Efficient Multi-rate Relaying (EMR) MAC Protocol for Ad hoc Networks

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***Abstract*—In this paper, we propose a multi-rate CSMA/CA-based MAC protocol, which we refer to as EMR, to enable fast forwarding of frames in a more efficient manner. We use the base-rate RTS and CTS frames to reserve a long transmission path and utilize intermediate nodes to relay the data frames using shorter transmission distance but with more efficient transmission rates. Results show that our EMR scheme can outperform the traditional multi-rate forwarding scheme by 18% and 49.4% in a low-density and high-density ad hoc network, respectively.**

Keywords-component; Multi-rate MAC, Relaying, ad hoc network , performance analysis.

I. INTRODUCTION

In a multi-rate network, long distance links operate at the slowest available rate, thus achieving low effective throughput. Intermediate nodes that are situated along the transmission path of a long distance link always remain silent during the ongoing transmission. This gives rise to the interesting possibility that, these nodes can actually offer a higher throughput relaying service to the original long distance link by using higher transmission rates. In this paper, we will explore an enhanced CSMA/CA MAC protocol design known as Enhanced Multi-rate Relaying (EMR) that relies on multi-rate capability and a relaying scheme to improve the throughput of wireless systems. In [4], an improved metric known as medium time metric (MTM) was proposed for route selection in a multi-rate ad hoc network. The scheme selects paths that have higher effective throughput instead of the minimum hop paths that have long but slow links. The MTM scheme however increases the number of contention and the queuing delay due to increase in hop count. Unlike the MTM scheme, we use the traditional shortest path routing to form the main route and subsequently use a secondary local messaging technique to transform the overall route to a multi-rate route. We propose a modification to the standard 4-way handshake of the CSMA/CA MAC protocol such that the contention and queuing is minimized when compared to the MTM scheme.

II. EFFICIENT MULTI-RATE RELAYING MAC (EMR)

In CSMA/CA protocols such as 802.11, the short RTS and CTS frames are used to reserve the channel and prevent collision due to hidden terminal problems. In 802.11b, even when the chosen transmission rate for data is higher, all RTS/CTS frames must be sent at the base rate, to ensure that all stations in the vicinity are able to receive the messages error free. In addition to this, the physical layer header for all frames including DATA and ACK frames are also modulated using the base rate. This is to ensure that the receiver is able to lock-on to the incoming message and synchronize the packet reception. In the EMR scheme, the primary routing protocol such as AODV, DSDV, etc. can be used to form the main route from sender to destination. Naturally, this main route has the least hop count with mostly long-range transmissions. A secondary protocol that operates locally between two consecutive nodes along the main path is used to select the relays. These relays, when combined with the nodes that form the main route, eventually form a multi-rate route.

A. Message Sequence

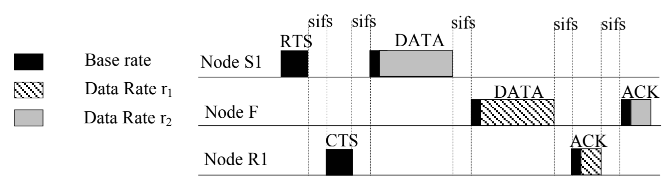

Figure 1. EMR MAC message sequence

The EMR MAC protocol message sequence is shown in Fig 1 above. Physical location of nodes S1, R1 and F are depicted in Fig 2a below. In Fig 2a, we assume that nodes S1 and R1 are reachable only by using the base rate of 1 Mbps. However, node F is capable of communicating with nodes S1 and R1 at data rates r_2 and r_1, respectively. A relay selection scheme, to be discussed later, is used to select node F. Node S1 sends out a RTS frame using the base rate and an encoded priority value. The use of a priority value greater than 1, explicitly informs the relay node and the receiver that this new message sequence will be used. The sender S1's and receiver R1's addresses are encoded as usual in the RTS frame. Node R1 also replies with a CTS using the base rate. Based on the pre-agreed transmission rate supplied by relay F, nodes S1 and R1 will calculate the appropriate timeout period required for this message sequence and encodes the value in the Network Allocation Vector (NAV). Once S1 receives the CTS, it will transmit the DATA frame to the relay using rate r_2. The destination address field in the DATA frame is replaced with the relay address. If the relay node receives the data successfully, it will now adjust the transmission rate to r_1 and re-send the DATA frame to receiver R1. The destination address field is encoded with receiver R1's address. Once node

R1 receives the DATA frame correctly, it sends the ACK in the reverse direction using rate r_1. The ACK frame is then relayed by node F to S1 using rate r_2. If the ACK frame is received by S1 correctly, the transmission is completed. The scheme essentially reserves an efficient multi-rate path with the same RTS-CTS overheads of the single rate scheme.

B. *Relay selection*

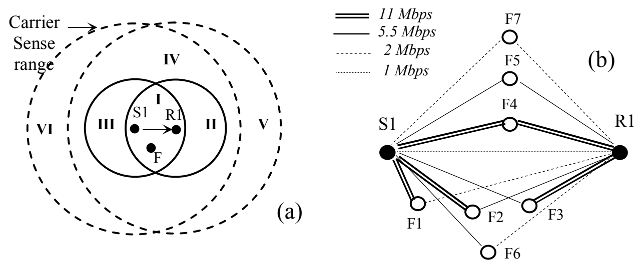

Figure 2. (a) Transmission Ranges and Regions (b) Example relay positions and link rates

Path	Path 1 capacity (Mbps)	Path 2 capacity (Mbps)	Effective Throughput (Mbps)	Priority
S1-R1	11	-	4.6885	10
S1-R1	5.5	-	3.2601	9
S1-F4-R1	11	11	2.9063	8
S1-F2-R1	11	5.5	2.2853	7
S1-F3-R1	5.5	11	2.2853	7
S1-F5-R1	5.5	5.5	1.8833	6
S1-R1	2	-	1.5777	5
S1-F1-R1	2	11	1.3078	4
S1-F6-R1	5.5	2	1.1653	3
S1-R1	1	-	0.8712	2
S1-F7-R1	2	2	0.8436	1

TABLE I. EFFECTIVE THROUGHPUT AND PRIORITY VALUES FOR VARIOUS RELAY COMBINATION

In EMR, we want to select the path that gives the best effective throughput. To estimate distances between relay and sender or receiver, relay nodes passively listen to the RTS and CTS frames transmitted at the base rate. The physical layer of the radio transceiver in 802.11 is capable of measuring the received signal strength, which can be used to estimate the distance to another node if the received frame is free of error. Fig 2a above shows the transmission range, carrier sense range and regions of a typical IEEE 802.11 system. In Fig 2b, we assume that nodes S1 and R1 can only communicate to each other using the base rate and this link is one of the hops discovered by the primary routing protocol. In Fig 2a above, the ideal nodes that act as relays are situated in region I since they receive both the RTS and CTS frames sent out by the sender S1 and the receiver R1, respectively. Consider the relay positions shown in Fig 2b above. Each of the relays contributes to different effective throughput when packets are sent via the relays. Based on the EMR scheme and data packet size of 1500 bytes, the effective throughput assuming no loss in the wireless channel for various combinations of sender-relay-receiver or sender-receiver paths are shown in Table I. The effective throughput of each sender-relay-receiver link combination is also mapped to a priority value as shown in Table I. A high priority value indicates a higher preference. In our design, it is possible for the primary routing protocol to discover shorter links even before the secondary scheme is used. This could especially happen for the last or the first link of the entire end-to-end route. For such links, relays might not be necessary if the direct S1-R1 link rates are more favorable.

C. *Relay discovery and selection*

In EMR, we encode the current link priority value into the RTS and CTS frames. The priority value, which is a 4-bit value, can be encoded into the unused fields of the Frame Control Field in RTS and CTS frame. In EMR, the multi-rate relaying path is not formed immediately after the shortest path route is discovered but after a relay selection process is used. We refer to Fig 2a to illustrate the selection process. If the initial capacity between nodes S1 and R1 is 1 Mbps, node S1 will set its priority value to 2 according to Table I. It will send out an RTS frame to node R1 using the base rate. Node R1 will also set the priority value similar to S1 and reply with the CTS frame. The relaying nodes that are in region I (Fig 2a) will be able to receive both the RTS and CTS frames. These relays will calculate the received signal strength for the RTS and CTS frames, deduce the effective link capacity and compute the appropriate priority value based on Table I. If the priority value computed by the relay is higher than the current priority, it will then send out a relay request broadcast packet, RELAY_RQST, to the sender S1. The RELAY_RQST message consists of the relay address and the path priority value. Sender S1 might possibly receive several RELAY_RQST messages from the other relays in the vicinity. Node S1 will select the best possible relaying node that has the highest priority value and send out a relay respond message, RELAY_RES, to the selected relay. The RELAY_RES message contains the selected relay address and the agreed priority value. This relay will then be used for the subsequent data transmission and the new priority value will be encoded into the subsequent RTS frames sent out by node S1. In case of persistent data transmission failures due to loss of connectivity to a selected relay, node S1 can reset its priority value to a low value. This will trigger relays that can offer higher throughput links to start sending RELAY_RQST packets again. The process of selection repeats itself.

III. THROUGHPUT ANALYSIS

We extend the model proposed by [6] and limit the analysis of the throughput to the links shown in Fig 2b above. This approach is still valid since the links considered are co-located and are within range of each other when the base rate contention with RTS is used. To study the multi-hop capacity, we assume that the links formed by nodes S1, F and R1 form a subset of a longer end-to-end path. The two main objectives of this performance analysis are to study the throughput performance of the MTM and EMR protocol under two different cases, i.e. due to 1) packet error and 2) contention. For all cases, we assume that the contending nodes reside in region I as shown in Fig 2a. To compute the throughput of the two different schemes, we extend the model proposed by [6] by considering the packet error probability and blocking probability due to hidden terminal interference. For the subsequent performance study, we assume that a constant amount of noise is generated from the surrounding nodes and all nodes are affected in the same manner. In a multi-hop network, it is common for senders to sense an idle channel state while receivers sense a busy channel state. Such a phenomenon causes severe throughput degradation in ad hoc networks [5] when the receivers do not reply to the RTS frame and the senders keep doubling their contention window. It is essential that we take into account this phenomenon, while studying the throughput of the two MAC protocols. For the remaining part of this paper, we quantify this parameter as the blocking probability, p_b. Similar to the channel noise assumption, we assume that nodes in region I as shown in Fig 2a are subjected to the same blocking probability.

A. Error Probability Model

In this paper, we consider the bit error probabilities of the different modulation schemes used in IEEE 802.11b under Additive White Gaussian Noise Channel (AWGN). The bit error probability (P_{be}) equations, for BPSK, QPSK and CCK can be easily obtained from [3] and substituted into (1) to obtain the signal to noise ratio (SNR).

$$SNR = \frac{E_b}{N_0} \cdot \frac{R_b}{B_t} \tag{1}$$

In (1), E_b, R_b, B_t and N_o, are the signal energy per bit, the maximum bit rate of the modulation scheme, the system bandwidth and the noise per bit, respectively. To calculate the path loss at a distance d, given by $P_l(d)$, we use the log-distance path loss model given by the following expression

$$P_l(d) = P_l(d_0) + 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{2}$$

where $P_l(d_0)$ is the median path loss at the reference distance of 1 meter and n is the path loss coefficient. We let the propagation model consist of two parts: 1) free-space propagation for distances less than the Friis cutoff distance, d_{friss} and 2) two-ray ground propagation for distances greater than d_{friss}. The path loss exponent, n, for the two propagation models are 2 and 4, respectively. We use the standard Orinoco Wireless Interface parameters [1], which are also used in NS-2 [2]. Consequently, the path loss in dB is given as

$$P_l(d) = 31.66 + 20 \cdot \log(d) \qquad \text{if } d < d_{friss} \tag{3}$$

$$P_l(d) = 70.365 + 40 \cdot \log(d/d_{friss}) \qquad \text{if } d > d_{friss} \tag{4}$$

Given the path loss, the receiver sensitivity, P_{rx} can be expressed in terms of the transmission power, P_{tx} as

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - P_l(d) - L_{fade} \tag{5}$$

where G_{tx}, G_{rx} and L_{fade} are the transmitter antenna gain, receiver antenna gain and fade margin, respectively. In addition, the receiver sensitivity, P_{rx}, can be expressed in terms of SNR by

$$P_{rx} = N_t + N_f + SNR \tag{6}$$

where N_f and N_t are the noise figure and noise floor, respectively. From (5) and (6), we are able to use the SNR value to compute the BER for different distances of d.

B. Enhancement to Bianchi's Markov Chain Model

We now discuss the enhancements to the model proposed by [6] with additional consideration for frame error probability and blocking probability. For convenience, we reuse the notations found in [6]. In [6], the conditional collision probability p, which we refer to as p_c in this paper, was the only factor that affected the transitions in the Markov Chain Model. We reuse the same Markov Chain Model proposed in [6] but assume that a new conditional probability, p_f, which we term as the conditional probability of failure, causes the states to transition in the same fashion. We note that this failure event consists of three independent but not necessarily mutually exclusive events, i.e. collision, blocking due to hidden terminal interference and frame error due to noise. Since any one of these events can cause the binary backoff window to double, we state the conditional probability of failure as

$$p_f = p_c + p_e + p_b - p_c p_e - p_c p_b - p_b p_e + p_b p_e p_c \tag{7}$$

where p_c is the conditional probability of collision, p_b is the conditional blocking probability and p_e is the conditional probability of packet error due to channel noise.

From [6], the probability τ that a station transmits in a randomly chosen slot time is given as

$$\tau = \frac{1 - p_f^{m+1}}{1 - p_f} b_{0,0} \tag{8}$$

where $b_{0,0}$ is given as

$$b_{0,0} = \frac{2(1-2p_f)(1-p_f)}{(1-2p_f)(W+1) + pW(1-(2p_f)^m)} \tag{9}$$

where m is the maximum backoff stage, W is the minimum window size. These values are set to 5 and 32, respectively. Instead of p used in [6], we express p_c as

$$p_c = 1 - (1-\tau)^{n-1} \tag{10}$$

where n is number of nodes directly contending with each other within the transmission range.

In the subsequent expressions, we assume that a packet of size L is transmitted using the PHY mode r, where r = 1, 2, 3, 4 represents the PHY rates of 1, 2, 5.5 and 11 Mbps, respectively. Since the conditional probability of frame error, p_e, is independent of τ, for the MTM scheme, we can express p_e as

$$\begin{aligned} p_e &= 1 - P_{succ}^r(L) \\ &= 1 - (1 - P_{e\_rts}^1)(1 - P_{e\_cts}^1)(1 - P_{e\_data}^r(L))(1 - P_{e\_ack}^r) \end{aligned} \tag{11}$$

where $P_{succ}^r(L)$ is the probability of successful transmission of a L-byte packet; $P_{e\_rts}^1$, $P_{e\_cts}^1$, $P_{e\_data}^r(L)$ and $P_{e\_ack}^r$ are the error probabilities for the RTS, CTS, DATA and ACK frames, respectively. Notice that RTS and CTS are always transmitted at base rate. For the EMR scheme, p_e can be expressed as

$$p_e = 1 - P_{succ}^r(L) = 1 - (1 - P_{e\_rts}^1)(1 - P_{e\_cts}^1) \cdot$$

$$(1-P^{r1}_{e\_data}(L))(1-P^{r2}_{e\_data}(L))(1-P^{r1}_{e\_ack})(1-P^{r2}_{e\_ack}) \quad (12)$$

where *r1* and *r2* signify the rates used by the relay in Fig 2b above. Based on the 802.11 Physical layer PDU format, we can express

$$P^{r}_{e\_data}(L) = 1-(1-P^{1}_{e}(24))\cdot(1-P^{r}_{e}(28+L)) \quad (13)$$

where $P^{1}_{e}(24)$ is the probability of error due to the transmission of the PLCP header using PHY mode 1 and $P^{r}_{e}(28+L)$ is the probability of error for the MPDU when mode *r* is used. The frame error probability $P^{r}_{e}(L)$, for different modes and distances, *d*, can be computed by using the BER value, P^{r}_{b}, obtained from the following equation. The value, *8L*, in equation (14) represents the number of bits in the frame.

$$P^{r}_{e}(L) = 1-(1-P^{r}_{b})^{8L} \quad (14)$$

As mentioned earlier, we will assume a constant blocking probability in this analysis. Since blocking is an independent event, we can easily substitute p_b and p_e into equation (7). Using numerical techniques, the unknowns p_f and τ can be solved by considering the equations (7), (9) and (10).

C. Computing Throughput

Similar to [6], we consider the saturation throughput in this analysis. The single link saturation throughput, S_{link}, for a MAC scheme, can be expressed as

$$S_{link} = \frac{\text{E[payload information transmitted in a slot time]}}{\text{E[length of slot time]}} \quad (15)$$

In the MTM scheme, we analyze two adjacent links as a single end-to-end link, whereas in EMR, we consider the two-hop links via the relay as a single end-to-end link. Since the two adjacent links are within contention range of each other, the end-to-end throughput for the MTM scheme, S_{MTM}, for nodes S1 to R1 can be approximated as

$$S_{MTM} = \frac{S^{MTM}_{link1}\cdot S^{MTM}_{link2}}{S^{MTM}_{link1}+S^{MTM}_{link2}} \quad (16)$$

where S^{MTM}_{link1} is the maximum throughput of the first link assuming that only the first link, denoted by link S1-R, exist in the circular area shown in Fig 2b. Similarly S^{MTM}_{link2} is computed by assuming that only the second link exists in region I of Fig 2a. We modify the expression obtained from [6] by adding the packet error and blocking events. S^{MTM}_{link1} can be expressed as:

$$\frac{P_s E[P]}{P_i\sigma + P_s T^{MTM}_{s} + P_c T_c + P_b T_c + P_{e1} T_{e\_rts} + P_{e2} T_{e\_cts} + P_{e3} T^{MTM}_{e\_data} + P_{e4} T^{MTM}_{e\_ack}} \quad (17)$$

In equation (17), we assume that collisions are due to two or more packets colliding, therefore resulting in indiscernible information whereas frame error happens when there is only a single transmission and packet is received properly but with wrong frame check sequence (FCS). Frames with errors will normally trigger the EIFS backoff. The fractional error probabilities P_{e1}, P_{e2}, P_{e3} and P_{e4} are used to express the probability of frame error at different stages of the entire RTS-CTS-DATA-ACK message exchange for the MTM scheme. The values, P_i, P_s, P_c and P_b denote the probability of idle, probability of success, probability of collision and probability of blocking during the interval of the slot time, respectively. The term *E[P]*, denotes the average payload transmitted in slot time. The values, σ, T^{MTM}_{s}, T_c, represent the average time of an empty slot time, average time of a successful message exchange and average time due to collision, respectively. Whereas the terms T_{e_rts}, T_{e_cts}, $T^{MTM}_{e\_data}$, $T^{MTM}_{e\_ack}$, denote the average time incurred at the various stages of frame error during the entire message exchange. The various probability expressions and parameters are expressed as follows.

$$\begin{aligned}
P_s &= n\tau(1-\tau)^{n-1}\cdot(1-p_e)\cdot(1-p_b)\\
P_{str} &= n\tau(1-\tau)^{n-1}\\
P_i &= (1-\tau)^n\\
P_c &= 1-n\tau(1-\tau)^{n-1}-(1-\tau)^n\\
P_b &= P_{str}\cdot p_b\\
P_{e1} &= P_{str}\cdot P^{1}_{e_rts}\\
P_{e2} &= P_{str}\cdot(1-P^{1}_{e_rts})\cdot P^{1}_{e_cts}\\
P_{e3} &= P_{str}\cdot(1-P^{1}_{e_rts})\cdot(1-P^{1}_{e_cts})\cdot P^{r}_{e_data}\\
P_{e4} &= P_{str}\cdot(1-P^{1}_{e_rts})\cdot(1-P^{1}_{e_cts})\cdot(1-P^{r}_{e_data})\cdot P^{r}_{e_ack}
\end{aligned} \quad (18)$$

$$\begin{aligned}
T_c &= RTS^1 + DIFS + \delta\\
T_{e_rts} &= RTS^1 + \delta + EIFS\\
T_{e_cts} &= RTS^1 + SIFS + \delta + CTS^1 + \delta + EIFS\\
T^{MTM}_{e_data} &= RTS^1 + SIFS + \delta + CTS^1 + SIFS + \delta + DATA^r + \delta + EIFS\\
T^{MTM}_{e_ack} &= T^{MTM}_{e_data} + SIFS + ACK^r + \delta\\
T^{MTM}_{s} &= RTS^1 + SIFS + \delta + CTS^1 + SIFS + \delta\\
&\quad + DATA^r + SIFS + \delta + ACK^r + DIFS + \delta
\end{aligned} \quad (19)$$

The term P_{str} in (18), denotes the probability that only a single transmission occurs. The $DATA^r$ and ACK^r terms shown in equations (19) include the physical layer headers and the superscript *r* represents the transmission mode used.

$$\begin{aligned}
P_{e5} &= P_{str}\cdot(1-P^{1}_{e_rts})\cdot(1-P^{1}_{e_cts})\cdot P^{r1}_{e_data}\\
P_{e6} &= P_{str}\cdot(1-P^{1}_{e_rts})\cdot(1-P^{1}_{e_cts})\cdot(1-P^{r1}_{e_data})\cdot P^{r2}_{e_data}\\
P_{e7} &= P_{str}\cdot(1-P^{1}_{e_rts})\cdot(1-P^{1}_{e_cts})\cdot(1-P^{r1}_{e_data})\cdot(1-P^{r2}_{e_data})\cdot P^{r2}_{e_ack}\\
P_{e8} &= P_{str}\cdot(1-P^{1}_{e_rts})\cdot(1-P^{1}_{e_cts})\cdot(1-P^{r1}_{e_data})\cdot\\
&\quad (1-P^{r2}_{e_data})\cdot(1-P^{r2}_{e_ack})\cdot P^{r1}_{e_ack}
\end{aligned} \quad (21)$$

$$\begin{aligned}
T^{EMR}_{e_data1} &= RTS^1 + SIFS + \delta + CTS^1 + SIFS + \delta + DATA^{r1} + \delta + EIFS\\
T^{EMR}_{e_data2} &= T^{EMR}_{e_data1} + SIFS + DATA^{r2} + \delta\\
T^{EMR}_{e_ack1} &= T^{EMR}_{e_data2} + SIFS + ACK^{r2} + \delta\\
T^{EMR}_{e_ack2} &= T^{EMR}_{e_ack1} + SIFS + ACK^{r1} + \delta
\end{aligned} \quad (22)$$

$$S_{link}^{EMR} = \frac{P_s E[P]}{P_i\sigma + P_s T_s^{EMR} + P_c T_c + P_b T_c + P_{e1} T_{e\_rts} + P_{e2} T_{e\_cts} + P_{e5} T_{e\_data1}^{EMR} + P_{e6} T_{e\_data2}^{EMR} + P_{e7} T_{e\_ack1}^{EMR} + P_{e8} T_{e\_ack2}^{EMR}} \quad (20)$$

$$T_s^{EMR} = RTS^1 + SIFS + \delta + CTS^1 + SIFS + \delta + DATA^{r1} + SIFS + \delta + DATA^{r2} + SIFS + \delta + ACK^{r1} + DIFS + \delta + ACK^{r2} + DIFS + \delta \quad (23)$$

The throughput for the EMR scheme can be expressed by equation (20). Similar to (17), the fractional error probabilities P_{e1}, P_{e2}, P_{e5}, P_{e6}, P_{e7}, P_{e8}, express the frame error at different stages of the entire RTS-CTS-DATA-DATA-ACK-ACK message exchange for the EMR scheme. T_s^{EMR} represents the average time of a successful EMR message exchange. Whereas the terms T_{e_rts}, T_{e_cts}, $T_{e\_data1}^{EMR}$, $T_{e\_data2}^{EMR}$, $T_{e\_ack1}^{EMR}$, $T_{e\_ack2}^{EMR}$, denote the average time incurred at the various stages of frame error during the EMR message exchange. The various probability expressions and parameters for the EMR scheme are expressed in equations (21), (22) and (23). Rates *r1* and *r2* in equations (22) and (23) signify the first and second link rates, respectively.

IV. Performance Evaluation

The results in this section have been obtained by using the standard parameters used in 802.11b and a data packet size of 1500 bytes. The nodes S1 and R1 are placed at a distance of 220 m from each other such that only the base rate of 1 Mbps can be used to communicate directly. The position of relay F is varied within region I as shown in Fig 2a to compute the aggregate throughput of the end-to-end links from S1 to R1. We will compare the two MAC schemes under low, medium and heavy node density settings but under a constant blocking probability factor of 0.5. Note that, while the total number of nodes (Fig 2b), *m*, in the two systems is the same; the number of contending nodes, *n*, in MTM is always indicated as double that of EMR for equal comparison. Table II shows the maximum and minimum aggregate end-to-end throughput of the two schemes under various node densities, no added noise interference and a fixed blocking probability of 0.5.

m	MTM *N*	EMR *n*	**MTM** - Aggregate Throughput (Mbps)		**EMR** - Aggregate Throughput (Mbps)	
			Max	Min	Max	Min
3	2	1	1.57	0.74	1.86	0.73
300	200	100	1.87	0.87	2.61	0.98
600	400	200	1.68	0.82	2.51	0.96

TABLE II. Aggregate End-to-End Throughput for MTM and EMR scheme - No Noise interference

Based on Table II, under low density (m = 3 nodes), the throughput of EMR scheme only exceeds the MTM scheme by 18.5%. Under medium contention, when the number of contending nodes in MTM and EMR are 200 and 100, respectively, the throughput of the EMR scheme shows a significant improvement of 39.6% over the MTM scheme. When the number of contending nodes in MTM and EMR are 400 and 200, respectively, the throughput of EMR scheme exceeds MTM by 49.4%. Figure 3 shows the throughput of the EMR schemes under a uniform noise interference of 3 dBm from the surroundings. The MTM scheme records a maximum and minimum throughput value of 1.37 kbps and 0.47 kbps, respectively. The throughput of the two systems drop but the improvement of EMR over MTM is only 13.1% as compared to the 18.5% improvement shown in Table II for the same number of nodes. This shows that under noise interference, the EMR scheme degrades faster compared to MTM. This is due to the fact that the RTS and CTS packets in EMR need to propagate further to secure the link as compared to the MTM case. Naturally, under a noisy environment, the base rate RTS and CTS packets will be affected the most in the EMR case.

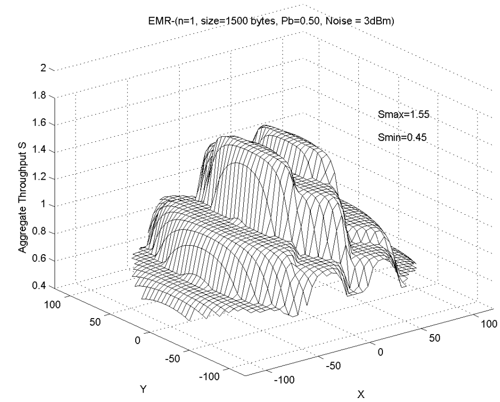

Figure 3. EMR with low density and added noise of 3dBm

V. Conclusion

In this paper, we introduced a new multi-rate relaying MAC protocol known as EMR, which is able to utilize the traditional shortest path routing algorithm and a localized secondary forwarding scheme to improve the throughput of a multi-hop network. We also enhanced an existing analytical model proposed by Bianchi [6], which is primarily used to study the performance of CSMA/CA in WLAN networks. We enhance the model by including factors such as blocking probability due to hidden terminal interference and noise interference to study the performance of our protocol. The throughput performance of the EMR scheme has been carefully studied and is shown to perform much better than the previously proposed multi-rate scheme.

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