IEEE 802.11b Cooperative Protocols: A Performance Study [*]

Niraj Agarwal, Divya ChanneGowda, Lakshmi Narasimhan Kannan, Marco Tacca, and Andrea Fumagalli

The OpNeAR Laboratory
Erik Jonsson School of Engineering and Computer Science
The University of Texas at Dallas
{nxa041000, dhc042000, lnk051000, mtacca, andreaf}@utdallas.edu

Abstract. This paper investigates the use of cooperative communications in the context of IEEE 802.11b to combat radio signal degradation. The performance gain of both an existing cooperative protocol and the one proposed in the paper is discussed. It is quantitatively shown how much the two cooperative protocols increase throughput, lower delivery latency, and extend transmission span, when compared to the conventional IEEE 802.11b protocol. These features may help improve connectivity and network performance in ad hoc applications.

1 Introduction

WLAN's (wireless local area networks) have experienced tremendous growth and become the prevailing technology in providing wireless access to data users. The family of IEEE 802.11 protocols is perhaps the most widely adopted solution [10]. It must be noted that wireless links do not have well defined coverage areas. Propagation and channel characteristics are dynamic and unpredictable. Small changes in the node position or direction of mobility may result in significant differences in the signal strength. Adaptation to such conditions is a key issue in today and future wireless communications.

One of the characteristics of the radio medium is its inherent broadcast nature. Besides the intended destination, a signal transmitted by a source may be received by other neighboring nodes that are within earshot. This broadcast nature of the radio medium can be used to improve the system throughput by having a node, other than the source and the destination, actively help deliver the data frame correctly. The cooperating node is referred to as the *relay*. The essence of the idea is that, the destination benefits from data frames arriving via two statistically independent paths, i.e., spatial diversity.

The advantages of cooperative communications include the ability to increase the radio channel capacity [6, 7, 14] and reduce the latency of automatic

---

[*] This research is supported in part by NSF Grants No. ECS-0225528 and CNS-0435429.

retransmission request protocols [8, 9, 15]. An IEEE 802.11b cooperative protocol was introduced to improve both throughput and latency of the medium access control (MAC) [3]. Data frames transmitted by the source are received by the relay, which in turn forwards them to the destination. The destination acknowledges the received data frame directly to the source.

Other protocols which exploit the broadcast nature of wireless medium to achieve potential gains have been proposed in [12, 13]. In [13], the source attempts to transmit the data to destination directly and when the direct transmission fails, the partner nodes help in retransmitting the same frame after a backoff process. In [12], the proposed protocol (ExOR), deals with routing a packet from the source to the destination using the help of intermediate nodes in a special way as compared to traditional routing.

In this paper, cooperative communications in the context of IEEE 802.11b is further investigated. With the studied protocol, attempts to receive the data frame transmitted by the source are simultaneously made at both the relay and the destination. It is only when the destination is not successful in the reception attempt, that the relay re-sends the data frame again. The advantage of this approach is to limit the relay's intervention to those cases when the source transmission attempt is not successful in reaching the destination.

As discussed in the paper cooperative MAC protocols help cope with radio signal degradation. They provide higher throughput and lower latency when compared to the conventional IEEE 802.11b protocol. For a given throughput target, they achieve a maximum transmission span between the source and the destination that is up to 50% greater than one of the conventional IEEE 802.11b protocol. These features combined may help achieve improved connectivity and performance.

2 The Proposed Cooperative Protocol

This section describes the cooperative protocol proposed in the paper to enhance the performance of IEEE 802.11b. For simplicity, the protocol is described ignoring some control frames, e.g., the request to send (RTS), clear to send (CTS). The extension of the protocol description to include these additional control frames is straightforward.

Assume that three nodes have agreed to cooperate[2], i.e., source S, destination D, and relay R. The proposed cooperative MAC protocol is based on the distributed coordination function (DCF) defined for the ad hoc mode of the IEEE 802.11b standard. As shown in Fig. 1, when transmitting a data frame, S makes a direct attempt to reach D. While transmission takes place, R receives

---

[2] The protocol required to reach a consensus among the three nodes willing to cooperate is beyond the scope of this paper. Routing protocols available in the literature can be extended and adapted to perform relay selection [11].

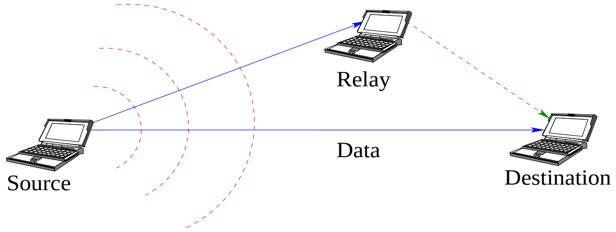


Fig. 1. Cooperation of three nodes

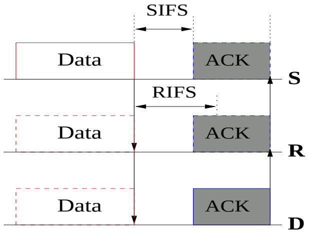


Fig. 2. Case 1: successful delivery of data and acknowledgement frames

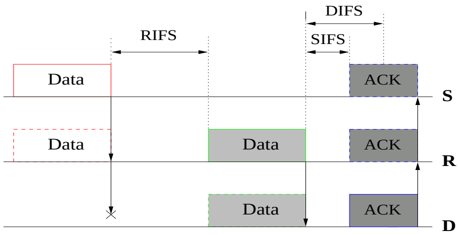


Fig. 3. Case 2: cooperation by R in retransmitting the data frame

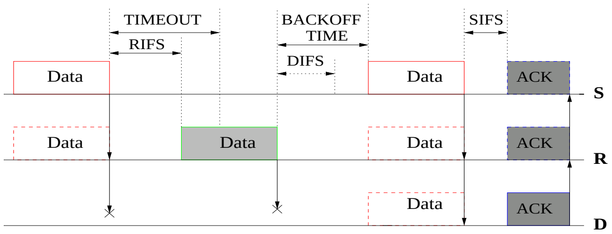


Fig. 4. Case 3: both S and R are unsuccessful

and stores a copy of the data frame temporarily. Four cases are possible[3]. The time diagrams of the transmitted frames are shown in Figs. 2-5, respectively.

---

[3] In the four cases it is assumed that the acknowledgment is always received correctly by S. The extension to account for acknowledgment loss is straightforward.

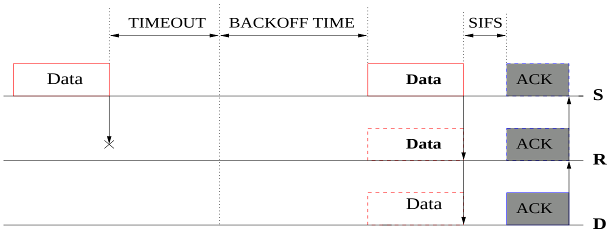


Fig. 5. Case 4: both D and R do not receive the data frame

1. Fig. 2: S transmitted frame is successfully received at D. D responds with a positive acknowledgment (ACK).
2. Fig. 3: S transmitted frame is successfully received at R, but not at D. D does not acknowledge the received data frame. Not receiving the ACK from D, R assumes that S's attempt to reach D has failed, and proceeds with the transmission of the data frame copy. R transmitted frame is successfully received at D. D responds to S with a positive ACK.
3. Fig. 4: Same as case 2, but D does not receive the frame transmitted by R.
4. Fig. 5: S transmitted frame is neither received successfully at R nor at D.

For the cooperation protocol to work as described, time intervals between transmission attempts must be chosen carefully. Specifically, for the transmission of a data frame, S must sense the channel idle and wait for a time interval denoted as distributed inter-frame space (DIFS)[4]. For ACK transmission, D does not need to wait. ACK is then received at S and R no later than a time interval denoted as short inter-frame space (SIFS). SIFS takes into account various latency factors, e.g., MAC software, transceiver hardware, and radio signal propagation. Both DIFS and SIFS are defined in IEEE 802.11b. For transmission of the data frame copy, R must wait a time interval denoted as relay inter-frame space (RIFS). RIFS is specifically introduced as a component of the cooperative protocol and is not defined in IEEE 802.11b. RIFS must be chosen to both allow the detection at R of the ACK transmitted by D (RIFS $>$ SIFS), and prevent frame transmission of other nodes while the cooperation is taking place (RIFS $<$ DIFS). A possible value for RIFS is the point (coordination function) inter-frame space (PIFS). PIFS is defined in IEEE 802.11b to allow the point coordination function to have collision-free access to the channel for coordinating data frame transmissions in the infrastructure mode. Choosing RIFS=PIFS is a possible option when operating the cooperative protocol in the ad hoc mode, as the point coordination function is not present. This choice is advantageous as the relay node will not need any special scheduling mechanism on its queues.

The backoff procedure at S is same as in IEEE 802.11b. When the predetermined maximum number of transmission attempts is reached, the data frame

---

[4] Exception to this rule is when multiple frames containing the fragments of the same packet are sequentially transmitted by the same sender.

is discarded. Special attention is required to handle the transmission sequence of case 2 (Fig. 3).

In this case, R senses the channel after SIFS. If the channel is idle, it indicates that the ACK frame is not being transmitted by D. Then, R begins the transmission of the data frame it received from S at RIFS. Due to the backoff procedure, S cannot start retransmission unless it senses the idle channel for at least DIFS $>$ RIFS. As explained above, RIFS is chosen carefully so that S finds the channel busy after SIFS if R is trying to help the transmission between S and D. If D receives the frame transmitted by R, D sends ACK to S. On receiving ACK, S cancels its backoff procedure for retransmission and start the transmission procedure for the next data frame. If S does not receive the ACK, it goes ahead with the backoff procedure as defined in the IEEE 802.11 standard.When R fails in its attempt to transmit the packet to D, S will continue its backoff process (which is frozen when R is transmitting) and when the backoff ends transmits the packet to D.Thus, when the transmission from R is not successful, the backoff procedure at S does not get affected.

As already mentioned, the proposed protocol does not change when RTS/CTS frames are considered. When R receives the RTS and/or CTS from S and/or D, it does not attempt transmission of its own data frames. However, it keeps listening and helps deliver the data frame from S to D whenever required.

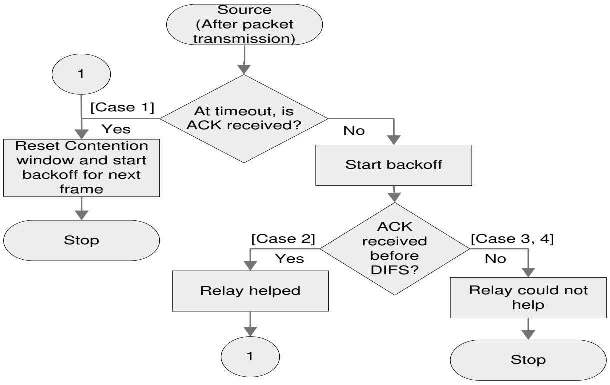


Fig. 6. Source's flowchart

The flowcharts of the cooperative protocol for S and R are shown in Figs. 6 and 7, respectively. As the flowcharts indicate, some changes are required in the MAC protocol for data transmission when compared to the IEEE 802.11b standard. No changes are required at D for data reception.

R must know the addresses of both S and D in order to relay data frames between the two nodes. Note that if traffic is bidirectional, R can help relay data frames in both directions. Conversely, S and D can function with or without R, and need not know the address of R. Thus, the protocol and the data flow between S and D can smoothly adapt to changing channel conditions and

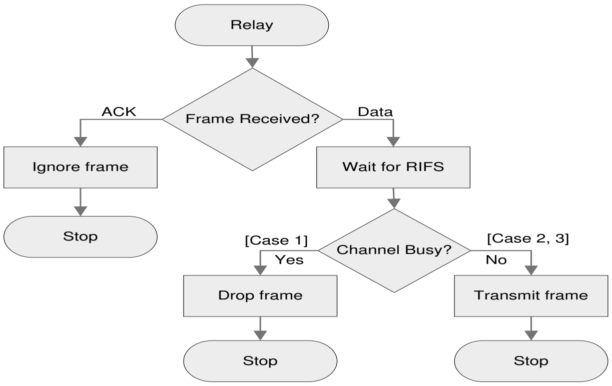


Fig. 7. Relay's flowchart

relative locations of the three nodes. As already mentioned, the main difference between the protocol proposed in this section and the one in [3] is the attempt made by S to reach both D and R with the same frame transmission.

3 Results

3.1 Channel Model

The path loss model used in the simulator is as follows:

$$E_{s_r} = E_{s_t} \cdot \frac{G_T \times G_R \times \lambda^2}{(4\pi)^2 (d)^\beta} \tag{1}$$

where,

- E_{s_r}, E_{s_t}: energy per symbol at the receiver and transmitter, respectively,
- G_T, G_R: transmitter and receiver antenna gain, respectively,
- d: transmitter-receiver distance,
- λ: wavelength at the channel center frequency in m,
- β: path loss exponent, $\beta = 2$ in free space, typically $2 \leq \beta \leq 4$ for environments with structures and obstacles [2, 16].

Fading is assumed to be Rayleigh slow and flat, i.e., the fading coefficients are considered constant over a single frame transmission. The fading experienced by any given frame transmission is statistically independent of the fading experienced by any other frame transmission.

The instantaneous signal to noise ratio at receiver j given a transmission from transmitter i is given by:

$$\gamma_{(i,j)} = ((E_{s_r} \times PG/N_o) \times r_{i,j}^2)/10^{\frac{F}{10}} \tag{2}$$

where,

- E_{s_r}: energy per symbol at the receiver,
- PG: processing gain due to spreading,
- N_o: noise spectral density of the additive white Gaussian noise (AWGN) channel

$$N_o = K_B \times T \tag{3}$$

- K_B: Boltzmann constant,
- $r_{i,j}$: Rayleigh distributed random variable to model the Rayleigh fading magnitude from node i to j,
- F: noise figure of the receiver (10 dB).

3.2 Simulation Results

In this section, simulation generated results are discussed to assess the performance gain in IEEE 802.11b when using cooperative protocols. In the study, three protocols are considered, i.e., the conventional IEEE 802.11b [1], MAC II in [3] (Poly MAC II), and the MAC protocol proposed in Section 2 (UTD MAC).

Table 1. Parameters used in simulation

Path Loss Exponent β	4
Flat Rayleigh Fading	constant across frame
Average Transmitter Power	100 mW
PHY Header	192 bits
SIFS	10 μs
RIFS	30 μs
DIFS	50 μs
Slot Time	20 μs
Vulnerable Period	20 μs
Max Retrans. Attempts	6
Frame Size	1023 bytes
Min Contention Window	31 slots
Max Contention Window	255 slots
Arrival Rate	1200 frames/s (saturation)
MAC Header	34 bytes
MAC ACK	14 bytes

The assumptions made and values chosen for the protocol parameters are shown in Table 1. Three nodes are used, i.e., S, R, and D. Data flow is either from S to D only (one-way traffic), or bidirectional between S and D (two-way traffic). R does not generate any own traffic. It is assumed that the three nodes have agreed to cooperate. They can freely use any of the four transmission rates provided by IEEE 802.11b, i.e., 1, 2, 5.5, and 11 Mbps. However, ACK frames are always transmitted at 1 Mbps to provide maximum reliability.

Fading is assumed independent of the destination, e.g., when S transmits, the fading experienced at R is independent of the one at D. Frame error rates are computed using [5]. Multiple concurrent transmission attempts always result in collision. Propagation delay is assumed negligible. The DCF mode of operation is used. Neither the virtual carrier sense (RTS/CTS) mechanism, nor fragmentation are used. The maximum number of transmission attempts per data frame is 6. Simulation results are obtained using a C++ custom simulator and have 5% confidence interval at 95% confidence level. Simulation results are validated against the analytical model presented in [4].

Saturation load condition is obtained by choosing data frame arrival rates that exceed the network capacity. Data frames in excess are dropped and not counted. Throughput is defined as the number of MAC payload bits that are successfully delivered and acknowledged by D normalized to time. The MAC and PHY header bits do not contribute to throughput. Access delay is the time taken for a data frame from the instant it reaches the head of the transmission queue at S till its first bit of the successful transmission attempt is aired by S.

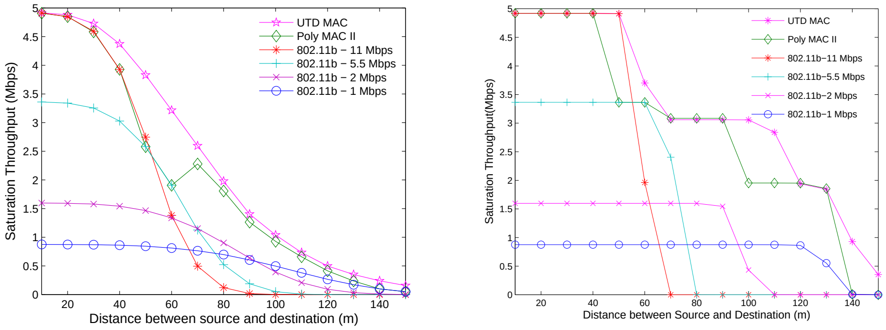
When obtaining the curves for the Poly MAC II protocol, the relay node is chosen based on the transmission time gain that can be achieved if the packet goes through the relay [3]. The transmission rate for S (R) is chosen based on the distance of S (R) from R (D), as indicated in [3]. Once a relay is chosen, all the packets from S to D go through the relay R only, i.e., S never attempts to transmit directly to D. Upon correct reception, D directly transmits the ACK to S. The UTD MAC curves are obtained by selecting the transmission rates for S and R, respectively, that jointly yield the maximal throughput for each experiment. Cooperation in the UTD MAC is always invoked, regardless of the location of the three nodes.

Fig. 8(a) shows throughput under saturation load for the three protocols as a function of the distance between S and D. Traffic is one-way. Four curves are reported for IEEE 802.11b, one for each transmission rate. R is always placed half way between S and D to provide good condition for cooperation. Under this condition, the two cooperative protocols offer increased throughput when compared to IEEE 802.11b for distances of 40 m and above. Poly MAC II best contribution is reached at 70 m and above.

Fig. 8(b) is similar to Fig. 8(a) except that fading is absent in the former.

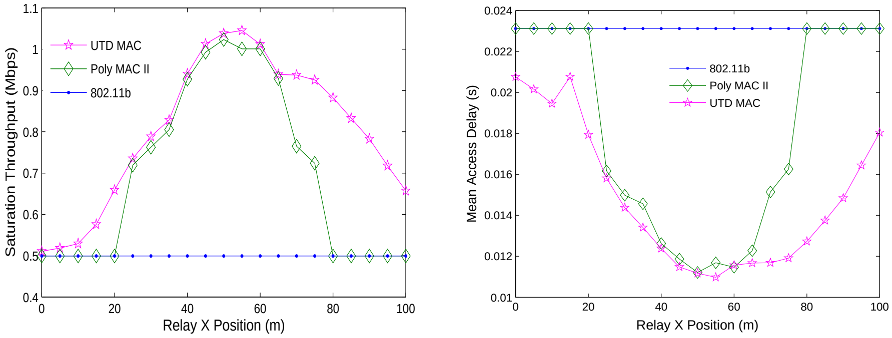
The cooperative protocols perform better than the IEEE 802.11b after a distance of 60 m, indicating that the performance gain is still there, irrespective of whether or not the channel is affected by fading. The sudden transitions in the throughput are due to the change in the transmission rates used. Fading smoothens the transition area, as clearly visible in Fig. 8(a).

Figs. 9(a) and 9(b) show throughput and expected access delay, respectively, under saturation load when the S-D distance is 100 m. R position varies along the S-D axis. S and D coordinates are $(0, 0)$ and $(100, 0)$, respectively. R coor-



(a) With Fading (b) Without Fading

Fig. 8. Throughput vs. S-D distance, R is half way



(a) Throughput (b) Expected Access Delay

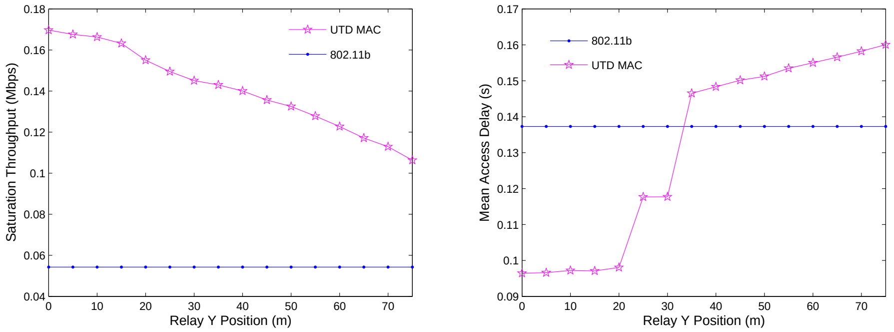
Fig. 9. R's position along the S-D axis, S-D distance is 100 m

dinates are $(X, 0)$, where X is the value on the horizontal axis in both figures. Traffic is one-way. The throughput of the cooperative protocols is significantly

Table 2. Bit rate pairs for UTD MAC in Figs. 9(a) and 9(b)

S-R distance (m)	0-10	15-35	40-45	50-55	60	65-100
S Rate (Mbps)	1	11	11	5.5	5.5	2
R Rate (Mbps)	1	2	5.5	5.5	11	11

affected by the position of R. Poly MAC II does not invoke cooperation when $X \leq 20$ and $X \geq 80$ m. The UTD MAC curves consist of a sequence of segments, each segment being obtained with a specific pair of transmission rates for S and R, respectively. The rate pairs are reported in Table 2 and help explain the UTD MAC plots. Sudden changes in the plots occur when the optimal transmission rate of either S or R changes. In the $0 \leq X \leq 10$ m region the transmission rate of both S and R is 1 Mbps, as both nodes attempt to reach D from approximately the same distance. In the $15 \leq X \leq 35$ m region, however, R increases its rate to 2 Mbps, thus providing a faster frame transmission time. In turn, S changes to 11 Mbps as it provides the fastest solution to send the frame to R. In the $65 \leq X \leq 100$ m region R increasingly approaches D. S rate goes down to 2 Mbps, which is a suitable rate to reach both R and D. When only R is reached successfully by the frame, R rate of 11 Mbps delivers the frame to D at full speed, taking advantage of the reduced distance to D.



(a) Throughput

(b) Expected Access Delay

Fig. 10. R's position orthogonal to the S-D axis, S-D distance is 150 m

Table 3. Bit rate pairs for UTD MAC in Figs. 10(a) and 10(b)

R's Y position from S-D axis (m)	0-20	25-30	35-75
S Rate (Mbps)	2	2	1
R Rate (Mbps)	2	1	1

Figs. 10(a) and 10(b) shows throughput and expected access delay, respectively, under saturation load when the S-D distance is 150 m. R position varies orthogonal to the S-D axis. S and D coordinates are $(0, 0)$ and $(150, 0)$, respectively. R coordinates are $(75, Y)$, where Y is the value on the horizontal axis in both figures. Traffic is two-way. In this scenario, Poly MAC II never invokes cooperation. Only IEEE 802.11b and UTD MAC are shown then. Even when R is 75 m away from the S-D axis, the cooperative protocol yields a noticeable throughput gain over IEEE 802.11b. The behavior of the access delay curve for UTD MAC as Y increases can be explained by inspecting the transmission rates used by S and R (Table 3). The step like delay increase in the $20 \leq Y \leq 30$ m region occurs due to the rate reduction from 1 to 2 Mbps performed by R first, then by S. It must be noted that R rate is decreased before S rate is, as R must ensure reliable delivery to D, whereas S can be more aggressive given that R can provide a backup transmission attempt. In the $35 \leq Y \leq 75$ m region the access delay increases slightly and it exceeds the delay of IEEE 802.11. This is because all nodes use 1 Mbps and the transmission via R takes longer time than the direct transmission from S to D. At $Y = 0$ m, UTD MAC performs three times better than IEEE 802.11b and when $Y = 75$ m UTD MAC performs two times better than IEEE 802.11b.

Overall, both cooperative protocols offer tangible performance gains when compared to IEEE 802.11b if R is conveniently located between S and D. UTD MAC appears to be somewhat more flexible in accommodating the various positions of R.

4 Conclusion

The paper investigated the use of cooperative communications techniques to enhance the IEEE 802.11b MAC protocol ability to cope with radio signal degradation with and without fading channel. Two cooperative MAC protocols were compared, i.e., the one in [3] and the one presented in the paper. Both cooperative protocols have the potential to yield higher throughput and lower latency when compared to the conventional IEEE 802.11b protocol. Alternatively, the maximum transmission span between the source and destination for a desired throughput target can be increased by up to 50% when using the cooperative protocols.

All these features may help achieve improved connectivity and network performance in ad hoc applications, where nodes' relative locations are difficult to control and predict. However, as indicated in this study, to fully harness cooperative communications in IEEE 802.11b, the cooperating nodes must be able to carefully select their transmission rates. This subject will be addressed in a future work on this topic.

References

1. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification: High speed physical layer extension in the 2.4 GHz band. sept 1999.

2. T. S. Rappaport (2001)Wireless Communications: Principles and Practice (2nd Edition), Prentice Hall PTR.
3. P. Liu and Z. Tao and S. Panwar (2005) A Co-operative MAC Protocol for Wireless Local Area Networks. Proc. IEEE International Conference on Communications (ICC) Seoul, Korea
4. Giuseppe Bianchi (march 2000) Performance Analysis of the IEEE 802.11 Distributed Coordination Function, IEEE Journal on Selected Areas in Communications, pages 535-547.
5. B. Kim and Y. Fang and T. Wong (2005) Throughput Enhancement Through Dynamic Fragmentation in Wireless LANs,Proc. IEEE Transactions on Vehicular Technology.
6. A. Sendonaris and E. Erkip and B. Aazhang (2003) User cooperation diversity Part I: System description IEEE Trans. Commun vol. 51 no. 11, pages 1927-1938
7. M. Janani and A. Hedyat and T. Hunter and A. Nosratinia (2004) Coded cooperation in wireless communications: Space-time transmission and iterative decoding, IEEE Trans. on Signal Processing, vol. 52, no. 2. pages 362-371.
8. E. Zimmermann and P. Herhold and G. Fettweis (2004) The impact of cooperation on diversity-exploiting protocols, Proc. of 59th IEEE Vehicular Technology Conference (VTC Spring) .
9. P. Gupta and I. Cerutti and A. Fumagalli (2004) Three transmission scheduling policies for a cooperative ARQ protocol in radio networks, Proc. WNCG conference.
10. Namgi Kim (2005) IEEE 802.11 MAC Performance with Variable Transmission Rates, IEICE Transaction on Communications", 2005, vol. E88-B, no. 9. pages 3524-3531
11. Aggelos Bletsas and Andrew Lippman and David.P.Reed (2005). A simple distributed method for relay selection in cooperative diversity wireless networks, based on reciprocity and channel measurements. Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st. Vol. 3 pages 1484- 1488
12. Sanjit Biswas and Robert Morris (2005) ExOR: opportunistic multi-hop routing for wireless networks, Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st, pages 133-144
13. Sai Shankar N and Chun-Ting Chou and Ghosh M (2005) Cooperative communication MAC (CMAC) - a new MAC protocol for next generation wireless LANs , International Conference on Wireless Networks, Communications and Mobile Computing, pages 133-144 .
14. J.N. Laneman, G.W.Wornell, and D. N. C. Tse (2001), "An efficient Protocol for realizing cooperative diversity in wireless networks," in Proc. IEEE ISIT, Washington, p.294.
15. B. Zhao and M. C. Valenti (2005), Practical relay networks: a generalization of hybrid-ARQ, IEEE Journal on Selected Areas in Communications, vol. 23, no. 1, pages 7-18.
16. J.Wall and J.Y. Khan (2003), An Advanced ARQ Mechanism for the 802.11 MAC Protocol, Proceedings of Australian Telecommunications, Networks and Applications Conference(ATNAC).