Performance Analysis of IEEE 802.11 Rate Adaptation Algorithms Categorized Under Rate Controlling Parameters

Subhransu Das
Haldia Institute of Techology
Haldia, Purba Medinipur
Pin-721657, WB ,India
subhransu.cs@gmail.com

Subhabrata Barman
Haldia Institute of Techology
Haldia, Purba Medinipur
Pin-721657, WB ,India
subha.barman@gmail.com

Suman Bhunia
University of Nevada
Reno, USA
sumanbhunia@gmail.com

ABSTRACT

Signal to Noise Ratio(SNR) and Frame Loss Statistic are two basic information used by IEEE 802.11 Rate Adaptation Algorithms for controlling data rates to achieve optimal data transfer. Despite these common information, different Rate Adaptation Algorithms initiate their Rate Control Activities depending on several other parameters such as successful or fail frame count, calculated SNR, Bit Error Rate (BER), loss ratio threshold, statistical analysis etc. In these paper we classify Rate Adaptation Algorithms into three rate controlling categories, Namely- i.Packet Count Based, ii.Analysis and Calculation Based, iii.Statistical Measurement Based. We survey algorithms from different categories and prepare a summarized activity table for better assessment. We also present a simulation based performance analysis of different algorithms using Network Simulator 3 (ns-3). The survey and performance analysis led us to enlist some open issues on Rate Adaptation technique, in the concluding section.

Categories and Subject Descriptors

H.4 [**Infrastructure and Computation**]: Wireless Network

General Terms

Comparison, simulation , performance

Keywords

Wireless, IEEE 802.11, Rate Adaptation Algorithm,

1. INTRODUCTION

Due to ubiquitous deployment and adhoc nature, wireless devices often experience signal fading, shadowing, attenuation, noise etc [1]. Under unstable channel conditions sending data with high rate can not guarantee better throughput. Therefore it is necessary to estimate the appropriate data rate in order to cope with changing network conditions. Rate Adaptation is the technique by which network devices achieve the most suitable data rate under varying network conditions. IEEE 802.11 supports multi rate transmission by adapting several Rate Adaptation Algorithms [2].

Rate adaptation algorithms need some sort of information to infer rate control decision. Primitive algorithms use frame delivery report (Link Layer info) to determine the data rate [3]. They count the number of successfully delivered and failed frames. When this count reaches to a certain threshold [4], they alter the data rate. Hence we place these algorithms in **"Packet Count Based Rate Controlling Category"**. Although some algorithms of this category use RTS/CTS exchange to detect and avoid collision, but none of these algorithms have any awareness about stochastic channel condition.

On the other hand, a large number of rate adaptation algorithms like [5] [6] provide much flexible and robust rate controlling decisions due to their awareness of network parameters. They depend on Physical layer information like- Signal-to-Noise Ratio(SNR) or other calculated parameter like- Bit Error Rate(BER) [1] to estimate the link quality. This estimation makes their rate selection accurate and dynamic. We name this category as **"Analysis and Calculation Based Rate Controlling Category"**.

We call the final category **"Statistical Analysis based Rate Controlling Category"**, Madwifi Projects Minstrel is belonging in this category. Minstrel determines the transfer rate based on some Statistical Analysis(EWMA) [7]. It may seem that statistical analysis based Rate Controlling Category is a subset of the previous category, but there are several issues which makes these two categories fairly distinguishable. To ensure variability Minstrel sometimes chooses non optimal data rates intentionally. It also prepares a retry chain, based on forecast and analysis. These enhancements give further flexibility to this algorithm and make it distinguishable from other categories.

With intentions to study the impact of different rate control initiation progress strategies, we organize the paper as follows. Section 2 presents a survey on some selected rate adaptation algorithms belonging from different Rate Controlling categories, The survey work is followed by a summarized activity table (Table 3) for better assessment. Section 3 contains simulation based performance analysis. This survey work and simulation based analysis open some question and issues on rate adaptation algorithms. Those issues are listed in concluding future work section in Section 4

2. CATEGORY WISE SURVEY ON SELECTED ALGORITHMS

Rate adaptation algorithms have been studied for almost two decade. Several Rate adaptation algorithms introduced new ideas [1]. While many algorithms made enhancements of the previous ones

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[2]. Some algorithms even alter default IEEE 802.11 RTS, CTS, and DATA frames [8] while some of them introduced new MAC protocols [9] in order to make Rate Control activity optimal. In this section we survey selected Rate Adaptation Algorithms belonging from different categories.

2.1 Packet Count Based Rate Controlling Algorithms

These algorithms adapt the simple most decision making strategy for controlling the data rate. They count the number of successful ACK (SAckCount) and failed ACKs(FAckCount)in order to alter the data rate according Algorithm 1. Here $Th_s$and Th_F represent success threshold and fail threshold respectively. **Automatic**

Algorithm 1: Rate Selection in Packet Count Based Rate Controlling Algorithms

Input: SAckCount , FAckCount , Th_S , Th_F
Output: BitRate
if *(SAckCount == Th_S)* **then**
    Increment BiteRate;
else if *(FAckCount == Th_F)* **then**
    Switch to Lower BiteRate;

Rate Fallback (ARF) [4] is the first Rate Adaptation Technique ever published. ARF has only two data rate options (1 Mbps & 2 Mbps) as it was introduced in the era of IEEE 802.11 DSSS. ARF prescribes a lower data rate (1 Mbps) for out of ARF boundary and High Data Rate (2 Mbps) to communicate within arf boundary. The Rate adaptation technique of ARF is very simple. It start with 2 Mbps data rate and counts the number of good and failed ACKs. It decreases the data rate to 1 Mbps when 2 consecutive failed ACKs are received. During low data rate transmission whenever a successful ACK is received it starts a timer. When the timer matures or good ACK count reaches 10. It switches back to the higher data rates (2 Mbps).
The main problem of ARF is that it uses fixed threshold values(ie. 10 for increment and 2 for decrement). **Adaptive Auto Rate Fallback (AARF)** [2] solves this by making some improvements in ARF , In AARF the sender dynamically adjusts the thresholds. If the sender experiences failure at the very first packet sent at new (increased) rate, It immediately switches back to previous data rate and sets the Success Threshold [1]twice of the previous success threshold. Success threshold has a upper bound of 50. If AARF experiences two consecutive failures, It decreases Success Threshold to 10. AARF uses Binary Exponential Throughput (BEB) for threshold determination. The Adaptive Multi Rate Retry enhancement helps AARF to work smoothly on low latency systems. AARF is much flexible then ARF but it has no collision detection mechanism. **Collision Aware Rate Adaptation (CARA)** [10] has similar decision making strategy like ARF . Additionally It detects and avoids collision by using two methods, RTS probing and Clear Channel Assessment(CCA). In RTS Probing CARA initiates transmission without RTS/CTS exchange. If the transmission succeeds then Successful Transmission Counter is incremented by 1. When this counter reaches to its threshold(M_{Th}),data rate is incremented. The default value of M_{th} is 10. If the packet (sent at incremented data rate) fails to be delivered CARA uses RTS/CTS exchange in retransmission. After enabling RTS/CTS even if the transmission fails again the consecutive failure counter become 2. As consecutive packet failure threshold N_{Th} is 2, CARA switches back to its old data rate immediately. On the Other hand CCA is the " Collision prediction mechanism " of CARA. CCA is used when RTS/CTS remains off. It assumes that, the channel will remain clear and idle for SIFS time period after the transmission of a frame. If the channel is found busy or ACK is not received afterwards, CARA predicts Collision. But failed transmission counter is not incremented in such collision.

[1]Success Threshold is the number of packets to be sent successfully to qualify for next higher data rate.

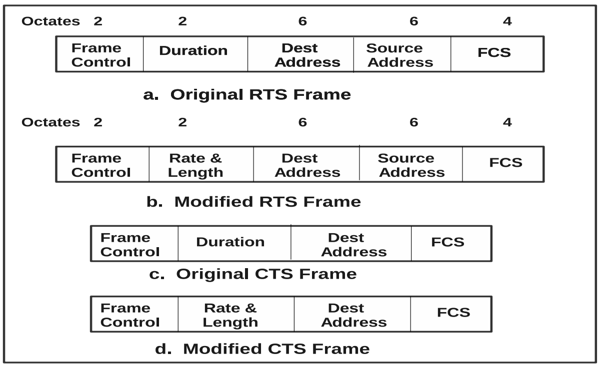

Figure 1: RBAR changes default IEEE 802.11 RTS/CTS frame

2.2 Analysis and Calculation Based Rate Controlling Algorithms

Packet Count based Rate controlling Algorithms can not cope with frequently changing channel conditions for two reasons. Firstly They are not concerned about varying network condition and secondly, They can change their rate only when their frame count reaches a threshold value. Algorithms which has awareness about network conditions can select and apply data rates easily. They undergo some analysis and calculation to determine suitable rate.
Receiver Bases Auto Rate Protocol (RBAR) [8] is the first receiver based Rate Adaptation Algorithm of this category . RBAR alters the existing IEEE 802.11 RTS/CTS frames and introduces some new MAC data frames. The *duration* filed of RTS/CTS frame is replaced by 16 bit Rate & Length frame *Rate*(4 bit) & *length*(12 bit)) frames (Shown in Figure 1). In RBAR data transfer is initiated with a RTS broadcast. The RTS receiver calculates the possible SNR for the received RTS packet based on some SNR threshold[2]. Then the receiver determines the suitable data rate for the upcoming data packet. It informs the sender about this determination using the modified CTS packet. Finally the data transfer is performed in the prescribed data rate. The Rate and Length field of modified RTS and CTS packet helps neighboring nodes to update Network Allocation Vector (NAV). RBAR determines the transfer rate inversely to the calculated SNR value. Packet transmission report does not effect this determination.
Despite all these enhancements RBAR has several drawbacks. It mandates the use of RTS/CTS packets even though the network has no Hidden or Exposed Terminals. The modification of RTS and CTS packet makes RBAR unsupportable for IEEE 802.11 standard.
Robust rate adaptation (RRAA) [5] is another algorithm belonging in this category. The basic Rate Control operation of RBAR depends on three parameters, Estimation Windows(E_W),Maximum tolerable Loss Threshold (M_{THL}) and Opportunistic Rate Increase Threshold (P_{ORI}). With every new rate RBAR, resets the Estimation Window (E_W). After a variable number of Packet transmission the Runtime Loss Ratio(P) is measured as (No of Lost

[2]SNR throld is derived using an *a priori* wireless channel model

Table 1: RRAA Rate Control Decision

Condition	Changes in rate
$P > P_{MTL}$	Decrease Current Rate
$P < P_{ORI}$	Increase Current Rate
$P_{ORI} < P < P_{MTL}$	Maintain Current Rate

Frame / Transmitted Frame). The transmitted frame and Lost frame count over the window includes the number of retries. Based on the threshold and Loss ratio the rate control decision is taken according to Table 1

Another algorithm called **Frequency Aware Rate Adaptation (FARA)** [9] uses Orthogonal Frequency Division Multiplexing or (OFDM) [11] to perform rate adaptation. OFDM divides the frequency-selective transmission channel into several sub-channels. FARA dynamically estimates the SNR for each sub-channel. In order to compute the SNR as accurate as possible, FARA calculates the SNR for i^{th} sub-band as SNR_i in terms of received power (S_i) and noise Power(N_i) according Equation 1.

$$SNR_i = \frac{S_i}{N_i} = \frac{S_i - N_I}{N_i}$$

So,

$$SNR_i = \frac{S_i}{N_i} - 1 \text{ where } N_0 = N_i, \forall i \tag{1}$$

FARA estimates SNR for every sub channel and determines separate bit rate for every OFDM sub band. Additionally it introduces a new frequency aware MAC protocol, which allows one transmitter to transmit data simultaneously to many receiver on different frequencies.

On Demand Feedback Rate Adaptation (OFRA) [6] is a receiver based rate adaptation algorithm, where the channel quality is estimated at the receiver based on SNR. This estimation helps the receiver to guess the state of the channel in future. The receiver selects the optimal bit rate from a lookup table. This lookup table was created previously, It contains a set of frame size and threshold values at which data rates will be changed. These information are fed back to the sender on demand. OFRA works even in ACK less traffics also. In case of ACK less traffics OFRA uses a specially designed feedback frame. Unlike other algorithms OFRA receiver does not always inform the sender about its estimation. Receiver feedback the essential information to the sender "on demand"[3]

So far we have discussed about algorithms that use either frame transmission report or SNR calculation to determine the optimal data rate. Now we focus on a **cross layer bit rate adaptation technique (SoftRate)**[1]. It calculates confidence information at physical layer and exports the information to higher layer via SoftPHY interface. At Higher layer Bit Rate Error(BER) is estimated using this Confidence value in a heuristic predictions methos. This estimated BER value is sent to the sender with the lowest available bit rate. Upon receiving the BER the sender computes optimal threshold α_i and β_i for each BER value R_i. This computation is used in SoftRate rate selection, We assume that b_i is the most recent interference free bit rate in Table 2 , where we show the rate selection procedure of SoftRate.

2.3 Statistical Analysis Based Rate Controlling Algorithms

MadWifi projects Minstrel Rate Adaptation Algorithm [7] performs a time bound Statistical Computation to infer and apply the suitable data rate. Minstrel is the only algorithm considered in this category. Minstrel Algorithm randomly selects 10% of total frames as Look Around (Test) frames. Statistical data collection is done using these frames. Exponential Weighted Moving Average(EWMA) [7] is a time bound statistical analysis performed 10 times within a second (100ms each) to estimate the link quality.
Minstrel apply different rate selection order for Look around and normal frames. Like - For a Look Around frame if the Randomly selected bit rate is less than the best throughput providing rate. The look around frame should be sent at the best throughput providing Link.Upon failure the retry will be on randomly selected rate. The complete retry chain is given in Table 3. Here best throughput denotes the data rate which gives the best throughput. Similarly best success probability denotes the data rate which has best success probability in frame delivery

[3]On demand means a dramatic change in channel condition which occurs suddenly.

Table 2: SoftRate Rate Control Decision

Condition	Set b_i
$b_i < \alpha_i$	Set Higher Bitrate
$b_i > \beta_i$	Set Lower Bitrate
$b_i \in (\alpha_i, \beta_i)$	Bitrate remains unchanged

Table 3: Retry chain in Minstrel

Attempt	Look Around Packet		Normal Packet
	Random <Best	Random >Best	
1	Best Throughput	Random Rate	Best Throughput
2	Random Rate	Best Throughput	Next Best Throughput
3	Best Success Probability	Best Success Probability	Best Success Probability
4	Lowest Base Rate	Lowest Base Rate	Lowest Base rate

To cope with frequent changes in channel, Minstrel implies higher priority to new result (result of the last 100ms EWMA) then the previous ones. EWMA determines the probability of success (P_{t+1}) for each data rate , at each timer interrupt using Eq 2.

$$P_{t+1} = \frac{(P_S(100 - \alpha) + \alpha \times P_t)}{100} \tag{2}$$

α is the EWMA parameter used to calculate the weight given to Ps for a new sampling period.
p_t is the success rate of packet at EWMA rate α.
P_S (probability of success in this time interval)= N_s/N_T.
N_s = Number of packet sent successfully at present rate.
N_T = Total number packet sent at present rate at present time interval. Expected Throughput(T) for each calculated P_{t+1} is measured using the ratio between number or bytes sent(B) and time(t). Throughput computation is shown in Eq 3.

$$T = P_{t+1} \times (B/t) \tag{3}$$

According to [7] EWMA allows minstrel to perform better then Constant Rate transmission in gradually improving channel conditions.

Table 5: Simulation Parameters for Single Pair Network

Parameters	Value
Energy Detection Threshold	-100 dbm
CcaMode1Threshold	-100 dbm
Interval between Packets	0.001 Sec
TxPowerStart	15.0 dbm
TxPowerEnd	15.0 dbm
RxGain	0 dB
Mobility Model for AccessPoint	Constant Position
Mobility Model for Stations	Constant Position
Mac Type	Infrastructure
Traffic	udp

Table 4: Summarized Activity Table For Rate Adaptation Algorithms

Algo	Probing Frame		Rate Control Activity			Info
	Starts With	On Failure	Rate Increment	Rate Decrement	Category	Info / (Layer)
ARF	High Data Rate	Use Lower Rate	10 consecutive Successful ACK	2 Consecutive Fail ACK	Packet Count Based	Loss Ratio (Link)
AARF	High Data Rate	Lower Data Rare	N Successful delivery 9 <N <49	Timeout Default Packet=15	Packet Count Based	Loss Ratio (Link)
CARA	Without RTS	Enable RTS/CTS	M_{TH}=10 Successive Success=10	N_{TH}=2 Consecutive Failure=2	Packet Count Based	Loss Ratio (Link)
RBAR	RTS	Transmit Again	Calculated SNR ,on RTS from Sender	Calculated SNR, on RTS from Sender	Analysis & Calculation	SNR (PHY)
RRAA	High Data Rate	Low Data Rate	P <P_{ORI} (P is Loss Ratio)	P >M_{THL}	Analysis & Calculation	Loss Ratio (Link)
FARA	Lowest bit Rate	Transmit Again	Calculated SNR at Receiver	Calculated SNR at Receiver	Analysis & Calculation	Loss Ratio (Link)
OFRA	Lowest base Rate	Transmit Again	Feedback from Receiver	Feedback from Receiver	Analysis & Calculation	Loss Ratio (Link)
SOFTRATE	High Rate	Transmit Again	Calculate BER	Calculate BER	Analysis & Calculation	BER (Cross)
MINSTREL	From Retry Chain	From Retry Chain	EWMA	EWMA	Statistical Measurement	Loss Ratio, (Link)

3. PERFORMANCE EVALUATION

In order to evaluate the performance of different categories we select AARF and CARA from Packet Count Based rate controlling category , RBAR(IDEAL) from Analysis & Calculation based rate controlling category , and Minstrel from Statistical Analysis based rate controlling category. We used Network Simulator-3(ns-3) [12] as our simulation tool. We run our simulations under Single Pair Topology , 4-Node Topology. Similar topologies were used in performance evaluation of [6]. Some main simulation parameters are listed in Table 5.

3.1 Single Pair Topology

Single pair topology means a network which contains only sender and one receiver as shown in Figure 2. The first set of experiments determine the throughput of selected algorithms with increasing distance, under different loss models. NS-3 loss models are divided into three basic categories [13]. Path loss model determines the signal strength (or the reduction of signal strength) at a single or a set of receivers, for any packet sent from a single transmitter. Our choice of loss models from different categories are listed in Table 6

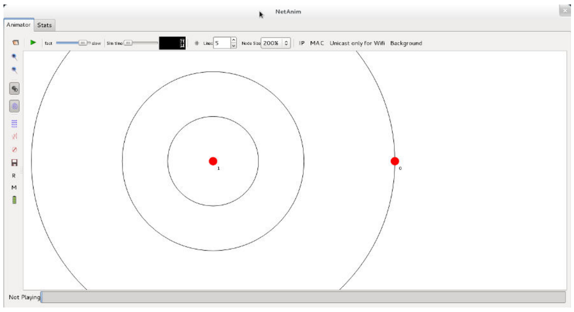

Figure 2: Single Pair Topology (NetAnim View)

Table 6: Path Loss Model Selection

Category	Selected Model
Abstract Propagation Loss Model	Random Propagation Loss
Deterministic Path Loss Model	Log Distance Path Loss Model
Stochastic Fading Model	Nakagami Model

• **Random Propagation Loss Model** [13]- This model follows a Random distribution to determine loss. The default loss constant of this model is 1 dB.

• **Log Distance Path Loss Model** [14]- This model assumes an exponential path loss (PL) over the distance (d) between sender and receiver. Equation 4 represents the Path Loss in dB. Here s is the shadow fading component and γ is the path loss exponent.

$$PL = A + \gamma \log_{10}(\frac{d}{d_0}) + s \qquad (4)$$

This model works properly beyond a close distance d_0. d is the distance such that $d_0 < d$. A is the free path propagation loss as shown in Eq 5 as λ is the wavelength.

$$A = 20 \log_{10}(\frac{4\pi d}{\lambda}) \qquad (5)$$

• **Nakagami Model** [15] -This model is similar to the Rayleigh model, but it describes different fading equations for short-distance and long-distance transmissions.

The result of our first experiment is presented in Figure 3. We examine the throughput of different algorithms with increasing communication distance under Random Propagation Loss, We noticed Ideal performs significantly better then other three. Ideal uses per frame SNR estimation to make frequent rate adaptation decisions. Whenever Ideal understands that the communication channel is clear and ideal,it continues with high data rate.

In our second experiment (Figure 4), we use Log distance path loss model, with Exponent (λ)=3 according the simulation environment of [6]. In log distance path loss model [14] first reference loss is calculated at Reference distance. Here we set reference distance =50m. The continuous degradation of throughput for all algorithms, prior reference distance (50m) is due to increasing distance. But whenever the experiment is performed beyond the reference distance the loss model causes massive fall in the throughput. Ideal again performs better in this experiment also. The Reference

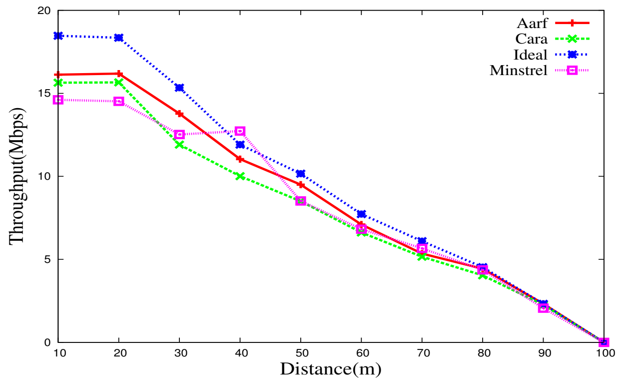

Figure 3: Throughput with Increasing Distance under Random Propagation Loss Model

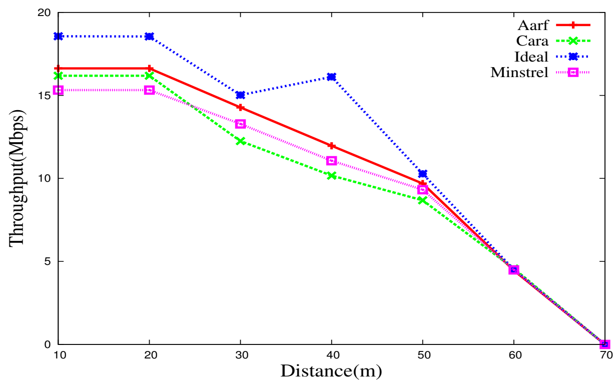

Figure 4: Throughput with Increasing Distance Under Log Distance Path Loss Model

loss used here was 1.5 db. The simulation with Nakagami Model is presented in Figure 5. We set the beginning of the second distance field (Distance1) and third distance field (Distance2) as 50m and 75m accordingly. In this experiment Aarf, Cara, and Minstrel performs better then Ideal, A similar degradation in throughput for Aarf, Cara and Minstrel at the beginning of first and third distance field, was according to our expectation. But we noticed a sudden fall in Ideals throughput between 20m and 30m, which could not be recovered afterwards.

In another experiment we increased the time interval between consecutive packets .The result was according to our expectations. If we gradually increase time interval between packets the data transfer capability of the network suffers unnecessary delay. The degradation of throughput due to this delay is shown in Fig 6. In this experiment Ideal performed better than others where minstrel provides lowest throughput all along.

3.2 4-Node Topology

So far we have considered only single hop networks which does not contain any hidden or exposed terminal. Now we present 4-node topology, where the access point is placed in center surrounded by 4 stations as shown in Figure 7. Our first experiment is to determine throughput with increasing distance. In this experiment Figure 8the Access point remains static along with 3 other stations.We measure the throughput of the station which keeps changing distance from the access point . Here Stations are placed in such a way that they form hidden terminal. CARA uses RTS /CTS mechanism

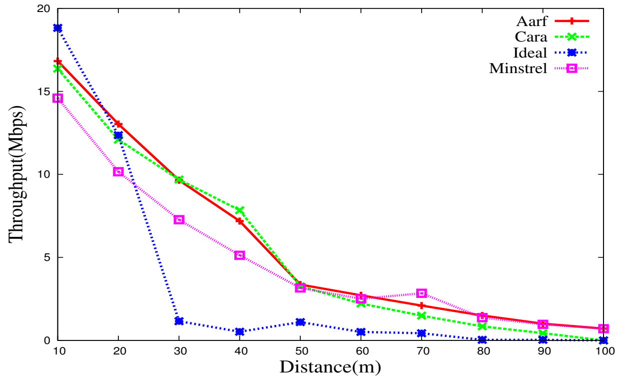

Figure 5: Throughput with Increasing Distance Under Nakagami Model

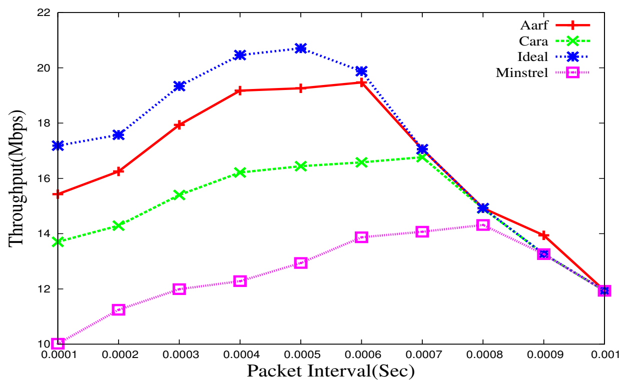

Figure 6: Throughput Against Increasing Packet Interval

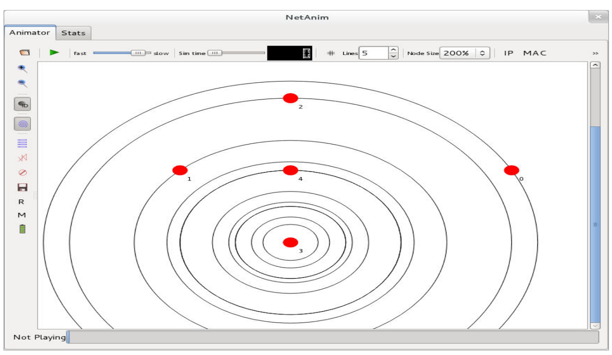

Figure 7: 4-Node Technology Network Animator View

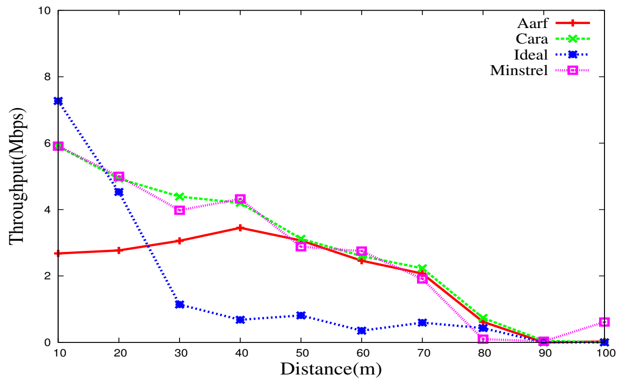

Figure 8: Throughput with Increasing Distance between 2 selected nodes in 4-Node topology

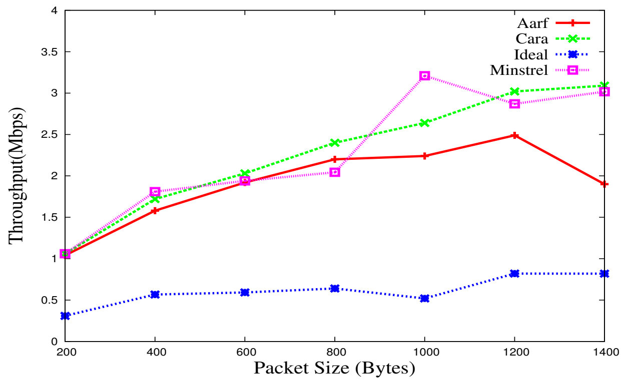

Figure 9: Throughput with Increasing Packet Size in 4-Node topology

hence it performs very well under this type of network. Minstrel has a prediction mechanism that allows it to continue with high data rates, even under hidden and exposed terminal conditions.

Our final experiment(Figure 9) is conducted by increasing packet length 200 bytes in each test case. The distance between our target sender and receiver was 50 m, and the value of MaxPacket attribute was 1000. In Figure 8 we noticed a low throughput of Ideal algorithm beyond 40 m communication distance. Ideal performs poorly in this experiment also, because of the same reason. Minstrel's over all performance was better than others. Minstrel provided the highest throughput (3.2 Mbps) when the packet length was 1000 bytes . Aarf and Cara's performance was almost similar, as they provided similar throughput in each test case.

Throughout all these experiments we noticed a similar performance of Aarf and Cara. This is due to their rate control strategies, As we said earlier, that Packet count based rate controlling algorithms change their rates slowly because of their bounded threshold values. On the other hand Analysis and Calculation based Rate controlling algorithms change their rates frequently. Some algorithms change their rate after each frame while some algorithms change their rate "On demand". Statistical Measurement based rate controlling algorithms depend on statistical analysis which helps them to cope up with both frequently changing and slowly changing channel conditions.

4. CONCLUSION & FUTURE WORK

Rate Adaptation techniques have been studied since last two decade. In this paper we survey some classical and modern algorithms together. Our expectation from these from theses algorithms have gone far beyond mare rate control task. We enlist some proposed future work on rate adaptation algorithms.

- End to end throughput of a multi hop network must be less then of equal to the bottle neck links throughput. Hence any rate adaptation algorithm which identifies and improves the bottle neck links performance will enhance the performance of the network remarkably.
- In this paper we tried to simulate different Rate Adaptation Algorithms under almost similar environment as prescribed in [3],yet there are many other parameters on which these algorithms can be examined.
- A secured rate control algorithm which has ability to detect security threats like "Worm Hole Attack" [16] will make the network secured and trust worthy.

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