Adaptive thresholding based optimal rate and MIMO mode selection scheme for IEEE 802.11n WLAN

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Abstract*: The emergence of multiple antenna technology in IEEE 802.11n wireless local area network (WLAN) has resulted in performance improvement in terms of throughput as well as transmission reliability as compared to legacy standards. Link adaptive transmission is critical to WLAN. Most of the existing algorithms for multiple-input multiple-output (MIMO) mode adaptation (between spatial multiplexing and diversity encoding) use fixed signal to noise ratio (SNR) switching thresholds for rate selection. The use of a fixed threshold in both MIMO modes, however, can only provide smaller throughput gain. The present studies on link adaptation do not consider the fundamental characteristic difference in the diversity encoding and spatial multiplexing encoding for MIMO. In this paper we propose a novel adaptive thresholding based optimal rate and MIMO mode selection (ORMM) algorithm for 802.11n wireless network. The proposed scheme adaptively switches between two SNR switching threshold vectors, separately determined for each MIMO mode analytically. Simulations over the Rayleigh fading channel shows that ORMM outperforms the existing approach of MIMO rate adaptation based on the use of fixed switching thresholds for rate selection.

***Keywords*: IEEE802.11n, MIMO, OFDM, BER, Throughput, Rayleigh channel, WLAN.**

(Article history: Received: 20th February 2020 and accepted 22nd June 2020)

I. INTRODUCTION

The performance of wireless networks degrades due to multipath fading effects caused by rapid variations in the radio path. The link adaptive transmission approach makes the system robust enough against a fading environment. The link adaptation problem in WLAN is a well-explored subject in the research literature [1–7]. The IEEE 802.11n [8] wireless standard has designed to support the ever-increasing demand for high-speed data transmission by the internet user community. Many new physical layer enhancements are included in the IEEE 802.11n amendment [9]. Support for multiple antenna technology with up to four spatial streams and the addition of space-time block coding (STBC) help in enhancing the capacity. Rate adaptation is employed in many commercial WLAN chip-sets. Early work on the rate adaptation such as ARF [10], AARF [5] for WLAN used frame loss count available at the media access control (MAC) layer for deciding on the appropriate rate. However, this MAC layer mechanism failed due to its inability in distinguishing frame loss due to channel multipath fading effect or due to collision. Algorithms such as RRAA [4] and CARA [11] use RTS/CTS signaling for loss differentiation. However, increased overhead makes these algorithms less effective to use in high-speed wireless networks. Recent work on rate adaptation concentrated on exploiting physical layer information to understand channel characteristics and to choose matching bit rate. State of art rate adaptation algorithms [12, 7, 13] considers SNR estimation as channel quality indicating metric to choose the rate most appropriate to present channel state. The measurement-based study conducted by researchers [14, 12] using 802.11n based hardware platforms in indoor/outdoor radio environments shows that SNR is the best metric to consider in rate adaptation algorithm as it reflects very closely the channel characteristic. MIMO is another key technology used in many existing wireless networks to excel the performance in terms of transmission reliability and/or capacity to a great extent. Existing study on MIMO technology that includes analysis of MIMO channels, design of much different diversity encoding (DIV) and spatial multiplex encoding (SM) scheme for MIMO [15–18] demonstrates improvement in the throughput performance as well as reliable transmission of the data symbols over fading channels. Diversity coding for MIMO aims at increasing the reliability of transmission to combat the multipath channel fading effect [19]. By sending the same information symbols on different transmit and receive antenna pairs using diversity encoding method, many independently faded versions of the same symbols are made available at the receiver. This helps the receiver in reliably decoding the data symbols using one of the different combining techniques. The improvement in the BER performance due to diversity encoding is called diversity gain. Recent work on the MIMO encoding concentrated on achieving multiplexing gain [16, 2, 20]. As the radio path between different transmit-receive pairs independently fades, the MIMO channel can be converted into multiple parallel independent spatial channels. By sending independent data symbols on these spatial channels the capacity gain also called multiplexing gain can be achieved. The state of the art research in the context of MIMO encoding has focused on link adaptive switching between diversity and spatial multiplexing encoding scheme [21–24]. However, all these MIMO switching algorithms use fixed SNR switching thresholds for rate adaptation in both MIMO modes. All these algorithms do not consider the function as well as the basic characteristic difference between diversity encoding and spatial multiplexing encoding method for a MIMO system. This paper put forth novel adaptive thresholding based optimal rate and MIMO mode selection (ORMM) algorithm for IEEE802.11n based wireless networks, which shows a significant rise in the throughput performance under bit error rate (BER) constraint. The proposed packet-based ORMM algorithm uses SNR and BER estimates made at the receiver and generates control signals, which are sent to the sender node for adjusting its transmission parameters before the next transmission opportunity. The closed loop approach is used in the proposed algorithm and needs a highly reliable feedback channel. The rest part of the paper is organized as follows. The discussion on the background is included in section II. Section III explains the proposed ORMM algorithm and also discusses the analytical approach used to find SNR switching threshold vectors for use with diversity encoding and spatial multiplexing encoded MIMO system separately. Section IV includes discussion on simulation results obtained by considering Rayleigh fading channel, while section V concludes the paper.

II. Background

A. IEEE 802.11n

IEEE 802.11n is today's most widely deployed WLAN standard, which has features that include: high data transmission rate; support for MIMO antenna technology using up to a maximum of four spatial streams; enhanced quality of service (QoS) through optional support for space-time coding; support for multiple rates that varies from 6.5 Mbps to maximum of 600 Mbps; support for channel bonding (wider channel bandwidth of 40 MHz).

1) *Physical parameters*

The main physical layer parameters specified in the 802.11n amendment [9] are summarized in the TABLE I. The WLAN product vendors went to a substantive understanding of the physical layer as well as MAC layer features of 802.11n standard in mid-2006 only. The first amendment for 802.11n was came in 2009. As expected, numerous WLAN products were made available by vendors in the market around the time of 802.11n standard launch in 2009.

TABLE I. PHYSICLA PARAMETERS OF IEEE 802.11n

Radio frequency (RF) Band (GHz)	2.4 or 5
Channel width (MHz)	20 or 40
Sub-channel spacing (KHz)	312.5
Maximum transmission capacity (Mbps)	600
Modulation	bpsk, qpsk, and qam
Forward error correction (FEC) method	Binary convolution coding (BCC)
OFDM Symbol period (Microseconds)	4
FFT size (No. of sub-channels)	64

2) *Support for different rates*

The IEEE 802.11n standard support for transmission at different rates based on different modulation-coding schemes (MCS). The TABLE II shows a portion of the MCS table specified in the amendment.

TABLE II. TRANSMISSION PARAMETERS AND MAXIMUM BIT RATE CAPACITY OF IEEE 802.11n

Rate Index	**Constellation**	**FEC with Code rate**	**Spatial streams**	**Maximum Bit Rate (Mbps)** *Cyclic Prefix 800 ns*
r_0	Bpsk	½	1	6.5
r_1	Qpsk	½	1	13
r_2	Qpsk	¾	1	19.5
r_3	qam-16	½	1	26
r_4	qam-16	¾	1	39
r_5	qam-64	2/3	1	52
r_6	qam-64	¾	1	58.5
r_7	qam-64	5/6	1	65
r_8	Bpsk	½	2	13
r_9	Qpsk	½	2	26
r_{10}	Qpsk	¾	2	39
r_{11}	qam-16	½	2	52
r_{12}	qam-16	¾	2	78
r_{13}	qam-64	2/3	2	104
r_{14}	qam-64	¾	2	117
r_{15}	qam-64	5/6	2	130

3) *Support to MIMO antenna technology*

To convey information at a high rate reliably on WLAN, often inside the home or office environment, the 802.11n amendment specifies support for MIMO antenna technology. MIMO technology utilizes multiple antennas deployed at transmitting as well as receiving end to empower signal transmission through different independently faded radio paths. This capability of MIMO technology can be used to increase the throughput and/or transmission reliability by using different MIMO encoding methods.

B. Spatial diversity and spatial multiplexing: Functional difference

MIMO channel allows spatial diversity encoding, which can improve the error performance of WLAN. The idea behind diversity encoding is to transmit multiple independently faded copies of the same data symbol using two or more transmit antennas. The diversity order is the product of the number of antennas on the sender side and that on the receiver side. As the error probability is a function of SNR and the diversity order [19], an increase in the diversity order results in improved transmission reliability at given SNR. MIMO channels can also be utilized to increase the data rate or throughput. The basic idea of spatial multiplexing [25] is to transmit independent data symbols simultaneously through multiple independently faded radio paths that exist between different transmit-receiver antenna pairs. Spatial multiplex encoding for the MIMO channel creates many independent single-input single-output (SISO) channels that allow parallel data transmission. The number of such SISO channels formed by the spatial encoding scheme is equal to the minimum of antennas on sending end or receiving end.

C. Related work

The existing rate adaptation algorithms for WLAN can be categorized as statistics based rate adaptation and signaling based rate adaptation. The ARF [10], AARF [5], and Samplelite [7] are the example statistic based rate adaptation algorithms. Examples of signalling based closed loop rate adaptation scheme include: RRAA [4], and CaRa [11]. Statistic based methods need not require any signaling between transmitter and receiver. However, signaling based algorithms require RTS/CTS signaling or channel state information (CSI). IEEE 802.11n support for both open-loop as well as closed-loop rate adaptation schemes. The state of art link adaptation schemes for IEEE 802.11n considers adjustment in multiple transmission parameters to maximize the throughput in a fast varying radio environment. The combined rate and MIMO mode selection algorithm proposed in [26] uses SNR estimations made at the receiver for each MIMO encoding method as a criterion for adapting between diversity and spatial multiplexing. The joint rate and MIMO encoding method scheme suggested in [14] is based on using intra-mode and inter-mode rate options.

III. Proposed Algorithm

A. Adaptive thresholding approach for joint rate and MIMO mode selection

Most of the existing rate adaptation algorithms for 802.11n based wireless networks use a thresholding method. These algorithms use a fixed SNR switching threshold vector for rate selection. As the MIMO channel characteristic changes according to change in the encoding scheme, the algorithms that consider a fixed set of SNR switching thresholds fell to select the optimal rate. It is observed empirically by researchers [14, 12] that fixed threshold based rate and MIMO adaptation results in only a small increase in the throughput. The measurement based studies by many researchers also confirm that algorithms for MIMO adaptation that uses fixed SNR switching thresholds for rate adaptation in each MIMO mode fells in optimal joint selection of rate and MIMO mode. In our proposed ORMM algorithm, we consider an adaptive switching between two sets of SNR switching threshold values separately determined for rate adaptation in each MIMO mode (DIV and SM). One conceivable way to determine the threshold vectors for rate selection joint with different MIMO encoding is to develop an analytical method based on BER equations for Rayleigh fading channel given in [27,19]. Before detailing the ORMM algorithm, in the following sub-section, we explain the analytical method of determination of thresholds vectors.

B. BER for Coded transmission over Rayleigh fading channel

1) BER of coded BPSK transmission:

As given in [19], Binary convolutional coding (BCC) offers a coding gain given as,

$$G_{BCC} = r_c.d_m \tag{1}$$

The BER equations for wireless transmission over a Rayleigh fading channel, given in [27] are modified by considering the Forward Error Check (FEC) coding gain.

$$ber_{BPSK}(\overline{snr}, r_b) = \frac{1}{2}[1 - \sqrt{\frac{G_{BCC}(\frac{W}{r_b})\overline{snr}}{1 + G_{BCC}(\frac{W}{r_b})\overline{snr}}}] \tag{2}$$

Where, $\overline{snr}$ is the average signal to noise ratio estimation, W is sub-channel bandwidth, and r_b is the maximum bit transmission rate as a function of modulation coding scheme.

2) BER of coded M-QAM transmission:

$$ber_{M-QAM}(\overline{snr}, r_b) = [2(1 - \frac{1}{\sqrt{M}})\frac{1}{\log_2 M}] \cdot \gamma \tag{3}$$

Where,

$$\gamma = \sum_{k=1}^{\sqrt{\frac{M}{2}}} [1 - \sqrt{\frac{1.5(2k-1)^2 G_{BCC}(\frac{W}{r_b})\overline{snr} log_2 M}{(M-1) + 1.5(2k-1)^2 \mathrm{G}_{BCC}(\frac{W}{r_b})\overline{snr} log_2 M}}] \tag{4}$$

C. Determination of threshold vectors

1) Rate adaptation threshold vector for diversity encoded MIMO system:

The error performance of the wireless system can be improved using a diversity encoding method for MIMO. In diversity encoding [28, 29, 18], the same data symbols are transmitted through differently faded multiple transmit-receive radio paths. This provides the receiver with multiple versions of the same data symbols and the receiver can decode the symbols with more reliability. The enhancement in the BER performance called diversity gain is as given below.

$$ber|_{DIV} = \binom{2D-1}{D} ber(\overline{snr}, r_b)^D \qquad (5)$$

Where D called the order of diverse transmission is the number of differently faded transmission paths that a data symbol goes through. In a system with two transmit antennas and a receive antenna with transmit diversity encoding, D will be 2. Using D = 2 in equation (5), the BER of the system with transmit diversity encoding for MIMO can be written as below.

$$ber|_{DIV(2\times1)} = 3ber(\overline{snr}, r_b)^2 \qquad (6)$$

By solving equation (6) using equations (2) to (4), for different bit rates, under the constraint of target BER equal to 10^{-1}, the rate adaptation SNR switching threshold vector for diversity encoded MIMO system can be determined.

$$T_{DIV} = [T_{DIV1}\ T_{DIV2}\ T_{DIV3}\ T_{DIV4}\ T_{DIV5}\ T_{DIV6}\ T_{DIV7}\ T_{DIV8}] \qquad (7)$$

2) Rate adaptation threshold vector for spatially multiplexed MIMO system

With 2x2 spatial multiplex encoding for MIMO [22], the transmission rate can be doubled without affecting the error performance. Hence equations (2) to (4) can be solved under target BER constraint of value equal to 10^{-1} to get the SNR switching thresholds vector for a spatially multiplexed MIMO system.

$$T_{SM} = [T_{SM1}\ T_{SM2}\ T_{SM3}\ T_{SM4}\ T_{SM5}\ T_{SM6}\ T_{SM7}\ T_{SM8}] \qquad (8)$$

D. ORMM algorithm:

Our method for joint rate and MIMO mode adaptation is in the reflection of the trade-off between throughput maximization and reliable transmission. To ensure minimum QoS requirement, ORMM works under BER constraint defined as ber_{PACKET} and maximizes the throughput as defined below.

$$throughput = R_b(1 - ber) \qquad (9)$$

ORMM is a closed-loop scheme, which generates following control signals based on the average SNR estimation ($\overline{snr}$) and BER estimation (ber_{PACKET}) made at the receiver on a per-packet base.

. The rate control signal (*rcs*)

. The MIMO mode control signal (*mmcs*)

These control signals are feedback to the sending node through the most reliable reverse control channel. Transmitter then adjusts its physical parameters such as modulation-coding scheme (rate) and MIMO encoding method to cope up with channel state. The SNR switching threshold vectors (T_{SM} and T_{DIV}) are adaptively used to select MIMO mode aware optimal rate. MIMO mode adaptation uses an empirical SNR threshold (snr_T). The pseudo-code presented in Algorithm 1, explains the steps incorporated in the algorithm.

Algorithm 1 ORMM Algorithm

Require: $\overline{snr}, ber_{PACKET}, T_{SM}, T_{DIV}, ber_{TARGET}, snr_T$

Ensure: Optimal Rate and MIMO mode selection

```
// Select-MIMO-MODE()
if ber_PACKET ≥ ber_TARGET then
    mmcs ← DIV
else
    if snr ≥ snr_T then
        mmcs ← SM
    else
        mmcs ← DIV
    end if
end if
// Select-Rate()
if mmcs = DIV then
    for j ← 0 to 7 do
        if T_DIV(j) < snr ≤ T_DIV(j+1) then
            rcs = r_j
        end if
    end for
else
    for j ← 8 to 15 do
        if T_SM(j) < snr ≤ T_SM(j+1) then
            rcs = r_j
        end if
    end for
end if
```

IV. Simulation Results and Discussion

This section presents the simulations carried out to evaluate the performance of the proposed ORMM algorithm for IEEE 802.11n. In all simulations, we consider a Rayleigh fading channel model, which best approximates the indoor office environment for WLAN. The experiment considers the transmission of a packet loaded with one thousand bytes of data with required information about the signal, training symbols, and control signals in the preamble part as shown in the TABLE II.

Simulations assume a packet size much smaller than the time coherence of the multipath fading channel. By varying the SNR value over the applicable range in practice (5 dB to 50 dB) simulations are accomplished.

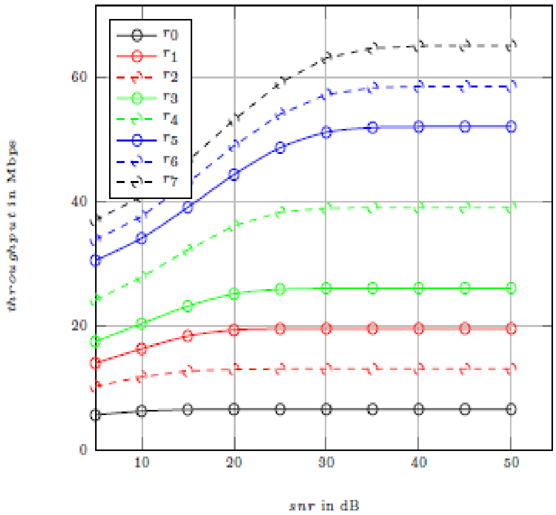

Fig. 1: Throughput of WLAN with different rate and diversity encoded MIMO

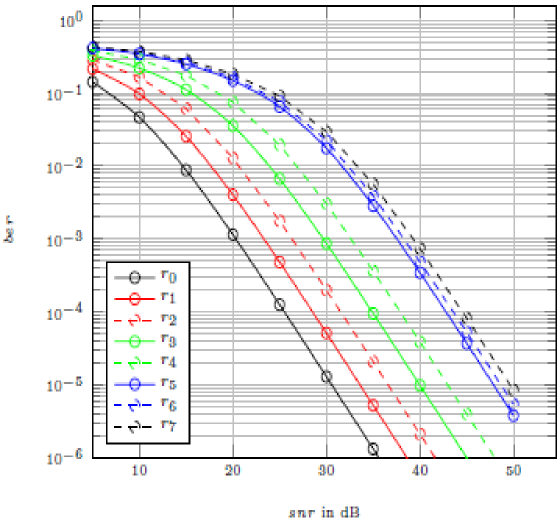

Fig.2: BER of WLAN with different rate and diversity encoded MIMO

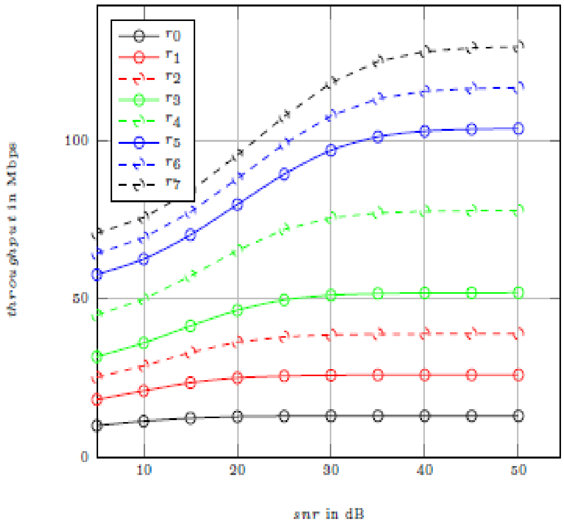

Fig. 3: Throughput of WLAN with different rate and spatial multiplexed MIMO

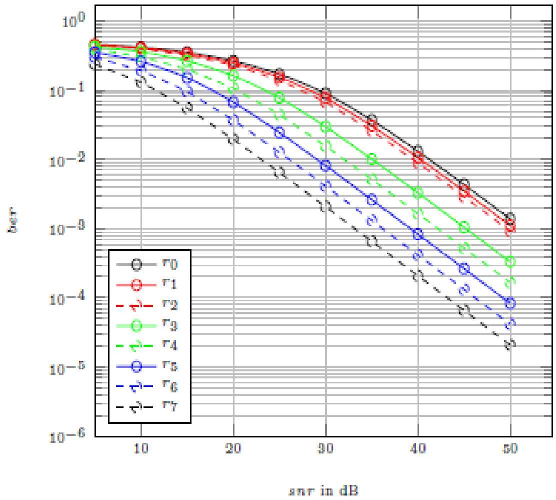

Fig. 4:BER of WLAN with different rate and spatial multiplexed MIMO

Simulation results plotted in Fig. 1 and Fig. 2 shows throughput and BER performance of the WLAN respectively, which considers packet transmission with different data rates specified in the IEEE 802.11n amendment [9] and 2x2 spatial encoding scheme for MIMO. Fig. 3 and Fig. 4 show the performance of WLAN over the Rayleigh fading channel under different fixed rates with packet transmission using 2x1 diversity encoded MIMO. Comparing the performance of the WLAN shown in Fig. 1 to Fig. 4, which considers data transmission with different fixed rates and different MIMO encoding schemes (DIV and SM) separately, we can observe that the different SNR switching thresholds vector in each MIMO mode for rate adaptation would be more beneficial.

The WLAN throughput and BER performance curves in Fig. 5 and Fig. 6 respectively show that the DIV encoding scheme for MIMO is better at smaller values of SNR (i.e. when the channel conditions are poor). At higher values of SNR, however, spatial multiplexing encoding for MIMO proved to be a better option for maximizing the throughput of WLAN.

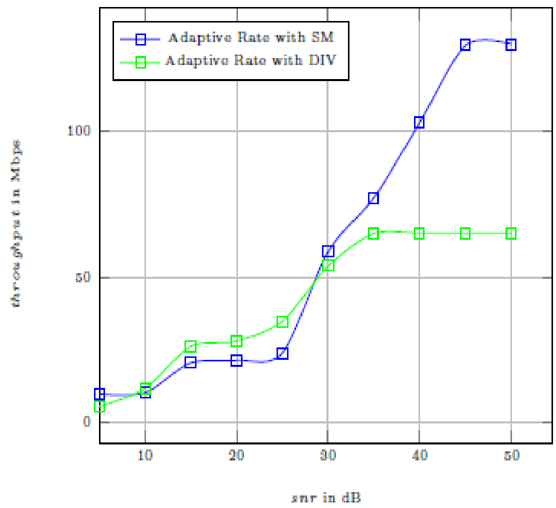

Fig. 5:Throughput performance of rate adaptive WLAN with different MIMO encoding schems

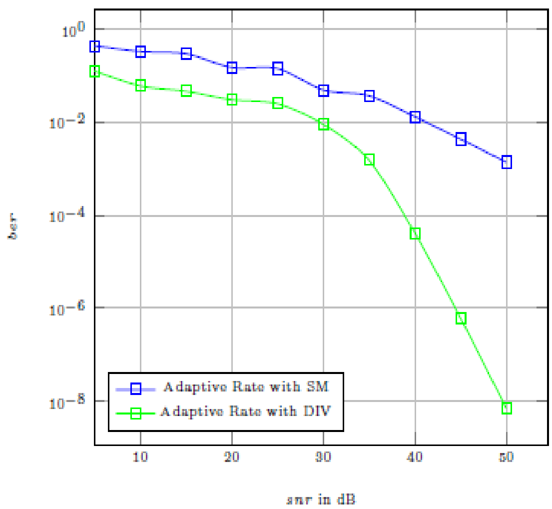

Fig. 6: BER performance of rate adaptive WLAN with different MIMO encoding schems

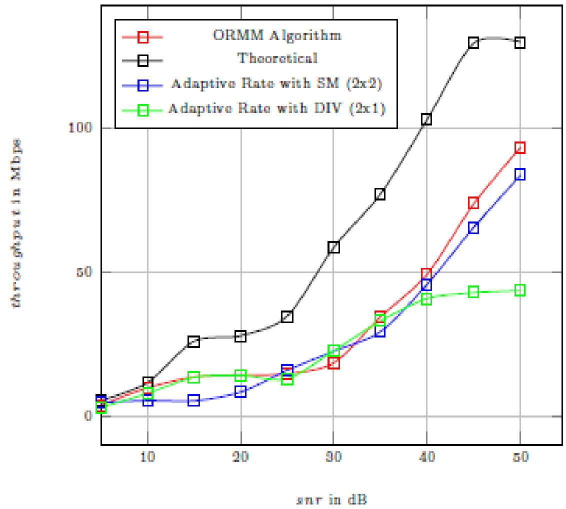

Fig. 7:Throughput performance of ORMM algorithm over Rayleigh fading channel

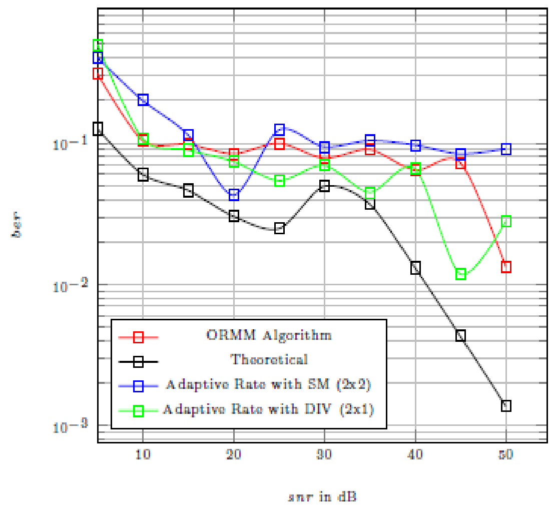

Fig. 8:BER performance of ORMM algorithm over Rayleigh fading channel

In Fig. 7 and Fig. 8 the following different algorithms are compared to evaluate the performance of the proposed ORMM algorithm.

1. Rate adaptation with SM: Fixed threshold based rate adaptation algorithm with spatial multiplexed MIMO
2. Rate adaptation with DIV: Fixed threshold based rate adaptation algorithm with diversity encoded MIMO
3. ORMM: Adaptive thresholding based joint rate and MIMO mode selection algorithm
4. Theoretical: These curves are plotted for validating the proposed algorithm and considered a performance comparison basis.

The simulation in the Rayleigh channel scenario confirms notable throughput gain using the proposed channel aware adaptive thresholding based ORMM algorithm as presented in TABLE III. Especially, ORMM outperforms the traditional approach of rate adaptation based on using fixed SNR thresholds.

TABLE III. THROUGHPUT PERFORMANCE OF ORMM ALGORITHM

Sr. No.	SNR in dB	Throughput in Mbps			
		ORMM Algorithm	*Adaptive rate with DIV*	*Adaptive rate with SM*	*Theoretical*
1	5	3.8907	3.1030	4.8476	5.5724
2	10	9.9680	8.0306	5.5689	11.7243
3	15	13.7123	13.5705	5.4806	26.0928
4	20	14.4176	14.2962	8.5164	28.0356
5	25	14.8525	13.1336	16.0840	34.8265
6	30	18.6926	22.9040	22.7362	58.6829
7	35	34.6123	33.1507	29.4826	77.2117
8	40	49.4653	40.9527	45.9483	103.0725
9	45	73.8735	42.9955	65.6960	129.4387
10	50	93.3664	43.7588	83.7269	129.8202
Average Throughput		48.6285	23.4309	44.2872	67.6963

V. CONCLUSION

This paper put forth a novel scheme of optimal rate and MIMO mode selection, which considers an adaptive thresholding method. The proposed ORMM algorithm uses SNR and BER estimations made at the receiver as an input triggering information and generates the required control signals needed by the transmitter to adjust its transmission parameters in accordance with present channel state. The ORMM algorithm adaptively switches between two MIMO modes (DIV and SM) in order to maximize throughput of WLAN under BER constraint. The optimal selection of SNR switching thresholds vector for link adaptive rate selection is a critical issue in WLAN. We present an analytical method to determine separately the SNR switching threshold vectors for optimal rate selection in each MIMO mode. The analysis of a wireless network with the ORMM algorithm over the Rayleigh fading channel shows significant enhancement in the throughput performance. The proposed adaptive thresholding based rate selection scheme with smaller hardware dependent adjustment would help to exist as well as emerging MIMO based networks for performance enhancement.

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