ERBAR: an Enhanced Receiver-Based Auto-Rate MAC Protocol for Wireless Ad Hoc Networks

Zhifei Li, Anil K. Gupta, and Sukumar Nandi
School of Computer Engineering, Nanyang Technological University, Singapore-639798

Abstract— **The multi-rate capability provided by the physical layer in IEEE 802.11 requires that the MAC layer adapts the transmission rate according to the channel conditions. In a multi-hop wireless ad hoc network, where the RTS/CTS is always used to combat with the common hidden-terminal problem, the receiver-based auto-rate (RBAR) [3] is more desirable compared to other rate adaptation algorithms. In this paper, we have introduced an enhanced receiver-based auto-rate (ERBAR) protocol, which improves the RBAR in two ways. First, a modified virtual carrier sensing (MVCS) mechanism is proposed, which reduces the overhead as well as the complexity compared to the VCS used in RBAR. Secondly, based on the MVCS, we also propose a rate adaptation algorithm, which aims to transmit the control frames at the highest attainable rate rather than always at a basic rate. Both analytical and simulation results show that the ERBAR greatly improve the performance of the RBAR.**

I. INTRODUCTION

Recently, wireless ad hoc networks have attracted considerable research interest. The Distributed Coordination Function (DCF) in IEEE 802.11 [4] is popularly adopted as the MAC protocol for ad hoc networks. The IEEE 802.11a, b, and g [4] standards provide the multi-rate capability at the physical layer. To make full use of this capability, the MAC protocol should choose a rate in an adaptive manner, known as *link adaptation*, *rate adaptation*, or *auto rate*. The basic idea of rate adaptation is to estimate the channel conditions and then dynamically select a transmission rate that will give the optimum throughput under the given channel conditions. In the IEEE 802.11, the rate adaptation part has been intentionally left open. Recently, numerous algorithms [1], [3], [5], [6], [9], [10] have been proposed to support multi-rate in IEEE 802.11. Based on whether the rate adaptation function is performed at the sender or at the receiver, these algorithms can be classified into two categories: sender-based and receiver-based. The algorithms in [1], [5], [6], and [9] fall into the first category while those in [3] and [10] belong to the second category. The sender-based algorithm is simple and easy to incorporate into the standards. However, it is the *receiver* that can perceive the channel quality, and thus determine the transmission rate more precisely. Observing this, the authors in [3] have presented a receiver-based auto-rate (RBAR) protocol assuming that the request-to-send and clear-to-send (RTS/CTS) mechanism is there. The basic idea of RBAR is as follows. First, the receiver estimates the wireless channel quality using a sample of signal strength of the received RTS, then selects an appropriate transmission rate for the Data frame, and piggybacks the chosen rate in the responding CTS frame. Then, the sender transmits the Data frame at the rate advertised by the CTS. The Opportunistic Auto Rate (OAR) [10] extends the RBAR by giving preference to the nodes who are experiencing good channel conditions. The OAR greatly improves the aggregate throughput of the network. However, it worsens the fairness (in terms of throughput) compared to the RBAR though the *temporal* fairness is the same as that of RBAR. In a multi-hop ad hoc network, since the RTS/CTS handshaking is always used to combat with the common hidden-terminal problem, the receiver-based algorithm is more desirable.

In the design of a receiver-based algorithm with RTS/CTS in place, in addition to the issue of how to choose a proper rate at the receiver, two other important issues are: *(i)* the proper operation of the virtual carrier sensing (VCS) mechanism in a multi-hop scenario; and *(ii)* the transmission rate of the control frames (i.e., RTS, CTS, and ACK). The VCS is achieved by distributing reservation information announcing the impending use of the medium. Specifically, the RTS and CTS frames contain a Duration field that indicates the time duration the medium is to be reserved for transmission of the actual Data frame and the ACK frame. All the overhearing nodes should defer their transmission by a time indicated by the duration field. The VCS in IEEE 802.11 is essentially designed for the fixed-rate scenario. In the receiver-based multi-rate algorithm, since the *actual* rate of the Data frame can be known only at the receiver after it has received an RTS, the sender has to *assume* a rate when it calculates the duration field carried in the RTS. When the actual rate of Data frame is different from the one assumed by the sender, the reservation needs to be corrected. In order to achieve this, the RBAR [3], which is the only rate adaptation algorithm that has addressed the VCS problem, proposes several modifications to both the MAC and physical layers, including defining a new sub-header. However, as pointed out in [9], since the protocol requires many changes to the standards, it may not be practically useful. Moreover, the new sub-header introduces extra overhead. In this paper, we propose a modified VCS (MVCS) mechanism, which reserves the medium only for the immediate next frame rather than for all the remaining frames in the sequence. The MVCS can operate properly with the help of physical carrier sensing mechanism adopted in IEEE 802.11 and it greatly reduces the overhead as well as the complexity.

All the above algorithms assume that the control frames are transmitted at a basic rate (e.g., 1 or 2 Mbps) to ensure all the nodes in the interference range can overhear the duration field clearly. However, operating in such a way, the bandwidth is greatly wasted by the control frames. Therefore, we explore the possibility of transmitting the control frames at a higher rate. Specifically, based on the MVCS, we propose that the control frames can be transmitted at the highest rate that the communicating pair can support under the given channel conditions, without considering whether they can be received correctly by the overhearing nodes. When the overhearing nodes cannot correctly receive the control frames, these nodes can still defer properly with the help of the Extended Inter Frame Space (EIFS) deferment defined in IEEE 802.11.

The above two proposals (i.e., the MVCS and the rate adaptation of control frames) can be viewed as extensions of the RBAR [3] and thus we call our protocol, the Enhanced RBAR (ERBAR). Both analytical and simulation results show that the ERBAR greatly improve the performance. The remainder of the paper is organized as follows. In Section II, we describe the DCF of IEEE 802.11. Then, in Section III, we define the problems of multi-rate algorithms in the multi-hop ad hoc networks. In Section IV, the ERBAR is presented. Sections V and VI present the analytical and simulation results, respectively. The paper is concluded in Section VII.

II. OVERVIEW OF IEEE 802.11 DCF

To combat with the hidden-terminal problem, DCF adopts a four-way handshaking, where a sequence of RTS, CTS, Data, and Acknowledgement (ACK) frames, is used for transmitting a single data packet. Figure 1 shows an example where the source node Src sends a data packet to the destination Dst. In the figure, node A is within the transmission range of the Src but out of the range of the Dst. On the other hand, node B is within the range of Dst but out of the range of Src.

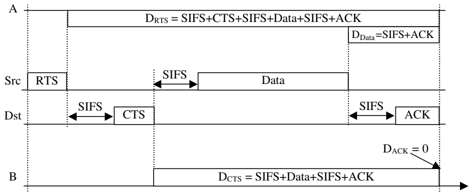

Fig. 1. Virtual Carrier Sensing in IEEE 802.11

When a frame exchange sequence between two nodes (e.g., nodes Src and Dst) is going on, all the other nodes (e.g., nodes A and B) that are within the range of the sender or the receiver should defer their transmission to prevent interference with the on-going sequence. In order to achieve this, every frame should contain a duration field, which stores the time duration that the medium is to be reserved for the sequence. In IEEE 802.11, the duration value carried in a given frame should be large enough to allow the transmission of all the remaining frames in the sequence. For example, in the RTS frame, the duration value should be equal to the time needed for the transmission of the CTS, Data, and ACK frames plus three Short Inter-frame Space (SIFS) intervals. This duration is represented by D_{RTS} in Figure 1. The duration values carried in the CTS, Data, and ACK frames are represented by D_{CTS}, D_{Data}, and D_{ACK}, respectively. When an overhearing node (e.g., node A or B) overhears a frame, it will update its variable called Network Allocation Vector (NAV) with the duration value carried in the overheard frame if the following conditions are satisfied: *(i)* the frame is received without error; *(ii)* the frame is not addressed to itself; and *(iii)* the duration value carried in the frame is greater than the current NAV value. The condition *(iii)* is required since a node may overhear many frames belonging to different exchange sequences, which is very likely in multi-hop ad hoc networks. Since a node with a NAV greater than zero will defer its transmission as if the medium is physically busy, the above mechanism is also called virtual carrier sensing (VCS).

In addition to the deferment enforced by VCS, whenever a node detects an erroneous frame, the node defers its transmission by a fixed duration indicated by the Extended Inter Frame Space (EIFS) constant [4]. We call this EIFS deferment.

III. PROBLEMS IN RECEIVER-BASED RATE ADAPTATION

A. Transmission Rate of the Control Frames

In IEEE 802.11, it specifies that all the control frames should be transmitted at one of the rates in the *basic rate set* so that all the potentially interfering nodes can decode the duration information carried in these frames. Obviously, the basic rate set contains only one or more lowest transmission rates among all the supported rates. For example, in the IEEE 802.11b that supports rates of 1, 2, 5.5 and 11 Mbps, the basic rate set normally contains only 1 and 2 Mbps. Another rule regarding the transmission rate of the control frames is as follows [4]: in order to allow the transmitting node to calculate the Duration field value, the responding node should transmit its Control Response frame (either CTS or ACK) at the highest rate in the basic rate set, which is smaller than or equal to the rate of the received frame. Since there is no rule about how to adapt the transmission rate of the RTS frame, a conservative implementation will choose to transmit it at the lowest rate, i.e., 1 Mbps. As a result, the CTS should also be transmitted at the 1 Mbps. On the other hand, the ACK frame can be transmitted at 2 Mbps according to the above rule whenever the transmission rate of the Data frame is equal to or greater than 2 Mbps. In fact, in most of rate adaptation algorithms [1], [3], [6], [10], they simply assume all the control frames are always transmitted at the lowest basic rate. As a result, the overhead introduced by the control frames is fixed irrespective of the length and the transmission rate of the Data frame.

B. VCS Issues in Receiver-based Multi-rate

VCS in IEEE 802.11 is essentially designed for the single-rate scenario. To calculate the duration value for a frame, the transmission rates and the lengths of all the remaining frames in the sequence must be known a priori. For example, to calculate the D_{RTS}, the node Src (Figure 1) must know the transmission rates and the lengths of CTS, Data and ACK frames. As the lengths of all the frames are known at the Src, and the transmission rate of the RTS/CTS is assumed to be 1 Mbps, so for the VCS to operate properly, only the transmission rate of the Data frame has to be known before the transmission of the RTS, which is certainly known for the sender-based algorithms [1], [5], [6], [9].

However, in the receiver-based rate adaptation algorithms such as RBAR [3] and OAR [10], since the *actual* transmission rate of the Data frame is determined by the receiver (e.g., Dst) after it has received the RTS frame, the sender (i.e., Src) has to assume a transmission rate for the Data frame to calculate the D_{RTS}. Whenever the rate chosen by the receiver is different from the one assumed by the sender, the reservation made by D_{RTS} is inaccurate. The reservation can be corrected by the D_{CTS} or D_{Data}, which will always be precise if the rate of the control frames follows the rules described in Section III.A. However, two problems arise. The first one is that since the Data frame may not be transmitted at the basic rate, it may not be decoded correctly by the overhearing nodes and thus the reservation cannot be corrected by the D_{Data}. The second problem occurs as follows. When the actual rate of the Data frame is larger than the rate assumed by the sender, the remaining NAV value previously updated according to D_{RTS} is larger than the new duration value contained in the CTS or Data frame. As mentioned before, to ensure the proper operation of the VCS in a multi-hop network, the IEEE 802.11 does not allow reduction in NAV. Therefore, the reservation made by D_{RTS} cannot be corrected.

To cope with the first problem, the RBAR [3] defines a sub-header, called the Reservation SubHeader (RSH), which replaces the original header of the Data frame. The RSH includes a separate Frame Check Sequence (FCS) and is transmitted at one of the basic rates to ensure all the overhearing nodes receive it correctly. Moreover, the physical layer frame needs to be modified to include fields indicating the rate of the RSH header and the rate of the actual Data part, and thus the physical layer may be required to switch transmission rates twice during the transmission of the payload. To cope with the second problem, the VCS is modified to allow the NAV value to be reduced by the frames belonging to the *same* frame exchange sequence. To achieve this, every node has to maintain a history of the NAV updates. Obviously, the RBAR designed as above increases the complexity as well as overheads, and thus it may not be practically useful [9].

The above discussion assumes that the rate of the control frames will follow the rules discussed in Section III.A. It is obvious that the situation is more complex when the transmission rate of the control frames is also made variable, which is one of the objectives in this paper.

IV. ENHANCED RECEIVER-BASED AUTO-RATE (ERBAR)

A. Modified Virtual Carrier Sensing (MVCS)

As discussed in Section III.B, the main problem in the current VCS for multi-rate is that it needs to know the transmission rate of all the remaining frames. However, we must realize that the main purpose of the VCS, a complementary component of the physical carrier sensing, is to allow the next frame in the ongoing sequence to go through. Therefore, instead of reserving the medium for all the remaining frames, we propose to reserve the medium only for the immediate next frame. We call it Modified Virtual Carrier Sensing (MVCS).

The MVCS can operate properly in a multi-hop network with the help of the physical carrier sensing. If a node is within the range of the sender as well as the receiver, the node can defer properly by using only the physical CS mechanism. Now let us consider the nodes that are within the range of the sender but not of the receiver. This is exemplified in Figure 2. For example, when node A overhears an RTS frame, under the MVCS, it will defer by a duration to allow the CTS to pass through. Then, when the Src is transmitting the Data frame, the physical CS at node A will force itself to defer. After node Src has transmitted the Data frame, node A will defer for a duration to allow the transmission of the ACK frame. Therefore, the nodes within the range of the sender but not of the receiver can defer properly. Note that it is not possible for node A to initiate its transmission during the SIFS delay at the Src (just before the transmission of the Data frame). The reason is, after node A has deferred by D_{RTS} it will further defer by a DCF Inter-Frame Space (DIFS), which is larger than the SIFS. One can also verify that the nodes (e.g., node B) within the range of the receiver but not of the sender can defer properly. Therefore, all the nodes that may potentially interfere with the ongoing frame exchange sequence, can defer properly. So far, we have assumed that all the frames will be overheard clearly, which may not be true in a practical scenario. However, with the help of the EIFS deferment, all the nodes will defer properly as discussed in Section IV.B.

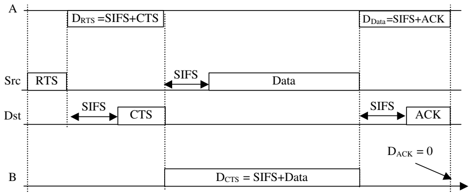

Fig. 2. Modified Virtual Carrier Sensing (MVCS)

Clearly, MVCS reduces the overheads and the complexity in the receiver-based multi-rate algorithms. For example, the addition of RSH sub-header, the maintenance of NAV update history, and the modifications to the physical layer are not required any more. More importantly, the MVCS forms the basis to adapt the transmission rates of the control frames.

B. Rate Adaptation of Control Frames

As discussed before, the IEEE 802.11 specifies that all the control frames (i.e., RTS, CTS and ACK) should be transmitted at one of the basic rates to ensure that all the nodes can interpret them. In fact, it can be easily verified by checking the frame format defined in the standards, that in an ad-hoc network the only useful information contained in the RTS/CTS/Data/ACK for the *overhearing* nodes is the duration value. On the other hand, with the MVCS, a frame needs to reserve the medium only for the next frame in the sequence. Therefore, if somehow the overhearing nodes can defer properly to allow the next frame pass through even when they cannot interpret the contents of the overheard frames, the control frames can also be transmitted at a rate higher than the basic rates. This can be achieved with the help of the EIFS deferment as explained in the following. Since the EIFS is equal to *SIFS + TxTime (ACK) + DIFS* (i.e., 364 μs in DSSS) [4], it is long enough for the transmission of the control frames at any rate. For example, when a node detects an erroneous frame corresponding to the RTS, it will defer by an EIFS value, which is large enough to allow the CTS to go through. This is also true when a node detects an erroneous frame corresponding to a Data or ACK. Therefore, we propose that the RTS and ACK frames should be transmitted at the highest attainable rate between the communicating pair under the given channel conditions. However, when a CTS frame cannot be overheard correctly, since the transmission time required by the Data frame may be greater than the EIFS, the overhearing nodes, relying solely on the EIFS deferment, may not defer properly. Therefore, when the transmission time of the Data is greater than the EIFS, the CTS frame should be transmitted at the lowest basic rate to ensure that the CTS could be clearly understood by the overhearing nodes.

C. *Enhanced Receiver Based Auto Rate (ERBAR)*

The above two proposals (i.e., MVCS and rate adaptation of the control frames) can be easily incorporated into the RBAR, leading to our Enhanced RBAR (ERBAR). We first discuss the rate adaptation of the frames. For the RTS frame, one can adopt any sender-based algorithm to decide the rate. However, for simplicity, the transmission rate of the RTS is chosen as follows. Every node will maintain a variable, which indicates the rate that should be used for the RTS. The initial value of this variable is set to the lowest basic rate (i.e., 1 Mbps). Whenever an attempt of transmitting an RTS or Data frame is successful, the variable will be updated with the rate being used for this successful transmission. Otherwise, whenever the attempt fails, the variable will be reset to the lowest basic rate. The rate selection of the CTS frame is much simpler. If the transmission time of the Data frame (which can be computed only at the receiver after it has chosen a rate for the Data frame) is greater than the EIFS value, the CTS frame, as mentioned before, is transmitted at the lowest basic rate. Otherwise, the CTS is transmitted at the same rate as that used for the RTS. The transmission rate of the Data frame is chosen by the receiver and is piggybacked in the CTS as in the RBAR. Moreover, to cope with the situation that the channel conditions between the same pair of nodes may be different in two directions, in contrast to the RBAR, the sender will choose a rate for the ACK and piggyback it in the Data.

Now we discuss how the MVCS operates in the ERBAR. Instead of having the duration value in the RTS frame, it carries the length of the Data frame, which is needed by the receiver to calculate the D_{CTS}. All the other frames carry the duration information, which is long enough for the next frame in the sequence to pass through. Note that the rate chosen for the Data and ACK frames can be easily derived from the duration value carried in the CTS and Data frames. Therefore, it is unnecessary to have an additional field to store the rate being chosen. For the overhearing nodes, when they overhear an RTS frame, they will defer by a fixed duration that is long enough for the CTS to be transmitted at the lowest basic rate. Otherwise, when they overhear any other types of frame, they will simply defer by a duration advertised in the overheard frame. The deferment when overhearing an RTS may be larger than the desired one since the CTS may be transmitted at a higher rate. However, the deviation is very small.

V. ANALYTICAL MODELING

In this section, under the assumptions that only one active single-hop flow is present in the network and that no wireless errors occur, we developed a simple model to show the advantages of ERBAR. The model considers in detail the overheads introduced by the physical and MAC layers.

A. *Maximum Throughput of IEEE 802.11*

The average time required for transmitting a data packet is:

$$T = DIFS + (CW_{min}/2)T_{slot} + 3SIFS + T_{RTS} + T_{CTS} + T_{Data} + T_{ACK} \tag{1}$$

where $DIFS$ is the time that a node should defer before initiating its transmission. The CW_{min} is the minimum Contention Window (CW) while the T_{slot} is the slot time in μs. Therefore, $(CW_{min}/2)T_{slot}$ is the average back-off time. T_{RTS}, T_{CTS}, T_{Data}, and T_{ACK} represent the transmission time of the corresponding physical layer frames. For a specific physical layer frame, the transmission time T_{frame} is:

$$T_{frame} = L_{frame}/R_{frame} + PHY_{hdr} \tag{2}$$

where L_{frame} and R_{frame} are the length of the MAC layer frame and the transmission rate chosen by the MAC layer, respectively. The PHY_{hdr} is the physical layer overhead in units of time. Since $DIFS$, CW_{min}, T_{slot}, $SIFS$, and PHY_{hdr} are fixed for a specific physical layer, we denote the sum of the fields containing them as C_{phy}. That is,

$$C_{phy} = DIFS + (CW_{min}/2)T_{slot} + 3SIFS + 4PHY_{hdr} \tag{3}$$

Since the lengths of the RTS, CTS, ACK, and the header of Data frame are fixed, i.e., 20, 14, 14, and 28 bytes, respectively, equation (1) becomes,

$$T = C_{phy} + 8(20/R_{RTS} + 14/R_{CTS} + (L+28)/R_{Data} + 14/R_{ACK}) \tag{4}$$

where L is the length of the data packet handed to the MAC layer from the upper layer, while R_{RTS}, R_{CTS}, R_{Data} and R_{ACK} are the transmission rates (in terms of Mbps) chosen by the MAC layer for the corresponding frames. Therefore, the maximum throughput (in terms of Mbps) is as follows:

$$Th = (L \times 8)/T \tag{5}$$

Figure 3 presents the numerical results corresponding to the IEEE 802.11b, where the R_{RTS} and R_{CTS} are equal to 1 Mbps, while the R_{ACK} is equal to 1 or 2 Mbps determined by R_{Data} as discussed in Section III.A. The C_{phy} correspondingly is 1168 μs. The results are obtained by varying the packet length L and the transmission rate of the Data frame R_{Data}. It is easy to see that the throughput increases with L or R_{Data}. Moreover, the overheard is considerable. For example, when L is 64 bytes and R_{Data} is 11 Mbps, the throughput is about 0.33 Mbps. The results give an upper bound on the throughput that a fixed rate algorithm can achieve, which are verified by the simulation results in Section VI.

B. Throughput Improvement in ERBAR

In this subsection, we compare the maximum throughputs of three schemes: RBAR, RBAR with MVCS, and ERBAR.

RBAR with MVCS versus RBAR: When the original VCS is used, the RBAR transmits the RSH sub-header of the Data frame at the same rate as that of RTS (i.e., 1 Mbps). Moreover, RSH sub-header needs a separate four-byte FCS. On the contrary, with MVCS all these are unnecessary. Therefore, using eq. (5), the ratio between the maximum throughputs of the RBAR with MVCS and the RBAR is:

$$r = \frac{C_{phy} + 8(48/R_{RTS} + 14/R_{CTS} + (L+4)/R_{Data} + 14/R_{ACK})}{C_{phy} + 8(20/R_{RTS} + 14/R_{CTS} + (L+28)/R_{Data} + 14/R_{ACK})} \tag{6}$$

ERBAR versus RBAR with MVCS: Under ERBAR, we assume that all the control frames are transmitted at the same rate as the Data frame, therefore the ratio is:

$$r = \frac{C_{phy} + 8(20/R_{RTS} + 14/R_{CTS} + (L+28)/R_{Data} + 14/R_{ACK})}{C_{phy} + 8(20/R_{Data} + 14/R_{Data} + (L+28)/R_{Data} + 14/R_{Data})} \tag{7}$$

ERBAR versus RBAR: It is easy to get the ratio as:

$$r = \frac{C_{phy} + 8(48/R_{RTS} + 14/R_{CTS} + (L+4)/R_{Data} + 14/R_{ACK})}{C_{phy} + 8(20/R_{Data} + 14/R_{Data} + (L+28)/R_{Data} + 14/R_{Data})} \tag{8}$$

Figures 4, 5, and 6 present the results computed from the equations (6), (7), and (8), respectively. Note that in Figure 5 when the R_{Data} is equal to 1 Mbps, the ratio is always equal to *one*, thus not shown in the figure. From these results, we see that when all the other parameters are fixed, as R_{Data} increases, the throughput ratio also increases. In fact, one can formally prove this by showing that the first-order derivative with respect to R_{Data} is always greater than zero. On the other hand, the first-order derivative with respect to C_{phy} is always smaller than zero, implying that a smaller C_{phy} leads to a higher ratio. This is also true with respect to L. However, when L increases, the throughput also increases as shown in Figure 3. Therefore, though the ratio is decreasing with the increase in L, the absolute throughput improvement (in terms of Mbps) is increasing, which is also observed from the simulation results in Section VI. The above properties of the ratio are crucial because the C_{phy} will become smaller while the R_{Data} will become larger as the IEEE 802.11 evolves. For example, in the IEEE 802.11a [4], the C_{phy} is reduced to 226.5 μs, while the R_{Data} can reach 54 Mbps.

VI. SIMULATION RESULTS

The simulations were performed under the NS-2 with CMU wireless extensions [2]. As in [10], we use the fading model with Ricean probability density that has been incorporated into the NS-2 by the authors of [8]. In the simulation, seven different algorithms are considered. Four of them are run at a fixed transmission rate while the other three are RBAR, RBAR with MVCS, and ERBAR. We conduct the simulation with five different packet lengths, i.e., 64, 128, 256, 512, 1024 bytes. For each of the flows, the source rate is large enough to occupy the whole bandwidth. The nominal transmission range is 250 meters. The maximum speed of mobility is 5 m/s while the pause time is zero. All the simulations are run for 250 seconds.

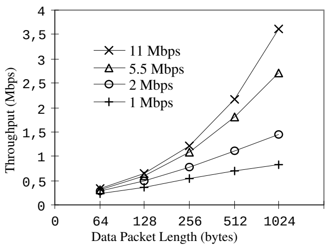

Fig. 3. Maximum Throughput in IEEE 802.11b

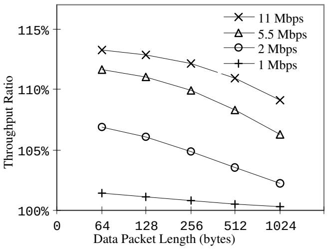

Fig. 4. Throughput Ratio between RBAR with MVCS and RBAR

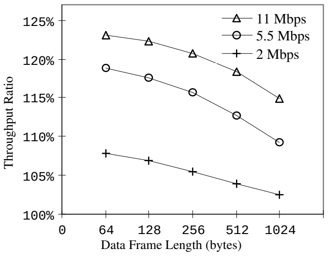

Fig. 5. Throughput Ratio between ERBAR and RBAR with MVCS

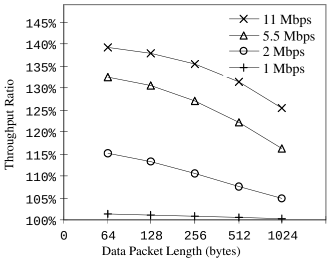

Fig. 6. Throughput Ratio between ERBAR and RBAR

A. Single Flow within Single-hop

In this simulation, there are only two nodes, which are continuously moving within a 200×200 meter arena. Figure 7 presents the average throughputs. It is easy to see that the algorithms with adaptive rate have better performance than the algorithms with fixed rate. Within the fixed rate algorithms, the one at the rate 5.5 Mbps shows the best performance. Moreover, for all the fixed rate algorithms, the throughputs conform to the upper bound derived in Section V.A.

Among the adaptive algorithms, as expected, the ERBAR shows the best performance while the RBAR with MVCS is the second best. Moreover, the longer the packet length is, the more absolute gain is achieved by the ERBAR over the RBAR. However, the results are somewhat different from the viewpoint of throughput ratio, which is presented in Figure 8. The larger the packet length, the smaller is the ratio, which has also been reflected by the analytical results. The ratio obtained from the simulation is smaller than that from the analytical results at the rate of 5.5 Mbps. The reason is, in the analysis the rate of RTS/CTS under ERBAR is assumed equal to the rate of the Data frame, which is not always true in practice.

B. Multiple Flows within Single-hop

In this simulation, there are ten nodes with five flows and all the nodes are moving within a 200×200 meter arena. Figure 9 presents the aggregate average throughput of all the flows. In general, the performance among the seven algorithms follows the same trend as in the previous scenario except for the following two observations: *(i)* among the fixed rate algorithms, it is the algorithm with 11 Mbps that shows the best performance rather than the one with 5.5 Mbps; and *(ii)* the throughput under RBAR is very close to the fixed rate algorithm with 11 Mbps. The reason for the first observation is as follows. Under the fixed rate algorithm with 11 Mbps, all the transmissions experiencing an SNR that is not large enough to support 11 Mbps will fail, making the flows continuously back off and defer. Moreover, since in this scenario 10 nodes are present within a small area, it is very likely that at least one of the flows can support the 11 Mbps. Therefore, most of the time the medium is occupied by the flows with 11 Mbps, explaining why the 11 Mbps gets the best performance in this scenario. On the other hand, in the previous scenario in which only two nodes are present, the nodes may be far apart most of the time, and thus not able to communicate at 11 Mbps, explaining why the 5.5 Mbps gets the best performance. Now we explain the second observation. Compared to the fixed rate algorithm with 11 Mbps, the RBAR will allocate more time to the flows that can only support rates lower than 11 Mbps, reducing the aggregate throughput of RBAR. On the other hand, the time wasted in the fixed rate algorithm by the flows that cannot support 11 Mbps is greatly reduced by the RBAR since it can adapt to the channel conditions. The above two effects cancel out each-other, and finally lead to similar performance for the two algorithms. However, the RBAR is better as it is fairer than the fixed 11 Mbps algorithm.

C. Multiple Flows within Multi-hop

In this scenario, there are twenty nodes with five flows and all the nodes are moving within a 1000×500 meter arena. AODV [7] is used as the routing protocol. Figure 10 presents the aggregate average throughput of all the flows. The performance of the adaptive rate algorithms follows the same trend as in the previous examples, i.e., the ERBAR is the best, followed by RBAR with MVCS, and then by RBAR. However, in terms of the aggregate throughput, the adaptive algorithms do not show any distinct advantage compared to some of the fixed rate algorithms. For example, the fixed rate algorithm with 5.5 Mbps always shows the best performance, while RBAR is inferior to most of the fixed rate algorithms except the one with 1 Mbps. Through detailed analysis of the simulation traces, we found that the interaction between MAC layer and the routing protocol plays a major rule in determining the performance. Under a fixed rate, whether or not a multi-hop flow can start depends on whether that flow can find a route from the source to the destination with all the hops having that fixed rate. When the fixed rate is very high (e.g., 11 Mbps), it is very likely that sometimes no flows in the network can find a route. On the other hand, when the fixed rate is very low (e.g., 1 or 2 Mbps), all the flows may be active but the medium is used at a very low rate. This explains why the 5.5 Mbps gets the best performance. Under the adaptive rate algorithms, it is very likely that all the flows find a route since the nodes can adjust the rate based on the channel conditions. Therefore, though the aggregate throughputs of the adaptive algorithms may be smaller than that under some of the fixed rate algorithms, the bandwidth is more evenly distributed among the flows.

VII. CONCLUSIONS

In this paper, we have introduced an enhanced receiver based auto rate (ERBAR) protocol, which extends the RBAR [3] in two manners. First, we have proposed the modified virtual carrier sensing (MVCS) mechanism that reserves the medium only for the next frame in the sequence rather than for all the remaining frames as done in the RBAR. The MVCS greatly reduces the overheads as well as the complexity. The second proposal, which is based on the MVCS, is the rate adaptation algorithm that aims to transmit the control frames at the highest attainable rate under the given channel conditions rather than always at a basic rate. To study the performance of ERBAR, both analytical and simulation methods are used, which show that the ERBAR greatly improves the performance of RBAR. Further improvements are possible by refining the routing protocols to enable them to make full use of the multi-rate capability provided by the MAC layer.

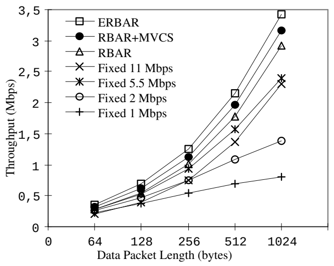

Fig. 7. Throughput under Single Flow within Single-hop

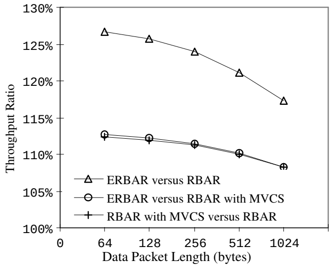

Fig. 8. Throughput Ratio among Adaptive Rate Algorithms

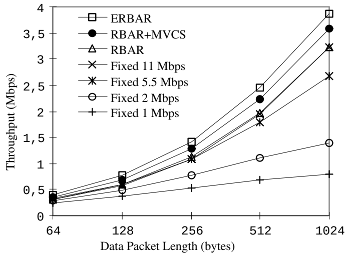

Fig. 9. Throughput under Multiple Flows within Single-hop

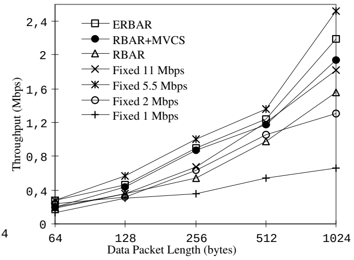

Fig. 10. Throughput under Multiple Flows within Multi-hop

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