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Correlation based Rate Adaptation via Insights from Incomplete Observations in 802.11 Networks

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***Abstract*—Rate adaptation, as a challenging issue for wireless network design, has been an active research topic for years. Existing schemes either assume perfect channel information, or conduct rate adaptation in a black box way, hence can not achieve desirable performance. In this paper, we propose a novel scheme called Correlation based Rate Adaptation (CORA) to address the rate adjustment problem. Unlike previous schemes, CORA splits rate into more atomic components and adjusts them according to the correlation between rate adaptation actions and transmission results. We use IEEE 802.11n as the context for CORA design, where transmission mode has been expanded to spatial dimension in addition to the usual modulation and convolution coding mechanisms. Performance evaluation shows that CORA can conduct rate adaptation in a more logical way and significantly outperform the comparison scheme.**

Keywords- rate adaptation; 802.11 wireless networks; 802.11n

I. INTRODUCTION

Multi-rate support is a common design in 802.11 systems. 802.11a/b/g supports various rates up to 11/54Mbps, and 802.11n supports higher rates even up to 600Mbps [1]. The scheme to choose rate among the rate set has great impact on the system performance and various rate adaptation algorithms have been proposed in recent years.

However, there are still many unsolved issues. One of them is due to some unrealistic assumptions made by many works such as [2] [3] that perfect channel information can be obtained. Yet firstly channel information such as Signal to Noise Ratio (SNR) is not readily available in existing 802.11 networks [8]. Furthermore, due to the inconstant feature of wireless channel, Received Signal Strength Indication (RSSI) information offered by the driver of Network Interface Card (NIC) may be smoothed value; instantaneous value is not available. Moreover, other factors like node mobility, hidden terminal, etc., also make the schemes based on perfect information less efficient as originally designed. Thus, realistic rate adaptation should be able to extract information from incomplete observations.

Another issue of existing rate adaptation schemes is to simply reduce/increase rate based on packet loss, without the consideration of whether the loss is correlated with the rate schemes. Specifically most previous works [4]-[6] focus on designing metric to estimate channel quality. Packet loss rate [4]-[5], long term statistics [6] have been proposed for this purpose. Relatively little attention has been paid on identifying whether root cause of transmission failure is correlated with data rate. Such black-box based schemes usually lead to throughput fluctuations and degradation. This observation motivates us to explore rate adjustment problem from correlation perspective.

On the other hand, nascent 802.11n [1] expands rate dependent parameters into spatial dimension by incorporating Multiple-Input-Multiple-Output (MIMO) technology. As a result, different combinations of these parameters may mirror the same data rate. Although with the same rate, these combinations behave quite differently under some similar channel conditions. Therefore, rate adaptation should be conducted in a more atomic way.

In this paper we put forth a novel methodology for rate adaptation in 802.11n scenario. We design Correlation based Rate Adaptation (CORA) strategy to seek the correlation between the tunable parameters and adjustment results. Therefore, correlated ones are recognized for tuning and uncorrelated adjustments are avoided, leading to efficient adjustment without unnecessary rate fallback. Our research contributions are as follows:

- We introduce a new perspective for rate adaptation. This is to adjust transmission parameters based on the correlation between adjustment action and results;
- We propose a more atomic scheme CORA to tune rate parameters in multi-dimension scenario systematically;
- We conduct 802.11n simulation to study the performance of transmission mode, and further validate the performance of CORA in 802.11n context.

The rest of the paper is organized as follows. We describe motivation in Section II. The design of CORA is illustrated in Section III. Section IV presents performance evaluation of CORA. We overview related work in Section V. Section VI concludes the paper and states future work.

II. MOTIVATION

A. *Observation from PHY Simulation of 802.11n*

In 802.11n system, essentially two gains from MIMO are provided [9]. The first one is achieved by spatial multiplexing,

[+]This work was performed during Xia Zhou 's internship at Wireless and Networking Group, Microsoft Research Asia.

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which transmits independent data streams simultaneously over multiple antennas leading to times of improvement in throughput. The other is spatial diversity gain, where transmitter introduces controlled redundancy in transmitted data via coding scheme yielding high quality of reception. Space-Time-Block-Coding (STBC) is a most widely used one.

Therefore, rate dependent parameters in 802.11n include not only modulation and convolution coding scheme, but also a spatial dimension parameter Nss (Number of Spatial Streams), which denotes the number of independent sub data streams split from the original one. 802.11n assigns an index named Modulation and Coding Scheme (MCS) to represent each combination <Nss, Modulation, Convolution Coding Rate>. Therefore one data rate may mirror several different MCS values. TABLE I lists those MCS values with the same data rate when Guard Interval (GI) is 800ns, and antenna numbers at both sender and recipient sides are two (namely 2x2 case).

TABLE I. PARAMETER COMBINATIONS OF THE SAME RATE

Data Rate	MCS	Parameter Combination		
		Nss	*Modulation*	*Coding Rate*
13Mbps	1	1	QPSK	1/2
	8	2	BPSK	1/2
26Mbps	3	1	16-QAM	1/2
	9	2	QPSK	1/2
39Mbps	4	1	16-QAM	3/4
	10	2	QPSK	3/4
52Mbps	5	1	64-QAM	2/3
	11	2	16-QAM	3/4

In order to study the performances of these transmission modes with the same data rate, we conduct Physical Layer (PHY) simulation of 802.11n in MATLAB by referring to its PHY specification [1]. Our simulation is for 2x2 case with Rayleigh multi-path channel. We assume Space-Time-Block-Coding is adopted when Nss is one. And under multiplexing case channel matrix is known for the receiver to extract individual signal out from mixed one. As what Figure 1 shows, different MCSs with the same data rate behave quite differently. Lower Nss with STBC owns much smaller Bit Error Rate (BER). This observation justifies the idea of adjusting rate in a smaller granularity.

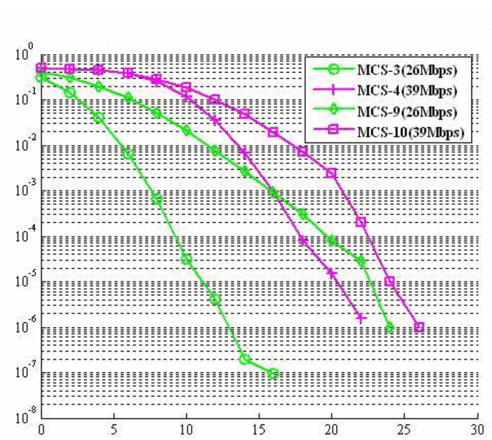

Figure 1: SNR-BER Curves of MCS 3, 4, 9, 10 under Rayleigh channel. Data rates of MCS 3 and 9 are both 26 Mbps. MCS 4 and 10 both mirror 39 Mbps.

B. Observation from MIMO NIC Testing

We conducted MIMO NIC testing in indoor office environment to study the actual performances of different MIMO transmission modes. Testing scenario (Figure 2) consists of one laptop station (STA 1) equipped with Airlink wireless card-bus adapter AWLC 5025, one Airklink101 AR525W MIMO router as Access Point (AP) and a desktop as STA 2. These MIMO products from Airlink are based on 802.11g standard.

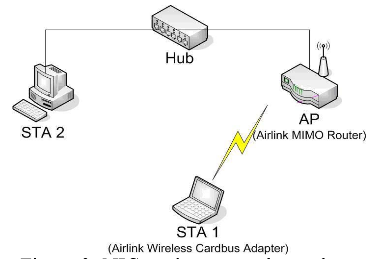

Figure 2: NIC testing network topology

We fixed each rate in MIMO AP, then test its performance at different positions within an indoor area of around 30m×30m as Figure 3. We use Iperf [10] to generate UDP traffic from STA 2 to STA 1 during an interval of 60 seconds.

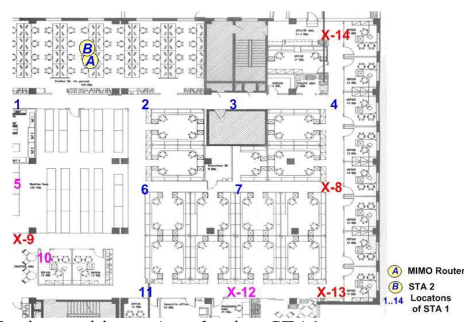

Figure 3: Testing positions. At red points STA1 can not connect with AP. At pink ones connection is unstable. Blue points are normal.

According to testing results in Figure 4, no data rate works at position 8, 9, 13, 14 since these positions are obstructed by either a large equipment room or too many cubicles. It serves as the evidence to our argument that rate adjustment can not help in some cases. We also observe that at the other positions auto rate may not always have better throughput than fixed data rate. Particularly at point 4 and 6, the throughput gap between 36 Mbps and auto rate is notable. It conveys to us a hint that rate adaptation should be conducted from correlated perspective.

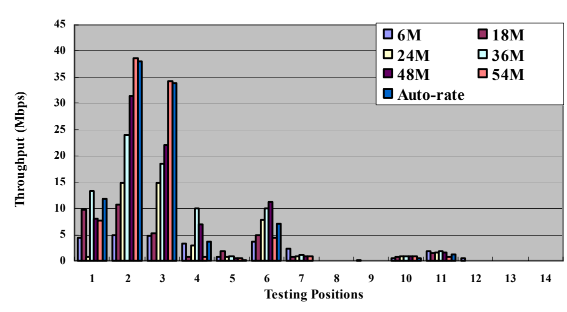

Figure 4: Measured throughputs at different positions when data rate is set to 6 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 54 Mbps and auto rate respectively

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III. DESIGN

In this section we first give the overall design of CORA. Then as a key part of CORA, the method for correlation identification is described. Lastly, we illustrate more details about CORA in the 802.11n context. In summary, there are three characteristics of our approach:

a) ATOMIC: More atomic rate dependent parameter is identified for adjustment so that data rate is no longer adapted as a whole.

b) CORRELATION-BASED: We tune atomic parameter based on the correlation between tuning action and results. Via extracting information from the transmission results, we seek the more possibly correlated parameter for adjustment.

c) SCALABLE: Our approach can be extended to the scenario of more than two tunable dimensions.

A. CORA Overall Design

CORA is aimed to be a general approach for seeking the correlation in the scenario of multiple tunable dimensions. Also, CORA conducts rate adaptation at more atomic level. Since previous link adaptation strategies are only dedicated to the adjustment of modulation and coding scheme, any of them can be integrated into CORA. According to transmission result, we define three states for sender, which are INITIATION, SUCCESS, and FAILURE. Transition among them is illustrated by Figure 5.

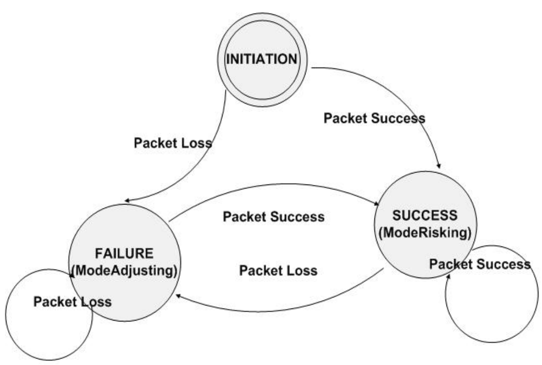

Figure 5: State transition diagram of CORA

- INITIATION: Starting point. Sender will be reset to this status after a certain predefined time interval in order to get rid of outdated information.
- FAILURE: Sender will be in this state when no reception of ACK after a timeout interval. *ModeAdjusting* procedure will be triggered for transmission mode adaptation.
- SUCCESS: Sender will be in this state after the reception of ACK. Then *ModeRisking* procedure will take charge of further rate adaptation.

The main methodology of correlation identification is to extract information from the transmission results after the action of adjusting certain dimension. Based on the action results, the correlation of this parameter can be evaluated. Therefore, the correlated parameter is recognized for adjustment. Figure 6 shows the basic flowchart.

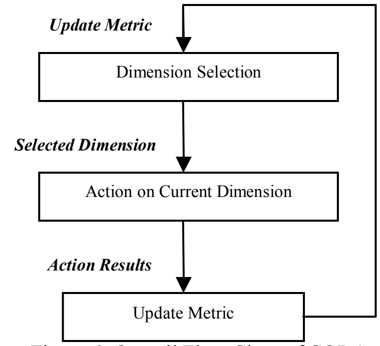

Figure 6: Overall Flow Chart of CORA

B. Correlation Identification

To be specific, assume there are k tunable dimensions / parameters denoted as set D=<d_0, d_1, d_2,….., d_{k-1}>. Our method to identify correlation of each dimension is based on threshold. Let $d_{current}$ be the dimension currently being tuned, we define metric M to evaluate tuning result on $d_{current}$, and assign a threshold T_i to each other dimension d_i. During the adjustment process on $d_{current}$, once M is above the threshold T_i of certain dimension d_i, d_i is recognized to be more correlated and hence switched to be tuned. If the attempt of adjusting d_i suffers failure reflected by the value of metric M, its threshold value T_i will be raised. In this way, thresholds of those dimensions are adjusted adaptively according to the transmission results so that un-correlated parameters will be chosen with lower possibility.

Figure 7 gives the procedure of *Dimension Selection*. *Adjustment_Identification* is to identify whether to adjust rate. *Flag* denotes its returned result. *AdaptThreshold* adapts the threshold of current dimension in terms of transmission result *current_state*. *Candidate_Dim_Set* contains possibly correlated dimensions, among which the one with the least threshold is regarded to be most correlated.

```
Flag = Adjustment_Identification ();
If (Flag) {
   AdaptThreshold(T_current, current_state );
   Candidate_Dim_Set =
      {d_i | d_i ∈ (D - {d_current }) && (M > Ti)};
   T_k = min (T_i | d_i ∈Candidate_Dim_Set )
   if (d_current != d_k) {
         d_current = d_k;
         Clear Metric;
   }
}
```

Figure 7: Dimension Selection in CORA

C. CORA in 802.11n Context

1). Modules

In 802.11n context we consider three dimensions among which two are tunable. One is MOD_CR, which denotes the modulation scheme and coding rate. The other is NSS_STBC denoting the spatial parameter in 802.11n context. Therefore, the dimension set D here can be represented as D=<d_0, d_1>, OTHER is defined to represent other factors which are un-correlated with rate adjustment. Figure 8 shows the flowchart of CORA in 802.11n context. Once *Dimension Selection* determines the dimension for adjustment, corresponding action will be conducted. When OTHER dimension is chosen, rate adjustment is not carried out. As for the case when dimension MOD_CR or NSS_STBC is selected, the parameters of that dimension will be adjusted accordingly. Then metric M is updated in terms of the results of adjustment on selected dimension.

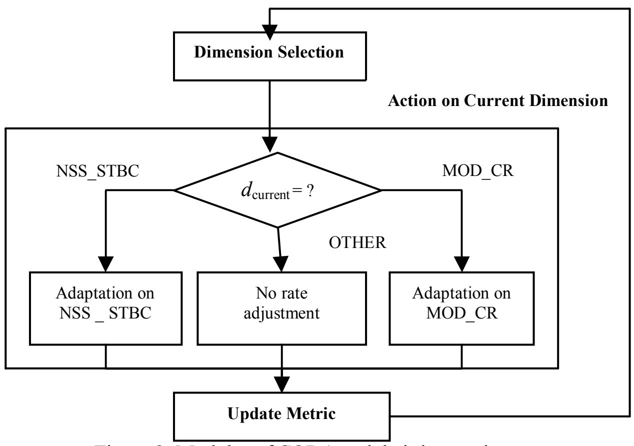

Figure 8: Modules of CORA and their interactions

2). Adjustment Procedure

a) Update Metric: Assume current transmission result is evaluated by metric M and thresholds for both dimensions are T_0 and T_1. The straightforward metric may be the number of consecutive transmission failures or successes. However, considering longer packet is more susceptible to channel errors, M is defined to incorporate the impact of packet length as

$$M = \sum_{i=1}^{SuccNum} Pkt\_Len_i / MTU\_LEN \quad (1)$$

in success case, and as

$$M = MTU\_LEN \times \sum_{i=1}^{FailureNum} 1 / Pkt\_Len_i \quad (2)$$

in failure case. Here *SuccNum* and *FailureNum* denote the number of consecutive successes and failures respectively. Pkt_Len_i represents the length of packet transmitted. *MTU_LEN* is the maximal length of MAC transfer unit, which is set to 1400 in our implementation.

As for the values of thresholds T_0 and T_1, they are initialized to be α_{dim_up} and α_{dim_down} for both success and failure cases. α_{dim_up} and α_{dim_down} are 11 and 2 respectively in our implementation.

b) Dimension Selection: This module is for selecting the potentially most correlated dimension for tuning. Once new dimension has been switched to, metric value M will be subsequently cleared to account the action results on new dimension. Selection details are introduced respectively in both failure and success cases.

Failure Case:

In failure case we firstly check whether to adjust rate via *Adjustment_Identification*. If consecutive failures is only one, or current MCS belongs to a very robust class (MCS < 3), it is highly possible that transmission failure is correlated with other factors such as collision. Therefore, rate adjustment is skipped for filtering out random packet losses (e.g., due to collisions). Otherwise, dimension selection will be conducted as following cases:

i. CASE 1: $d_{current} = d_1$, $Candidate\_Dim\_Set = \{d_0\}$

If the dimension currently being tuned is modulation and coding scheme, namely $d_{current} = d_1$, the *Candidate_Dim_Set* is hence $\{d_0\}$. First we identify whether the metric value M, which evaluates the action of adjustment on the parameter of modulation and coding scheme, is above T_0, the threshold of d_0. If so, then it indicates that the adjustment on modulation and coding parameter does not help. The failure may due to a wrong choice made on spatial dimension. Therefore, we need adapt the threshold value of current dimension T_1 through *AdaptThreshold*. And next switch to spatial dimension to do adjustment since most likely current channel status can not afford current Nss value. In this way, $d_{current} = d_0$, so those MCS values with lower Nss value will be subsequently attempted by sender via specified link adaptation scheme on modulation scheme and coding rate.

ii. CASE 2: $d_{current} = d_0$, $Candidate\_Dim\_Set = \{d_1\}$

If the failure is caused by current adjustment on the spatial dimension, namely $d_{current} = d_0$, *Candidate_Dim_Set* is hence $\{d_1\}$. It implies that present channel quality can not afford this new Nss value. Then adaptation should only be conducted on modulation and coding scheme. Thus, the threshold of raising Nss T_0 is adaptively doubled by *AdaptThreshold*. In this way, further throughput reduction brought by failure attempt of higher Nss can be avoided.

Success Case:

If the action on current dimension succeeds, then the threshold of current dimension $d_{current}$ is returned to the initial value via *AdaptThreshold*. Utilizing the general rule described in the second subsection, the dimension for tuning next time will be selected based on their threshold values.

c) Action on Current Dimension: As what the Figure 8 shows, there are three different cases of action according to chosen dimension. Since selecting dimension OTHER means no rate adjustment. We focus on explaining the left two cases.

Adaptation on MOD_CR

Since current rate adaptation method is dedicated to the parameter of modulation and coding scheme, any of them can be directly utilized in this part.

Adaptation on NSS_STBC

Firstly Nss value will be increased or decreased according to current transmission state. Next, this part selects the initial MCS with this new Nss value to start by based on previous MCS. If there is MCS with the new Nss value achieving the same data rate as that of previous one, we select that MCS to begin with. Otherwise, if Nss has been tuned to be lower, for high throughput consideration, we chose the largest MCS with that lower Nss to begin with. If Nss has been tuned to be higher, we pick the MCS with the data rate which is nearest to previous one.

IV. PERFORMANCE EVALUATION

A. Simulation Setup

We conduct simulations in NS2 [11] to evaluate our scheme. We utilize the PHY simulator mentioned in Section II to generate all the SNR- BER curves of sixteen MCS values in 2x2 case under channel correlation degrees of 0, 0.5 and 0.9 respectively. These SNR-BER tables are referred to in NS2 for the purpose of simulating 802.11n PHY. We adopted the extension of Ricean fading model for NS2 [12]. Besides, for accurate computation of SNR, the reactive model proposed in [13] is incorporated to consider the accumulative interference from other nodes. We choose Auto Rate Fallback (ARF) as the base line for comparison. Control and broadcast packets are transmitted by MCS of 7. For simplicity, RTS/CTS exchange is disabled. The parameters related to MAC layer are specified according to [14] for 802.11n simulation. Table II shows the parameters set in our simulation for a summary.

TABLE II. PARAMETERS SET IN SIMULATION

Parameter	Value
Preamble Length	94bits
PLCP Header Length	24bits
PLCP Data Rate	6Mbps
Slot Time	9 μ s
SIFS Time	16 μ s
CBR	40M
Contention Window Size	15-1023
Background Noise Level	-90dbm
Transmission Power	24dbm
Routing Protocol	DSDV
Simulation Time	30 seconds

B. Simulation Scenarios

1) Single Flow Scenario: We first evaluate the performances of ARF and CORA in static single flow case. This scenario consists of an AP and a station. AP continuously sends out packets of 1000 bytes to station. Maximal Doppler frequency is assumed to be 30Hz. Simulation is performed under the channels with correlated degree of 0, 0.5 and 0.9 respectively. Figure 9 shows the comparison between CORA and ARF. As the channel correlated degree changes from 0 to 0.9, the gap between CORA and ARF becomes larger. The reason is that under highly correlated channel, the system can not support high Nss value. Our algorithm can recognize this and tune the right parameter Nss more quickly thereby outperforming ARF up to 67%.

2) Collision Scenario: We then conduct the simulation under the collision scenario, where 3 nodes concurrently transmit packets to a single node. Figure 10 (a) and (b) show the overall throughputs of ARF and CORA. The distance *d* between neighbor nodes is 2m and 20m respectively. We observe that throughputs achieved by ARF in these two cases differ little, yet the gain of our algorithm over ARF is much larger in the former case. By analyzing the NS2 trace files of ARF, we find that around 98% packet losses in the first case are caused by collision, whereas in the latter case when distance is longer, only around 25% packet losses are due to collision. It clearly demonstrates that when facing transmission failures incurred by collision our algorithm constantly outperform ARF by reducing unnecessary rate fallback.

3) Multiple Pairs Scenario under Different Channel Cases: We finally conduct simulation in the scenario consisting of 10 concurrent transmitting pairs within a flag grid of 500m ×500m. The distance of the two nodes in each pair is 2m, and the gap between two pairs is 10m. Packet size of the traffic for each pair is a random number ranging from 400 bytes to 1400 bytes. Figure 11 shows the throughputs of different rate adaptation algorithms. When the correlated degree of channel becomes larger, achievable throughputs of all algorithms generally suffer degradation. Whereas in each case, the performance gains of CORA over ARF are constantly around 200%~300% on average.

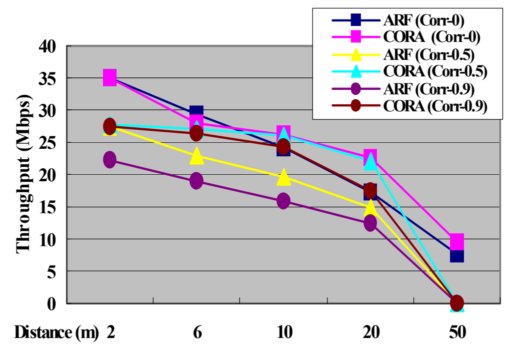

Figure 9: Throughput of single flow under different correlated channels

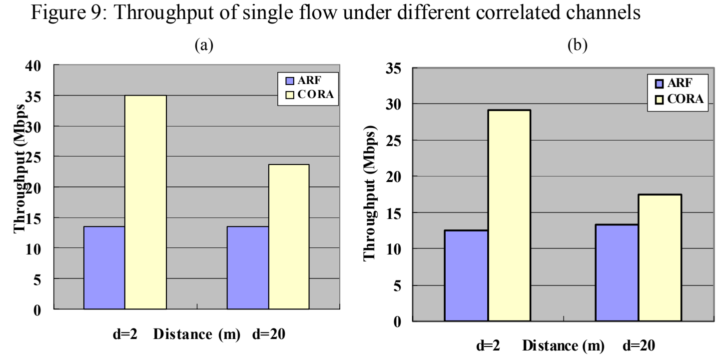

Figure 10: Collision scenario (a): with packet size from 1000 to 1400bytes (b): with packet size from 400 to 1400bytes

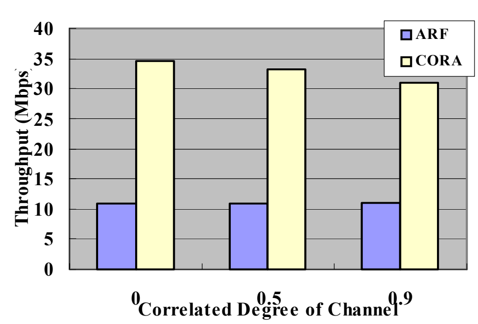

Figure 11: Throughput of multiple flows under different correlated channels

V. RELATED WORK

Prior works on rate adaptation fall into two categories. The first category including [4]-[6] is based on the statistics of historical transmission information. The basic idea is that if lower data rate faces failures, then higher data rate will not be used. Whereas one disadvantage of these schemes is that historical statistics may not be able to track the fast-changing channel in time. Performance evaluation in [6] is just for MIT Roofnet [16] where channel experiences relatively slow change. Implementation of SampleRate described in [6] updates historical records over a 10-second time window.

The other category proposes to utilize SNR or RSS (Received Signal Strength) for choosing data rate [2]-[3]. However, these methods commonly suffer difficulties in practical systems. Let us take SNR based scheme as an instance for illustration. Firstly, it is hard to obtain precise SNR in practice [17]. Secondly, even given the perfect SNR value, the mapping between SNR and optimal transmission rate highly depends on the model of wireless channel, which is variable and hard to model. As the evidence, measurements in [8] [15] show that SNR value gives little indication to the choice of data rate in practice. Lastly, some of these methods like [2] require receiver to feedback SNR to sender. It results in additional Medium Access Control (MAC) overhead.

The common feature shared by the methods listed above is that they attribute the transmission failure to data rate and thus reduce rate. Yet as for failures caused by hidden terminal, collision, interferences from non-802.11 sources, rate adjustment without considering causes may not help and only lead to reduction on throughput. In this regard, we argue that it is helpful to add some recognition ability into rate adaptation, so that the correct parameters are recognized for efficient adjustment.

More recently, several other pieces of work also point out the same shortcoming of existent rate adaptation. For a solution, MOJO in [18] troubleshoots the abnormity at PHY according to the root causes. CARA in [19] tries to distinguish transmission failures caused by collision thereby deducing useless rate adjustment. Like our work, they both propose to perform rate adaptation in more sensible way. Besides, among various studies on MAC protocol design of MIMO PHY, MIMAC [20] is similar to our work. Yet their method is based on the SNR value thus suffering common problems of SNR-based schemes.

VI. CONCLUSION AND FUTURE WORK

In this paper we study the necessity of tuning more atomic rate parameter based on correlations extracted from incomplete observations. We set this discussion in the context of 802.11n, where more dimensions of rate dependent parameters are offered. The proposed Correlation based Rate Adaptation (CORA) can efficiently adjust transmission rate in multi-dimension scenario. Through evaluation in various scenarios, CORA demonstrates promising performance and achieves significant throughput gain.

Actually this work is just the first step to our vision of correlation based transmission scheme adaptation. It points out several directions for future work to pursue: the adjustments on other dimensions to help efficient rate adaptation, seeking correlation between tuning rate parameters and transmission result under much more diverse channel conditions. Moreover, we expect more work to identify other correlated reasons during rate adjustment.

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