Effects of Hidden Terminals and their Alleviation in Multi Rate Ad Hoc Networks

Ms. Sunita Varma
Deptt. of Computer Technology and application
. Shri G.S. Institute of Technology and Science
Indore, India
Sunita.varma19@gmail.com

Dr.(Mrs.) Vrinda Tokekar
Deptt. of Information Technology
Institute of Engineering and Technology
Indore, India
vrindatokekar@yahoo.com

Abstract— In multi rate ad hoc networks the hidden terminal problem is unique and there is a limited understanding of its effect on network performance. In this paper we studied the effects of hidden terminals in multi rate mobile ad hoc networks environments. In IEEE 802.11 base WLANs only the nodes which are within the transmission range of receiver can become the hidden nodes, where as the nodes falling within interference range of the receiver are not the part of WLAN. IEEE 802.11 standard strongly addresses the issues of those hidden nodes which are within the transmission range. In this paper we have shown that in multi rate ad hoc networks the nodes falling within the interference range can also act as hidden terminals. These hidden terminals can have detrimental effect on the performance of the multi rate ad hoc networks that can not be solved by conventional RTS/CTS mechanism of IEEE 802.11. In the present study a mechanism has been proposed by adjusting the required transmit power and maintaining receiver side Signal to Interference and Noise Ratio (SINR) above threshold value to nullify the presence of such hidden terminal. The results indicate an improved performance of multi rate ad hoc networks by employing such mechanisms.

Keywords-component: multi rate ad hoc networks, hidden terminal, transmission range, interference range, SINR, RTS, CTS.

I. INTRODUCTION

The ad hoc wireless networks are multi hop wireless networks without the support of established infrastructure or centralized administration. Each mobile host in an ad hoc network functions as a router to establish end-to-end multi hop connection between any two nodes. The application areas of such networks include battle fields, emergency searches, rescue sites and data acquisition in remote access [1]. The emerging radio interfaces such as IEEE 802.11 a/b/g can provide multi rate capabilities to ad hoc networks. For instance the popular IEEE 802.11b can dynamically select data rates between 1, 2, 5.5 and 11 Mbps based on channel conditions [2]. The transmission and interference range of the terminals vary with the data rates in multi rate environments. As the data rate of the node increases the transmission range decreases and the interference range of the node increases [3].

There are several issues related to performance of wireless networks. One of the major issues to be addressed in wireless network is hidden terminal problem. The hidden terminal problem adversely affects the performance of the wireless network. The effects of hidden terminal problem have been addressed in traditional WLAN very effectively in IEEE 802.11 through DFWMAC [4]. In this paper conventional hidden terminal problem is called type-1 hidden terminal problem. In multi rate ad hoc networks the hidden terminal problem is unique and there is a limited understanding of its effect on network performance. Such an effect is quite prominent in this network due to their multi hop nature and limited transmission range. Various researchers have attempted to address this issue [5] [6] [7] [8]. However, still certain aspects need more attention and need to be explored. One of this is the existence of nodes falling within the interference range of the multi rate ad hoc networks. Fig. 1 represents an ad hoc network setup consisting of five terminals as A, B, C, D and X with multi rate data transmission capability. The terminals A and B are within the transmission range of each other. The terminals C and D are in the transmission range of terminals A and B respectively. However node C is hidden to B and node D is hidden to node A. The node such as X, when transmits data to another node falling within its transmission range also causes noise to nodes which are within its interference range, such as nodes A and B. Thus deteriorate the signal quality of nodes A and B.

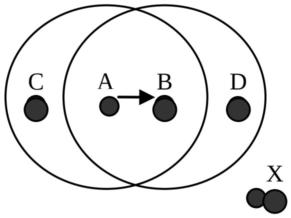

Fig. 1: Node A is transmitting a data frame to B. Node C is a hidden terminal to node A and nodes D and X are hidden terminals to node B

This problem is similar to the hidden terminal problem for conventional WLANs. This problem can not be solved by using conventional DFWMAC with RTS/CTS mechanism. The RTS/CTS provision in conventional WLANs do not allow the hidden terminals to transmit when the sender is transmitting data to the receiver, even if the hidden terminals are within the transmission range of the receiver node. The nodes which are within the interference range of the receiver do not become the part of WLANs. However, in the present study we have found that in multi rate ad hoc networks such nodes which are falling within the interference range will be able to transmit data to some other nodes which are within its transmission range on different channels. The transmitted signal of such nodes will add noise in ad hoc networks. These nodes are also acting as a hidden node and called type 2 hidden terminals in this paper. We studied the effects of type-2 hidden terminals on throughput and access delay of the network. Further in the present work we have suggested that type-2 hidden terminal problem is alleviated by controlling transmit power and maintaining SINR of the receiver above the threshold value.

The rest of this paper is organised as follows: Section 2 discusses related work. Section 3 presents analysis of hidden terminal problem. Section 4 contains simulation model. Section 5 presents results and discussion. Section 6 discusses alleviation of hidden terminal. Finally the paper is concluded in section 7.

II. RELATED WORK

There are many proposals for tackling the hidden terminal problem. Reference [9] proposed MACA as an improvement of CSMA by using the RTS/CTS handshake. MACAW [10] introduced RTS/CTS/DATA/ACK four way handshakes to enhance MACA’s performance. FAMA [11] added to MACAW carrier sensing before the transmissions of RTS packets. Recognizing that hidden terminal problem mainly affects the receiver, MACA-BI [12] proposed a receiver initiated scheme. BTMA [13] and DBTMA [14] tried to solve the hidden terminal problem by using multiple channels. They are not effective for eliminating type-2 hidden terminal because they assumed that hidden nodes are always within the transmission range of sender or receiver. Reference [15,16,17] proposed to increase the carrier sensing range to eliminate type-2 hidden terminals. This may work if all potential interfering stations can sense the radio signal from the transmitter. But in practise, this assumption is not possible because walls and other transmission barriers are always present. A longer carrier sensing range will also aggravate the exposed terminal problem [10, 18].

One paper related to our work is reference [19]. Because the interference range varies with the received signal’s power at the receiver, [19] suggested that a node should reply an RTS packet only when the received RTS’s power exceeds a certain threshold. Equivalently, this means to artificially shorten the communication distances so that CTS packets can reach all potential type-2 hidden terminals. This obviously has a negative impact on network throughput. This also goes against the trend followed by most routing protocols such as DSR, AODV, which maximize the performance by using the farthest node to relay traffic [20, 21].

Another element related to our study is multirate transmissions, which has already been supported by IEEE 802.11 standards. Till now, the discussion on the impact of multirate in most papers focused on routing metrics [22] and rate adaptation [2], and not on the hidden terminal problem. One related example is reference [16]. Its goal is to maximize network throughput by determining optimal carrier sensing range and routing metrics under multirate scenario. References [17,18,23,24] also assumed different rates for RTS/CTS and DATA packets. But they also assumed the same transmission range and the same SNR requirement for all transmissions. This is obvious not true in a practical network. As a result, their models can only be considered as a single-rate model.

In our proposed work we study the effect of hidden terminals which are not in the transmission range of either transmitter or receiver but in their interference range of multi rate ad hoc network topology. We have found that this hidden terminal problem can not be solved by conventional RTS/CTS method but it can be solved by regulating the transmitting power and by keeping SINR of the receiver above the threshold value.

III. ANALYSIS OF HIDDEN TERMINAL PROBLEM

Some notations and terminology are introduced first.

- Transmission Range (TX_Range): The range within which a packet can be successfully received. This value is mainly determined by the transmission power, the receiver sensitivity threshold, the SNR requirement, and radio propagation environments.
- Carrier Sense Range (CS_Range): for sending node, CS_Range is the range within which all other nodes will detect the channel busy. It is determined by the power sensing threshold (CS_Thresh), the antenna sensitivity, and radio propagation properties.
- Interference Range (I_Range): For a receiving node, I_Range is the range within which an unrelated transmitter can corrupt the packet at the receiver.

Homogeneous radios, fixed transmitter power, and one common channel for all nodes are assumed in the analysis. In real networks, Tx_range, affected by the shadowing and fading effects, is a random variable. But in analysis, we often ignore the shadowing and the fading effect and use a deterministic model where Tx_Range can be computed from the following widely used two-ray ground reflection path loss model [25],

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^{\alpha}} \qquad (1)$$

Where P_r is the received signal's power, P_t the transmitting power, d the distance between transmitter and receiver, α the path loss exponent (normally $3 \leq \alpha \leq 4$, based on the ITU (International Telecommunications Union) recommendation), G_t and G_r the antenna gains of transmitter and receiver respectively, h_t and h_r the height of both antennas.

To correctly decode a received packet, two conditions must be met. First, the received signal's power must be larger than a threshold, called receiver sensitivity in the paper and is denoted by *Rcv_Thresh.* Given *Rcv_Thresh,* we can use equation (1) to determine the maximum d i.e. Tx_Range. Second, the SNR at the receiver must be above a certain threshold, denoted by *SNR_Thresh*. Given *SNR_Thresh,* we can calculate how much interference a transmission pair can tolerate.

When interference P_i is present, the SNR for an ongoing reception is given as SNR = $P_r / (P_i + P_n)$, where P_n is the noise power. Under most conditions, P_n (100 dBm) is much weaker than P_i at the receiver and SNR can be reduced to P_r / P_i. Because carrier sensing is also used in the network, the chance of multiple interferes transmitting simultaneously is usually small and one interfere is normally assumed in analyses [3]. For simplicity, the same assumption is also used in the paper. But our analysis can be easily extended to the cases with multiple interferers. Let d_r be the distance between interferer and receiver. Then the SNR at receiver side is given as follows

$$\text{SNR} = P_r / P_i = (d_i / d_r)^{\alpha} \qquad (2))$$

Even when a receiver is located at the fringe of the transmission range (i.e. d_r = Tx_Range) of a terminal, the received signal still needs to meet the SNR requirement (*SNR_Thresh*) is represented in decibel (dB). To ensure the correct reception, interferer's distance d_i must be $\geq (10^{\text{SNR\_Thresh}/10})^{1/\alpha}$. Tx_Range. This leads to

$$\text{I\_Range} = (10^{\text{SNR\_Thresh}/10})^{1/\alpha} \,.\, \text{Tx\_Range} \qquad (3)$$

Once Tx_Range and I_Range are determined, the area within which type-2 hidden terminals may exist can also be determined.

3.1 SNR_Thresh, transmission rate and tx_range

As indicated by equation (3), *SNR_Thresh* is the key factor to determine the value of *I_Range.* Prior analyses often assumed that *SNR_Thresh* is fixed. But in fact, it varies with the transmission rate. By shannon's theorem, we have

$$R = W \log(1 + \textit{SNR\_Thrseh}), \qquad (4)$$

Where R = {transmission bit rate} and W = {channel bandwidth}. The equation can be expressed as

$$\textit{SNR\_Thresh} = 2^{R/W} - 1 \qquad (5)$$

Equation (3) shows that *SNR_Thresh* is rate dependent and is a monotonic increment function of R (W is fixed in a bandwidth-limited system). This result is independent of the modulation schemes used in a network.

The exact relationship between *SNR_Thresh* and transmission rate depends on the BER (bit error rate) requirement of the modulation scheme used by the network [26, 27]. The BER is determined by E_b / N_o (E_b is the energy per bit and N_o the average power spectral density of the noise). The relationship between E_b / N_o and SNR is the following,

$$SNR = \frac{P_r}{P_i + P_n} = \frac{R}{W}\frac{E_b}{N_0} \qquad (6)$$

Where $P_r = R \cdot E_b$, $P_n + P_i = WN_0$. Given the BER requirement, E_b / N_0 will be fixed and the SNR requirement will change with rate (see equation (4)). Replacing P_r by *Rcv_Thresh* in equation (1), we have

$$Tx\_Range = \left(\frac{P_T G_t G_r h_t^2 h_r^2}{Rcv\_Thresh} \right)^{1/\alpha} \qquad (7)$$

Equation (7) shows that different values of *Rcv_Thresh* lead to different *Tx_Ranges.* As *Rcv_Thresh* is rate dependent, so is *Tx_Ranges* from equation (7)

3.2 A new look at the hidden terminal problem

In single-rate networks, all packets are sent with the same rate. The transmission range (Tx_Range) is fixed for data packets as well as for RTS/CTS control packets. Let's rewrite equation (3) as

$$\frac{I\_Range}{Tx\_Range} = (10^{SNR\_Thresh/10})^{1/\alpha} \qquad (8)$$

We have the following cases.

- Case i: I_Range/Tx_Range > 1 if SNR_Thresh > 0 dB. Under this condition, the interference area is larger than transmission area. Type-2 hidden terminals cannot be eliminated by the RTS/CTS scheme. Type-2 hidden terminal problem increases with the SNR requirement.

- Case ii: I_Range/Tx_Range < 1 if SNR_Thresh < 0 dB. Under this condition, I_Range is even smaller than Tx_Range. Hidden terminals can be eliminated by the RTS/CTS scheme. Although terminals located between the two circles of radius I_Range and of Tx_Range cannot corrupt an on-going transmission, they will not transmit because they receive the RTS/CTS packets correctly. This is a case of the so called exposed terminal problem [10].

- Case iii: I_Range/Tx_Range = 1 if SNR_Thresh = 0dB. This represents the best condition. Under this condition (i.e.I_Range = Tx_Range) neither type-2 hidden terminals nor exposed terminals can exist.

3.3 Application to 802.11 wireless networks

Table 1 shows the transmission range and interference range of different data rates for 802.11b devices. Tx_Range and I_Range in table 1 are normalized by the Tx_Range of 1 Mbps in 802.11b

Table1

Mbps	Tx_Range	$(10^{SNR\_Thresh})^{1/\alpha}$	I_Range
11	0.5012	1.4954	0.7495
5.5	0.6683	1.4109	0.9430
2	0.8414	1.0958	0.9220
1	1	0.8453	0.8453

- Hidden terminals can be eliminated in 802.11b networks as the Tx_Range of 1 Mbps can cover the I_Range of all the data rates. But 1 Mbps may not be the best rate for RTS/CTS packets. From the table, we can see that 2 Mbps can cover of the I_Range of 11 Mbps, and it has a smaller reservation area than that of the 1 Mbps.
  - A higher data rates does not necessarily mean a larger I_Range. 5.5 Mbps-not 11 Mbps has the largest I_Range in 802.11b.
  - The value of |Tx_Range – I_Range| for each rate varies with the path loss coefficient α.

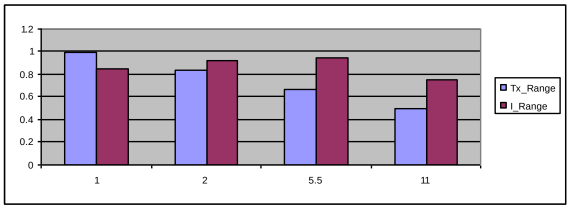

Fig.2: Tx_range and I_range comparisons of the rates in IEEE 802.11b, normalized by 1 Mbps with α = 4

IV. SIMULATION

NCTUns-5.0 simulator is used for our simulation. To filter out the impact from other factors, the CS_Range parameter is disabled and only the RTS/CTS virtual carrier sensing scheme is used. Since the network we simulate has only four nodes, this change does not affect the simulation time significantly. The strategy of sending CTS packets is made the same as that for sending ACK packets. This removes the possibility that a node receives a RTS correctly but does not reply with a CTS packet because the channel is sensed busy.

The detail of the scenario used in the simulation is given below.

1. The Tx_Range of 1 M is set to 100m, and the Tx_Range of 2 M, 5.5 M and 11 M, are set to 84 m, 67m, and 50m respectively.
2. There are two simultaneous transmissions: A-to-B and C-to-D. Data packets are generated by continuously backlogged CBR/UDP flows with the packet size of 1 KB.
3. The distances between A and B and between C and D are the same and equal to Tx-Range. The distance between B and C is originally set to (2 x Tx_Range) so that the two transmission do not interfere with each other. The pair A-B then moves at a constant speed toward the pair C-D which is always stationary. In the process, node C will gradually becomes a type 2 hidden terminal for the A-B pair, then a type-1 hidden terminal, and finally a non hidden terminal (when A and C can hear each other).
4. The moving speed for A-B is a constant and equal to (2 x Tx_Range)/50 i.e. the corresponding speeds for rates 1 M, 2 M, 5.5 M, and 11 M will be 4, 3.36, 2.68, and 2 m/s. Since SNR is determined by the moving speed given above will make the SNR value the same for all different rates at any given point of time. This makes it easier to compare and plot the results.

V. RESULTS AND DISCUSSION

In this section discussions have been done for the various simulation results implemented in NCTUns-5.0

5.1 Effects of type-2 hidden terminal on throughputs

Fig. 3 plots the throughput of A–B link when DATA is transmitted at different data rates. A-B moves toward C-D and C is a sender (in the C-D link) and B is a receiver (in the A-B link), C will be the hidden terminal for B. As B approaches C, the effect of the hidden terminal becomes more serious. The throughput of A-B at 11Mbps and 5.5Mbps drops to 0 much earlier than 2Mbps and 1Mbps due to the higher SNR requirement for decoding. When operating at 2Mbps and 1Mbps, link A-B can still maintain the same performance as that of C-D even when node B is (1.1 x Tx_Range2M) and (1.0 x Tx_Range1M) away from node C. This indicates that the type-2 hidden terminal problem is much less severe for low rates than for high rates.

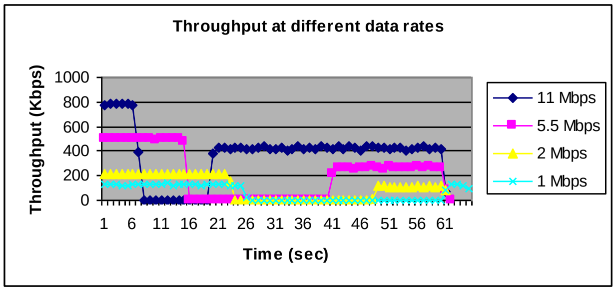

Fig. 3: Effect of type2 hidden terminal on throughput

5.2 Effects of type -2 hidden terminal on access delay

Access delay reduces with data rates. Access delay is 0.45 sec at 1 Mbps and 0.15 sec at 11 Mbps.

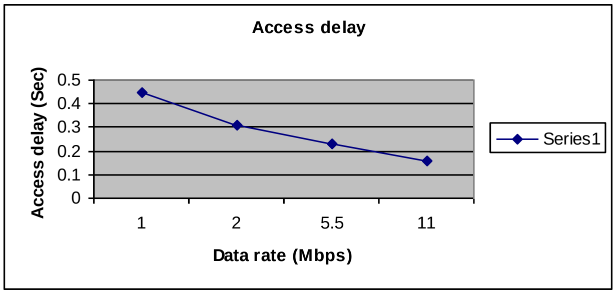

Fig. 4 Effect of type 2 hidden terminal on access delay.

VI. ALLEVIATION OF HIDDEN TERMINAL PROBLEM

It is inferred in the last section that the hidden terminals deteriorate the performance of the mobile ad hoc networks. This problem can partially be solved by RTS/CTS handshaking signals if the terminal is in the transmission range of the receiver. Such a problem can not be solved by RTS/CTS signals if the hidden terminal is out of transmission range but within the interference range of the receivers. The method of solving the hidden terminal problem in mobile ad hoc networks conceptually is given in the following section

6.1 Transmit power control in multi rate MAC protocol

In the present research we proposed a simple multi-rate MAC protocol that can be used when transmit power control (TPC) is employed. In order that nodes receive a data frame correctly, it must satisfy two conditions. First, the receiver power should exceed a certain receive power threshold (RPT). Second, the SINR should also surpass a certain threshold value. We would call the two thresholds as, RPT and SINR threshold respectively. The RBAR protocol [2] and the IEEE 802.11 [28] are used for multi-rate physical and MAC, so that the available data rates are 1, 2, 5.5 and 11 Mbps.

6.1.1 Transmit power control (TPC)

In order to receive correctly a data frame, the receive power should go beyond the RPT. The RPT should vary along with the selected data rate. Assume that the RPT value for each data rate is RPT_{R1}, RPT_{R2}, $RPT_{R5.5}$ and RPT_{R11}. As the higher data rate would require a higher receive power, $RPT_{R1} < RPT_{R2} < RPT_{R5.5} < RPT_{R11}$. If a node was using data rate i, the following condition would hold to correctly receive a data frame.

$$P_R = \frac{CP_t}{D^4} \geq RPT_{R_i} \tag{9}$$

Where P_R was the receive power of the RTS frame, P_t is the transmit power of the RTS frame, C is a constant, D is the distance between the sender and receiver, and RPT_{Ri} is the RPT when using data rate i. Although the receiver can receive correctly the data frame when the sender transmits with power P_t, it can still receive properly the data frame when the sender transmits with a lower power P_t' ($P_t' \leq P_t$), as long as it satisfied the equation (9). Using this philosophy, we performed transmit power control (TPC) by adjusting the transmit power of the sender as indicated by equation (10).

$$P_t' = P_t \cdot \frac{RPT_{R_i}}{P_R} \tag{10}$$

p'_t indicates the transmit power of the sender when using rate i. The receiver should send this information to the sender by adding it to the CTS frame along with the selected data rate in RBAR.

6.1.2 Preventing hidden terminal interference

In order that a node to receive a data frames correctly, the SINR would surpass the SINR threshold ($SINR_{th}$). The SINR threshold value would change with the selected data rate. For data rates 1, 2, 5.5 and 11 Mbps, the $SINT_{th}$ values are $SINR_{th\_1}$, $SINR_{th\_2}$, $SINR_{th\_5.5}$ and $SINR_{th\_11}$, respectively. We have assumed that the current SINR value of the RTS reception can be estimated as in [2]. It is also assumed that there was no interference other than noise in the current RTS reception.

$$SINR = \frac{P_R}{\eta} \tag{11}$$

Where η is the value of thermal noise. Also, a node uses data rate R_i selected by RBAR The node would follow the next constraint to correctly receive a data frame:

$$\frac{P_{R_i}}{\eta + \frac{CP_t}{d^4}} \geq SINR_{th\_i} \tag{12}$$

P_{Ri} is the receiver power for each data rate i when TPC is employed as explained in section 6.1.1. In equation (10) the right hand part of the denominator denoted the interference that a node outside the CTS transmission range can cause. In other words, equation (12) takes into account the effects of the hidden terminal that is outside the CTS transmission range. Therefore, d was the interference range of that transmission. We have controlled the transmit power of the CTS frame to cover the interference range. So that the following equation should hold:

$$\frac{CP_{t\_CTS}}{d^4} \geq RPT_{R1} \tag{13}$$

P_{t_CST} is the controlled transmit power of the CTS frame, and RPT_{R1} is the receive power threshold of the CTS frame. Therefore, by combining equations (10) and (11), the controlled CTS transmit power is

$$P_{t\_CTS} \geq \frac{d^4}{C} RPT_{R1} \geq \frac{P_{tRTS} \cdot RPT_{R1}}{SNR_{th\_i} \cdot P_{R_i} - \eta} \tag{14}$$

We can avoid the hidden terminals interference by using the above equation.

VII. CONCLUSION

In this paper we have studied the performance of multi rate ad hoc networks in the presence of hidden terminals. In such networks the nodes which are out of transmission range but within the interference range of the receiver act as hidden terminals. These hidden terminals have a detrimental effect on the performance of the multi rate ad hoc networks. The effect is more serious at higher data rates.

Further we proposed a simple multi rate MAC protocol to prevent the hidden terminal problem when Transmit power control (TPC) was employed. The proposed protocol would be very effective when using multi rate data transmission, since the CTS frames would effectively cover the interference range of the receiver.

VIII. REFRENCES

[1] G. Binachi, L. Fratta and M. Oliveri, "Performance evaluation and enhancement of the CSMA/CA MAC protocol for 802.11 LANs", in Proc. PIMRC, 1996.

[2] G. Holland, N. Vaidya, "A rate adaptive MAC protocol for multi-hop wireless networks", proc. ACM Mobicom'01, (2001).

[3] K. Xu, M. Gerla and S. Baeo, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks", Proc. IEEE Globecom'02, 2002.

[4] Jost Weinmilter, Morten Schlager, Andreas Festag and Adam Wolisz, "Performance study of access control in wireless LANs – IEEE 802.11 DFWMAC and ETSI RES 10 Hiper LAN", Tranc. Moible networks and application, vol. 2, Number 1, pp. 55-67, June 1997.

[5] Wang, J. Li & Bin, "The impact of RTS Threshold on the performance of multi-rate network", In Proc. of IEEE Wireless and Mobile computing conference (CCWMC), pp 651-656, 2009.

[6] Da Rui Chen and Ying Juh Zhang, "Is dynamic backoff effective for multirate WLANs", IEEE Communications Letters, 11(8), pp 647-649, 2007.

[7] Hyungu Park, Chong Kwon Kim, "Performance analysis of multirate IEEE 802.11 WLANs with channel Error", Proc. 9th International conference on Advanced Communication Technology, pp 1479-1481, 2007.

[8] Der Jiunn Deng, Bin Li, Lianfch Huang, chih-Heng Ke and Yueh-Min Huang, "Saturation throughput analysis of multirate IEEE 802.11 wireless networks", Journal of Wireless Communication and Mobile Computing, 2008.

[9] P. Karn, "MACA: A new channel access protocol for packet radio, ARRL/CRRL amateur radio", 9th Computer Network Conference, pp 134-40, 1990.

[10] V. Bharghavan, A. Demers, S. Shenker, L. Zhang, " MACAW: A medium access protocol for wireless LANs", SIGCOMM'94.

[11] C. L. Fullmer, J. J. Garcia-Luna-Aceves, "Floor Acquisition Multiple Access (FAMA) for Packet-Radio Networks", SIGCOMM'97 pp 262-73.

[12] F. Talucci, M. Gerla & L. Fi-atta,"MACA-BI(MACA By Invitation): A receiver oriented accesss protocol for wireless multiple networks", PIMRC'97.

[13] F. A. Tobagi, L. Kleinrock, "Packet switching in radio cahnnels: Part II-the hidden terminal problem in carrier sense multiple-access and the busy-tone solution," IEEE Transactions on Communications, 23(12), pp1417-1433, 1975.

[14] J. Z. Hass, J. Deng, "Dual busy tone multiple access (DBTMA): A multiple access control scheme for Ad Hoc networks", IEEE transctions on Comunications 50(6) pp 975-985, 2002.

[15] X. Yang & N. Vaidya, "On physical carrier sensing in wireless Ad Hoc networks", In Proceedings of the IEEE Infocom'05.

[16] H. Zhai & Y. Fang, "Physical carrier sensing and spatial reuse in multirate and multihop wireless Ad Hoc networks", In Proceedings of the IEEE Infocom'06.

[17] J. Zhu, X. Guo, L.L. Yang & W.S. Conner, "Lever aging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing", IEEE ICC, 2004.

[18] S. Xu. & T. Saadawi, "Does the IEEE 802.11 MAC protocol work well in multihop wireless Ad Hoc networks?" IEEE Communication Mag. pp 130-137, 2001.

[19] K. Xu., M. Gerla & S. Bae,"How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks?", Proceeding of IEEE Globecom, 2002.

[20] D.B. Johnson, D.A. Maltz, "Dynamic source routing in Ad Hoc wireless networks", Kulwer Academic Publisher,vol. 353, 1996.

[21] C. E. Perkins & E.M. Royer, "Ad Hoc on demand distance vector routing", In Proccedings of the 2nd IEEE workshop on Mobile Computing Systems and Applications, pp 90-100, 1999.

[22] H. Zhai & Y. Fang, "Impact of Routing Metrics on path capacity in multirate and multihiop wireless Ad Hoc networks", ICNP'06.

[23] J. Li, C. Blake, D.S.J. Decoato, I.H. Lee & R. Morris, "Capacity of Ad Hoc wireless networks", In Proceeding of ACM Mobicom, pp 61-69, 2001.

[24] C. Chen & H. Luo, "The case for Heterogenous Wireless Macs", HotNet'05.

[25] T.S. Rappaport, "Wireless Communications: Principles and Practice. New Jersy: Prentice Hall, 1996.

[26] J. G. Proakis, "Digital Communications", 4th ed. McGraw Hil, 2001.

[27] G. Nguyen, A. Ephermides & J. Wieselthier, "On capture in random-access systems", ISIT'06.

[28] IEEE standard for Wireless LAN Medium Access Control (MAC) and Physical Layer specifications. ISO/IEC 8802-11: (1999E) Aug. 1999.