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Performance Investigation of Capacity Enhancement Algorithm for IEEE 802.11 Wireless Ad-hoc Networks

Satish Ket
Research Scholar
Veermata Jijabai Tech.
Institute, Mumbai

R. N. Awale
Professor, Elect. Dept.
Veermata Jijabai Tech.
Institute, Mumbai

ABSTRACT

The performance of IEEE 802.11 with different network densities and protocol configurations is of interest, particularly in distributed coordination function (DCF) mode. A mathematical model for single hop network IEEE 802.11 protocol was introduced by Bianchi [1] to analytically derive the saturated throughput. The ultimate goal is to enhance the capacity of Ad-hoc network closer to the analytical values of this model. As an attempt, the Receiver Based Capacity Enhancement Algorithm using Cross-Layer Design Approach (RCECLD) is proposed which dynamically adapts the data rate. It uses Signal-to-Noise Ratio (SNR) values calculated by Physical layer and exported to Medium Access Control (MAC) layer via the cross-layer interface to estimate the prevailing channel state. In RCECLD the receiver decides the transmission data rate by calculating the SNR value of received RTS (Ready-to-Send), which is in turn an estimate of the prevailing channel state, and piggybacking it through CTS (Clear-to-Send) to the transmitter. Accordingly, transmitter transmits the data frame with adopted data rate.

The capacity of the Ad-hoc network is enhanced with RCECLD. It is investigated through an extensive set of single hop and multi-hop simulations. The results indicate that the enhancement is very close to analytical values for smaller network size and it is about 2.5 times more than Auto-Rate Fallback (ARF) [2], in-spite of fading and mobility effects in case of single hop, whereas in case of multi-hop with a chain of nodes it is almost doubled.

General Terms

Algorithms, Performance, Design.

Keywords

RCECLD, ARF, Ad-hoc Networks, Multi-hop Networks.

1. INTRODUCTION

The IEEE 802.11 standards [3] are widely used for Wireless LAN (WLAN). The 802.11 PHYs (physical layers) provide multiple transmission rates by employing different modulation and channel coding schemes. For example, the original 802.11 standard [3] specifies two low-speed PHYs operating at 1 and 2 Mbps, and two high-speed PHYs were additionally defined as supplements to the original standard: the 802.11b PHY [4] supporting four PHY rates up to 11 Mbps at the 2.4 GHz band.

Rate adaptive transmission schemes 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 [5]. At each SINR point, the coded modulation scheme that gives the highest throughput with minimal bit error rate (i.e. below a certain bit error rate threshold) is selected. Following this principle, standards such as IEEE 802.11 medium access protocols have introduced the physical layer multi-rate capability. As the multi-rate schemes exist in the physical layer, adaptive MAC mechanisms are required to exploit this capability. Sender-based rate adaptation schemes (e.g. [2]) and Receiver-based adaptation schemes (e.g. [6]) enable multi-rate features into MAC. Generally receiver based rate adaptive MAC performs better than the sender-based rate adaptive MACs [6]. In receiver-based rate adaptive MACs, the channel quality measurement is done at the receiver during the RTS/CTS exchange. Hence, the channel estimates in these MACs are close to the channel condition during the actual data transmission time opposed to the sender-based approaches. Receiver Based Auto Rate (RBAR) [6] and Opportunistic Auto Rate (OAR) [7] are two prominent examples of receiver-based MACs. In RBAR, every RTS-CTS-DATA-ACK handshaking mechanism (it is defined as a cycle) is rate adaptive. In other words, all data packets within a cycle are transmitted with the optimal data rate selected by the receiver, based on the received RTS power within that cycle. In OAR, on the other hand, a number of packets are transmitted within a cycle (i.e. after a single RTS-CTS exchange) based on the channel coherence interval and the feasible data rate selected in the similar way as RBAR protocol. However, it is possible that the channel condition will significantly change during the multi-packet transmission sequences of OAR. If the transmission at the original rate is maintained (selected by RTS-CTS exchange), error rates may become large if the channel quality worsens leading to packet losses. Conversely, the rate selection becomes sub-optimal if the channel quality is further improved during the multiple data transmissions. Moreover, if the perfect channel condition is known, each transmitter-receiver pair can fully utilize its non-fade duration using a rate-adaptive transmission, if a common probability of good channel persists in the network.

In ad-hoc routing it is required that nodes cooperate to forward each others' packets through the network, which means that the throughput available to each node is limited not only by the raw channel capacity, but also by the forwarding load imposed by distant nodes. It is required to exploit the channel condition and forward the data packets at possible higher rates to enhance the usefulness of ad-hoc routing.

As in multi-hop networks, radios that are sufficiently distant can transmit concurrently; the total amount of data that can be simultaneously transmitted for one hop increases linearly with the total area of the ad-hoc network. Gupta and Kumar [8] estimates the per node capacity to be expected in an ad-hoc network. If node density is constant, this means that the total one-hop capacity is $O(n)$, where n is the total number of nodes. However, as the network grows larger, the number of hops between each source and destination may also grow larger, depending on communication patterns. One might expect the average path length to grow with the spatial diameter of the network, or equivalently the square root of the area, or $O\left(\sqrt{n}\right)$. With this assumption, the total end-to-end capacity is roughly $O\left(\frac{n}{\sqrt{n}}\right)$, and the end-to-end throughput available to each node is $O\left(\frac{1}{\sqrt{n}}\right)$.

In this paper, an enhanced protocol for multi-rate IEEE 802.11 in Wireless Ad-hoc Networks is proposed. The key idea is to exploit high quality channels when they occur, via transmission with higher rates. As an attempt, the algorithm RCECLD is proposed which adapts the data rate dynamically. It uses SNR values calculated by Physical layer and exported to MAC layer via the Cross-Layer Communication [9] to estimate the prevailing channel state. In RCECLD the receiver decides the transmission data rate by calculating the SNR value of received RTS, which is in turn an estimate of the prevailing channel state, and piggybacking it through CTS to the transmitter. Accordingly transmitter transmits the data frame with adopted data rate. As the receiver decides the data rate and dictates it to the transmitter, the proposal is Receiver Based. Multi-hop wireless network scenarios are also tested by creating a chain of static nodes.

To study the performance of the proposal, an analytical model is adopted that characterizes the throughput gains as compared to IEEE 802.11 as a function of the physical layer channel conditions. Finally, the extensive simulation study is performed to evaluate the proposal in realistic scenarios and to isolate the performance factors that determine throughput gains. Only ad-hoc network scenarios single hop and multi-hop are considered. Example findings are as follows. (1) In single hop cases, the throughput gain is about 2 to 2.5 times more compared to ARF. (2) Similar gain is observed in mobile scenarios as well. (3) In multi-hop scenarios even in fading channel conditions the chain throughput is almost doubled as compared to ARF. (4) Ultimately load carrying capacity of the ad-hoc network increases in RCECLD.

The rest of the paper is organized as follows. Related work is presented in Section 2. Channel model and adopted Analytical model are discussed in Sections 3 and 4 respectively. Section 5 presents the proposal. Simulation results and performance analysis are discussed in Section 6, and finally the paper concludes in Section 7.

2. RELATED WORK

In [6], 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 [2,10], 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 [7] the high quality channels are exploited by sending multiple back-to-back packets. In [10] 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 [2,11,12], the local ACK is used and is very simple to implement. It has been pointed out in [12] 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 [11,12] this issue is addressed.

Jinyang and others [13] examine the capacity of wireless ad-hoc networks via simulations and analysis from first principles. In particular, studied 802.11 MAC interactions with ad-hoc forwarding, their effect on network capacity and the scaling behavior of per node capacity as networks grow bigger. This work is extension of theirs for capacity enhancement by addition of Cross-layer interaction for different traffic patterns and channel conditions.

Gupta and Kumar [8] show that, using a geometric analysis, the capacity per node in an n-node random ad-hoc network is $\Theta\left(\frac{1}{\sqrt{n\log n}}\right)$. Shepard [14] considers limits on capacity imposed by aggregate interference from many senders spread over a large area, concluding that such networks are scalable. It is pointed out that capacity can be increased with minimum energy routing, and proposes an efficient distributed channel access technique.

Grossglauser and Tse [15] consider ad-hoc networks of mobile nodes, showing that long term per node throughput can stay constant in a network where node movement process is ergodic with a uniform stationary distribution over the network. The basic idea is for a source node to distribute packets to as many different nodes as possible; these nodes relay the packets to the final destination whenever they get close to the destination. Therefore, the expected path length remains constant. However, this result depends critically on the movement model. Furthermore, the fixed throughput guarantee is achieved only over very long time frames.

Some existing studies have focused on the fairness of 802.11 in the context of ad-hoc forwarding. Nandagopal et al. [16] propose an algorithm that gives each flow in the network a fair allocation of capacity no matter how much more contention it perceives in comparison to other flows.

3. CHANNEL MODEL

The transmitted radio frequency signal is reflected by both natural and man made objects. Thus, the signal at the receiver is a superimposition of different reflections of the same signal, received with varying delays and attenuations. Based on the relative phases of different reflections at the receiver, the different copies of the same signal may add coherently or tend to cancel out. Coherent addition of the copies can 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 [17] is;

$$y(t)=\sum_{i=1}^{p(t)} A_i(t)\,x\big(t-\tau_i(t)\big)+z(t) \qquad (1)$$

where *x(t)* is the transmitted signal and *y(t)* is the received signal. 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 *p(t)*. The additive term *z(t)* is generally labeled as the background noise and represents the thermal noise of the receiver. Note that the loss suffered by the signal during its propagation along different paths is captured in $A_i(t)$, and depends on the distance between the sender and the receiver.

Recognizing that the received SNR can be used to capture the packet level performance of any physical layer implementation, the following model is used for the received signal to noise ratio for transmitter power *P* at packet transmission time t_p,

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

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

The short time-scale variation in the received SNR is captured by the time-varying parameter $\rho(t_p)$, known as the fast fading component of the fading process. The time-variation of $\rho(t_p)$ is typically modeled by a probability distribution and its rate of change [17]. An accurate and commonly used distribution for $\rho(\cdot)$ is the Ricean distribution,

$$p(\rho)=\frac{\rho}{\sigma^2}e^{-\left(\frac{\rho}{2\sigma^2}+K\right)}I_0(2K\rho) \qquad (3)$$

where *K* is the distribution parameter representing the strength of the line-of-sight component of the received signal and $I_0(\cdot)$ is the modified Bessel function of the first kind and zero-order [17]. For $K = 0$, the Ricean distribution reduces to the Rayleigh distribution, in which there is no line-of-sight component.

The rate of change of $\rho(t_p)$ depends on a mobile host's relative speed with respect to its surroundings. Among the several models available in the literature we use the Clarke and Gans model [17]. The motion of nodes causes a Doppler shift in the frequency of the received signal, and the extent of the Doppler shift depends on the relative velocity of the sender and the receiver. Let, f_m denote the maximum Doppler frequency during the communication between the two nodes. Then according to the Clarke-Gans model, the received signal is modulated in the frequency domain by the following spectrum:

$$S(f)=\frac{1.5}{\pi f_m b\sqrt{1-\left(\frac{f-f_c}{f_m}\right)^2}} \qquad (4)$$

In Equation (4), f_c represents the carrier frequency of the transmitted signal. The spectral shape of the Doppler spectrum in Equation (4) determines the time domain fading waveform and hence the temporal correlation. The inverse of the maximum Doppler frequency of f_m, $T_c=\frac{1}{f_m}$, is known as the coherence interval. In essence, the channel SNR values $\rho(\cdot)$ separated by more than T_c, are approximately independent. At mobile speeds of 1 m/s, the coherence interval is approximately 122.88 ms for a center frequency of 2.4 GHz. The coherence interval reduces to 24.57 ms, 12.28 ms and 6.14 ms for mobile speeds of 5 m/s, 10 m/s and 20 m/s. In engineering design [17], a more conservative estimate of coherence interval is used which is around 43% of the above numbers: 51.98 ms, 10.39 ms, 5.20 ms and 2.59 ms for speeds of 1, 5, 10 and 20 m/s. At 2, 5.5 and 11 Mbps, a 500 byte packet takes 2 ms, 0.725 ms and 0.365 ms respectively. The fact that coherence intervals are on the order of multiple packet transmission times provides a key motivating factor for designing dynamic scheduling policies.

4. ANALYTICAL MODEL

In this paper for the analytical evaluation of the saturation throughput the same method as suggested by Binachi [1] is used, assuming the ideal channel conditions with no hidden terminals.

The normalized system throughput *S* is represented as;

$$S=\frac{E\left[payload\_\inf ormation\_transmitted\_in\_a\_slot\_time\right]}{E\left[length\_of\_a\_slot\_time\right]}$$

Let, *E[P]* be the average packet payload size, the average amount of payload information successfully transmitted in a slot time is $P_{tr}P_sE[P]$, since a successful transmission occurs in a slot time with probability $P_{tr}P_s$ and with probability $P_{tr}(1-P_s)$ it contains a collision. Hence *S* becomes;

$$S=\frac{P_{tr}P_sE[P]}{(1-P_{tr})\sigma+P_{tr}P_sT_s+P_{tr}(1-P_s)T_c} \qquad (5)$$

where,

$$P_{tr}=1-(1-\tau)^n,\ P_s=\frac{n\tau(1-\tau)^{n-1}}{P_{tr}},$$

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

$$T_c=RTS+SIFS+\delta$$

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

$$\tau=\frac{2(1-2p)}{(1-2p)(W+1)+pW\left(1-(2p)^m\right)} \text{ and}$$

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

where $W = CW_{min}$, $CW_{max} = 2^m\ CW_{min}$, 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.

Assumed that each packet is transmitted by means of the RTS/CTS Access mechanism and it is obvious that in such a case, collision can occur only on RTS frames. Also, as this RTS and CTS are exchanged with the rate 2 Mbps, T_s, T_c, $E[P]$ and σ are constants. Hence, the throughput expression depends on τ, in turn the network size n. The value of τ is approximated as;

$$\tau = \frac{1}{n\sqrt{\frac{T_c}{2\sigma}}} \qquad (6)$$

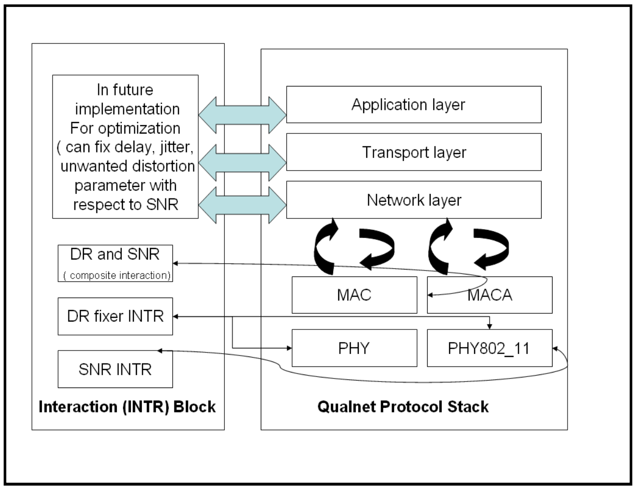
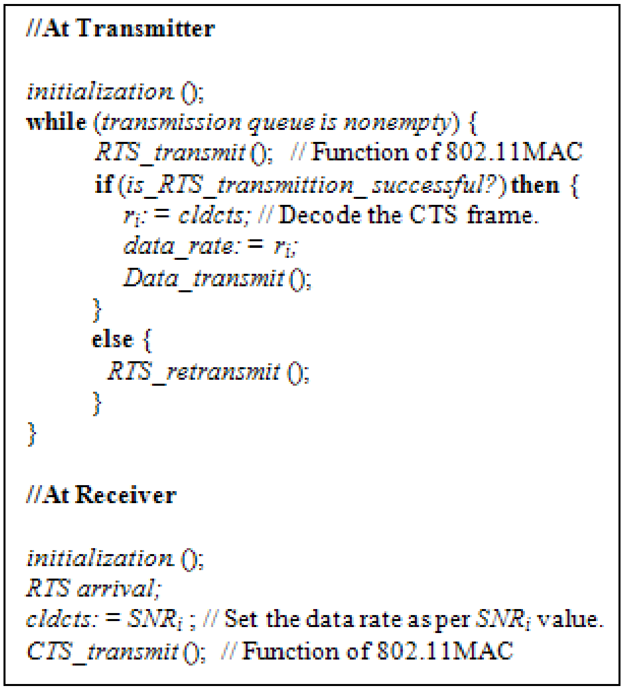


Figure 1. Model Implementation in MAC with Cross-Layer Approach.

5. THE PROPOSAL

A generic model for Cross-Layer interactions is proposed as shown in Figure 1. 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. The present work 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 condition in time varying and mobile environment. Exploitation of channel condition to increase the network capacity is the aim, which is achieved by this additional Cross-Layer interaction without changing the basic architecture of the Protocol Stack as seen in [3]. The optimization is achieved in the system by adjusting the data rate using threshold-based technique [7]. 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_{m-1} are SNR thresholds for different suitable rate limits. For example, p_1 indicates that if the received SNR level is below p_1, rate r_1 is feasible. In case the received SNR level is above p_1 but below p_2, rate r_2 is feasible and so on. A region surrounded by two subsequent SNR thresholds, which is suitable for a particular rate.



```
//At Transmitter

initialization ();
while (transmission queue is nonempty) {
        RTS_transmit (); // Function of 802.11MAC
        if (is_RTS_transmittion_successful?) then {
           $r_i$: = cldcts; // Decode the CTS frame.
           data_rate: = $r_i$;
           Data_transmit ();
        }
        else {
          RTS_retransmit ();
        }
}

//At Receiver

initialization ();
RTS arrival;
cldcts: = $SNR_i$ ; // Set the data rate as per $SNR_i$ value.
CTS_transmit (); // Function of 802.11MAC
```

Figure 2. RCECLD Algorithm.

5.1 RCECLD Algorithm

In a fully connected ad-hoc topology all nodes are in the 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 low signal strength such that it can only transmit at the base rate of 2 Mbps and the other with high signal strength so that it can transmit at rate 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. To improve the system performance in terms of throughput, i.e. to improve the system capacity RCECLD algorithm for wireless ad-hoc networks is proposed.

In RCECLD the parameter tuned is data rate. As shown in Figure 1, additional interface is created between Physical and MAC layer. 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, the transmission of data frame 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.

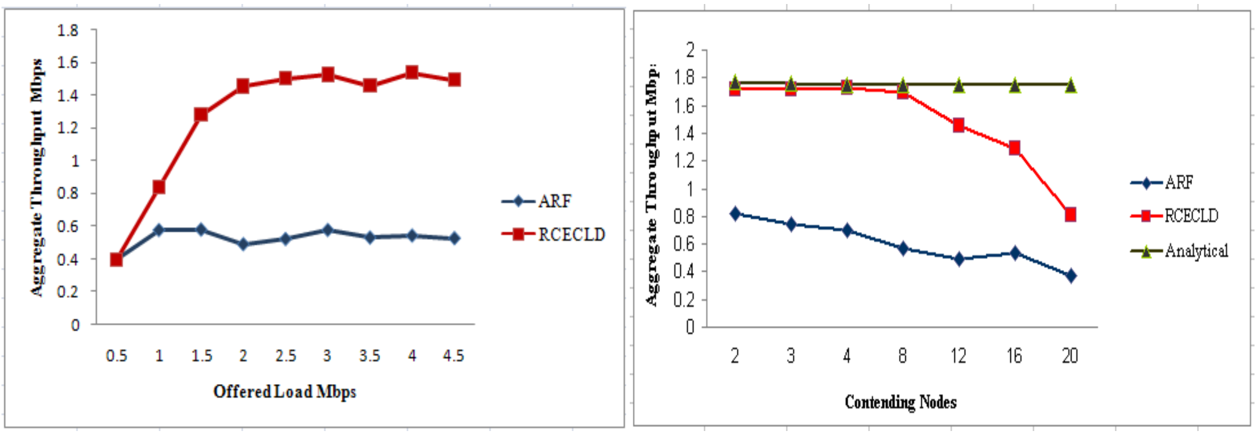


Figure 3. Aggregate Throughput as a Function of a) Offered Load. b) Contending Nodes in Time Varying Channel Conditions.

Note that, in RCECLD each data frame transmission is carried over with RTS/CTS exchange, 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. The algorithm is given in Figure 2. Table 1 gives the list of notations used in the algorithm.

Table 1. List of Notations Used in the Algorithm.

Notations	Comments
r_i	Data rate i, from 802.11b data rate set, {1,2,5.5,11}
cldcts	Data rate set by Receiver in CTS
SNR_i	*SNR* value at instant *i*

6. PERFORMANCE EVALUATION

In this section, the effectiveness of the proposal is evaluated by using Qualnet 4.5 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 unless stated within the range of each other. For the simulations 12 node topology is used unless stated. Two Ray Path-loss model [17] is used to simulate the environment. Moreover, the multi-path fading and mobility effects are considered with which the channel condition between the transmitter and receiver varies over the time. The Ricean fading model [18] is used to simulate the time varying wireless channel conditions. The Ricean distribution is given by Equation (3) as addressed in Section 3. 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 512 bytes unless specified otherwise. Simulations under various network topologies and network size are conducted and results are compared with ARF. Table 2 gives the system parameters.

6.1 Saturated Throughput with Time Varying Channel

RCECLD is tested in Ad-hoc mode topology, with Ricean fading in which the offered load of the system is increased gradually up to 4.5 Mbps. From Figure 3a, it is observed that the saturated throughput of RCECLD is almost 3 times better than ARF even in time varying channel conditions. ARF and RCECLD adapt different mechanisms to select the data rate but because of slow responsive nature of ARF even in good conditions it can't exploit the channel up to its maximum capacity. As seen, the network is saturated for the offered load of 2 Mbps. Hence, 2 Mbps is considered as offered load for all the other simulations.

Table 2. System Parameters

Parameter	Value
Packet Payload	4096/8184 bits
MAC Header	272 bits
PHY Header	192 bits
RTS	160 bits + PHY Header
CTS	144 bits + PHY Header
ACK	112 bits + PHY Header
Packet Arrival Rate	2 Mbps
Propagation Delay	1 µs
Slot Time	20 µs
SIFS	10 µs
DIFS	50 µs

6.2 Topology with Varying Number of Contending Stations in 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 500mX500m making sure that all are static and within each others range. The wireless channel model is time varying with Ricean fading model. The

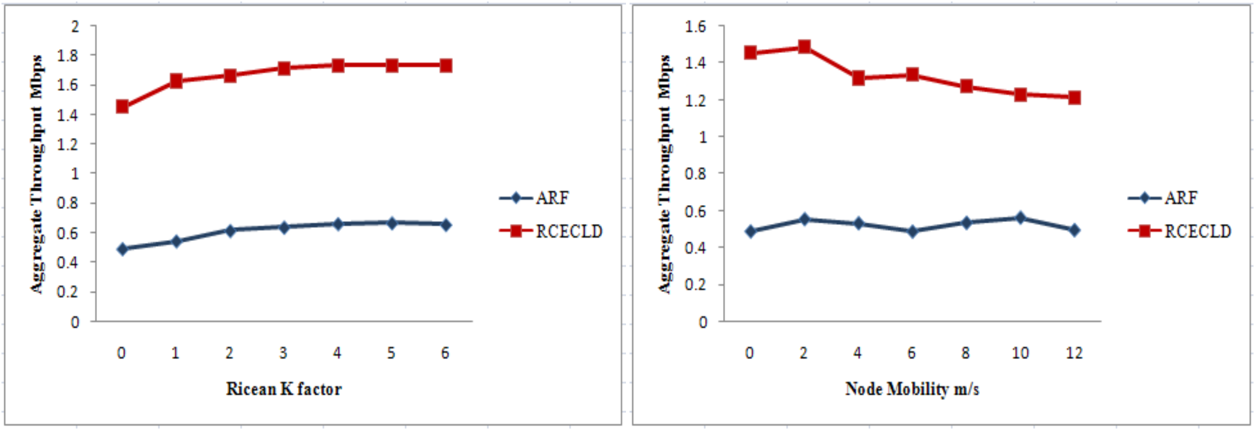


Figure 4. Aggregate Throughput as a Function of a) Line-of-Sight Factor K b) Node Mobility.

nodes are transmitting the data packets at 2 Mbps. Simulation results are plotted in Figure 3b. RCECLD gives the throughput similar to Analytical throughput calculated by Equations (5) and (6) up to the network size of 8 contending nodes. In case of ARF, the aggregate system throughput is degraded with increased number of contending nodes in the network. ARF gives inferior performance than RCECLD.

There are two main reasons for the poor performance of ARF. First, since ARF waits for 10 successful transmissions to increase the rate by one step, even channel condition is far better and a wireless station may decrease its frame transmission rate over-aggressively, and then operate with a lower transmission rate than the actual achievable higher rate. Second, since each contending station conducts its rate adaptation independently, they may end up with transmitting data at different rates. Such transmission rate diversity causes the performance anomaly that was first discovered experimentally in [19]. Since the 802.11 DCF is designed to offer equal transmission opportunities (or long-term equal medium access probabilities) to all contending stations, the throughput of a high-rate station is always bounded below the lowest transmission rate in the network.

6.3 Effect of Line of Sight Parameter K

Here, the effect of the Ricean parameter K is explored on the performance of ARF and RCECLD. 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 Equation (3), and a higher transmission rate is feasible more often.

Figure 4a depicts the aggregate throughput for ARF and RCECLD as a function of the Ricean parameter K. Observe that RCECLD exploits the improved channel conditions represented with increasing K and obtain correspondingly greater system-wide throughputs. Moreover, note that RCECLD achieves a higher aggregate throughput compared to ARF over the simulated range of K due to its enhanced exploitation of high-quality channel conditions when they occur.

6.4 Effect of Node Mobility

Node mobility affects its channel in two ways. First, it changes the location of node which affects the line-of-sight parameter (Ricean factor K) of pair of nodes. Second, it affects the average channel coherence time as a node with higher velocity has a lower average coherence time hindering the ability to exploit opportunistic scheduling.

To study the effect of mobility on ARF and RCECLD, the same 12 node topology is considered. All nodes travel to and from each other with Random Way Point mobility. The throughputs are depicted in Figure 4b for speeds up to 12 m/s. As described in Section 3, this corresponds to an average coherence time of approximately 4.4 ms, which corresponds to slightly larger than 2 packet transmission times at the base rate of 2 Mbps and 13 packet transmission times at 11 Mbps (Equation 4). As shown, the throughput that is nearly independent of velocity and with RCECLD it is approximately 2.5 times greater than ARF. The key reason is that within this range of velocities, the coherence time is sufficiently large to extract the full performance gain of RCECLD.

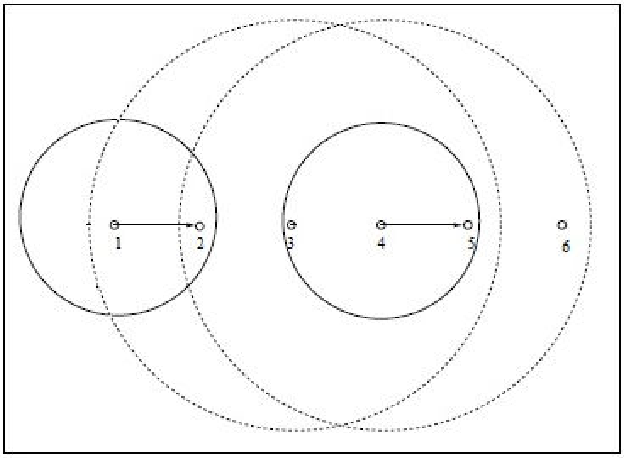


Figure 5. Chain of Nodes

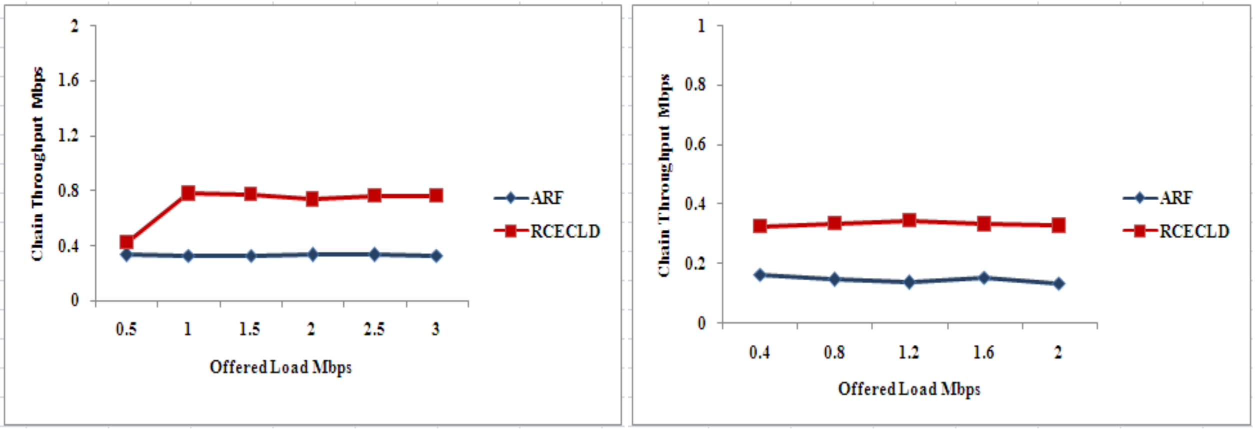


Figure 6. Chain Throughput in Time Varying Channel Conditions as a Function of Offered Load for a) Chain of 3 Nodes b) Chain of 4 Nodes

6.5 Chain Node Topologies

This subsection examines the realizable capacity of a single chain of nodes where packets originate at the first node and are forwarded to the last node in the chain. In an ad-hoc network, packets travel along a chain of intermediate nodes toward the destinations. The successive packets of a single greedy connection interfere with each other as they move down the chain, forcing contention in the MAC protocol.

An ideal MAC protocol could achieve chain utilization as high as 1/3. Consider the network shown in Figure 5, where the solid-line circle denotes a node's valid transmission range. The dotted-line circle denotes a node's interference range. Node 1 is the source and 6 is the sink. Assume for the moment that the radios of nodes that are not neighbors do not interfere with each other. If chain of only 3 nodes is considered, nodes 1 and 2 cannot transmit at the same time because node 2 cannot receive and transmit simultaneously. So the channel utilization is ½. If chain of 4 nodes is considered, 1 and 3 cannot transmit at the same time because node 2 cannot correctly hear 1 if 3 is sending. This leads to a channel utilization of 1/3.

However, if one assumes that radios can interfere with each other beyond the range at which they can communicate successfully, the situation is worse. For example, 802.11 nodes in the simulator can correctly receive packets from 250 meters away, but can interfere at 550 meters. Hence, in Figure 7, node 4's packet transmissions will interfere with RTS packets sent from 1 to 2, preventing 2 from correctly receiving node 1's RTS transmissions or sending the corresponding CTS. If the time varying channel conditions are considered by adding the fading effect, the performance will be degraded further. Therefore, the maximum utilization of a chain of ad-hoc nodes in the simulator is expected to be less than 1/3. For the data packets of 1024 bytes the maximum capacity with 2 Mbps offered load, of a two node capacity considering the overhead of headers, RTS, CTS, and ACK packets is; 1024/(1024+52+44+42+38) X 2 = 1.7 Mbps. A chain of only 3 nodes achieves a throughput of about 1.7 X (1/2) = 0.85 Mbps. A chain of only 4 nodes achieves a throughput of about 1.7 X (1/3) = 0.57 Mbps. Figure 6a gives the performance for the chain of 3 nodes, whereas, Figure 6b for chain of 4 nodes. For the simulations nodes in the chain are considered to be 200 meters away from its immediate neighbors. Node 1 is the source and the last node in the chain is the traffic sink. The data packets are of 1024 bytes.

It is seen that the chain throughput is almost doubled in case of RCECLD. This is due to the modified MAC for better channel utilization even in case of time varying channel conditions due to fading effect.

6.6 Effect of Length of Chain

Figure 7a shows simulation results for a single chain. The simulated chain capacity that the 802.11 MAC achieves with a greedy sender is about 1/7, because nodes early in the chain starve later nodes [13]. So for a chain of 8 nodes it is about 1.7 X (1/7) = 0.24 Mbps. As observed, the chain throughput is better than ARF and as the nodes in the chain grow it is almost doubled in case of RCECLD. This is due to the rate adaptive nature of MAC for better channel exploitation. As discussed earlier, RCECLD selects the data rate as per the channel condition, data packets are transmitted or forwarded at higher rate.

Figure 7b shows simulation results with time varying channel. Ricean fading is added in the network (Equation (3)). As RCECLD responds faster for variable channel conditions, the performance in terms of chain throughput, as seen is better. It is also observed that as chain length grows the performance is poor, tending towards zero.

7. CONCLUSION

In this paper, a novel Receiver based Capacity Enhancement algorithm with Cross-Layer Design approach in wireless ad-hoc networks is proposed. The key idea is that the receiver station estimates the channel condition, accordingly selects the data rate for transmission and it is dictated to the transmitter. The parameter transmission data rate is tuned to exploit the channel conditions which is also used for ad-hoc forwarding to the next hop. MAC interactions does play important role for the process ad-hoc forwarding. Therefore, compared with ARF, the most well-known and widely-deployed rate adaptation scheme in the commercial 802.11 WLAN devices, it is more likely to make the correct rate adaptation decisions. Small change is required in the CTS frame structure with which it can be deployed with existing 802.11 devices. Due to correct rate adaptation decisions throughput, in turn capacity is observed to be improved.

The performance is evaluated via in depth simulations over various scenarios in terms of network topology, offered load, node mobility and time varying wireless channel. Multi-hop

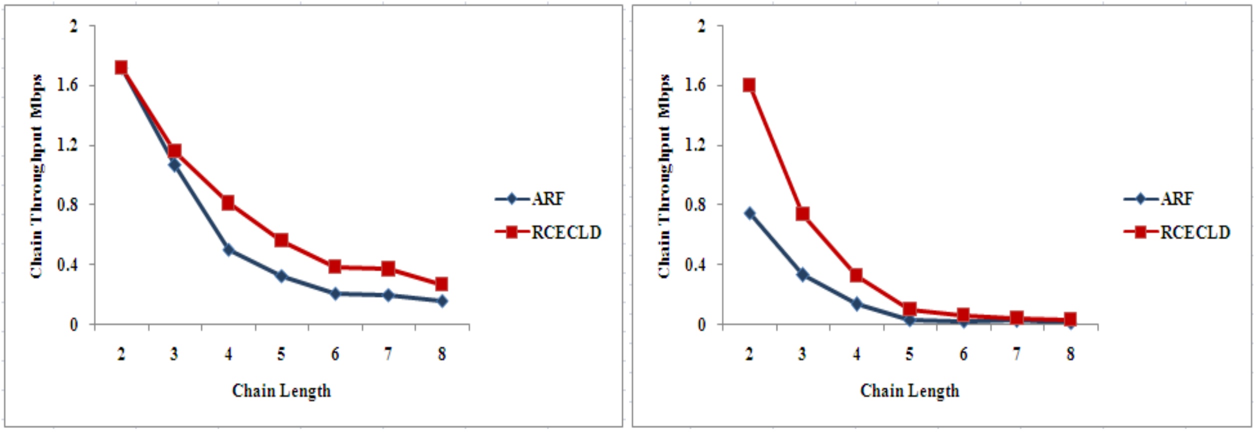


Figure 7. Chain Throughput as a Function of Chain Length with a) Stationary Channel Conditions b) Time Varying Channel Conditions.

chain topology is also considered. It is demonstrated that the proposal significantly outperforms ARF in all the simulated multiple contending station environments, whereas the performance enhancement becomes more and more evident as the number of contending stations increases.

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