Comparative Analysis of Transmitter and Receiver Based Rate Adaptation Algorithms for IEEE 802.11 Wireless Ad-hoc Networks

Satish Ket, R. N. Awale

1 Veermata Jijabai Technological Institute, Mumbai, India
satishket@gmail.com

2 Veermata Jijabai Technological Institute, Mumbai, India
rnawale@vjti.org.in

Abstract—The capacity of wireless ad-hoc network is enhanced with rate adaptive algorithms. For rate adaptation, feedback of channel condition is essential. One of the ways to achieve this is the Cross-Layer Design (CLD) approach. The key idea is to exploit the channel condition by optimal selection of data rate. The data rate can be decided at transmitter or receiver to achieve the goal of capacity enhancement. For comparative analysis two proposals for single hop networks namely Transmitter Based Capacity Enhancement Algorithm for Wireless Ad-hoc Networks using Cross-Layer Design Approach (TCECLD) [1] and Receiver Based Capacity Enhancement Algorithm for Wireless Ad-hoc Networks using Cross-Layer Design Approach (RCECLD) [2] are considered. The analytical and simulation study is performed to characterize the gains in throughput as a function of the channel conditions. Finally an extensive set of simulations are performed on IEEE 802.11b media access protocols to observe the comparative system throughput.

Index Terms—TCECLD, RCECLD, ARF, Wireless Ad-hoc Networks

I. INTRODUCTION

Rate adaptive transmission schemes in Wireless Ad-hoc Networks use bandwidth efficient coded modulation techniques to increase throughput over the channels with variable Signal-to-Interference and Noise (SINR) ratio due to fading and interference from other transmissions [3]. As the multi-rate schemes exist in the IEEE 802.11 (physical layer, adaptive MAC (Medium Access Control) mechanisms are required to exploit this capability. Receiver Based Auto Rate (RBAR) [4] and Opportunistic Auto Rate (OAR) [5] are two prominent examples of receiver-based MACs. In RBAR, every RTS-CTS-DATA-ACK (Ready to Send-Clear to Send-DATA-Acknowledgement) handshaking mechanism (referred as a cycle) is rate adaptive. In OAR, throughput improvement is possible if the sender adapts the data rate during a cycle.

In this paper, the comparative analysis of Transmitter-based and Receiver-based algorithms for multi-rate IEEE 802.11 in Wireless Ad-hoc Networks is presented. The algorithms considered for comparison are TCECLD [1] and RCECLD [2]. The key idea is to exploit high quality channels when they occur, via transmission with higher rates by adapting the data rate dynamically. The SNR (Signal-to-Noise Ratio) values calculated by Physical layer are exported to MAC layer via the Cross-Layer Design (CLD) interface [6] to estimate the prevailing channel state. In RCECLD the receiver decides the transmission data rate whereas in TCECLD it is decided by the transmitter.

For analysis and comparison of the performances, same analytical model [7] is adopted and simulation study is performed. Only single hop Ad-hoc network scenarios are considered. Example findings are as follows. (1) The load carrying capacity of the Ad-hoc network is almost similar in both. (2) TCECLD performs little better if Line-of-Sight is improved. (3) There is almost no effect of initial contention window size in case of RCECLD. (4) For small size packets RCECLD performs better.

The rest of the paper is organized as follows. Related work is discussed in Section II. Channel model and adopted Analytical model are presented in Sections III and IV respectively. Section V presents the CLD proposal and both algorithms. Simulation results and performance analysis are discussed in Section VI, and finally the paper concludes in Section VII.

II. RELATED WORK

In [4], after the receiver specifies its desired transmission rate and feeds back to the transmitter as part of a modified RTS/CTS exchange; the transmitter adapts its transmission rate accordingly. In few of the approaches [8,9], a transmitter station makes the rate adaptation decision solely based on its local ACK information. The transmitter assumes a successful delivery if an ACK frame is received. On the other hand, if an ACK frame is received in error or no ACK frame is received at all, the transmitter assumes failure. In [5] the high quality channels are exploited by sending multiple back-to-back packets. In [9] the data rate is decided based on local channel estimation made during ACK frame receptions. In such cases a very good performance is observed, but with extra implementation efforts. In [8,10,11], the local ACK is used and very simple to implement. It has been pointed out in [11] the issue of when to increase and when to decrease the transmission rate. The effectiveness of a rate adaptation depends greatly on how fast it may respond to the wireless channel variation. In [10,11] this issue is addressed.
In TCECLD [1] the data rate decided by the transmitter is used for next transmission/retransmission attempt. Whereas in RCECLD [2] data rate is decided during the cycle, just before transmission of data packet by the receiver.

III. CHANNEL MODEL

The transmitted radio frequency signal at the receiver is a superimposition of different reflections of the same, received with varying delays and attenuations. Coherent addition of the copies result in large received signal powers and cancellation eventually leads to zero received signal power. An accurate and widely utilized model which considers time varying multi-path propagation [12] is

$$y(t) = \sum_{i=1}^{\rho(t)} A_i(t) x(t - \tau_i(t)) + z(t)$$  \hspace{1cm} (1)

where \(x(t)\) and \(y(t)\) are transmitted and received signals. The time-varying multi-path propagation is captured by the attenuation of each path \(A_i(t)\), the time delays \(\tau_i(t)\) and the number of paths \(\rho(t)\). The additive term \(z(t)\) is the background noise and represents the thermal noise of the receiver.

The following model is used for the received SNR for transmitter power \(P\) at packet transmission time \(t_p\)

$$SNR(t_p) = Pd(t_p) - \beta \frac{\rho(t_p)}{\sigma^2}$$  \hspace{1cm} (2)

where \(d(t_p)\) is the distance between the sender and the receiver at time \(t_p\), \(\beta\) is the path loss exponent, \(\rho(t_p)\) is the average channel gain for the packet at time \(t_p\), and \(\sigma\) variance of the background noise \(z(t)\).

The short time-scale variation in the received SNR is captured by \(\rho(t_p)\), known as the fast fading component of the fading process. The time-variation of \(\rho(t_p)\) is modeled by a probability distribution and its rate of change [12]. An accurate and commonly used distribution for \(\rho(t)\) is the Ricean distribution,

$$p(\rho) = \frac{\rho}{\sigma^2} e^{-\frac{\rho^2}{2\sigma^2}} I_0(2 K \rho)$$  \hspace{1cm} (3)

where \(K\) is the distribution parameter representing the strength of the line of sight. \(I_0(\cdot)\) is the modified Bessel function. For \(K = 0\), the Ricean distribution reduces to the Rayleigh, with no line-of-sight.

IV. ANALYTICAL MODEL

For the analytical model for saturation throughput is adopted from [7]. In the analysis, it is assumed that a fixed number of stations, each always having a packet available for transmission.

The normalized system throughput \(S\) is represented as;

$$S = \frac{E[payload \_ information \_ transmitted \_ in \_ a \_ slot \_ time]}{E[length \_ of \_ a \_ slot \_ time]}$$

Let \(E[P]\) be the average packet payload size, the average payload information successfully transmitted in a slot time is \(P \cdot E[P]\), since a successful transmission occurs in a slot time with probability \(P\), \(P_s\) and with probability \(P_s(1-P_s)\) it contains a collision. Hence \(S\) becomes;

$$S = \frac{P_s \cdot E[P]}{(1-P_s) \sigma + P_s \cdot P_T s + P_s (1-P_s) t_c}$$  \hspace{1cm} (4)

where,

$$P_s = 1 - (1-\tau)^n, \quad P_c = \frac{n \tau (1-\tau)^{n-1}}{P_s}$$

$$T_c = RTS + CTS + H + E(P) + ACK + DIFS + 3SIFS + 3\delta$$

$$T_s = RTS + SIFS + \delta$$

The probability \(\tau\) that a station transmits in a randomly chosen slot time can be found by solving the two equations;

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-2p)^n}$$  \hspace{1cm} (5)

$$p = 1 - (1-\tau)^{1-n}$$  \hspace{1cm} (6)

where \(W = CW_{min}\), \(CW_{max} = 2^n \cdot CW_{min}\). \(p\) is the probability that each packet collides at each transmission attempt, and regardless of the number of retransmission attempts, \(m\) is the back-off stage and \(n\) is the total contending nodes.

V. THE CLD PROPOSAL

A generic model for cross-layer interactions is proposed as shown in Fig. 1 [6,14]. Interaction block keeps a track of the instantaneous value of SNR, which is grabbed from received signal in the Physical layer. This value is accessible by all the layers as and when required for specific decision making. At present it is restricted up to MAC layer only. However, this can be extended to upper layers. In 802.11 the data rate of transmission is decided at MAC layer and instantaneous SNR value reflects the channel state in time varying environment. Exploitation of channel condition to increase the network capacity is the aim, which is achieved by this additional CLD interaction without changing the architecture of the Protocol Stack [13]. The optimization is achieved in the system by adjusting the data rate using threshold-based technique [5]. In a threshold-based scheme, the rate is chosen by comparing the received SNR value of the signal against an array of thresholds representing performance limits of the available modulation techniques. The modulation technique with the highest data rate for the estimated SNR value is chosen.

The selected modulation technique results in the feasible data rate to be used in subsequent transmissions. Let \(P_1\), \(P_2\), \(P_3\), ..., \(P_{max}\) are SNR thresholds for different suitable
rate limits. For example, \( p_r \) indicates that if the received SNR level is below \( p_r \), rate \( r \) is feasible. In case the received SNR level is above \( p_r \), but below \( p_s \), rate \( r \) is feasible and so on. A region surrounded by two subsequent SNR thresholds, which is suitable for a particular rate.

To be specific with 802.11b, given the channel and SNR model with Equations (1) and (2); its distribution of Equation (3), the distribution of available data rates can be calculated as follows. Let \( SNR_r, SNR_{\sigma}, SNR_{\delta 5}, \) and \( SNR_{\mu} \) denote the minimum required SNR to support the 802.11b standard transmission data rates 1, 2, 5.5 and 11 Mbps respectively. Then the probability that rate \( r \) is feasible is calculated as follows:

\[
\begin{align*}
  p(r = 0) &= p(SNR < SNR_{\mu}) \\
  p(r = 1) &= p(SNR_1 \leq SNR < SNR_2) \\
  p(r = 2) &= p(SNR_2 \leq SNR < SNR_{\delta 5}) \\
  p(r = 5.5) &= p(SNR_{\delta 5} \leq SNR < SNR_{11}) \\
  p(r = 11) &= p(SNR_{11} < SNR)
\end{align*}
\]

Where, \( p(SNR) = \left( \frac{\rho \sigma^2 d(t_p)}{P} \right)^\beta \) is the distribution of the SNR, \( SNR(t_p) \).

For fully connected topologies let \( p(r) \) is the probability distribution of the instantaneous transmission rate \( r \) obtained when a node gains access to the channel. Further assuming that all sender-receiver pairs have statistically identical and independent channels, denote the average transmission rate of any node by \([5]\):

\[
r_{av} = \sum_i r_i p(r_i)
\]

To find the value of \( r_{av} \) we did certain experimentations and assumed the values as 3 Mbps and 2 Mbps for stationary and time varying channels respectively to find the saturated throughput as discussed in [7].

### A. TCECLD Algorithm

In a fully connected ad-hoc topology in which all nodes are in radio range of each other, base rate IEEE 802.11 indeed provides long-term fairness. If multi-rate is adopted, still identical long-term time shares can be obtained but at different throughputs. For example, suppose there are two flows, one with a low signal strength such that it can only transmit at the base rate of 2 Mbps and the other with a high signal strength so that it can transmit at rate of 11 Mbps. Thus, in contrast to the focus on throughput fairness of which attempt to normalize flow throughputs, temporal fairness is more suitable for multi-rate networks as normalizing flow throughputs would cancel the throughput gains available due to a multi-rate physical layer.

In TCECLD the parameter tuned is data rate. As shown in Fig. 1, additional interface is created between Physical and MAC layer. Channel condition is estimated by recent SNR value of received signal. As seen from the algorithm [Fig. 2], the count \( m \) is incremented for every successful transmission. If \( m \) \( < m_{\sigma} \), the higher rate \( r \) is selected according to the current SNR value for next transmission attempt, resetting \( n \). The count \( n \) is incremented for every unsuccessful transmission. If \( n \) \( < n_{\sigma} \), the next lower rate \( r \) is selected for next retransmission attempt resetting \( m \). Note that data rate selection is done before the start of RTS/CTS exchange and used for next attempt of transmission/retransmission. The channel estimation is done at transmitter and no modification is required in the any of the original frame structure of 802.11 MAC. Table I gives the list of notations used in the algorithm.

<table>
<thead>
<tr>
<th>Notations</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m )</td>
<td>Consecutive success count</td>
</tr>
<tr>
<td>( n )</td>
<td>Consecutive failure count</td>
</tr>
<tr>
<td>( m_{\sigma} )</td>
<td>Successive failure threshold = 2</td>
</tr>
<tr>
<td>( n_{\sigma} )</td>
<td>Successive failure threshold = 2</td>
</tr>
<tr>
<td>( r )</td>
<td>Data rate i, from 802.11b data rate set, ( {1, 2, 5.5, 11 \text{ Mbps}} )</td>
</tr>
<tr>
<td>( SNR_r )</td>
<td>SNR value at instant i</td>
</tr>
</tbody>
</table>

### B. RCECLD Algorithm

In RCECLD receiver estimates the channel condition by recent SNR value of received RTS frame. According to the SNR thresholds decided in the algorithm for 802.11b data rates, transmission data rate is set to the additional field created in the CTS frame. The transmitter concludes that the RTS frame transmission is successful and channel access is reserved after receiving this CTS frame. Transmitter then decodes this CTS frame and transmits the data frame with the rate dictated by the receiver.

In RCECLD every time RTS frame is available for SNR calculation, in turn channel condition estimation. Hence, if channel condition is good, higher data rate is selected and if it is bad, lower data rate is selected. Note that data rate selection is done during the RTS/CTS exchange and used for
current data frame transmission/retransmission. The channel estimation is done at the receiver and piggybacked to the transmitter with CTS. So modification is required in the CTS frame structure. As the data rate is decided for every packet the channel estimation is accurate giving better performance. The algorithm is given in Fig. 3. Table II gives the list of notations used in the algorithm.

VI. PERFORMANCE EVALUATION

In this section, the effectiveness is evaluated by using Qualnet 4.5 [15] after enhancing the original 802.11 DCF module to support the 802.11b PHY and the time varying wireless channel model.

Mainly 802.11b Ad-hoc networks are simulated. Equations (1) and (2) are used for the channel and SNR estimations respectively. Each station transmits with 15 dBm power, and all the stations are static and within the range of each other. For the simulations 20 node topology is used unless stated. Two Ray Path-loss model [9] is used to simulate the environments. Moreover, the multi-path topology is considered with which the channel condition between the transmitter and receiver varies over the time. The Ricean fading model [12] is used to simulate the time varying wireless channel conditions. The Ricean distribution is given by (3) as addressed in Section III. The Ricean factor $K$ is set to 0 unless stated. Different SNR thresholds are set for different data rates. Each node transmits in a greedy mode, i.e. its data queue is never empty and all the data frames are transmitted without fragmentation. The data payload length is 1024 bytes unless specified otherwise. Simulations under various network topologies and network size are conducted and results are compared with ARF. Table III gives the system parameters.

A. Ad-hoc Topology with Varying Number of Contending Stations and Time Varying Channel

Fully connected Ad-hoc networks with varying number of contending nodes are considered in order to study the system performance. In this scenario, various number of contending nodes are evenly spaced in a terrain of 200mX200m making sure that all are static and within each other’s range. The wireless channel model is time varying with Ricean fading model. The nodes are transmitting the data packets at 2 Mbps. Simulation results are plotted in Fig. 4. Both the algorithms give similar performance and the throughput is very close to Analytical throughput calculated by (4), (5) and (6) up to the network size of 8 contending nodes. Since $m_{th}$ and $n_{th}$ are set to 2 in TCECLD, data rate is decided after every 2 successful/unsuccessful packet transmission, the throughput is little lower, whereas, in RCECLD it is decided at each packet transmission giving accurate channel estimation resulting better performance than TCECLD. In case of ARF, the data rate is decided after 10 successful or 2 unsuccessful packet transmissions resulting inferior performance.

**TABLE II**

<table>
<thead>
<tr>
<th>Notations</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_i$</td>
<td>Data rate $i$, from 802.11b data rate set, {1,2,5,5,11}</td>
</tr>
<tr>
<td>$cilcts$</td>
<td>Data rate set by Receiver in CTS</td>
</tr>
<tr>
<td>$SNR_i$</td>
<td>SNR value at instant $i$</td>
</tr>
</tbody>
</table>
TABLE III
SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Payload</td>
<td>8154 bits</td>
</tr>
<tr>
<td>MAC Header</td>
<td>272 bits</td>
</tr>
<tr>
<td>PHY Header</td>
<td>192 bits</td>
</tr>
<tr>
<td>RTS</td>
<td>160 bits - PHY Header</td>
</tr>
<tr>
<td>CTS</td>
<td>144 bits - PHY Header</td>
</tr>
<tr>
<td>ACK</td>
<td>112 bits - PHY Header</td>
</tr>
<tr>
<td>Packet Arrival Rate</td>
<td>2 Mbps</td>
</tr>
<tr>
<td>Propagation Delay</td>
<td>1 µs</td>
</tr>
<tr>
<td>Slot Time</td>
<td>20 µs</td>
</tr>
<tr>
<td>SIFS</td>
<td>10 µs</td>
</tr>
<tr>
<td>DIFS</td>
<td>30 µs</td>
</tr>
</tbody>
</table>

B. Effect of Contention Window Size (\( CW_{\min} \))

It is clear from (5) and (6) that the throughput \( S \) in turn depends on the value of \( W \) and \( m \). But the arrangement of (5) is such that there is very small gradual increase of \( S \) initially, attains maximum value at \( W = 64 \) and then gradual decrease which is observed from Fig. 5. RCECLD performs in the similar manner giving higher \( S \) because data packet transmission rate is decided for each packet during the cycle with precise channel condition estimation for current transmission. The contention process takes place before the start of the cycle and due correct estimation of data rate there are fewer chances of channel errors and packet loss. Whereas in TCECLD the data rate estimation is after 2 successful/ unsuccessful transmissions and it is used for next attempt. If the initial window size is small the probability of getting a transmission slot during contention process for each node is less and if the transmission is unsuccessful, even after doubling it, due to incorrect channel estimation, in turn data rate selection there are more chances of unsuccessful transmission again. As a cumulative effect bandwidth is wasted resulting poor performance. On the hand if the initial window size is large the probability of getting a transmission slot during contention process for each node is more which reduces the probability of further cumulative effect resulting better performance as seen.

C. Effect of Packet Size

The denominator of (4) contains idle time which includes contention as well, successful transmission time and collision time. Successful transmission time includes constant overhead of RTS/CTS exchange irrespective of packet size. For smaller packets this overhead time is considerable. So as seen from Fig. 6 both the algorithms performs poorly for smaller packet size. RCECLD performs little better because of better channel estimation and data rate selection for every packet during the cycle as discussed earlier.

D. Effect of Line of Sight Component \( K \)

The effect of the Ricean parameter \( K \) is explored here. For \( K = 0 \), the channel has no line-of-sight component such that only reflected signals are received and hence, overall channel quality is poor. With increasing \( K \), the line-of-sight component is stronger such that the overall channel SNR increases as described by (3), and a higher transmission rate is feasible more often.

Fig. 7 depicts the aggregate throughput as a function of the Ricean parameter \( K \) for a fully connected 20 node random topology. Observe that both TCECLD and RCECLD exploit the improved channel conditions represented with increasing \( K \) and obtain correspondingly greater system-wide throughputs. Moreover, TCECLD performs little better for higher values of \( K \). For worst channel conditions RCECLD reacts very fast by giving correct channel estimations, in turn better performance. On the other hand this over
processing acts negatively for very good channel conditions. As seen from Fig. 7 the performance of RCECLD is little inferior at higher values of $K$ but it is far better than ARF.

Figure 7: Aggregate Throughput as a Function of $K$

VII. CONCLUSION

In this paper, comparative analysis of TCECLD and RCECLD is presented for single-hop wireless ad-hoc networks. The key idea in both is that estimate the channel condition and accordingly selects the data rate for transmission. The parameter transmission data rate is tuned to exploit the channel conditions. It is observed that the capacity is increased by 2 to 2.5 times than ARF. In RCECLD the transmission data rate is decided during the cycle for every packet and used for current transmission but in TCECLD it is decided after every 2 transmissions/retransmissions for next attempt. RCECLD performs better for smaller initial contention window size and smaller sized data packets. For very good channel conditions and line-of-sight TCECLD performs little better. CTS frame is required to be modified in RCECLD, whereas in TCECLD no frame is modified.

It is concluded that for single hop 802.11 wireless ad-hoc networks with time varying channel conditions RCECLD performs better.

REFERENCES