I. INTRODUCTION

Ad-hoc wireless networks are currently receiving a significant amount of interest. Some of this interest may be attributed to the distributed nature of IEEE 802.11 DCF, which allows for instant deployment and routing of packets around nodes in multi-hop ad-hoc wireless networks. However, in IEEE 802.11 DCF, the wireless channel needs to be shared efficiently among contending nodes, and considerable research efforts are being dedicated to improving the energy consumption in these networks. One important approach to reducing the energy consumed in an ad-hoc network is to change the power levels of transmissions to that required to be received by the destination and no more. This is normally performed as an iterative process whereby the transmitted power level is adjusted based on feedback from the receiver [3,8,15,16]. In addition to providing energy consumption, transmission power control can potentially be used to improve spatial reuse of the wireless channel [4]. However, most power control algorithms result in lower throughput [11] because it reduces the power level of transmission which causes more packets losses due to interference from hidden nodes.

The DCF mode of the IEEE 802.11 standard [1,2] is used as the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol for multi-hop ad-hoc wireless networks. The protocol allows for the exchange of RTS/CTS (request-to-send/clear-to-send) handshake packets between the sender and the receiver. Nodes transmit control and data packets at a fixed (maximum) power level. The maximum transmission range is used to prevent all other potentially interfering nodes in the channel carrier sense area from starting their transmissions while the channel is currently occupied. Any node that senses the RTS or the CTS defers its transmission using the binary exponential backoff (BEB) mechanism until the channel is sensed clear.

In this work a control scheme for dynamically varying the contention window in multi-hop and ad-hoc wireless networks with variable transmit power is proposed. The scheme is cross-layer in nature and operates in the MAC and PHY layers. The scheme attempts to optimize the number of competing nodes in the carrier sense and physical interference ranges of a receiver according to the radio transmission power.

The rest of the paper is organized as follows. Section 2 describes the variable transmitter power approach to reducing energy consumption in ad-hoc networks and presents a performance analysis of the interference range of the variable transmit power mechanism. Section 3 presents a throughput analysis of the IEEE 802.11 DCF. Section 4 presents the dynamic contention window algorithm (*DCWA*). Section 5 describes the simulation results and performance comparison between *DCWA* and standard IEEE 802.11 DCF. Finally, we conclude the paper in Section 6.

II. VARIABLE TRANSMITTER POWER

In the IEEE 802.11 MAC protocol with DCF, we assume that all radios are identical, use single channel and omni-directional antennas. A two-way path loss model is used for analyses and simulations. We first define three radio ranges related to a wireless radio as the following:

- Transmission range (R_d), the range within which a data packet is successfully received.
- Carrier Sensing Range (R_c), the range within which a transmitter triggers carrier sense detection. In IEEE 802.11 MAC sub-layer, a transmission only starts when the transmitter sense the medium is free.
- Interference Range (R_i), the range within which nodes receive interference signal from an unrelated transmitter.

The physical interference range R_i is typically larger than the carrier sensing range R_c, and that in turn is larger than the data transmission range R_d [5].

$$\begin{aligned} &R_i \geq R_c \geq R_d \geq d \\ &P_{\min imum} \leq P_d \leq P_{\max imum} \end{aligned} \quad (1)$$

The maximum transmission power $P_{maximum}$ and the minimum transmission power $P_{minimum}$ are usually 20dBm and 0dBm respectively [1,2]. R_d is the transmission range obtained using a transmission power level of P_d dBm. The distance between the transmitter and receiver is d.

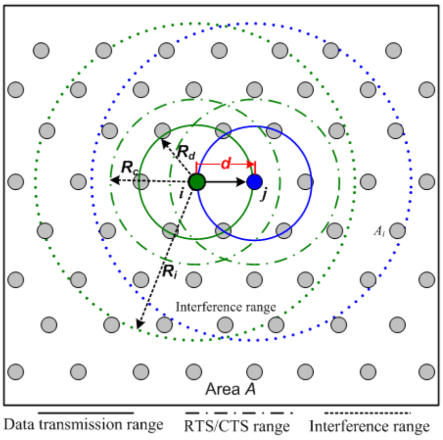

Figure 1: A IEEE 802.11 wireless network scenario with uniformly distributed *G(V,E)* in area *A*

As shown in Figure 1, there are n nodes in an 802.11 DCF wireless network uniformly distributed in area A. Obviously, if the area A is covered, every point in it will have access to at least one mobile node. Ignoring additional signal degradation factors such as multipath fading, shadowing, environment noise etc. The received signal power (P_r) from a transmitter d meters away is then described by:

$$P_r = P_d G_t G_r \frac{h_t^2 h_r^2}{d^\alpha} \tag{2}$$

Where, G_t and G_r are the antenna gains of the transmitter and receiver respectively. h_t and h_r are the height of both antennas (In our simulation, we set G_t=G_r=1 and h_t=h_r=1.) We assume that all the radio parameters are same at each node. Under the TWO-RAY GROUND path-loss model, α is equal to 4 [14].

Consider a graph $G(V,E)$ with a vertex set $V = \{Node_1, Node_2, ...Node_n\}$ with n wireless nodes and edge set $E = (i, j)$, each mobile node has transmission range R_d, and wishes to communicate with some or all of the other nodes by wireless multi-hop routing.

The wireless nodes in G use different transmission power levels to communicate with other neighbouring nodes. This results in a variation in the transmission range.

$$D = \frac{n}{A} \qquad PF_d = D \times \pi R_d^2 \tag{3}$$

Where D is the wireless node density in A. PF_d is the average number of nodes within the data transmission range R_d. If we assume that a packet can be received error free when the Signal-to-Noise ratio, $SNR \geq SNR_{Threshold}$. We set $SNR_{Threshold}$=10 in our simulation model,

$$SNR = \frac{P_r}{P_{ri}} = \frac{P_d G_t G_r \frac{h_t^2 h_r^2}{R_d^\alpha}}{P_d G_t G_r \frac{h_t^2 h_r^2}{R_i^\alpha}} = \left(\frac{R_i}{R_d}\right)^\alpha \geq SNR_{Threshold} \qquad R_i \approx \sqrt[\alpha]{SNR_{Threshold}} \times R_d \tag{4}$$

Here R_d is the transmission range of the data communication in 1Mbps, 2Mbps 5.5 Mbps and 11Mbps bit-rates. Four data transmission ranges (R_d) in figure 2 due to the differentiation of receive sensitivity in different transmission bit-rates. For instance, the receive sensitivity are -94 dBm, -91 dBm, -87 dBm and -83 dBm in 1 Mbps , 2Mbps, 5.5M bps and 11M bps respectively.

From equation (4), we obtain the interference range to be $R_i = \sqrt[4]{10} \times R_d = 1.78 \times R_d$. When d is larger than $(R_d/R_i)*R_d$ = $0.561*R_d$, the interference range R_i will larger than data transmission range R_d.

The three ranges: R_d (in 4 different bit-rates), R_c and R_i of the dynamic transmission power level are shown in figure 2, the transmission range and carrier sensing ranges are easily obtainable as they are fixed ranges that are mainly influenced by the transmission power at the transmitter and the receive sensitivity at the receiver.

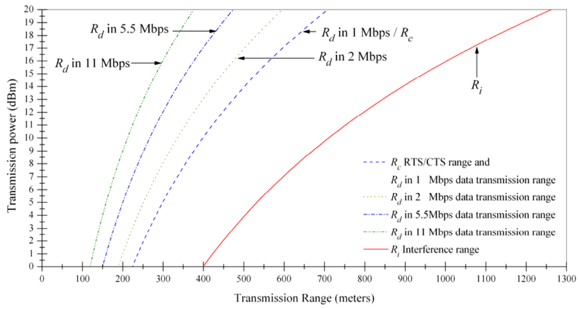

Figure 2: Dynamic transmission power level vs. transmission range in different data rate.

The nodes in a receiver's interference area (A_i In figure 1) are usually called hidden nodes. The hidden node problem occurs when two nodes, Node i and node h cannot detect each other's transmissions, due to being outside each other's transmission range. A collision may occur, when node i and node h start transmitting toward the same receiver node j. We can now define the interference area A_i around the receiver as:

$$A_i = \pi \cdot R_i^2 - \pi \cdot R_c^2 \qquad PF_d = D \cdot \pi \cdot R_d^2 \qquad PF_i = D \cdot A_i \qquad PF_c = D \cdot \pi \cdot R_c^2 \tag{5}$$

PF_c and PF_i are the average number of nodes within the channel carrier sense and physical interference ranges respectively. Thus, in our variable power control scheme the necessary transmission power level P_d for a distance d from transmitter to receiver is:

$$P_r = P_d G_t G_r \frac{h_t^2 h_r^2}{d^\alpha}$$
$$SNR = \frac{P_r}{\sum_{n-1} P_{ri}} \geq SNR_{Threshold} \quad (6)$$

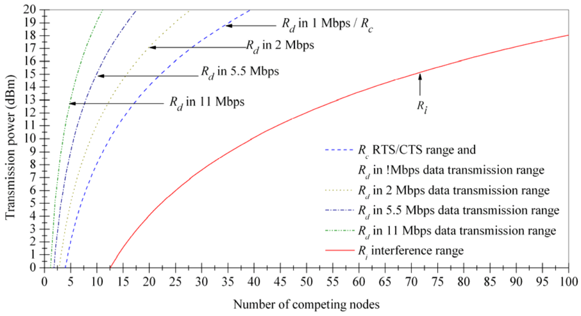

Figure 3: Transmission power vs. number of competing nodes (D=2.5*10-5)

Figure 3 shows the relationship between the transmission power level Pd and number of competing nodes. The hidden nodes in this simulation are from 8 to 60 nodes when the transmission power increased from 0 dBm to 20 dBm in 1M bit-rate. The transmission range and carrier sensing ranges are easily obtainable as they are fixed ranges that are mainly influenced by the transmission power at the transmitter and the receive sensitivity at the receiver. However, a lot of research into ad-hoc wireless networks usually ignores the interference range [13].

III. THROUGHPUT ANALYSIS OF IEEE 802.11 WITH CSMA/CA

The binary exponential backoff mechanism (BEB) plays an important role in the IEEE 802.11 DCF. It is based on a CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) MAC protocol. The performance of this type of MAC protocol depends on the contention window mechanism employed. In this paper, we use saturation throughput analysis for the backoff contention window mechanism. We use the same analysis model as [6,7]. We assume that n nodes in the interference range always have data to transmit. From equation (5), n is the total competing nodes in both channel carrier sensing (2 π R_c^2 includes data transmission range) and interference ranges (A_i).

$$n = PFc + PFi = D \cdot R_i^2 = D \cdot (1.78 \cdot R_d)^2$$
(7)

Consider a station i with a new packet to transmit monitoring the channel activity. There are two possibilities:

• The channel is idle for a period of time equal to a Distributed Inter Frame Space (DIFS) and starts transmitting.

• The channel is sensed busy. The station defers until the channel is measured idle for a DIFS period and then starts transmitting. If a collision occurs, the station generates a random backoff interval before transmitting, to minimize the probability of collision with packets being transmitted by other stations. This method is based on physical Channel Sensing.

Consider a fixed number n of contending nodes. The conditional collision probability ρ is the probability that in a time slot at least one of the n-1 remaining nodes transmits. This is given by:

$$\rho = 1 - (1-\tau)^{n-1} \quad (8)$$

Where τ is the probability that a node transmits in a generic slot time.

$$\tau = \frac{2(1-2\rho)}{(1-2\rho)(W+1) + \rho W(1-(2\rho)^m)} \quad (9)$$

Where $W = CW_{min}+1$, CW_{min} is the minimum backoff window size. After each unsuccessful transmission, the backoff window is doubled, up to a maximum backoff size $2^m W = CW_{max}-1$. m is the number of retransmission times.

$$m = \log_2 \frac{CW_{\max}}{CW_{\min}}$$

From equations (8) and (9), we define Ptr as the probability in a slot time, of at least one or more transmissions. n active nodes contend to access the medium and each node has transmission probability τ.

$$P_{tr} = 1 - (1-\tau)^n \quad (10)$$

The probability of successful transmission Ps is given by:

$$P_s = \frac{n \cdot \tau \cdot (1-\tau)^{n-1}}{P_{tr}} = \frac{n \cdot \tau \cdot (1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (11)$$

Finally, we can determine the system throughput S,

$$S = \frac{P_{tr} P_s E[P]}{(1-P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1-P_s) T_c} \quad (12)$$

For the situation where RTS/CTS exchanges are employed, we can specify the values Ts and Tc.

$$T_S = RTS + SIFS + \delta + CTS + SIFS + \delta + H + E[P] + SIFS + \delta + ACK + DIFS + \delta \qquad (13)$$

$$T_C = RTS + DIFS + \delta$$

Where δ is the slot time and $H=PHY_{hdr}+MAC_{hdr}$. $E[P]$ in the average length of the longest packet payload involved in a collision. In the case that all packets have the same fixed length. The average medium access delay υ is given by:

$$\upsilon = n \times T_S + T_C \times \frac{1-(1-\tau)^n - n\cdot\tau(1-\tau)^{n-1}}{\tau(1-\tau)^{n-1}} + \delta \times \frac{1-\tau}{\tau} \qquad (14)$$

IV. DYNAMIC CONTENTION WINDOW ALGORITHM(DCWA)

The goal is to use the variable transmission power level to coordinate the contention window size depending on the number of competing nodes. In [9,10], the authors show that a large interference range is one of the major problems causing poor performance (due to increased collisions) and unfairness in the network.

Figure 4 shows a simulation result for the channel throughput of IEEE 802.11 DCF. The bit rate of the wireless channel is 1Mbps. The frame payload is 8184 bits. The transmitting node with the minimum contention window CW_{min} will be guaranteed to occupy the medium for transmission.

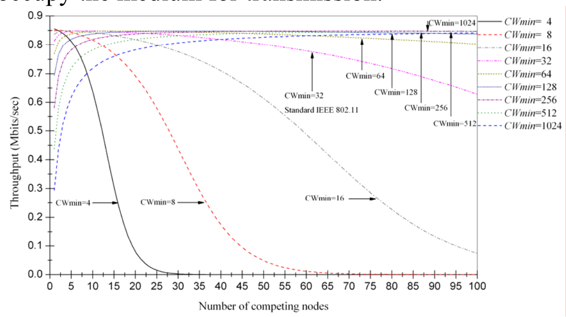

Figure 4, Throughput vs. number of competing nodes using RTS/CTS exchange method

After a node has acquired the channel and starts transmitting data, the others nodes inside the interference range will sense the busy medium and defer their pending transmissions. They suspend their backoff counters and resume their timers after the medium is released. The results show that when a small contention window (e.g. CW_{min}=3) is used, the throughput drops after only a small number of competing nodes.

While figure 3 shows that a larger CWmin will improve the throughput of an individual node, it will also increase the channel access delay for all nodes using this large window. It also wastes channel bandwidth and consumes unnecessary energy in idle slots This highlights the ineffectiveness of a static window size in resolving a variable number of competing nodes, which in turn will be dependent on the interference range.

Thus, the derivative of (12) with respect to τ, and imposing it equal to 0, we obtain the following equation:

$$\frac{dS}{d\tau} = 0 \qquad (15)$$

From (10) and (11), we can determine the system throughput S,

$$S = \frac{n\cdot\tau\cdot(1-\tau)^{n-1}}{\sigma\cdot(1-\tau)^n + T_s\cdot n\cdot\tau\cdot(1-\tau)^{n-1} + T_c\cdot(1-(1-\tau)^n - n\cdot\tau\cdot(1-\tau)^{n-1})}\cdot E[P] \qquad (16)$$

We obtain,

$$\frac{dS}{d\tau} = \frac{(n\cdot(1-\tau)^{n-1} - n\cdot\tau\cdot(n-1)\cdot(1-\tau)^{n-2})\cdot f_1(\tau) - n\cdot\tau\cdot(1-\tau)^{n-1}\cdot f_2(\tau)}{f_1^2(\tau)}\cdot E[P] \qquad (17)$$

where,

$$f_1(\tau) = \sigma\cdot(1-\tau)^n + T_s\cdot n\cdot\tau\cdot(1-\tau)^{n-1} + T_c\cdot(1-(1-\tau)^n - n\cdot\tau\cdot(1-\tau)^{n-1})$$

$$f_2(\tau) = -\sigma\cdot n\cdot(1-\tau)^{n-1} + T_s\cdot(n-n^2\tau)\cdot(1-\tau)^{n-2} + T_c\cdot n\cdot\tau\cdot(n-1)\cdot(1-\tau)^{n-2}$$

From equations (17), we can obtain $(1-\tau)^{n-1}\approx 1$. Thus, we can specify the equation as follows:

$$n^2\cdot\tau\cdot T_c - n\cdot\tau\cdot\delta = n\cdot\delta$$

We approximate optimal τ as τ_{opt}, which can obtain as follows,

$$\tau_{opt} = \frac{\delta}{n\cdot T_c - \delta} \qquad (18)$$

From (8) and (9), finally, we can determine the optimal W, denoted as W_{opt},

$$W_{opt} = \frac{(2-\frac{\delta}{n\cdot T_c-\delta})\cdot(2\cdot(1-\frac{\delta}{n\cdot T_c-\delta})^{n-1}-1)}{\frac{\delta}{n\cdot T_c-\delta}\cdot\left[2\cdot(1-\frac{\delta}{n\cdot T_c-\delta})^{n-1}-1+(1-(1-\frac{\delta}{n\cdot T_c-\delta})^{n-1})\cdot(1-(2\cdot(1-\frac{\delta}{n\cdot T_c-\delta})^{n-1})^m)\right]}$$

V. NUMERICAL RESULTS

In this section, we present simulation results for the channel throughput and access delay. The simulation scenario consisted of 100 nodes that are random distributed in the area of 2000m * 2000m square (D=2.5E-05). Table 1 gives the simulation parameters. A simulation environment was developed using the OriginLab [12].

Packet payload	2304 bytes
PHY/MAC	DSSS, CCK-DSSS/IEEE 802.11b
MAC header, PHY header	34 bytes, 16 bytes
Physical Layer	DSSS
ACK	14 bytes + PHY header
RTS	20 bytes + PHY header
CTS	14 bytes + PHY header
Channel bit rate	1, 2, 5.5, 11 Mbit/sec
Propagation delay	1 µs
Slot time, SIFS, DIFS	20 µs, 10 µs, 50 µs

Table 1: Simulation parameters

Although extensive simulations have been conducted, in this paper, we only present a summary of those results that focus on performance and system delay in IEEE 802.11 DCF wireless networks.

In the standard IEEE 802.11 W=32 and m=7 (SRC, Short Retry Counter), when the number of competing nodes is more than 38 the conditional collision probability P will be over 0.5. Therefore, in Table 2, the result using the proposed dynamic contention window scheme shows that the size of CWmin is directly proportional to the number of competing nodes as the transmission power is increased.

W_{opt} (CW_{min})	Number of competing nodes
192	5
385	10
770	20
1155	30

Table 2: W_{opt} vs. number of competing nodes in interference range

Figure 5 and 6 show the effective system throughputs of the DCWA in the situation with n nodes in the interference range. We observe that DCWA is able to eliminate most of the collisions from hidden nodes. The higher bit-rate transmission is more sensitive from hidden nodes problem. From this result, our solution can solve this influence.

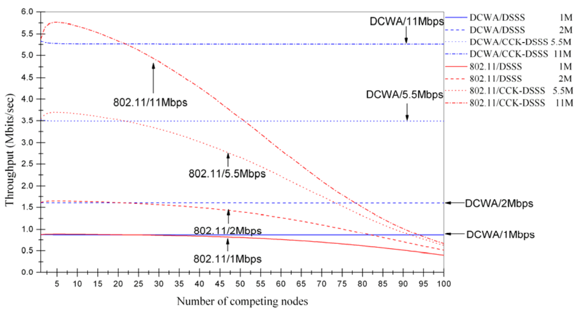

Figure 5, Throughput vs. number of competing nodes using RTS/CTS exchange method

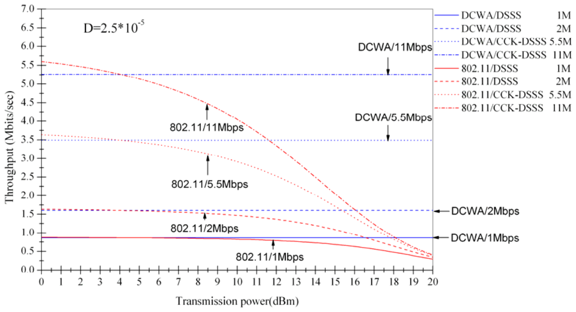

Figure 6, Throughput vs. transmission power (dBm) using RTS/CTS exchange method

Figure 7 and 8 show the result for the access delay. DCWA has lower access delay than standard IEEE802.11 as the number of competing nodes increases. The result also shows that the *DCWA*'s access delay is directly proportional to the number of competing nodes. Effectively these results show a trade-off between a longer contention window and higher system delay.

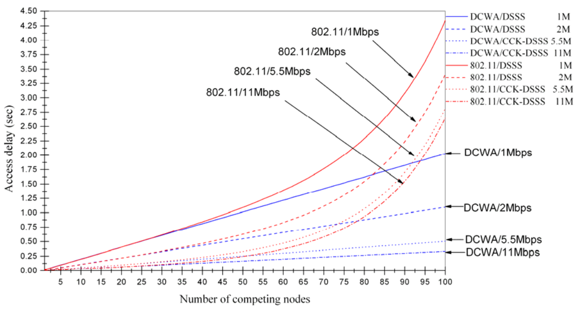

Figure 7, Access delay vs. number of competing nodes using RTS/CTS exchange method

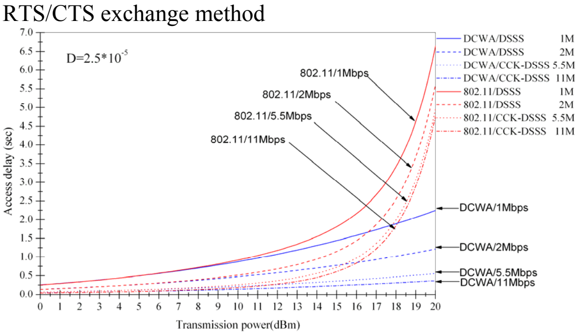

Figure 8, Access delay vs. transmission power (dBm) using RTS/CTS exchange method

VI. CONCLUSION

In this work a control scheme for dynamically varying the contention window in multi-hop and ad-hoc wireless networks with variable transmit power is proposed. The scheme is cross-layer in nature and operates in the MAC and PHY layers. The scheme attempts to optimize the number of competing nodes in the carrier sense and physical interference ranges of a receiver according to the radio transmission power.

The simulation results show that our mechanism can not only achieve a higher throughput, less access delay and lower system collision probability than the standard IEEE 802.11 DCF, but it can also improve the stability of system performance under a dynamically varying number of competing stations.

This paper describes research that is applied in the PHY and MAC layers. An interesting area of future research will be to extend the approach for a cross-layer architecture to provide further MAC-layer parameters for multi-hop wireless routing information such as AODV and DSR to optimise multi-hop routing protocol capacity.

Acknowledgment

This work is supported by the UK funding body EPSRC, under the project GR/S02105/01 "Programmable Routing Strategies for Multi-Hop Wireless Networks".

References

[1] IEEE 802.11 Work Group, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," ANSI/IEEE Std 802.11, New York, Sept. 1999.

[2] IEEE 802.11 Work Group, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band,", ANSI/IEEE Std 802.11b, Sept. 1999.

[3] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian, "Conserving Transmission Power in Wireless Ad Hoc Networks," in Proceeding of ICNP 2001.

[4] R. Ramanathan, R. Rosales-Hain, "Topology control of multihop wireless networks using transmit power adjustment," IEEE INFOCOM, 2000, pp. 404-413.

[5] Xu, K. and M. Gerla, "TCP over an IEEE 802.11 ad hoc network: unfairness problems and solutions," UCLA Computer Science Department Technical Report--020019, May 2002._96, London, UK., pp:1411-1416.

[6] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," vol. 46, no. 2, pp. 388-404, March 2000.

[7] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," IEEE, J. Select. Areas Commun, vol. 18, pp. 535-547, Mar. 2000

[8] T.H. Lee, A. Marshall and B. Zhou, "Energy-Conserving On-demand Routing for Multi-rate Multi-hop Networks," in the Proceeding of the ICETE 2005.

[9] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?," IEEE Communication Magazine, vol. 39, no. 6, Jun. 2001.

[10] B. Zhou, A. Marshall and T.H. Lee, "A Half-Restraint Carrier Sense Scheme for Mobile Ad-hoc Networks," in the Proceeding of the IEEE ICT 2004.

[11] E.-S. Jung and N. H. Vaidya, "A Power Control MAC Protocol for Ad Hoc Networks," in the Proceeding of the. MOBICOM 2002.

[12] OriginLab, http://www.originlab.com/.

[13] H. Wu, S. Cheng1, Y. Peng, K. Long and J. Ma, "IEEE 802.11 Distributed Coordination Function (DCF): Analysis and Enhancement," in the Proceeding of the IEEE ICC 2002.

[14] Hata, M., 1980. "Empirical Formula for Propagation Loss in Land Mobile Radio". IEEE Trans. pp. 317-325.

[15] S. Agarwal, S. Krishnamurthy, R. H. Katz, and S. K. Dao, "Distributed Power Control in Ad-hoc Wireless Networks," in Proceeding of the PIMRC 2001.

[16] M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-Efficient Transmission and Routing Protocols for Wireless Multiple-hop Networks and Spread-Spectrum Radios," In Proceeding of the EUROCOMM 2000.