

The mapping shown in eq-4 is a non-convex function that cannot be optimized using convex optimal techniques unless it is made convex according to [14]. However, this function is optimized by the proposed Fuzzy Rule Base System described in next section. The steps involved in creation of FRBS are described in the flowchart given in figure 6. The brief description of each phase of the flowchart is given below.

A. Graphs

Graphs for different combinations of Codes and Modulation schemes are obtained that are depicted in section-III.

B. Data Acquisition

Data is obtained from the graphs in terms of input/output (IO) pairs. This is taken by putting the horizontal lines for various bit error rates and points of intersection with the curves are noted.

C. Rule Formulation

Rules for each pair are obtained by the appropriate fuzzy set used. That is by putting complete pair in input/output set and a rule generated for each pair.

D. Elimination of Conflicting Rule

The rules having same IF part but different THEN parts are known as conflicting rules. This appears when more than one modulation code pair (MCP) are available for given specification. For instance, there is a rule whose THEN part contains three different MCP namely, [8,1/2], [16,2/3] and [16,3/4]. Now [16,3/4] is best among the rest since its throughput is 4x3/4=3 while others have 3x1/2=1.5 and 4x2/3=2.67 respectively. Similarly, sometime there could be two different pairs with same throughput like [2,1/2] and [4,1/4] both have same throughput that is 1x1/2=0.5, then [2,1/2] will be chosen since it exhibits less modulation/demodulation and coding/decoding cost.

E. Completion of Lookup Table

Since in lookup table scheme we may not have complete number of IO pairs, then those parts are filled by heuristic or expert knowledge. For example, a modulation code pair is suggested by rule for a certain SNR and QoS. Then that rule can also be used for slightly above SNR and poor QoS. For instance, [128,3/4] is suggested for 25dB SNR and BER 10^{-3} then this pair can be used for 26-30dB SNR and 10^{-2} BER cases as well. Since if a modulation code pair performs for lower SNR, then it can easily sustain in higher SNR situations. Similarly, if a MCP performs for a good QoS then it can sustain for poor QoS demands.

F. Fuzzy Rule Base Creation

Using the Lookup table in above phase Fuzzy Rule Base is created using Fuzzy Logic Toolbox in MATLAB. Further details are given in next section.

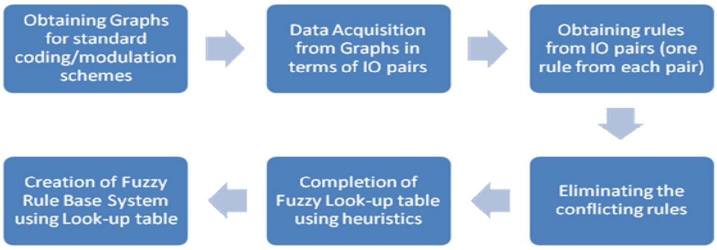


Figure 6. Fuzzy Rule Base System Creation Flowchart

V. FUZZY RULE BASE SYSTEM

We propose a fuzzy rule base system (FRBS), which is capable of deciding the best modulation code pair (MCP) for the next transmission, based upon the heuristics. Fuzzy logic is best suited for the situations that are vague, ambiguous, noisy or missing certain information. Also fuzzy systems are very easy to implement in hardware.

This fuzzy rule base system (FRBS) is used to optimize the cost function given in equ-3. It will be decided that which modulation code pair is suitable for a specific subcarrier based upon the individual channel state information (CSI) at the subcarriers and the Quality of Service demand.

A table look-up scheme is used for design of this fuzzy rule base system using the following steps. The input-output pairs needed for design of FRBS are provided in table-I. They are of the form;

$$(x_1^p, x_2^p; y^p); p = 1,2,3.......M \qquad (6)$$

Where x_1^p represents received SNR, x_2^p represents required BER (QoS) and y^p represents the output MCP suggested by FRBS, so the rule format will be given as below;

$$\{\text{IF } (x_1 \text{ is L1 and } x_2 \text{ is Q7) THEN y is P2}\} \qquad (7)$$

Following is the brief description of different components of fuzzy rule based system used. Design of the FRBS is carried out in MATLAB 7.0 standard Fuzzy System Toolbox.

A. Fuzzy Sets

Sufficient numbers of fuzzy sets are used to cover the input output spaces. There are two input variables received SNR and minus log bit error rate (MLBER) that represents a QoS. The reason taking MLBER is because BER of a required QoS is given by $10^{-2}, 10^{-3}, 10^{-4}$ etc while the range of fuzzy variable should be equally spaced and quantifiable. So to get this, following operation is done first.

$$\begin{aligned} MLBER &= -\log(BER) \\ BER &= 10^{-q} \qquad (8) \\ MLBER &= -\log(10^{-q}) = q \end{aligned}$$

There is one output variable for modulation code pair MCP. All of these input and output variables are depicted in figures 7, 8 and 9 respectively. There are thirty-one, sixteen and twenty-five fuzzy sets used for the variables SNR, MLBER and MCP, respectively.

B. Fuzzifier

Standard triangular fuzzifier is used with AND as MIN and OR as MAX. These functions can be seen in figures 7, 8 and 9 respectively.

C. Rule Base

Rule base contains rules against all the IO pairs. As there are thirty-one sets (L0 to L30) for first input variable named SNR and about sixteen sets (Q1 to Q16) for input variable MLBER. Hence there are 496 rules in rule base. Rule base is complete in a sense that rules are defined for all possible combinations of input space.

D. *Inference Engine*

Standard Mamdani Inference Engine (MIE) is used that will infer which input pair will be mapped on to which output point. It is shown in figures 10 and 11.

E. *De-Fuzzifier*

Standard Center Average Defuzzifier (CAD) is used for defuzzification.

Figure 12 depicts the rule surface that shows that by increasing SNR the throughput is maximized. Also on the other hand for poor QoS throughput is more than that of high QoS. A combined effect of both input variables namely SNR and QoS can be seen in that figure. For the highest value of SNR and lowest value of QoS, throughput of the system approaches to 5bits/s/Hz.

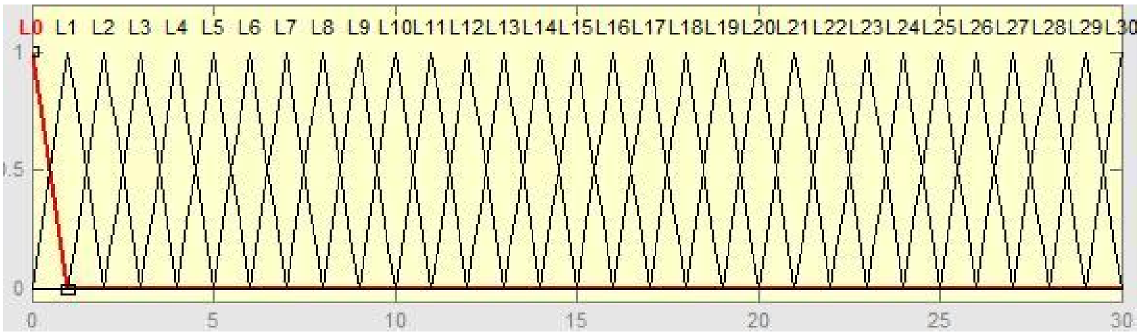


Figure 7. Membership function of first input variable “SNR”

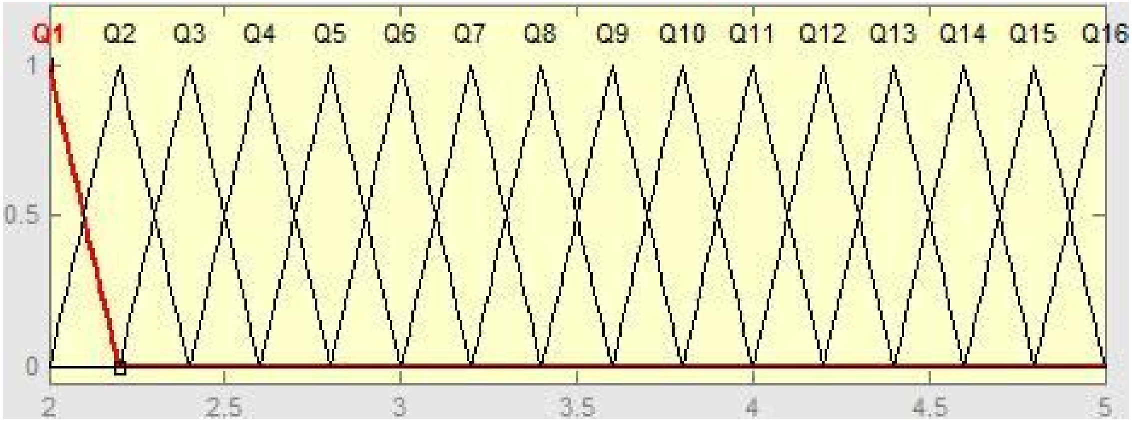


Figure 8. Membership function of second input variable “QoS”

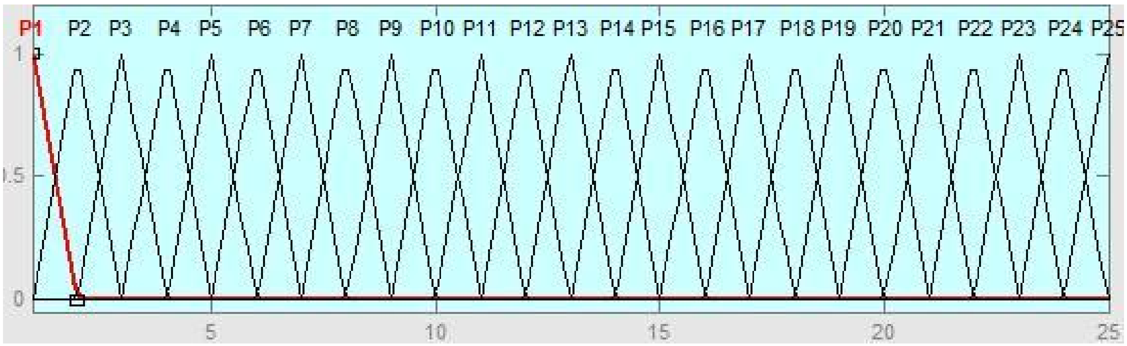
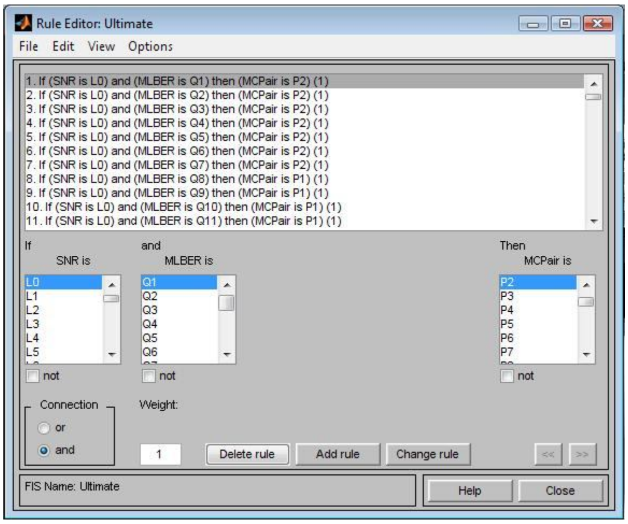


Figure 9. Membership function of output variable “MCP”

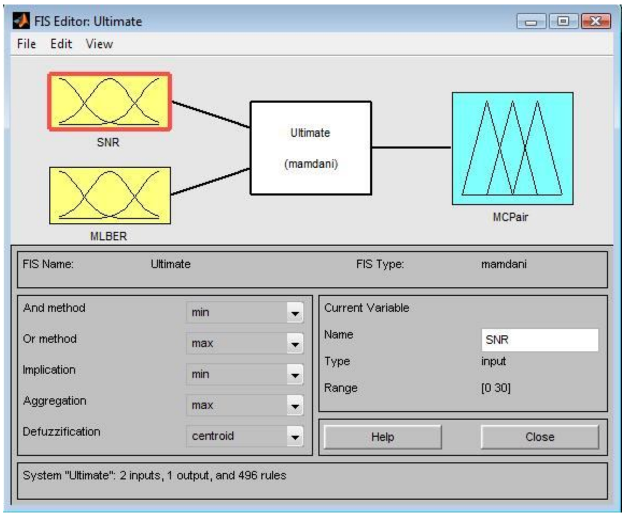


1. If (SNR is L0) and (MLBER is Q1) then (MCPair is P2) (1)
2. If (SNR is L0) and (MLBER is Q2) then (MCPair is P2) (1)
3. If (SNR is L0) and (MLBER is Q3) then (MCPair is P2) (1)
4. If (SNR is L0) and (MLBER is Q4) then (MCPair is P2) (1)
5. If (SNR is L0) and (MLBER is Q5) then (MCPair is P2) (1)
6. If (SNR is L0) and (MLBER is Q6) then (MCPair is P2) (1)
7. If (SNR is L0) and (MLBER is Q7) then (MCPair is P2) (1)
8. If (SNR is L0) and (MLBER is Q8) then (MCPair is P1) (1)
9. If (SNR is L0) and (MLBER is Q9) then (MCPair is P1) (1)
10. If (SNR is L0) and (MLBER is Q10) then (MCPair is P1) (1)
11. If (SNR is L0) and (MLBER is Q11) then (MCPair is P1) (1)

Weight: 1

FIS Name: Ultimate

Figure 10. Fuzzy Rule Editor



FIS Name: Ultimate

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name: SNR

Type: input

Range: [0 30]

System "Ultimate": 2 inputs, 1 output, and 496 rules

Figure 11. Fuzzy Rule Base System at a glance

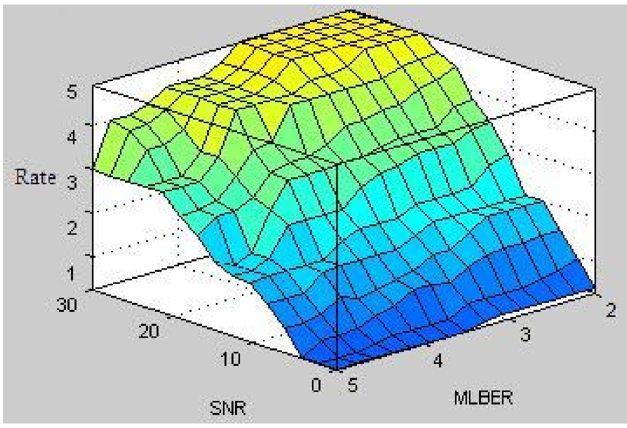


Figure 12. Rule surface

VI. RESULTS

In this section we shall compare the proposed scheme with the well-known adaptive techniques as well as non-adaptive techniques. Power per subcarrier in assumed to be flat in the simulations. Rayleigh flat fading channel is used for simulations.

Fig-13 shows significance of the scheme over fixed modulation and coding. In this case, same modulation code pair is used for all OFDM subcarriers after each adaptation interval. In this simulation the value for fixed modulation code pair (MCP) is found by same fuzzy rule base system. In this scenario the decision of next MCP is taken on behalf of average received SNR from all subcarriers and the suggested MCP is used for all the subcarriers regardless of their individual channel conditions. In this way some subcarriers may have the appropriate MCP but some may not, since the decision is made on average channel conditions rather than individual channel conditions.

Fig-14 shows the comparison of FRBS assisted adaptive coding and modulation with various well known schemes. First comparison is done with [14], where authors used Coded Bisection Method to choose the appropriate modulation code pair for next transmission. Second comparison is given with [5], in which there were used Switching Thresholds to adaptive the appropriate modulation scheme for next interval. In this scheme subcarriers were grouped, then based upon the average group channel conditions modulation was chosen for that group. Though in this paper there given coded modulation as well that is adaptive modulation (AM) with fixed code rate but we compare it with the uncoded case only, that was the best case in that paper.

Third comparison is given with another adaptive modulation scheme that was proposed by Krongold [15]. In this technique decision for suitable modulation was taken by virtue of average received SNR then switching threshold decided the type of modulation. This result shows that only Adaptive Modulation could not achieve that throughput alone which can be achieved by combined adaptive coding and modulation. A significant superiority of the proposed scheme can be observed in the simulation. Lastly, FRBS performance was compared with non-adaptive case, there is superiority of proposed scheme was more than 1.5bits/s/Hz.

Performance of Fuzzy Rule Base System for different fixed Quality of Services for all subcarriers is demonstrated in Fig-15. It shows that for high power per subcarrier and relatively poor QoS values throughput of the system approaches above 5bits/s/Hz while for high QoS achievable throughput is 2.5bits/s/Hz at 30dB of power per subcarrier

Fig-16 reveals the performance of FRBS for different QoS per subcarrier, which is more practical scenario. In this case each subcarrier has a different QoS demand. Results show that with even a diverse scenario, performance of Fuzzy Rule Base System is remarkable and more than 4bits/s/Hz throughput is achievable. This very performance is compared with two fixed QoS for all subcarriers that is 10^{-2} and 10^{-5}. These two cases put the lower and upper bound on its performance, respectively. It means the performance of random QoS cannot be more than 10^{-5} and less than 10^{-2}.

This scenario is practical in s sense that it perfectly matches with IEEE wireless standards like IEEE802.16 (fixed) [16] and IEEE802.16/e (mobile) [17], where variety of mobile users having different reception power levels and different Quality of Service Demands are present.

In ordinary adaptive schemes, such channels are chosen to shut down where channel conditions are very poor and resources like power are redistributed among rest of the subcarriers [5] [13]. But as far as the proposed scheme is concerned transmission is even possible at channel with such a hostile scenario.

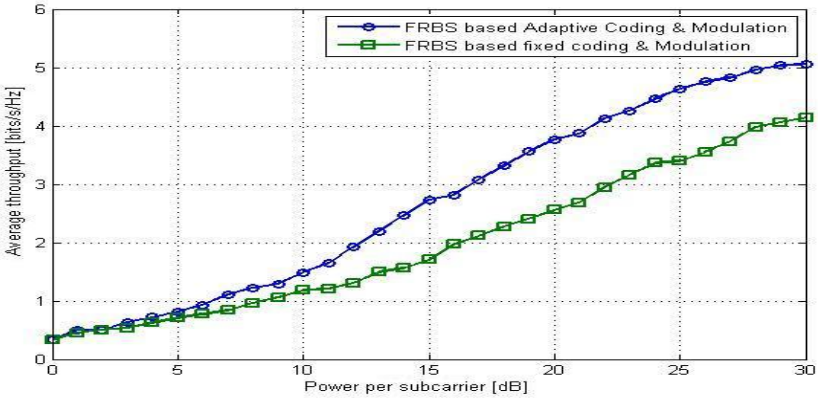


Figure 13. Comparison of FRBS based AMC with Fixed MC using QoS=10e-2 and *N*=256

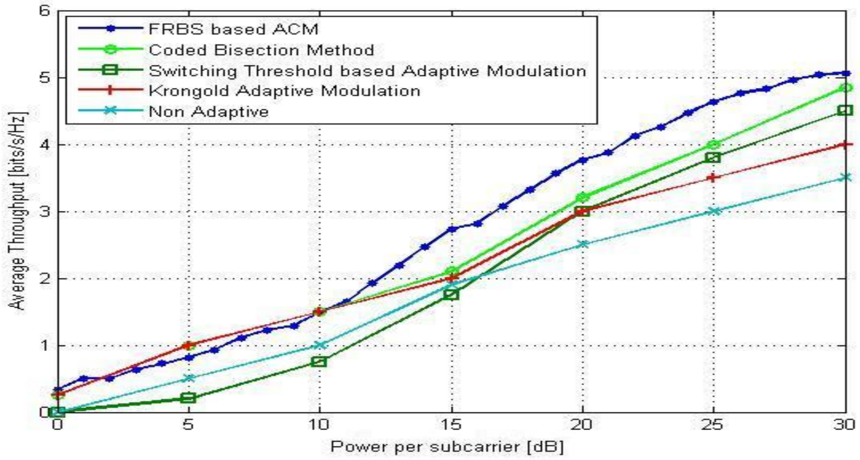


Figure 14. Comparison of FRBS based AMC with Coded Bisection AMC, switching threshold based AM, Krongold Adaptive Modulation and Non adaptive scheme, where QoS=10e-2 and *N*=1024

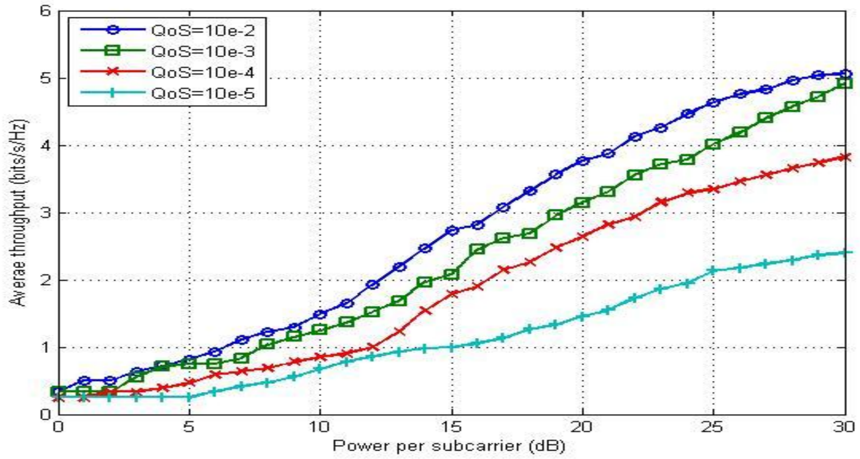


Figure 15. Performance of FRBS based AMC for different fixed QoS for all the subcarrier and *N* =256

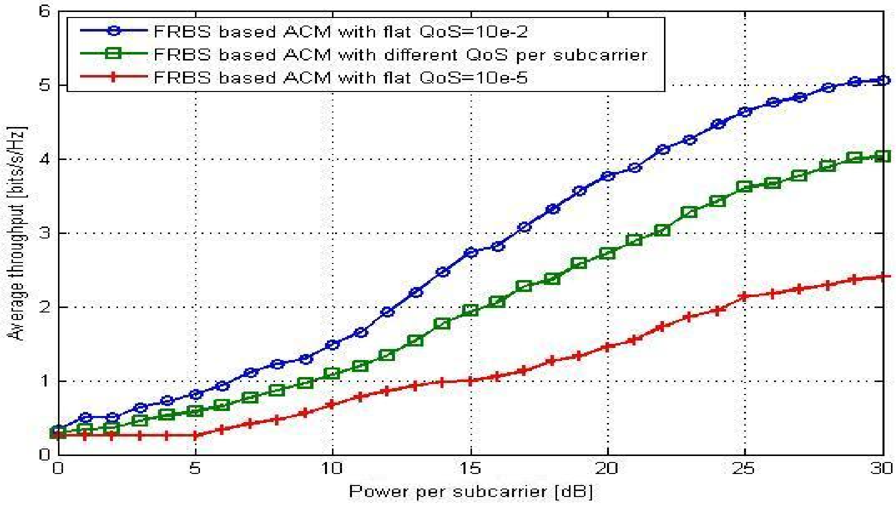


Figure 16. Performance comparison of FRBS based AMC for different QoS for each subcarrier with fixed QoS for all subcarriers while *N* =256

VII. CONCLUSIONS

Fuzzy Rule Based System assisted Adaptive Coding and Modulation scheme is proposed and analyzed in contrast to other adaptive techniques as well as fixed techniques. It is shown that FRBS is more powerful in terms of throughput and bit error rate especially when bit error rates are $10^{-2}, 10^{-3}, 10^{-4}$. Moreover, in literature there is no analytical solutions exists that incorporate both coding gain and spectral efficiency in terms of power per subcarrier and bit error rate due to its highly non-linear nature. Fuzzy system on the other hand has specialty to outperform in such vague scenarios. So cost function is formulated and optimized that maximize the system's throughput under certain constraints. Due to its non-convex nature ordinary convex optimization techniques may not solve it. Another prominent feature of proposed scheme is that it best suits IEEE802.16/e (WiMAX) standards where there are fixed as well as mobile users having different quality of service demands or where some users may be more/less privileged in terms of speed and data rates. Fuzzy Rule Base System performs wonderful in such a diverse scenario where each subcarrier has its own channel state as well as Quality of Service demand.

VIII. ACKNOWLEDGMENT

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