Chapter 7

Fuzzy Logic Decision model for MIMO mode switching

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7.1 Introduction

This chapter discusses the FL-Decision model developed for MIMO mode switching to optimize the throughput of LTE-A Downlink Physical Layer. A MIMO system can provide two types of gains: diversity gain and spatial multiplexing gain. Both types of gain can, in fact, be simultaneously achievable in a given channel, but there is a tradeoff between them [1] as discussed in Section 2.4. Most of current research focuses on designing schemes to extract either maximal diversity gain or maximal spatial multiplexing gain [2]. Existing adaptive schemes that switch between spatial multiplexing and diversity are based on various parameters for switching criteria. These parameters include Channel Condition Number [3, 4], Constellation Size [5], Signal-to-Noise Ratio [6, 7], Throughput [8], Probability of MIMO mode [9], and Error Rates [10].

Fuzzy Logic is well suited for nonlinear and complex systems where human knowledge can be utilized. Fuzzy Logic has been successfully applied in various areas of wireless communication systems [11]. This leads to motivation for the switching between MIMO modes using FL Decision model. A similar approach for MIMO Mode and Modulation and Coding Scheme (MCS) selection using Fuzzy Q-Learning was applied for High Speed Packet Access Evolution (HSPA$^+$) Systems [12, 13]. This chapter discusses the design of proposed FL Decision model for MIMO mode switching scheme which considers Channel Condition Number and Receive Signal-to-Noise Ratio to decide the appropriate MIMO mode which gives optimal throughput. The FL Decision model designed for MIMO switching considers two MIMO modes: Transmit Diversity and Open Loop Spatial Multiplexing in LTE-A context.

7.2 MIMO Channel Condition Number

The channel condition number is a well known indicator of the spatial selectivity of a MIMO wireless channel [14, 15]. In MIMO context, the condition number indicates the multipath richness of the channel [16]. Many adaptive MIMO systems that have been proposed employ the condition number as a criterion for choosing appropriate MIMO Scheme. The system proposed in [5] chooses either BLAST or STBC based on the instantaneous channel condition number. Extending this scheme, in [4] a "dual-mode" antenna selection scheme is outlined, which uses the condition number to choose between multiplexing and general diversity techniques. Performance of Linear detectors: Zero-Forcing (ZF), Maximum-Likelihood (ML) and Minimum-Mean Square Error (MMSE) has been investigated based on Channel Condition Number. For MIMO Systems, theoretical investigations and experiments suggest that the performance of linear detectors strongly depends on the channel condition number [17,18]. Channel Condition Number has also been shown to drastically affect the detection and error performance in spatial multiplexing systems [19,20].

Channel Condition Number of MIMO wireless channel measures the independence or correlation between channel paths. Lower the values of channel condition number, low is the correlation between channel paths. Condition number can be used to analyze the causes for throughput issues. The relation between the condition number and its effect on throughput according to industry published approximations is listed in Table 7.1 [21].

Condition Number	Indication
0 dB	Two totally independent channels, ideal condition to achieve maximum throughput
$\leq$ 13 dB	Favorable condition which enables higher throughput as compare to SISO/MISO
13 dB to 19 dB	Medium Correlation which provides marginal throughput improvement
$\geq$ 19dB	High correlation where MIMO would not be able to increase throughput

Table 7.1: Channel Condition Number and its indications

To obtain high throughput of LTE-A Downlink Physical Layer, the channel condition number should be approximately less than 19 dB. When the channel condition number is high, means the channel paths are highly correlated so the MIMO scheme will not be able to maximize the throughput of the system. Hence the quality of MIMO wireless channel plays a vital role to optimize the throughput of LTE-A Downlink Physical Layer.

7.2.1 Statistics of Demmel Condition Number

MIMO wireless communication system delivers significant capacity gains as compared with conventional SISO system. For a MIMO System with n_T transmit antennas and n_R receive antennas, the performance and capacity of MIMO transmission schemes are dictated by the eigenvalues of instantaneous MIMO channel correlation matrix given by:

$$W = \begin{cases} HH^*, & n_R < n_T \\ H^*H, & n_R \geq n_T \end{cases} \tag{7.1}$$

where H is the channel matrix of MIMO channel gains modeled as Complex Gaussian. MIMO Channel Correlation Matrix W is known to follow a complex Wishart distribution [14]. The Wishart distribution is the multivariate extension of the gamma distribution [22]. The statistical properties of Wishart matrices have been applied to MIMO applications. The eigenvalue distributions and determinate properties of Wishart matrices have been extensively studied to explore the ergodic capacity of the MIMO channel under different conditions [23, 24]. The eigenvalues of matrix W is denoted by the vector:

$$\lambda \triangleq [\lambda_1, \lambda_2, ..., \lambda_s], \tag{7.2}$$

with $\lambda_1 \geq \lambda_2 ... \geq \lambda_s$ 0.

The Condition Number of MIMO Correlation matrix W is defined as:

$$z \triangleq \frac{\lambda_{max}}{\lambda_{min}}, \quad z \geq 1 \tag{7.3}$$

where λ_{max} and λ_{min} are the largest and smallest eigenvalues of W, respectively. Channel Condition Number is a metric which determines the invertibility of a matrix. A condition number close to one indicates a well-conditioned full-rank matrix with equal eigenvalues, whereas a very high condition number implies a near rank-deficient matrix.

The impact of condition number on MIMO channel capacity assuming perfect channel knowledge at the receiver and no knowledge at transmitter for 2x2 system is given by following equation:

$$C = log_2(det(I_2 + \frac{\rho}{2}W) \tag{7.4}$$

$$= log_2((1 + \frac{\rho}{2}\lambda_{max})(1 + \frac{\rho}{2}\frac{\lambda_{max}}{z})) \tag{7.5}$$

where ρ is SNR and from Equation 7.5 we can say that there is no analytical relation and one-to-one mapping between condition number and MIMO Channel capacity.

The relation between Channel capacity with fixed SNR and varying condition number is shown in Figure 7.1. The effect of channel condition number on channel capacity is shown in Figure 7.2. It is evident that as the channel condition number increases the MIMO channel capacity decreases and vice-versa. We can conclude that channels with low condition number or highly uncorrelated channels yields high MIMO channel capacity.

To get a deeper understanding, the Cumulative Distribution Function (CDF) and Probability Density Function (PDF) of MIMO Channel condition number is studied. For statistical analysis of Channel Condition number the two classes of channels are considered for which, $W \in \mathcal{C}^{s \times s}$ follows

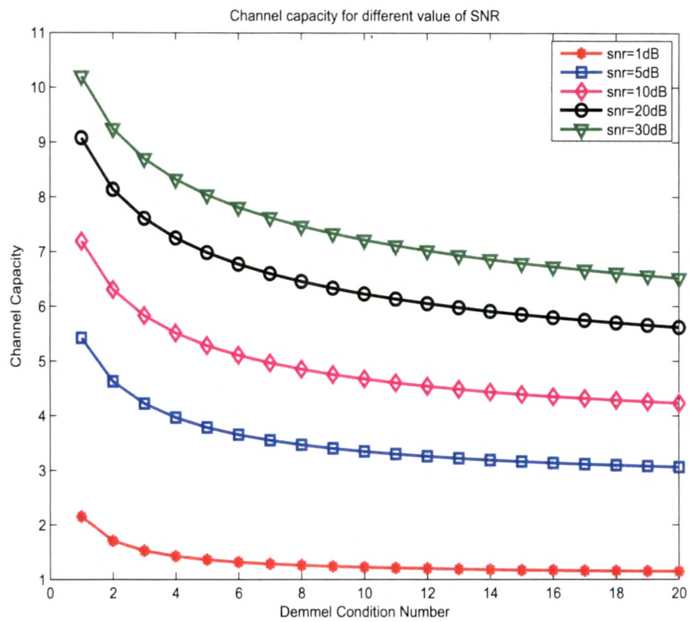

Figure 7.1: Channel capacity with varying SNR

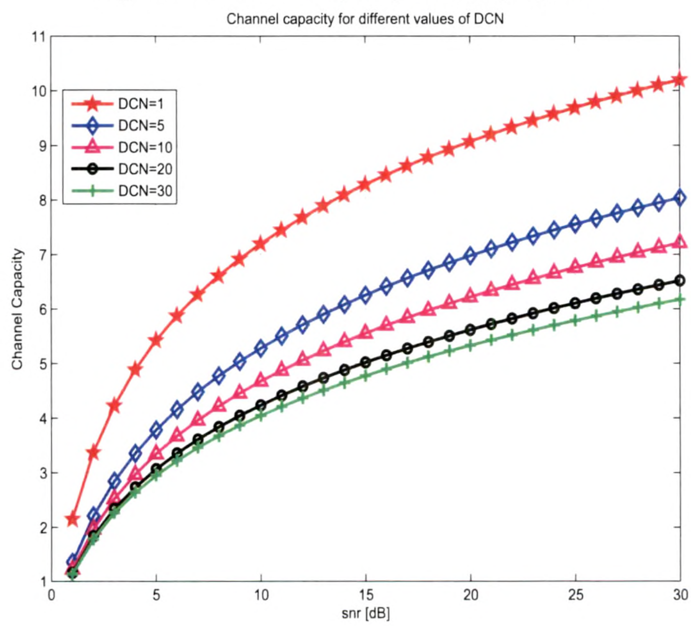

Figure 7.2: Channel capacity with varying Condition Number

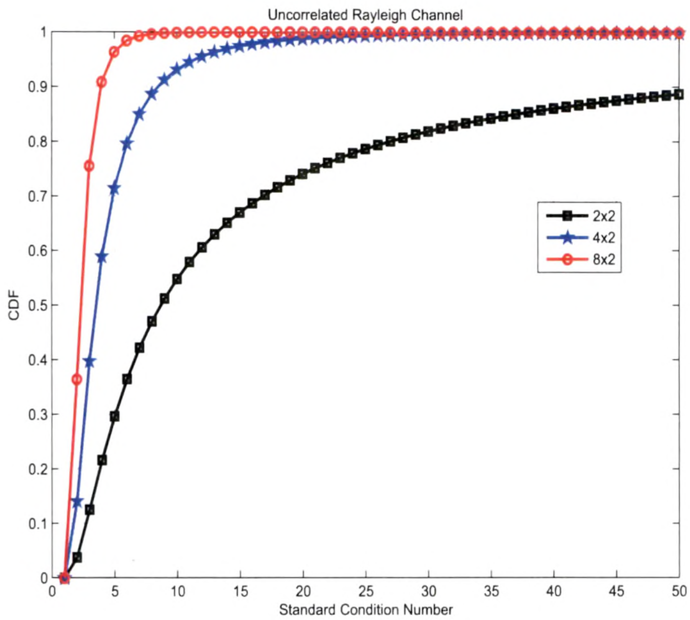

Figure 7.3: CDF of SCN for Uncorrelated Rayleigh Channel

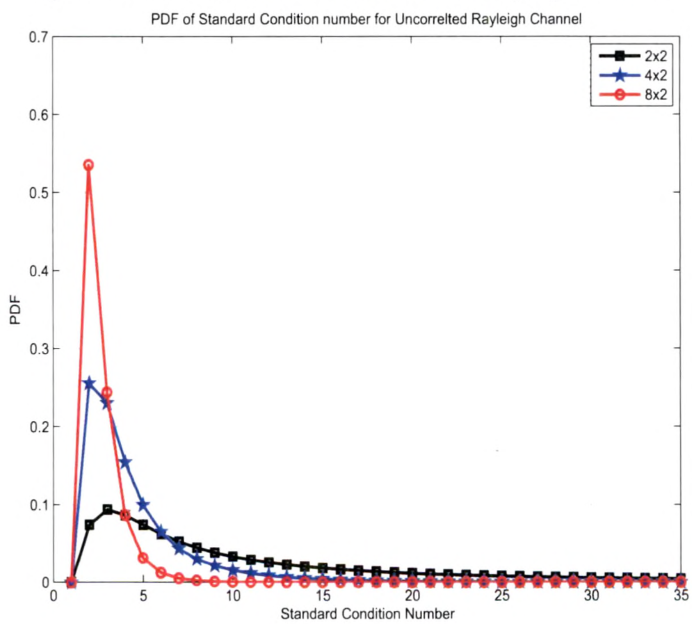

Figure 7.4: PDF of SCN for Uncorrelated Rayleigh Channel

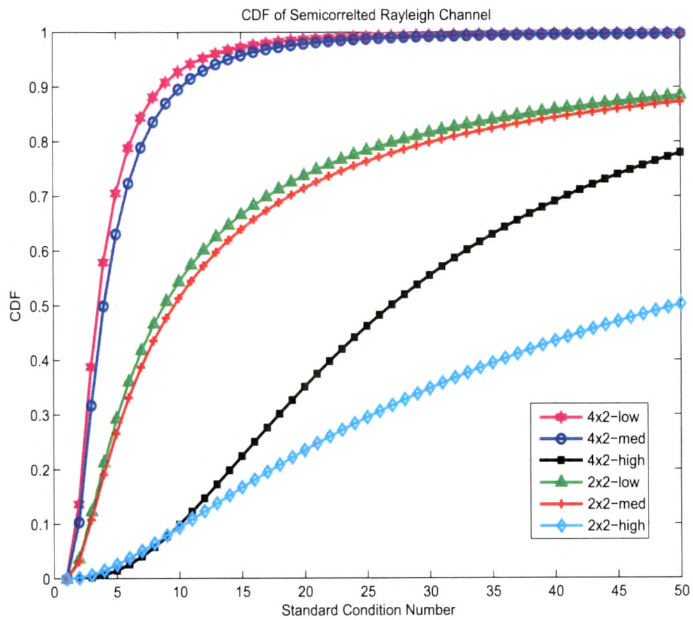

Figure 7.5: CDF of SCN for semicorrelated Rayleigh Channel

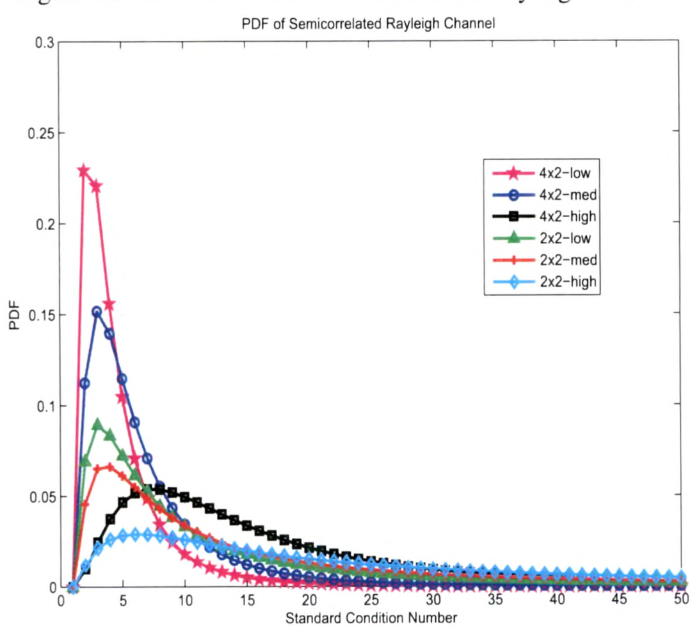

Figure 7.6: PDF of SCN for semicorrelated Rayleigh Channel

Wishart distribution with t degrees of freedom, where $s = min(n_T, n_R)$ and $t = max(n_T, n_R)$. Following are the two channel models considered for study:

1). Uncorrelated Rayleigh Fading: The uncorrelated Rayleigh model is valid when the antenna spacing is high enough to induce independent fading, and there is no LoS path between the transmitter and receiver and W is uncorrelated central Wishart matrix.

2). Semi-Correlated Rayleigh Fading: The MIMO spatial subchannels are often correlated due to the limited angular spreads or restrictions on the array sizes. Hence, spatial correlation between is considered for modeling the channel. Here, we have assumed that correlation occurs only at the side with minimum number of antennas,in which case W is semi-correlated central Wishart matrix.

The exact closed form expressions for both the channel cases have been derived in paper [15]. The same equations are used to plot the distributions and densities of Channel Condition Number. As shown in Figure 7.3, CDF of condition number for uncorrelated Rayleigh channel for different antenna configurations. For a system with two receive antenna, as the number of transmit antennas increases, the channel condition significantly improves. The CDF plot for 2x2 system is spread over the entire range [0,1] which indicates the the channel consists of highly correlated paths as compared to 8x2 system. As the number of antenna increases, it leads to improvements of the channel condition number. The PDF of standard condition number is as shown in Figure 7.4. The probability of having low condition number channel is high in 8x2 system when compared to 4x2 and 2x2 system.

The effect of spatial correlation on the channel condition number has been studied by plotting the CDF and PDF for Semi-correlated Rayleigh channel. As shown in Figure 7.5, as the spatial correlation increases the CDF plot spread over the entire region [0,1] and hence the channel becomes ill-conditioned. For low spatial correlation for 2x2 and 4x2 system the channel is well conditioned as compare to medium or high correlation. Hence, correlation in the channel matrix results in ill-conditioned channel and also increases the channel condition number.

Similarly, the PDF plot for different spatial correlation for 2x2 and 4x4 system is as shown in Figure 7.6. The probability of low condition number i.e well conditioned channel is highest in 4x2 system with low spatial correlation as compare to other systems. The probability of ill-conditioned channel is maximum in 2x2 system with high correlation.

7.3 Investigation of Switching Point between TxD and OLSM for 2x2 MIMO

Switching point between various MIMO modes has been investigated in [2, 26]. In context of LTE-A, MIMO schemes Transmit Diversity and Open-Loop Spatial Multiplexing offers trade-off between diversity gain and multiplexing gain. The switching point between both the scheme is studied in conjunction with transmit correlation for consideration of single sided correlation with minimum number of antennas.

Different values of Transmit correlation were considered and its effect on switching point between two schemes are studied. The plots are generated using the Vienna LTE-A Link Level Simulator. As shown in Fig. 7.7, SNR v/s throughput for 2x2 TxD and OLSM the switching point moves towards higher SNR as the transmit correlation increases. Table 7.2 analyses the numerical relation between Transmit Correlation and Switching point between TxD and OLSM.

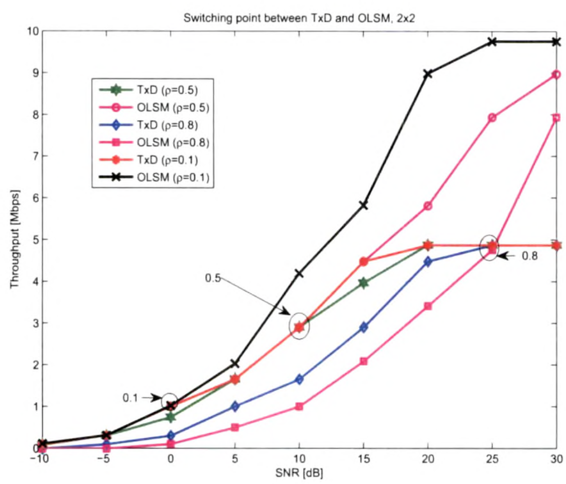

Figure 7.7: Switching point between 2x2 TxD and OLSM for different transmit correlation

Transmit Correlation	Switching Point SNR[dB]
0.1	0
0.5	10
0.8	25

Table 7.2: Switching point between TxD and OLSM for 2x2 MIMO

For transmit correlation of 0.1 the switching point is at 0 dB and for Transmit Correlation of 0.8 the switching point is at 25 dB. As we increase the correlation the switching point moves towards the higher SNR. The switching point depends on the SNR value and the correlation between MIMO channel paths. Hence the channel condition number which depends on the correlation between channel paths and the Receive SNR can be considered for making decision on switching between TxD and OLSM to maximize throughput. By making decision based on the channel condition and the receive SNR regarding the MIMO mode for transmission can optimize the throughput of LTE-A Downlink Physical Layer.

7.4 FL Decision model for MIMO mode switching

Fuzzy Logic is used for decision making and is capable of dealing with non-linearities and uncertainty in the system. Decision-making in a fuzzy environment is a decision process in which the goals and/or the constraints, are fuzzy in nature. The object of the fuzzy decision methodology is to obtain a decision, optimum in the sense that some set of goals are attained, while observing set of constraints [27].

The MIMO wireless channel is non-linear and continuously time-varying in nature. Hence, the channel condition number and Receive-SNR are fuzzy in nature. The decision regarding switching of MIMO mode is done through the FL Decision model. A heuristic knowledge regarding the Channel Condition Number and Receive-SNR influence the appropriate MIMO mode Switching. This heuristic knowledge can be expressed well in terms of a fuzzy logic using the so-called fuzzy IF-THEN rules. This fact provides the motivation for the design and implementation of FL decision model for MIMO mode switching.

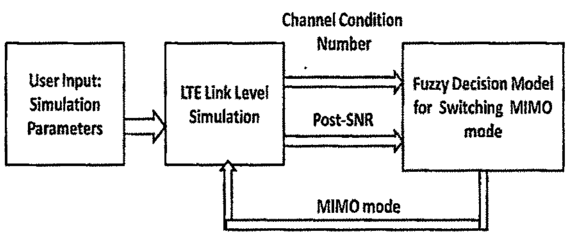

Figure 7.8: Block Diagram for FL Decision based MIMO mode Switching

The FL Decision model is designed using MATLAB based Fuzzy Logic Toolbox [28], which provides a set of GUI editors that builds a Fuzzy Inference System (FIS). As shown in Fig. 7.8, the FL Decision model with two input, one output is designed for MIMO mode switching. Channel condition number and Receive-SNR from receiver are taken as input and MIMO mode output from FL Decision model is feedback to transmitter of LTE-A Link level simulator, which selects the appropriate MIMO mode which maximizes throughput. The characteristics of FL Decision model

Parameters	Characteristic
Type of Fuzzy Inference	Sugeno-Type
Inputs	2
Outputs	1
Antecedent MFs	3 triangular shaped
Consequent MFs	2 singleton type
Aggregation method	MIN
Implication method	MAX
MF overlapping degree	2
Defuzzification method	Weighted average

Table 7.3: Characteristics of FL Decision model

are summarized in Table 7.3. The FL Decision model consists of Fuzzification, Fuzzy Rule Base and Defuzzification block, as described in following sections.

7.4.1 Fuzzification

The crisp inputs to FL Decision model are converted into a set of membership values in the interval [0, 1] in the corresponding fuzzy sets. Three partially overlapping Triangular Membership functions (MFs) are used for input Channel Condition Number and Receive-SNR. Variables for FL Decision model, their membership functions with range are as shown in Table 7.4.

Variables	Channel Condition Number (Input-1)	Receive-SNR (Input-2)	MIMO Mode (Output)
Type of Variable	Fuzzy	Fuzzy	Binary
Type of MF's	Triangular	Triangular	Constant
Range	Low: [0 5.95 12.4] Medium: [11.28 27.91 41.64] High: [40.34 61.49 100]	Low: [-30 -12.4 10.87] Medium: [9.29 14.05 17.5] High: [16.96 53.73 70]	1:OLSM 0:TxD

Table 7.4: Variables for FL Decision model

The linguistic variables used for Channel Condition Number are **Low, Medium** and **High.** The range for the Channel Condition Number is decided based on the PDF and CDF of Channel Condition Number as discussed in Section 7.3. Similarly linguistic variable for Receive-SNR are **Low, Medium** and **High.** The range for Receive-SNR is decided from the Switching Point be-

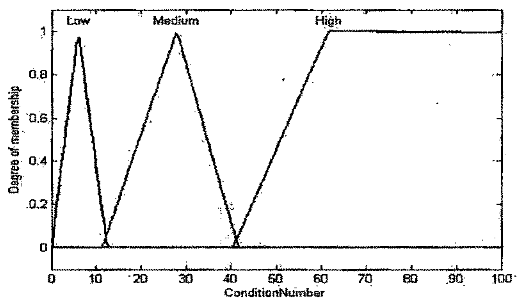

Figure 7.9: Membership function for Channel Condition Number

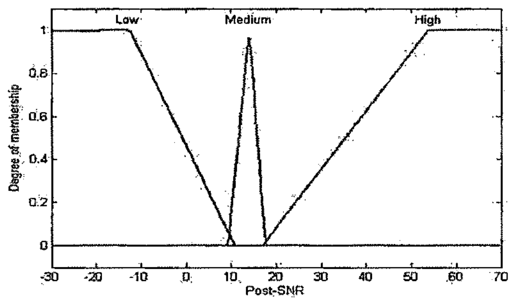

Figure 7.10: Membership function for Receive-SNR

tween MIMO modes (Fig. 7.7). Hence the membership functions of channel condition number and Receive-SNR are designed based on the analysis and simulation results. The Receive-SNR values are designed based onn the receive SNR obtained from the simulation results of LTE-A Link Level simulator for various MIMO Schemes, Channel conditions, antenna configurations and Receiver configurations.

The output MF's of the MIMO mode of Sugeno-Type Fuzzy Inference System consists of Singleton MF's. As the switching is to be carried out between two MIMO modes: TxD and OLSM. The output MF's consists of two singleton values, 0 for TxD mode and 1 for OLSM MIMO mode.

7.4.2 Fuzzy Rule Base

The Fuzzy Rule Base is an IF-THEN linguistic rule using the fuzzy input and output sets. This rule base is generated based on an experts heuristic knowledge such as Transmit diversity is preferred if Channel Condition number is high and Receive-SNR is Low. If the Channel condition number is Low it requires high SNR to give better throughput, hence Spatial Multiplexing is preferred. For example, in the case of the rule,"**IF** Channel Condition Number is **High** and Receive-SNR is **High THEN** MIMO mode is **TxD**", an expert thinks that as the Channel condition number is high, transmit diversity scheme is preferred. In a similar way, the other rules are generated based on human knowledge. According to the fuzzified input value, the fuzzy decision for the MIMO mode is taken based on the Fuzzy Decision Rules. The 9 rules in the form of 3x3 matrix are listed in Table 7.5.

		Receive-SNR		
		Low	Medium	High
Channel	Low	TxD	SM	SM
Condition	Medium	TxD	SM	SM
Number	High	TxD	TxD	TxD

Table 7.5: FL Decision model Rule base

7.4.3 Defuzzification

After the set of Fuzzy rules are applied to the fuzzified input, the output need to be converted to scalar output quantity. The process of converting the fuzzy output is called defuzzification. There are many different mathematical techniques to perform defuzzification. The Weighted-Average method [29] is used to obtain the final output MIMO mode.

7.4.4 FL Decision Algorithm

The FL Decision Algorithm takes the user input as initial parameters for LTE-A Link level simulations. Initial Simulation parameters and selection Choice is as shown in Table 7.6. The basic idea for the FL Decision Algorithm is to use the MIMO mode which maximizes throughput. The decision for appropriate MIMO mode is based on Average Channel Condition Number and Receive-SNR. The pseudo code for FL Decision Algorithm is as shown in Algorithm 7.1.

Algorithm 7.1 FL Decision based MIMO mode Switching Algorithm

- Get User input Simulation Parameters as in Table 7.6.
while $SNRRange$ **do**
  - Run LTE sim batch quick test.m
  - Calculate Channel Condition Number and Receive-SNR
  - Fuzzification: Convert crisp input data to fuzzy values using the membership functions
  - Inference: Evaluate the rules in the rule base
  - Output the MIMO mode selected
  - Run LTE sim batch quick test for new MIMO mode
end while
- Plot SNR v/s Throughput

The part of the MATLAB code which performs the fuzzy inference calculation is as given below. The out of the Weighted Average Defuzzification is in the range [0,1]. So the Threshold value of

Parameters	Selection Choice
Antenna Configuration	2x2/4x2
Channel Configuration	Flat Rayleigh/PedA/PedB VehA/VehB
Antenna Correlation	Low/Medium/High
MIMO Mode	Transmit Diversity/ Spatial Multiplexing
Receiver Configuration	Zero-Forcing (ZF)/ Minimum Mean Square Error (MMSE)/ Soft-Sphere Decoder (SSD)
MCS Scheme	1-15

Table 7.6: Initial Selection of Simulation Parameters

0.5 is set to select the MIMO mode. The Channel Condition number and Receive SNR is given as input to fis and the command evalfis performs the fuzzy inference calculation and gives the output, which selects the MIMO mode to be switched based on FL Decision model designed.

```
fis_1=readfis('FIS1.fis');    %read the fis model designed
in=[receive_snr;avergeconditionumber] %create an input vector for fis
out=evalfis(in,fis_1); %evaluate fis for output
if out >= 0.5
    LTE_params.UE_config.mode = 3; %OLSM Config mode is selected
else
    LTE_params.UE_config.mode = 2;  %TxD config mode is selected
end
```

7.5 Simulation Parameters and Results

The designed FL Decision model for MIMO mode switching is verified with Vienna LTE-A Link Level Simulator. Graphical User Interface (GUI) is developed in MATLAB, which enables user to select the Initial parameters for Simulation, and observe the switching to the MIMO mode decided by FL Decision model. The GUI also compares the Throughput (Mbps) and Time for processing (sec). Figure. 7.11 shows a snapshot of the GUI for analysis of FL Decision model for

MIMO mode switching.

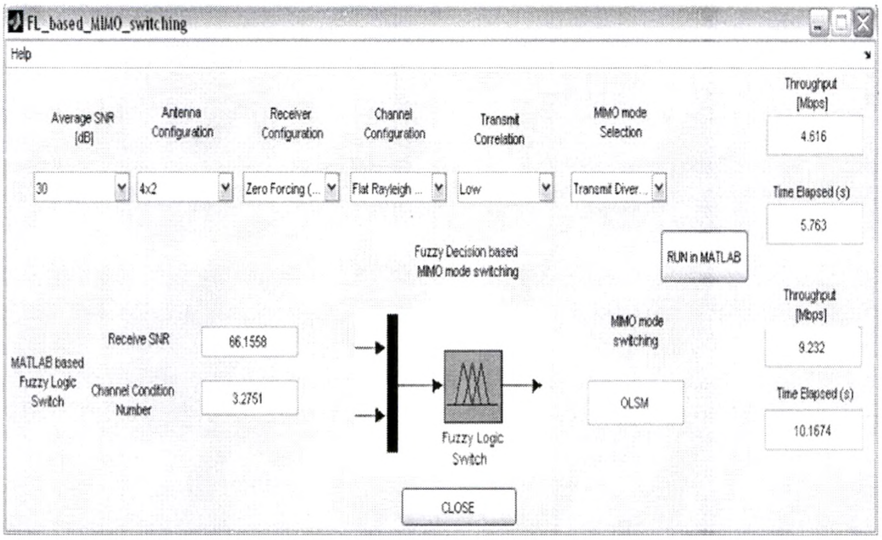

Figure 7.11: User Interface for FL Decision model for MIMO mode switching

The input Channel condition number and the Receive SNR value from the LTE-A receiver are given to the fis model designed for mode switching. By evaluating the fis model developed the MIMO mode output is given to the transmitter for switching the MIMO mode to maximize the throughput. Using the Pop-up menu list the user can select the initial parameters for simulation such as SNR, Antenna configuration, receiver configuration and MIMO mode. After running the simulation using the push button, the results are viewed in display text. For example, for SNR=30dB and MIMO mode selected is Transmit Diversity it gives Throughput of 4.616 Mbps. The obtained average channel condition number for the initial simulation parameter is 3.2751 and the Receive SNR is 66.1558, using this input parameters the MIMO mode selected by FL Decision Model is OLSM and the resultant throughput comes out to be 9.232, which is more as compare to initial MIMO mode Throughput.

Result analysis is carried out for initial mode selection of TxD and OLSM for different antenna configuration for Flat Rayleigh Correlated channel and various transmit correlation as shown in Figure [7.12 - 7.14], respectively.

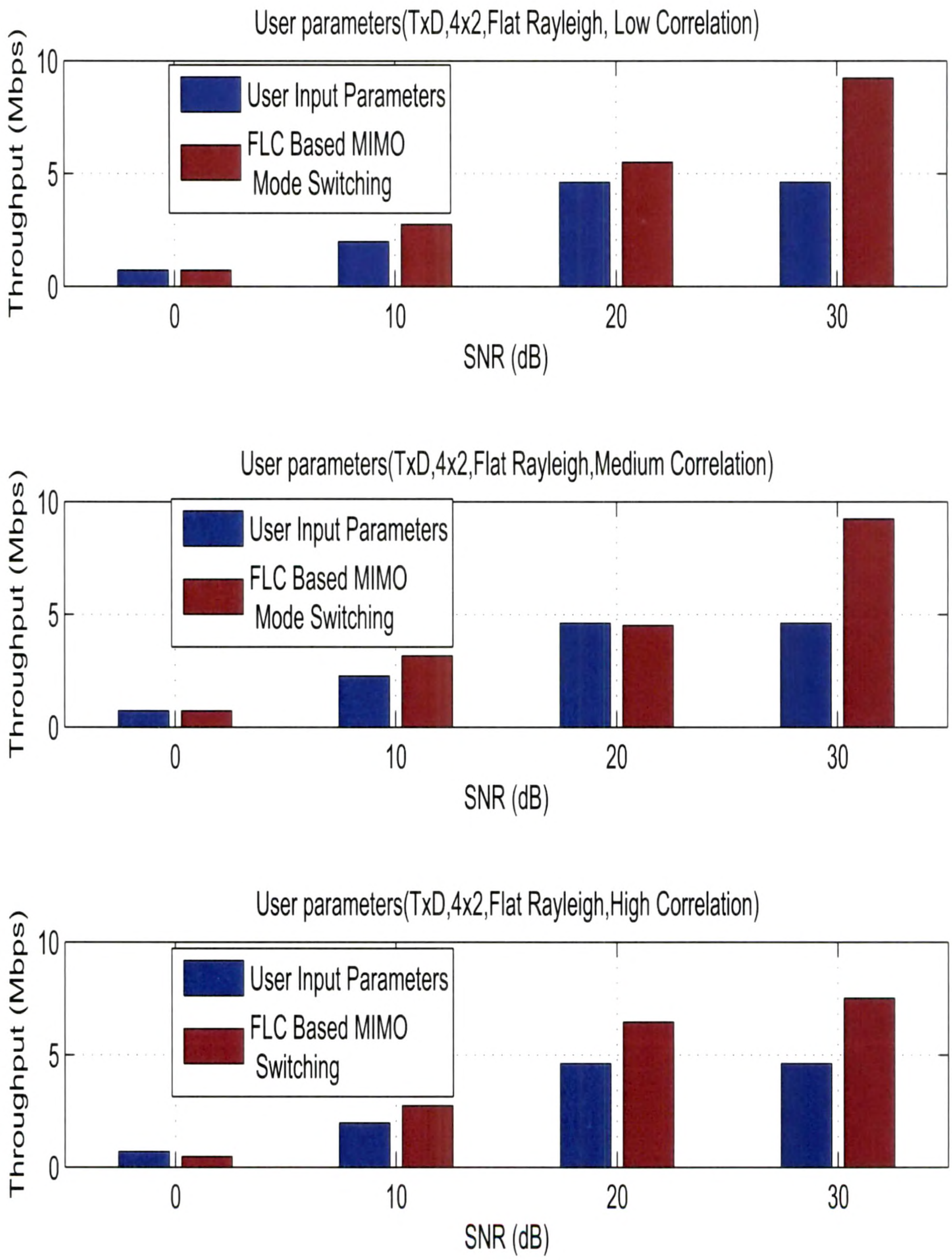

Figure 7.12: Comparative Analysis of FL Decision Model for Initial mode of TxD 4x2

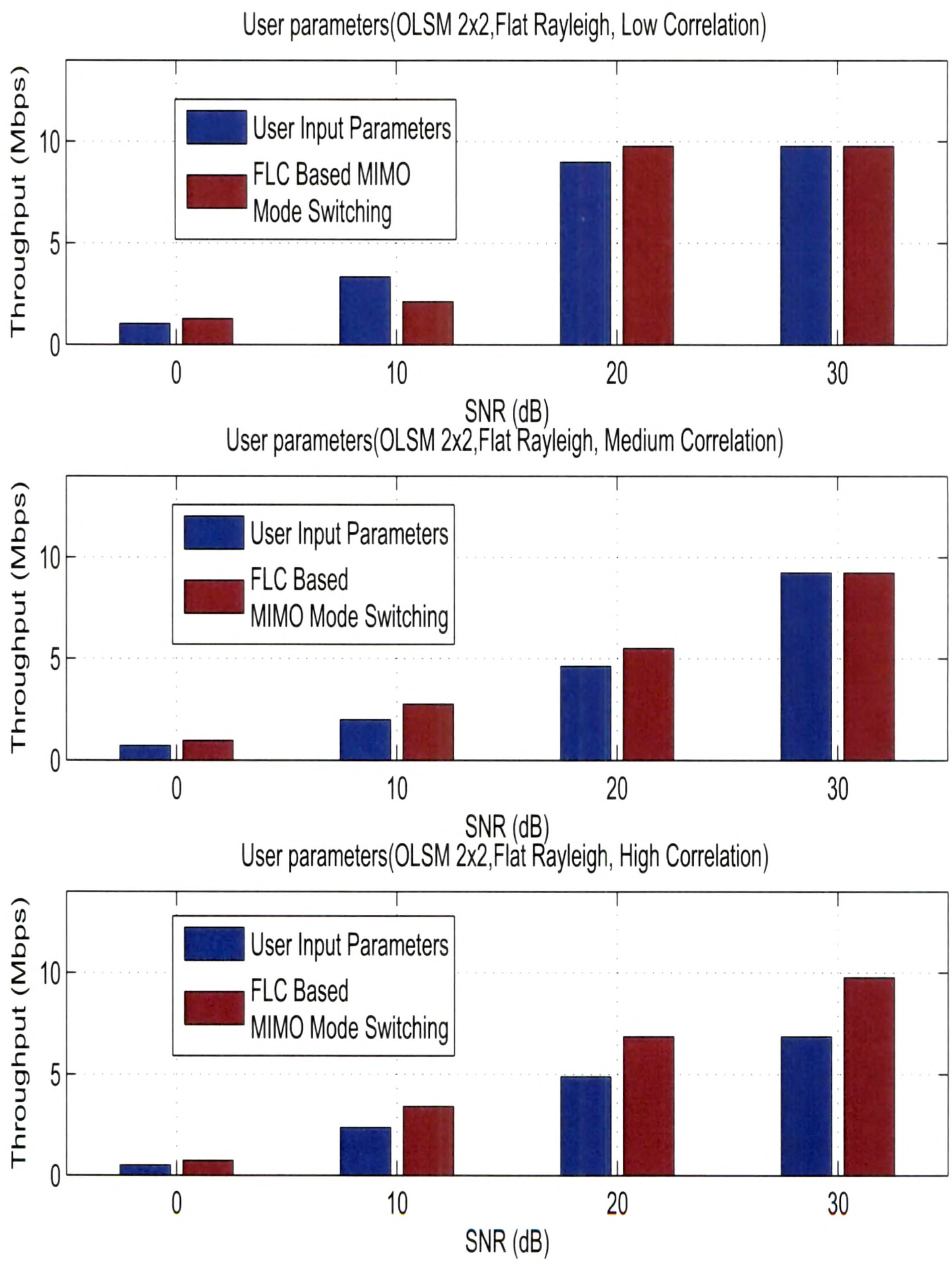

Figure 7.13: Comparative Analysis of FL Decision Model for Initial mode of OLSM 2x2

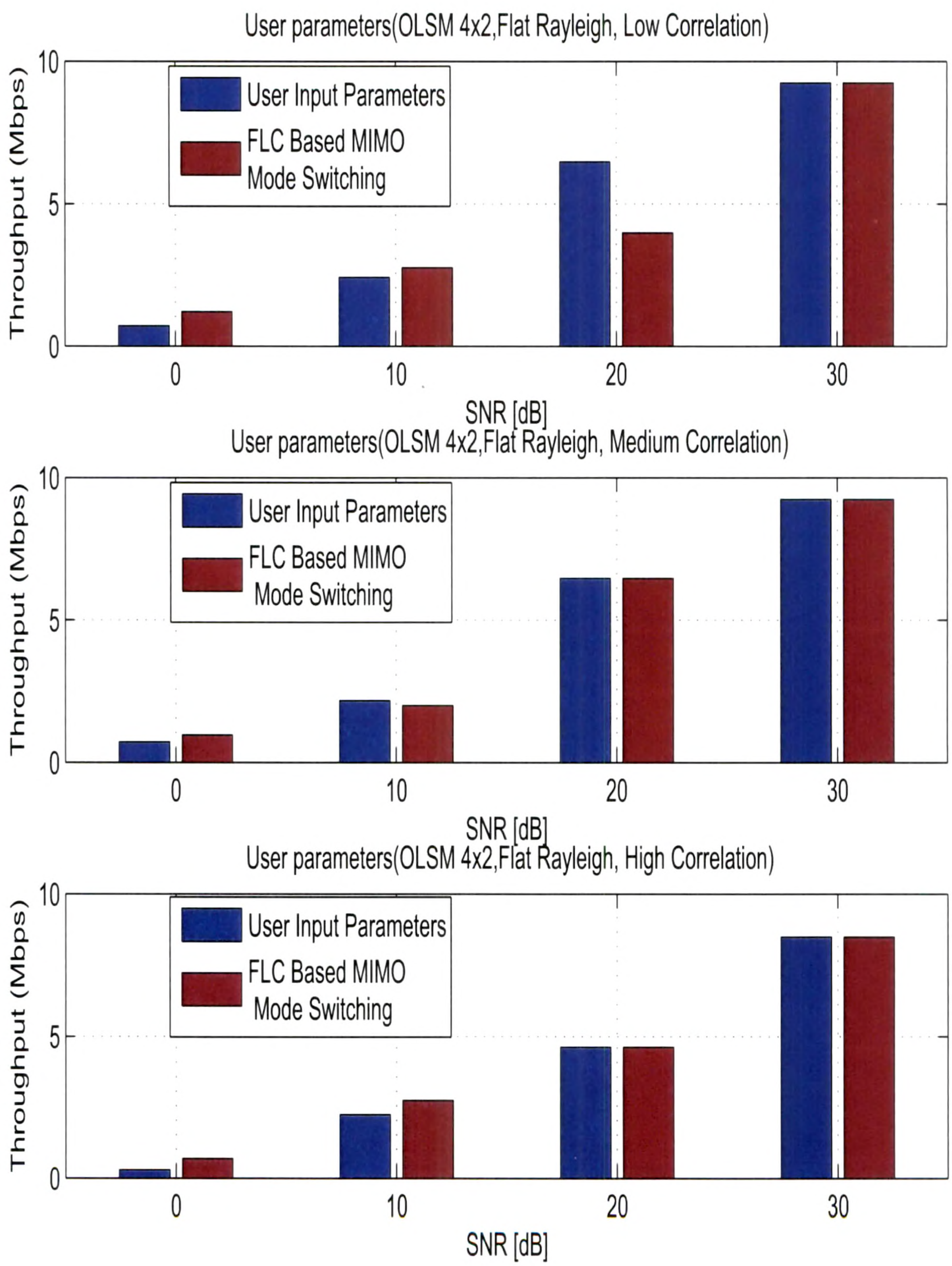

Figure 7.14: Comparative Analysis of FL Decision Model for Initial mode of OLSM 4x2

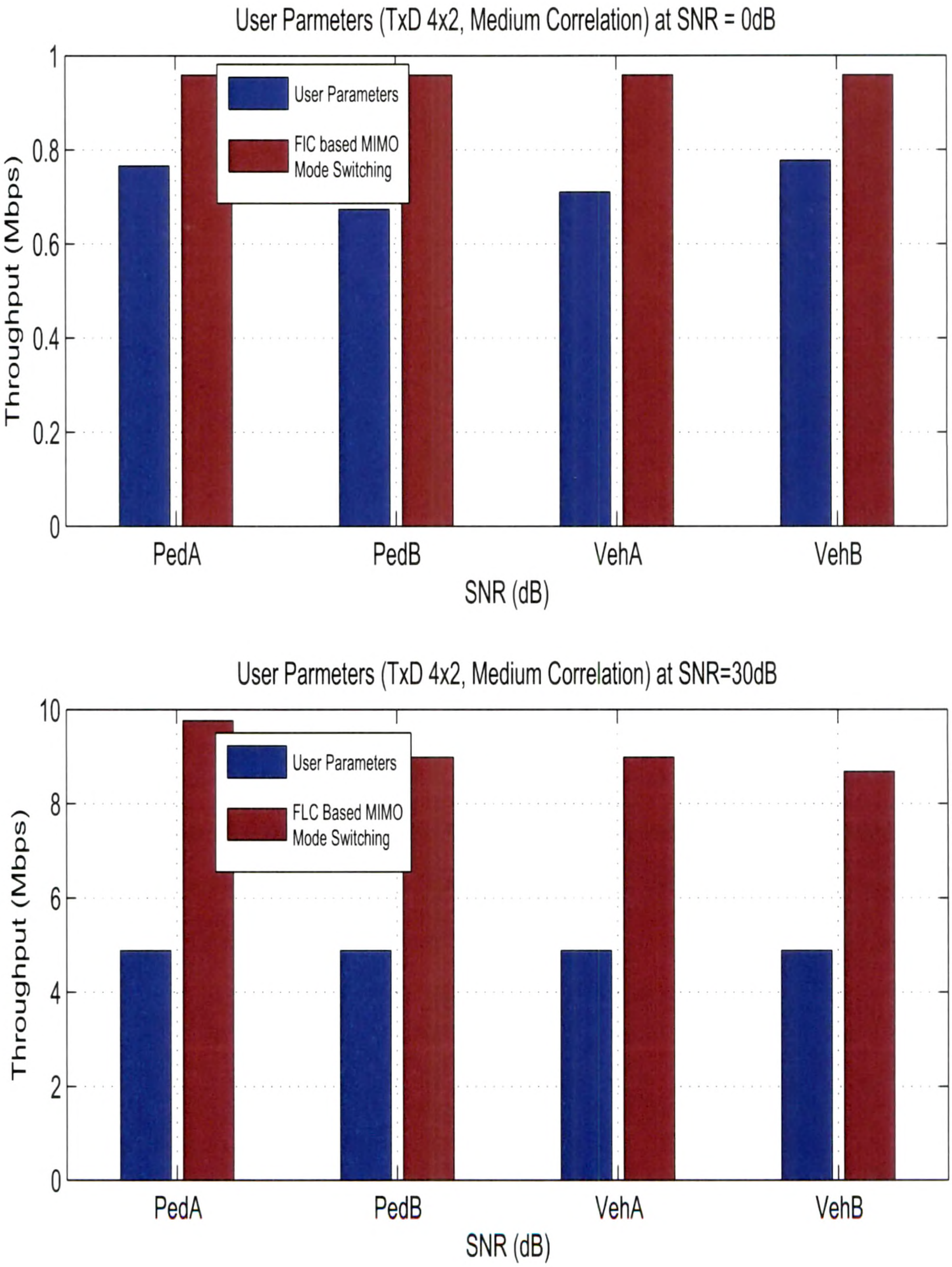

Figure 7.15: Comparative Analysis of FL Decision Model for Initial mode of TxD 4x2.

The FL Decision model developed is also verified for its performance in different channel configuration of PedA, PedB, VehA and VehB channels. The result analysis of Throughput is as shown in Figure 7.15, it can be seen the FL Decision model is able to select the appropriate MIMO mod to maximize the Throughput at Low SNR of 0dB and also at High SNR of 30dB scenario for all channel configurations.

From the comparative analysis we can conclude that for Initial Antenna configuration of 2x2 or 4x2, if initial MIMO mode is TxD or OLSM, the FL Decision model is able to successfully switch to the MIMO mode which gives maximum throughput. The decision made based on the Receive SNR and Channel Condition number is able to optimize the throughput of LTE-A Downlink Physical Layer.

7.6 Conclusion

The chapter discusses the FL-Decision model for MIMO mode switching for Throughput Optimization in LTE Downlink Physical Layer. The model takes into account the channel condition number and the Receive-SNR. The model switches between Transmit Diversity and OLSM Transmission mode of LTE Downlink Physical Layer. Based on the Fuzzy Rule base it takes decision and switches to the appropriate MIMO mode. The rules are designed based on the relation between the Switching point between MIMO modes and Channel Condition Number. The FL Decision Model is able to maximize throughput for LTE Downlink Physical Layer for various Channel Configurations and Antenna Configurations.