Throughput Analysis of Cooperative Access with Relay's Data Protocol for Unsaturated WLANs

Samir Sayed
Department of Electronic and Electrical Engineering
University College London, London WC1E 7JE, UK
Department of Communications and Electronics Engineering
Helwan University,Cairo, Egypt
s.sayed@ee.ucl.ac.uk

Yang Yang
Department of Electronic and Electrical Engineering
University College London, London WC1E 7JE, UK
Shanghai Research Center for Wireless Communications (WiCO),China
y.yang@ee.ucl.ac.uk

Honglin Hu
Shanghai Research Center for Wireless Communications (WiCO), China
hlhu@ieee.org

ABSTRACT

The concept of cooperative communication has been proposed to improve link capacity, transmission reliability and network coverage in multiuser wireless communication networks. Different from conventional point-to-point and point-to-multipoint communications, cooperative communication allows multiple users or nodes in a wireless network to coordinate their packet transmissions and share each other's resources, thus achieving *cooperative diversity*. In this paper, we analyze the throughput performance of a cooperative MAC protocol called Cooperative Access with Relay's Data (CARD) under unsaturated traffic conditions in wireless local area networks (WLANs). A Markov chain model is developed to derive the analytical results which are verified by extensive computer simulations.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and design**]: Wireless communications; C.2.2 [**Network Protocols**]: performance measures

General Terms

performance analysis

Keywords

cooperative communications, MAC, WLANs

1. INTRODUCTION

The IEEE 802.11 [2, 3] is the most commonly used and known WLANs standard today. it can support multiple transmission data rates according to the channel conditions between wireless users (or nodes) and Access Point (AP). Specifically, Fig. 1 shows an IEEE 802.11b network [3], where nodes A, B, C and D in zones I, II, III and IV can access the AP at the data-rates of 11, 5.5, 2 and 1 Mbps, respectively. In such networks, low data rate nodes have negative effects on the overall throughput of the network [5]. This is because the transmission time of low data rate nodes, e.g. nodes D, E and F in Fig. 1, is significantly longer than higher data rate nodes (nodes A and B), when transmitting the same packet. In other words, the channel is occupied for a longer period which reduces the efficiency of the system.

As a promising application of cooperative communication in multi-rate WLANs, a low data-rate node can use a neighboring node as a relay to forward its information to the AP [8, 9, 6]. This relay-type cooperative communication is mainly focusing on improving *cooperative diversity* gain and the transmission data-rate of source nodes. Therefore, in [7] we propose a novel cooperative MAC protocol called Cooperative Access with Relay's Data (CARD). This protocol can achieve both *cooperative diversity* and *cooperative multiplexing* gains and effectively improve network coverage, reliability, and system throughput of multi-rate WLANs.

In this paper, we make the following main contributions:

1. Data traffic such as web and e-mail is typically bursty in nature while streaming traffic such as voice operates in an on-off manner. Therefore, for most real traffic, wireless nodes are usually far from being saturated. Thus, we introduce a Markov chain model of 802.11 that relaxes the restriction of saturated condition in Bianchi's model [4].

2. A mathematical model is driven for the overall system throughput of the CARD protocol under unsaturated condition, and throughput analysis is evaluated by extensive simulations for WLANs.

The rest of this paper is organized as follows. The system model is given in Section 2. The CARD protocol is described in Section 3. An analytical model is derived to analyze the throughput performance of CARD in Section 4. Analytical and simulation results are presented and discussed in Section 5, followed by our conclusions in Section 6.

IWCMC'09 June 21-24, 2009, Leipzig, Germany.

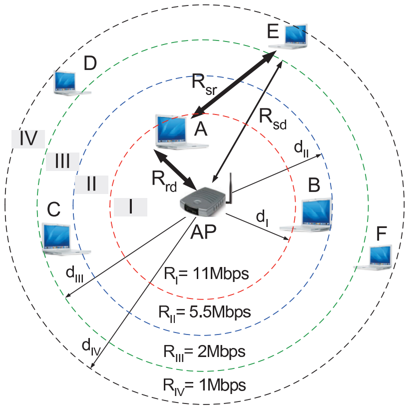


Figure 1: Multi-rate IEEE 802.11b WLAN.

2. SYSTEM MODEL

Referring to Fig. 1, this research considers a typical IEEE 802.11b WLAN consisting of an AP at the center of the network and N contending users/nodes distributed in four data-rate zones. Those in zones I and II are defined as high data-rate nodes, e.g. nodes A and B in the figure, which can act as source and relay nodes and always communicate directly with the AP; while those in zones III and IV are low data-rate nodes, e.g. nodes C-F, which can only act as source nodes and each of them needs a high data-rate relay node to improve its communication performance with the AP. In a distributed manner, a low data-rate source node continuously evaluates its high data-rate neighboring nodes and selects the best one (in terms of effective throughput or time saving) as its potential relay node.

3. THE CARD PROTOCOL

We provide a high level overview in order for the reader to be able to get a basic idea and to follow the performance analysis of the CARD protocol. Readers are referred to [7] for a detailed description of the CARD protocol.

The basic operation of CARD protocol is described in Fig. 2. A node in zone III or IV, called source node, looks up a relay node with minimum weights in the *relay-weights* table. Once source node decides to leverage a cooperative transmission involving relay node, it transmits a Cooperative RTS (CRTS) to both AP and relay node. This frame is an extension of extension of regular RTS frame and includes the MAC address of the potential relay node. The AP upon receiving the CRTS, it sends a Cooperative CTS (CCTS) indicating that it is ready to receive. Finally, The relay node sends a Relay-Ready-To-Send (RRTS) packet, if it is able to participate in cooperative transmission. This handshake procedure of control packets is shown in Fig. 2(a).

If both CCTS and RRTS packets are successfully received, then the source node sends its data packet "DATA-S" to the relay node at the data-rate R_{sr}. After that, the relay node sends "DATA-S" and its own data packet "DATA-R" to the AP at the data-rate R_{rd}. Finally, the AP sends a CACK packet after receiving "DATA-S" and "DATA-R"as shown in Fig. 2(b).

If the source node does not receive a RRTS packet, i.e. the selected relay node is not available, it directly sends the data packet "DATA-S" to the AP at the low data-rate R_{sd}, and then waits for an ACK packet. Therefore, the proposed CARD protocol can flexibly support both relay-capable nodes and legacy nodes, and is fully compatible with the IEEE 802.11b standard.

4. PERFORMANCE EVALUATION

4.1 Markov Chain Model

The performance of IEEE 802.11 DCF MAC has been well studied under the saturation conditions, where each node always has packets in its transmission queue [4]. The saturated assumption avoids the need for modeling of traffic characteristics, making this networks tractable. In real networks, traffic is mostly unsaturated, so it is important to derive a model accounting for practical network operations. In this paper, we extend the previous works on the subject by looking at two issues, unsaturated traffic, and frame retry limits. As a reference standard, we use network parameters belonging to the IEEE 802.11b protocol, even though the proposed mathematical models hold for any type of the IEEE 802.11 family or other wireless protocols with similar MAC layer functionality.

As in [4], we proposed a two-dimensional Markov chain model shown in Fig. 3. Two parameters, backoff stage and backoff counter value, are used to describe the state of an IEEE 802.11 node. The pair (backoff stage, backoff counter value), referred to as (i, k), describes the state of a node. The backoff stage, i, starts at 0 at the first attempt to transmit a packet and is increased by 1 every time a transmission attempt results in a collision, up to a maximum value m. The counter k is initially chosen uniformly between $[0, W_i - 1]$ where typically W_i is the range of the counter.

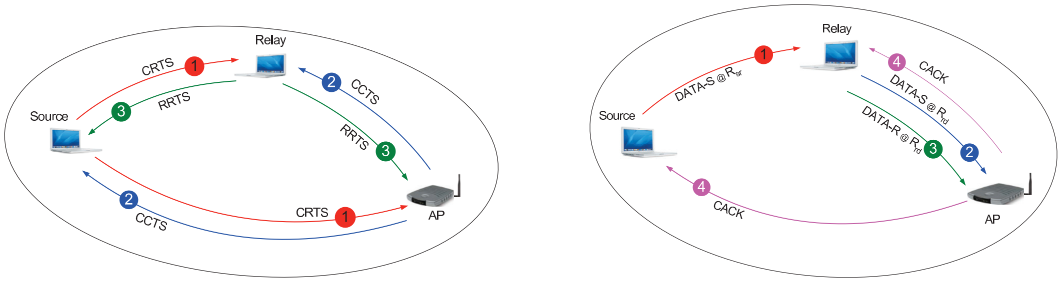
We introduce a new states $(0, k)_p$ for $k \in [0, W_0 - 1]$, representing a node which has transmitted a packet, but has none waiting packet which is called *post backoff*. This enables us to derive the relation between the quantities: p, the probability of collision seen by a packet being transmitted on the channel; τ, the probability that a node transmits in a randomly chosen slot time; q, the probability of at least one packet awaiting transmission at the start of a counter decrement; m, the maximum backoff stage; P, the Markov chain's matrix; π, the chain's stationary distribution. These relationships can be solved for p, τ and network throughput predicted.

We remain in the state $(0, 0)_p$ where the post backoff is complete, but the node's buffer is empty. If the packet arrives, we have three probabilities which are successful transmission, collision if the medium is busy with probability $(1 - P_{idle})$, the MAC begins another backoff stage-0. The probability that the medium is sensed idle during a typical slot is P_{idle}. Let $\pi(i, k)$ and $\pi(0, k)_b$ denoting the stationary distribution of being in states (i, k) and $(0, k)_p$ respectively. First not that

$$\pi(i-1, 0) \cdot p = \pi(i, 0) \quad 1 < i \leq m \tag{1}$$

$$\pi(i, k) = \frac{W_i - k}{W_i} p^{i-1} \pi(1, 0) \quad 1 \leq i \leq m \tag{2}$$

If the relay node does not have a data packet to transmit, CARD becomes a normal relay protocol and, after a RRTS packet, only the packet "DATA-S" will be forwarded from the relay node to the AP.



(a) Control packets handshake (b) Data transmission.

Figure 2: Access mechanism of CARD protocol.

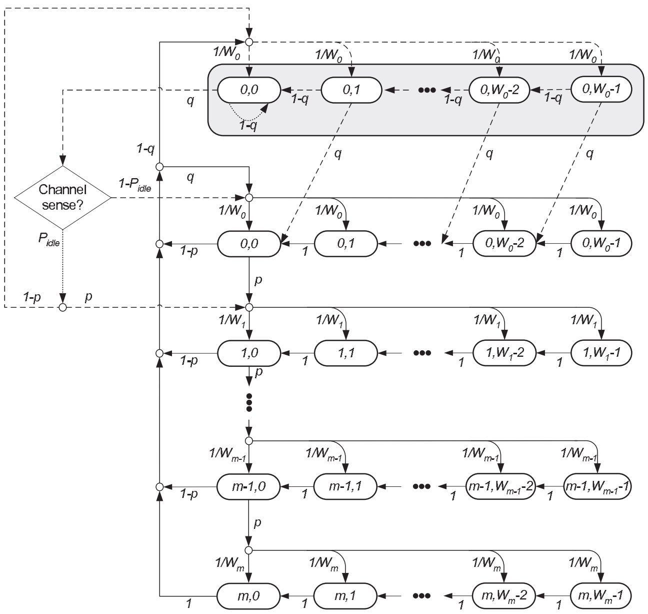


Figure 3: Markov chain model.

$$\pi(1,0) = p \cdot \pi(0,0) + qpP_{idle} \cdot \pi(0,0)_p \tag{3}$$

Therefore, by using the normalization condition for stationary distribution, we have

$$\sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \pi(i,k) + \sum_{k=0}^{W_0-1} \pi(0,k)_p = 1 \tag{4}$$

We will write all probabilities in term of $\pi(0,0)_p$ and use the normalization in (4) to determine $\pi(0,0)_p$. To calculate the second sum in (4), we determine $\pi(0, W_0-1)_p$. Transitions into $\pi(0, W_0-1)_p$ occur from $(0,0)_p$ and from $(i,0)$, we have

$$\begin{aligned}\pi(0, W_0-1)_p \quad = \quad & \frac{q(1-p)P_{idle}}{W_0}\pi(0,0)_e + \frac{1-q}{W_0}\pi(m,0) \\ & + \frac{(1-p)(1-q)}{W_0}\pi(0,0) \\ & + \frac{(1-p)(1-q)}{W_0}\sum_{i=1}^{m-1}\pi(i,0)\end{aligned} \tag{5}$$

Substituting (1) and (3) into (5) gives

$$\pi(0, W_0-1)_p = \frac{q(1-pq)P_{idle}}{W_0}\pi(0,0)_p + \frac{1-q}{W_0}\pi(0,0)$$

where

$$\pi(0,0) = \frac{q}{1-q}\left(\frac{qW_0}{1-(1-q)^{W_0}} - (1-pq)P_{idle}\right)\pi(0,0)_p \tag{6}$$

$$\begin{aligned}\pi(0,0)_p \quad = \quad & \Bigg[(1-q) + \frac{q^2W_0(1+W_0)}{2(1-(1-q)^{W_0})} + \frac{q(1+W_0)}{2(1-q)} \\ & \cdot\left((1-q) + \frac{q^2W_0}{(1-(1-q)^{W_0}} - (1-pq)P_{idle}\right) \\ & + \frac{pq^2}{1-q}\left(\frac{W_0}{1-(1-q)^{W_0}} - (1-p)P_{idle}\right) \\ & \cdot \sum_{i=1}^{m} p^{i-1} \sum_{k=0}^{W_i-1} \frac{W_i-k}{W_i}\Bigg]^{-1}\end{aligned} \tag{7}$$

Now the probability τ that a node transmits in a randomly chosen slot time can be expressed as

$$\tau = qP_{idle}\pi(0,0)_p + \sum_{i=0}^{m}\pi(i,0)$$

which reduces to

$$\begin{aligned}\tau \quad = \quad & \pi(0,0)_p \frac{1-p^{m+1}}{(1-p)(1-q)} \\ & \cdot\left(\frac{q^2W_0}{(1-(1-q)^{W_0})} - q^2P_{idle}(1-p)\right)\end{aligned} \tag{8}$$

where $\pi(0,0)_p$ is given in (7), so that τ is expressed in terms of p, q, P_{idle}, W_0, m, and m'.

If the MAC checks the buffer for a new packet at the beginning of each slot, then the probability, P_{idle}, that the medium is sensed idle is the probability that the next slot is empty and is given as $P_{idle} = 1 - p$.

If packets arrive at the MAC layer in a Poisson distribution with average rate λ, then $q = 1 - e^{\lambda T_{slot}}$, where

$$T_{slot} = (1-P_{tr})\sigma + P_{tr}P_sT_s + (1-P_s)P_{tr}T_c \tag{9}$$

where $P_{tr} = 1-(1-\tau)^n$ is the probability that there is at least one node transmitting in the considered time slot. $P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}}$ represents the probability of successful transmission conditioned on the fact that at least one node transmits. T_s and T_c are the average time the channel is sensed busy because of a successful transmission or a collision respectively. σ is the duration of empty slot time.

In the stationary state, a station transmits a packet with probability τ, so we have

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

Therefore, equations (7), (8), and (10) represent a non-linear system which can be solved numerically for p and τ. Note that we must have $p \in (0,1)$ and $\tau \in (0,1)$.

4.2 System Throughput

In the analysis we assume a fixed number of nodes. From the perspective of medium activity, the average time spent on the channel in order to observe the successful transmission of a packet payload is decomposed into three events. The first event, the average time spent in order to transmit a packet successfully. The second event represents the average idle time. The third represents the average time wasted on the channel because of collisions. Therefore, the saturated throughput S can be written as

$$S = \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_{tr}P_sT_s + (1-P_s)P_{tr}T_c} \tag{11}$$

where $P_sP_{tr}E[P]$ is the average payload data transmitted in a time slot and L is the data packet length in bytes. $T_c = T_{RTS} + T_{CTS} + T_{SIFS} + T_{DIFS}$. The average transmission time, T_s for one packet can be calculated by

$$T_s = f_IT_I + f_{II}T_{II} + f_{III}T_{III} + f_{IV}T_{IV} \tag{12}$$

where $f_I = \frac{d_I^2}{d_{IV}^2}, f_{II} = \frac{d_{II}^2 - d_I^2}{d_{IV}^2}, f_{III} = \frac{d_{III}^2 - d_{II}^2}{d_{IV}^2}, f_{IV} = \frac{d_{IV}^2 - d_{III}^2}{d_{IV}^2}$ are the fraction of nodes at rates $11, 5.5, 2,$ and 1 Mbps, respectively. $d_I, d_{II}, d_{III},$ and d_{IV} meters are the maximum transmission range for $11, 5.5, 2,$ and 1 Mbps, respectively.

T_I and T_{II} represent the transmission time of a packet at data rate 11 and 5.5 Mbps, respectively, where $T_I = \frac{8L}{R_I} + T_{OH}$, and $T_{II} = \frac{8L}{R_{II}} + T_{OH}$.

For nodes at 1 and 2 Mbps direct data rate, we have the average transmission time when a relay node is available is and when is not available. The total average transmission time needed for 2 Mbps nodes, T_{III} is given by equation (13). In the same manner, we can obtain the average transmission time T_{IV} for nodes at direct transmission rate 1 Mbps.

$$\begin{aligned} T_{III} \quad = \quad & 8L\left(\frac{2+\beta_I}{R_I}P_{I,I} + \left(\frac{1}{R_{II}} + \frac{1+\beta_I}{R_I}\right)P_{II,I}\right. \\ & \left. + \left(\frac{1}{R_I} + \frac{1+\beta_{II}}{R_{II}}\right)P_{I,II} + \frac{2+\beta_{II}}{R_{II}}P_{II,II}\right) \\ & +(1-P_2)(\frac{8L}{R_{III}} + T_{OH}) + P_2T_{COH} \end{aligned} \tag{13}$$

where β_I and β_{II} stand for the probability that a relay node at direct rate I and II, respectively has a data packet to send when forwarding a packet for a source node. These values are calculated from simulations. $T_{OH} = T_{PLCP} + T_{DIFS} + T_{RTS} + T_{CTS} + 3T_{SIFS} + T_{ACK}$, and $T_{COH} = 3T_{PLCP} + T_{DIFS} + T_{CRTS} + T_{CCTS} + T_{RRTS} + 6T_{SIFS} + T_{CACK}$ are the overhead time under noncooperative and cooperative transmission respectively. And $P_2 = P_{I,I} + P_{II,I} + P_{I,II} + P_{II,II}$. where $P_{x,y}$ is the probability that the optimum transmission scheme for nodes, in zone III, at 2 Mbps direct rate is through a two-hop transmission with rate $R_{sh} = R_x$ and $R_{hd} = R_y$ of zones x and y respectively.

Table 1: Parameters used in analysis

$MACheader$	272 $bits$
$PHYheader$	192 $bits$
RTS	352 $bits$
CTS	304 $bits$
ACK	304 $bits$
$Slot\ time$, $SIFS$, $DIFS$	$20, 10, 50\mu s$
m', m	5, 7
CW_{min}, CW_{max}	$31, 1023$ $slots$

5. SIMULATION RESULTS

In the following, to validate the analysis above, we have modified the Mobility Framework (MF) package which is built upon OMNET++ [1] simulator to work with CARD algorithm. In addition we have implemented CoopMAC [6] protocol. In simulations, nodes are uniformly distributed in the coverage area, while the base station is located at the center. The parameters values based on IEEE 802.11b are summarized in Table 1. The curves presented hereafter was averaged over several runs, each of which had a different topology and ran for a period of time that was long enough to get stabilized results. Packets are transmitted at different rates, depending on the location of the nodes with respect to the AP. Specifically, the distance thresholds for 11Mbps, 5.5Mbps, 2Mbps and 1Mbps are 75m, 150m, 200m and 250m, respectively. The traffic is uniformly distributed across all the nodes in the network, and the packets arrive in the network according to the Poisson distribution. In Fig. 4, we compare predictions of the model from Section 4.2 with simulation results for various arrival rates. There is good agreement between the model and simulations. The figure shows the linear relationship between the offered load and throughput when well below saturation; the three protocols have the same throughput under light traffic load. This because the channel has a very long idle time interval which cancels the throughput improvements. The CARD protocol outperforms both 802.11 and CoopMAC when the user traffic load increases. Simulation results of throughput gain for various number of nodes is given in Fig. 5. As shown in the figure, throughput gain of CARD protocol is better than CoopMAC protocol for the offered load higher than 20 packet/sec.

It is well known that the packet length has a major effect on the performance of any MAC protocol. In Fig. 6, we study the relationship between packet length and throughput gain of CoopMAC and CARD protocols. When the packet length increases, the throughput gain that can be achieved by CARD protocol becomes more significant than that can be achieved by CoopMAC protocol.

6. CONCLUSIONS

In this paper, we study the throughput of cooperative access mechanism called CARD under different traffic arrival rates. The results show that CARD protocol significantly outperforms CoopMAC and IEEE 802.11 of WLANs under medium traffic arrival rates. This is due to the fact that

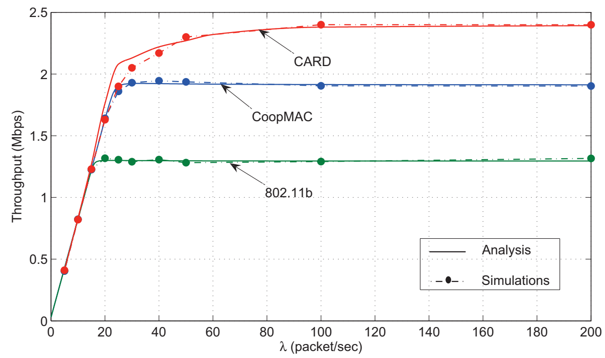


Figure 4: Throughput vs. offered load, L=1024 bytes byte.

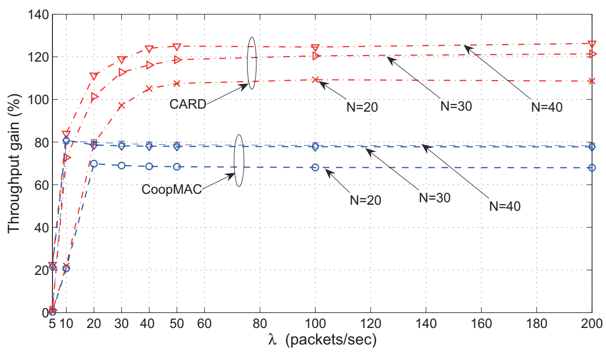


Figure 5: Throughput gain vs. offered load, L=1024 bytes nodes.

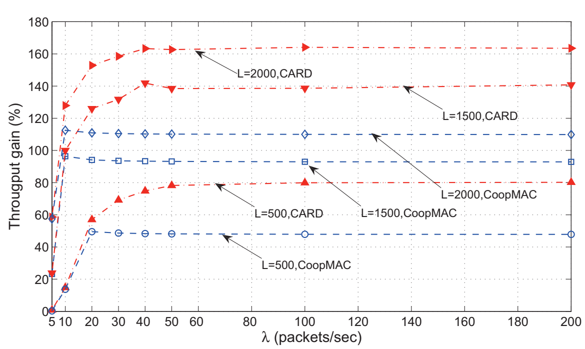


Figure 6: Throughput gain vs. offered load, N=30 nodes.

CARD leverages both cooperative diversity gain and cooperative multiplexing gain.

Acknowledgment

The author would like to express their sincere thanks to the Egyptian government for providing opportunities and supporting this work. Yang's work is partially supported by a UK-China Fellowship for Excellence, Dept for Innovation, Universities and Skills (DIUS), UK, from Sept 2008 to Dec 2008.

7. REFERENCES

[1] *Objective Modular Network Testbed in C++ (OMNET++). http://www.omnetpp.org/index.php.*

[2] *IEEE Std. 802.11-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications*, 1999.

[3] *IEEE Std. 802.11b-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-Speed Physical Layer Extension in the 2.4GHz Band*, 1999.

[4] G. Bianchi. Performance Analysis of the IEEE 802.11 Distributed Coordination Function. *IEEE Journal on Selected Areas in Communications*, 18(3):535–547, March 2000.

[5] G. B.-S. M. Heusse, F. Rousseau and A. Duda. Performance anomaly of 802.11b. In *Proc. of IEEE INFOCOM*, San Francisco, USA, March-April 2003.

[6] S. N.-T. K. Pei Liu, Zhifeng Tao and S. S. Panwar. CoopMAC: A Cooperative MAC for Wireless LANs. *IEEE Journal on Selected Areas in Communications*, 25(2):340–354, February 2007.

[7] S. Sayed and Y. Yang. CARD: Cooperative Access with Relay's Data for Multi-rate Wireless Local Area Networks. In *Accepted for publication in IEEE International Conference on Communications (ICC'09), June 14-18, Dresden, Germany*, 2009.

[8] H. Zhu and G. Cao. On Improving the Performance of IEEE 802.11 with Relay-Enabled PCF. *Mobile Networking and Applications (MONET)*, 9:423–434, 2004.

[9] H. Zhu and G. Cao. rDCF: A Relay-Enabled Medium Access Control Protocol for Wireless Ad Hoc Networks. *IEEE Transactions on Mobile Computing*, 5(9):1201–1213, Sept. 2006.