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CD-MAC: Cooperative Diversity MAC for Robust Communication in Wireless Ad Hoc Networks — Source link

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CD-MAC: Cooperative Diversity MAC for Robust Communication in Wireless Ad Hoc Networks

Sangman Moh, Chansu Yu, Seung-Min Park, and Heung-Nam Kim

Abstract— **In interference-rich and noisy environment, wireless communication is often hampered by unreliable communication links. Recently, there has been active research on *cooperative communication* that improves the communication reliability by having a collection of radio terminals transmit signals in a cooperative way. This paper proposes a medium access control (MAC) algorithm, called Cooperative Diversity Medium Access Control (CD-MAC), which exploits the cooperative communication capability to provide robust communication in *wireless ad hoc networks*. In CD-MAC, each terminal proactively selects a relay and lets it transmit simultaneously whenever necessary, mitigating interference from nearby terminals and thus improving the network performance. The proposed CD-MAC algorithm is designed based on the widely adopted IEEE 802.11 MAC for practicality. For accurate evaluation, this study presents and uses a realistic reception model by taking *bit error rate* (*BER*), derived from Intersil HFA3861B radio hardware, as well as *frame error rate* (*FER*) into consideration. System-level simulation study shows that CD-MAC significantly outperforms the original IEEE 802.11 MAC in terms of packet delivery ratio.**

Index Terms—**Wireless ad hoc network, cooperative diversity, cooperative transmission, relay selection.**

I. Introduction

In wireless ad hoc networks, signal fading (due to communication environment) and interference (due to other nodes) are two major obstacles in realizing their full potential capability in delivering signals. Cooperation among the nodes in various forms is critically required to alleviate these problems. Conventional routing layer solutions support the cooperative delivery of information by selecting intermediate forwarding nodes for a given source-destination pair. However, unless nodes cooperate at lower levels, it may be difficult to maximize the performance because the network capacity is inherently determined by the underlying MAC and PHY layer protocols. For example, in a carrier sense-based *medium access control* (*MAC*) protocol such as *Distributed Coordination Function* (*DCF*) in IEEE 802.11 standard [6], a node can be regarded as a greedy adversary to other nodes in its proximity as they compete with each other to grab the shared medium, interfere each other's communication, and cause collisions. At the physical layer, a node's data transfer not only provides interference to other nodes depriving their opportunity of using the medium but also incurs energy wastage by rendering them to overhear.

Recently, there has been active research in developing cooperative MAC algorithms, where nodes cooperate to accomplish the path-centric medium access rather than hop-centric [2], to salvage a collided packet for each other's behalf at the MAC layer [35], and so on. On the other hand, *cooperative communication* at the PHY layer attracts a lot of researchers' attention as well [1, 3-5] because it makes communication links more reliable. It refers to scenarios in which distributed radios interact with each other to jointly transmit information in wireless environments [4]. In other words, cooperative communication exploits diversity offered by multiple users, known as *cooperative diversity*, and improves the *bit error rate* (*BER*) dramatically, resulting in more reliable transmission and higher throughput. It is important to note that the primary motivation of cooperative diversity is to improve link reliability over wireless fading channels rather than lengthen the transmission range [3-5].

There are two types of cooperative diversity algorithms: *repetition-based* and *space–time-coded* [13]. The former consists of the sender broadcasting its transmission both to its receiver and potential relays (or partners) and the relays repeating the sender's message individually on orthogonal channels (frequency or time). The latter operates in a similar fashion except that all the relays transmit simultaneously on the same channel using a suitable coding scheme such as *orthogonal distributed space-time code* (*DSTC*) [13].

This paper presents a MAC layer protocol, called *cooperative diversity MAC* (*CD-MAC*), that exploits the above-mentioned cooperative communication capability in wireless ad hoc networks. Unlike many previous studies, the proposed CD-MAC operates on a single channel and a single relay (partner) assuming that radio hardware supports cooperative space-time coding. Each transmitter sends its signal together with its relay in a cooperative manner whenever necessary to improve the communication reliability. A key

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element of the CD-MAC is the selection of *relay*; each node monitors its neighbors and dynamically determines a single relay as the one that exhibits the best link quality. There are three reasons behind this choice: (i) Communication between a node and its relay is highly reliable. (ii) A relay with the best link quality is most probably the closest node[1]. Therefore, cooperative communication in CD-MAC does not impair the spatial diversity because the spatial area reserved by the original sender almost overlaps with that required for both the sender and the relay. (iii) It ensures that the sender and the relay share the same communication environment so that they can make a consistent decision on cooperation.

Contributions of this paper are two-fold:

- First, this paper introduces a DCF-based MAC algorithm, called CD-MAC, which is amenable to immediate implementation using existing technologies by neither requiring drastic changes in underlying network protocols nor assuming multi-channel, multi-radio device. This is a clear contrast to similar approaches proposed recently in the literature [17-19]. For example, *Cooperative MAC* (*C-MAC*) [18] requires positional information of the receiver for its operation. *Virtual MISO* (*multiple-input-single-output*) approach introduced in [19] requires modifications in routing layer protocols and new frame formats not defined in the underlying MAC standards.
- Second, while most of previous studies concentrated on evaluating how much the cooperative diversity improves BER and outage probability, this paper evaluates system-level performance such as packet delivery capability and packet delay over multi-hop routing paths. For more accurate evaluation, we take BER and *frame error rate* (*FER*) into consideration. It is contrasted to the deterministic reception model implemented in ns-2 network simulator [26], which is based on three fixed thresholds such as *carrier sense*, *receive* and *capture threshold*. To the best of the authors' knowledge, this is the first study on cooperative communication that offers detailed system-level comparisons with the BER and FER considered.

The rest of the paper is organized as follows: Related work on cooperative communication is summarized in the following section. Section III presents the proposed CD-MAC protocol; four-way handshaking algorithm and relay selection mechanism are described. Performance study including reception model, simulation environment, and evaluation results is discussed in Section IV. Finally, conclusions are given in Section V.

[1] Note that cooperative diversity can be effective when a node and its relay are spaced at least $\lambda/4$ apart, where λ is the wavelength [7]. In the IEEE 802.11 standard [6] using 2.4 GHz band, $\lambda/4$ is 3.125 *cm* (1.23 inches) and, thus, inter-node spacing is not a critical factor in achieving cooperative diversity in practical environments.

II. Related Work

A. Cooperative Diversity

Diversity techniques such as co-located antenna array can mitigate the interference problem by transmitting redundant signals over essentially independent channels. However, due to the physical size and hardware complexity, it may not be always feasible in practice for each node to have multiple antennas. Recently, a new class of diversity techniques called *cooperative diversity* has been proposed, in which distributed radios interact with each other to jointly transmit information exploiting diversity offered by multiple users [1, 3-5]. Several cooperative signaling or relaying methods have been studied. Among them, *amplify-and-forward* and *decode-and-forward* method are two well-known techniques [3, 4]. Relays (partners) amplify or fully decode their received signals and repeat information to the intended receiver; hence, they are called repetition-based cooperative algorithms. The corresponding benefits come at a price of decreasing bandwidth efficiency (increasing time delay) because each relay requires its own channel (time) for repetition [13].

For realizing cooperative diversity while allowing relays to transmit on the same channel, *orthogonal distributed space-time coding* (*DSTC*) has been studied [13, 14]. Historically, *space-time coding* (*STC*) and *space-time block coding* (*STBC*) were initially developed to offer transmit diversity in multi-antenna systems [15, 16]. In other words, multiple copies of a data stream are encoded based on the space-time code and transmitted through multiple antennas to improve the reliability of data transfer. STBC has been dominant for both *MISO* and *multiple-input-multiple-output* (*MIMO*) system architectures because maximum likelihood decoding can be accomplished with only linear processing at the receiver while achieving full diversity. It is now a part of W-CDMA and CDMA-2000 standards [15].

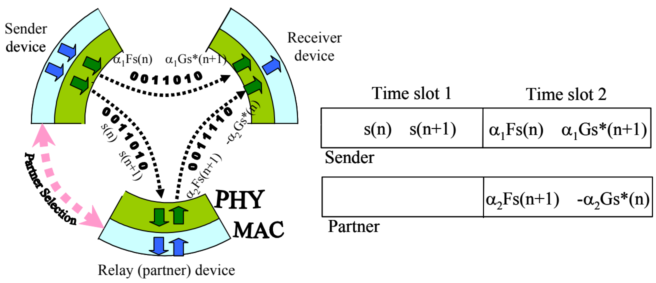


Fig. 1. Cooperative communication using distributed space-time coding scheme based on single channel model. s(n) and s(n+1) transmitted by the relay are not necessarily the same as those transmitted from the sender because the former is the estimation of them received by the relay. * denotes conjugation and two real coefficients α_1 and α_2 are related to each other by $\alpha_1^2 + \alpha_2^2 = 1$ [14].)

DSTC is a distributed multi-user version of STBC. In other words, transmission of multiple copies of a data stream is distributed among the cooperating nodes. Consider a simple three-node example with sender, relay (partner) and receiver devices as in Fig. 1. In time slot 1, the sender device transmits two symbol blocks of s(n) and s(n+1). If they are not successfully received by the intended receiver device, the sender and its relay cooperatively transmit the two blocks in time slot 2 as in the figure. Here, those two symbol blocks are encoded using the given space-time coding matrix F and G. By virtue of the orthogonality of the two matrices, it is not only possible for both the sender and the relay to transmit simultaneously on the same channel but also improves the reliability of the communication. An interested reader should refer to [14] for more details.

B. Cooperative Diversity in Wireless Ad hoc Networks

Communication reliability is more important in wireless ad hoc networks because they are deployed as a temporary network in noisy and unstable environments. A number of recent studies consistently note the benefit of cooperative transmission in such wireless ad hoc networks [8-12].

On the other hand, cooperative diversity in wireless ad hoc networks requires the support at the MAC layer [17-19]. Kojima *et al.* studied *distributed automatic repeat request* mechanism, where a source and distributed repeater nodes (relays) simultaneously transmit the same data packet repeatedly until the source correctly receives an acknowledgement from the destination [17]. Each node contributes to obtain the diversity gain by encoding the repeated data based on DSTC. This mechanism improves the communication reliability at the cost of more power dissipation, more routing overhead, and more network traffic, and consequently results in the reduction of network throughput.

Azgin *et al.* proposed *Cooperative MAC* (*C-MAC*) and the corresponding routing protocols for wireless ad hoc networks [18]. In C-MAC, four control packets such as *relaying start* (RS), *relay acknowledgement* (RA), *relay broadcasting* (RB) and *transmission start* (TS) are defined in addition to *request-to-send* (RTS), *clear-to-send* (CTS), and ACK. All control packets (RTS, CTS, RS, RA, RB, TS, and ACK) are transmitted through the conventional *single-input-single-output* (*SISO*) link without exploiting the cooperative diversity, but only DATA packet is transmitted using cooperative diversity. However, this results in unreliable delivery of control packets, which may limit the applicability of this protocol. In addition, directional knowledge of neighbors is required for routing.

Jakllari *et al.* introduced a MAC protocol that supports the virtual MISO and multiple relays [19]. In this approach, a SISO path between a source and a destination is discovered using an existing routing protocol such as *Ad-hoc On-demand Distance Vector* (AODV) [24] and *Dynamic Source Routing* (DSR) [25] and multiple relays are selected by exchanging periodic one-hop hello packets. The source and its relays cooperatively transmit to an intermediate node which is several-hop away on the routing path. This algorithm exploits the cooperative diversity to lengthen the transmission range. A clear shortcoming is that the receiver must have at least k relays when the sender uses k relays. For a transmission, multiple relays should be chosen and they transmit pilot tones in orthogonal channels to estimate the channel state.

III. Cooperative Diversity MAC

In a wireless ad hoc network, many nodes are spread over a network area and communicate with each other using multihop routed transmission rather than direct connection. A link breakage at one hop of a multihop route, caused by either the fluctuating communication environment, interference or node mobility, would bring a lot of overheads: Data transmission up to that point becomes useless, the intermediate node experiencing the link breakage needs to report this event to the original source of the data stream, a new alternative route must be discovered, and data must be retransmitted.

This section proposes a new MAC protocol called *cooperative diversity MAC* (*CD-MAC*) in a single-channel wireless ad hoc network. It exploits cooperative diversity via DSTC discussed in Section II to overcome the link breakage problem due to unreliable, fluctuating communication environment. CD-MAC uses exactly one relay for each cooperative transmission. More precisely, each node proactively selects one relay device for its cooperative communication. Two-node cooperation is advantageous compared to multi-node cooperation because orthogonal code design is not possible with more than two cooperating nodes without decreasing the data rate [20, 21, 22]. In other words, selecting the single best relay is a better option to maximize the capacity. Moreover, two-node cooperation is easier to coordinate than multi-node cooperation and the relay selection is simpler. Section III.A explains 4-way handshaking in the proposed CD-MAC followed by the discussion on relay selection in Section III.B.

A. Four-way Handshaking of CD-MAC

The proposed CD-MAC is based on DCF of IEEE 802.11 standard. If a primary link imposed by the upper layer routing protocol is strong enough to successfully transmit packets, the conventional MAC (*i.e.,* DCF) is used and no cooperative transmission is enabled. If it fails, however, the sender retransmits the packet but cooperatively with its relay. Fig. 2 shows the cooperative transmission of a data stream along a routing path between source (s) and destination (d). Each node is paired with its relay, both of which share the communication activities in the proximity. For example, node i transmits its packet to the next hop node j over the primary link. If it fails, node i and its relay r_i retransmit the packet cooperatively. Note that the relay r_i decodes the packet received from the sender i in time slot 1, encodes it using DSTC, and transmits in time slot 2 as discussed in Section II. Likewise, the node j transmits its packet (*e.g.*, ACK) to node i cooperatively with its relay r_j.

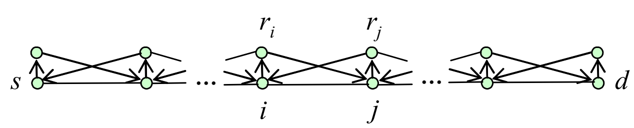
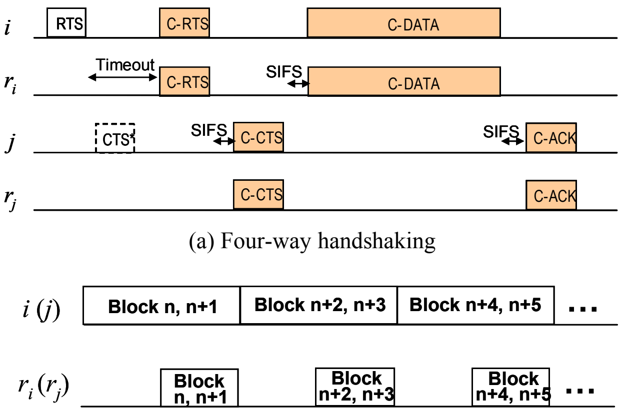


Fig. 2. Cooperative transmission with relays along a routing path.

Since DCF recommends to use RTS and CTS packets to avoid interference from hidden terminals [6], CD-MAC utilizes these control packets to make a decision whether or not to cooperate. That is, if node *i* receives a CTS packet successfully from receiver *j* after transmitting an RTS packet, it transmits a data packet according to the DCF principle without cooperation. This is followed by an acknowledgement (ACK) packet from *j*. However, if *i* does not receive a CTS from *j* (either *i*'s RTS fails to reach *j*, *j* determines not to reply to *i*, or *j*'s CTS fails to reach *i*), then cooperative transmission with relays r_i and r_j on the weak link (*i*, *j*) follows as shown in Fig. 3(a). That is, *i* and r_i cooperatively transmit *cooperative RTS* (C-RTS) and *j* and r_j cooperatively transmit *cooperative CTS* (C-CTS). After receiving C-CTS, *i* and r_i cooperatively transmit data packet to *j* (and r_j). After receiving the data packet, *j* and r_j cooperatively transmit *cooperative ACK* (C-ACK) to node *i*.



(a) Four-way handshaking

(b) Transmission blocks of C-RTS, C-CTS, C-DATA and C-ACK

Fig. 3. Four-way handshaking of CD-MAC for cooperative transmission with relays r_i and r_j on a weak link (*i*, *j*).

It is important to note that each cooperative transmission follows the same transmission principle as drawn in Fig. 1 and redrawn in Fig. 3(b); namely, two symbol blocks from the sender to the relay and then from both the sender and the relay to the receiver (*i* and r_i to *j* for C-RTS and C-DATA and *j* and r_j to *i* for C-CTS and C-ACK). This means that the transmission duration is normally the double than that without cooperation because we assume to use off-the-shelf radios with half-duplex antenna that operates on a single channel.

CD-MAC does not require any data format changes in the original DCF, *i.e.*, C-RTS, C-CTS, C-DATA and C-ACK have the same data format as RTS, CTS, DATA and ACK, respectively. For instance, C-DATA packet format is exactly the same as DATA as in Fig. 4. A sender and a relay transmit the exactly same copy at the MAC layer while they are different at the physical layer as they use space-time block code. However, in order to differentiate cooperate transmission from a normal transmission, CD-MAC uses Addr4 (logical address filed) to identify the relay, which is still conformant to the DCF standard.

A difference between the DCF and CD-MAC, but not violating the standard operation principle, is their handling of Duration/Connection ID (DI) field in DATA and C-DATA frame and the setting of *network allocation vector* (NAV) in their MAC algorithms. The DI filed is used in IEEE 802.11 MAC to support the *virtual carrier sense* mechanism. It is included in RTS, CTS and DATA frames and defines the time period needed to finish the whole communication session including the final ACK frame. Neighboring nodes set their NAV according to the value in the DI field and thus avoids collisions. In the proposed CD-MAC, the sender needs to take the extended transmission time into consideration when calculating the DI for the packet transmitted in a cooperative way.

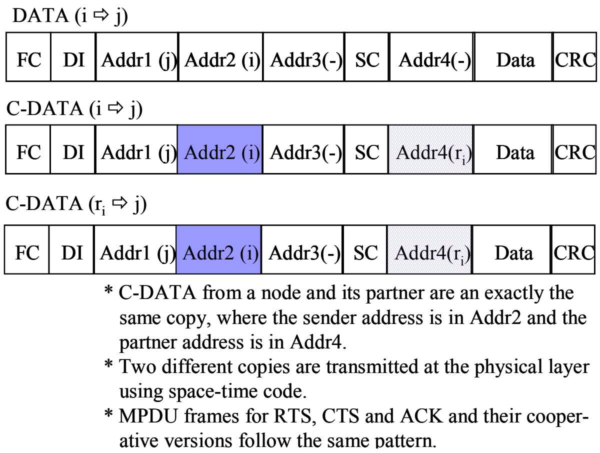


Fig. 4. Format of MPDU frames for DATA and C-DATA in the CD-MAC protocol (MPDU: MAC protocol data unit, FC: Frame control, DI: Duration/ Connection ID, SC: Sequence control).

B. Relay Selection

To exploit cooperative transmission in CD-MAC, every node proactively selects its relay by monitoring or overhearing its neighbors with respect to *link quality*. The one with the best quality is selected as its relay. The node includes the identity of the relay in the Addr4 field of C-DATA as in Fig. 4 so that its neighbors as well as the selected relay become to know about the selection. When the node does not have a packet to transmit for an extended period of time, it will broadcast a hello packet, the format of which follows C-DATA, with the destination (Addr1) and the source (Addr2) to be the transmitter itself. Note that the idea of hello packet is not new as it is extensively used in many popular network protocols such as AODV [24].

If a node receives a frame, it measures and records the link quality between itself and the transmitter. And, it looks up the neighbor table and selects a neighbor with the maximum link quality among all neighbors as its relay. When it has a packet to send (DATA or C-DATA) or needs to send its own hello packet, it includes its selection in Addr4 as described earlier. Note that metrics that can be used to indicate link quality are distance, load, interference level, signal strength (SS) and *signal-to-noise plus interference ratio* (SNIR) [23]. SNIR is used in this study because it takes noise and interference into account and is measurable with no additional support [29, 30].

IV. Performance Evaluation

In this section, the performance of the proposed CD-MAC protocol is evaluated in comparison to the conventional IEEE 802.11 DCF using ns-2 network simulator [26]. Section IV.A introduces the realistic reception model we have used in this study and Section IV.B explains the simulation parameters. Simulation results are presented in Section IV.C.

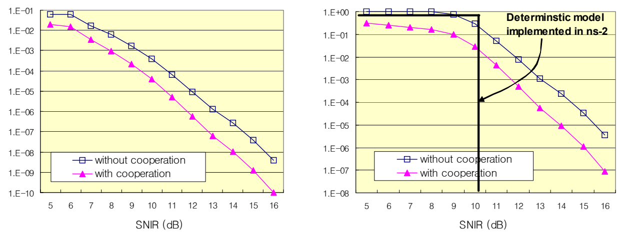
A. Reception Model

The signal reception model implemented in ns-2 network simulator is based on three fixed thresholds, *i.e., carrier sense threshold* (CSThresh), *receive threshold* (RxThresh) and *capture threshold* (CPThresh). When a frame is received, each node in the proximity compares the received signal power against CSThresh and RxThresh. If it is smaller than CSThresh, the receiver ignores the signal. If it is in between the two thresholds, the receiver considers the medium busy but does not decode the signal. If it is higher than RXThresh, the receiver receives the frame. However, when the node receives another signal during receiving the first signal, their ratio is compared against CPThresh. If one of them is much stronger, it survives and the weaker signal is dropped; otherwise, both frames are considered failed.

The abovementioned deterministic reception model serves reasonably well when evaluating high level protocols such as network and transport layer algorithms. However, when evaluating lower layer protocols, it is important to simulate a more realistic reception model. We modified ns-2 network simulator [26] to consider *bit error rate* (*BER*) when determining the success or failure of a received signal. It is based on the following 3-step process: (i) Compute SNIR, (ii) Look up the BER-SNIR curve to obtain BER, and (iii) Calculate *frame error rate* (*FER*) and determine whether to receive or drop the frame.

First, SNIR is calculated based on the following equation in the modified ns-2. In other words, $SNIR = \frac{P_r}{N + \sum_{i \neq r} P_i}$, where P_r is the received signal power, N is the effective noise at the receiver, and P_i denotes the receive power of other frame arrived at the receiver. Noise can be generated by the receiver itself as well as by environment. The effective noise level from the receiver can be obtained by adding up the noise figure of a network interface card (NIC) plus the thermal noise [33]. We first compute the thermal noise level within the channel bandwidth of 22 MHz in the IEEE 802.11 standard [6]. This bandwidth is 73 dB above -174 dBm/Hz, or -101 dBm. Assuming a system noise figure of 6 dB as in [33], the effective noise level generated by the receiver is -95 dBm. The environment noise or channel noise is the *additive white Gaussian noise* (*AWGN*) that is modeled as a Gaussian random variable. It is assumed that the environment noise is fixed to be -83 or -90 dBm in this work.

Second, the BER-SNIR curve used in our simulation study is shown in Fig. 5(a). It is obtained from the product specification of the Intersil HFA3861B radio chip [36], which models the QPSK modulation with 2 Mbps and reasonably matches with the empirical curves in [34, 14][2]. The BER-SNIR curve with cooperation, also shown in Fig. 5(a), is obtained based on the fact that BER is inversely proportional to SNIR without cooperative diversity while it is improved to be inversely proportional to SNIR^2 with diversity of order two [32]. As can be inferred from Fig. 5(a), cooperation reduces BER to about one tenth for the same SNIR. In an IEEE 802.11 frame, *physical layer convergence protocol* (PLCP) *preamble*, PLCP header and payload (data) may be transmitted at different rate with different modulation method. Hence, BER should be calculated separately for the three parts of a frame because BER is a function of SNIR and modulation method [31] as well as the cooperative diversity.



(a) BER versus SNIR (b) FER versus SNIR

Fig. 5. BER and FER comparison with and without cooperation for QPSK with 2 Mbps in the Intersil HFA3861B radio chip. (The PHY frame size for calculating FER is assumed to be 864 bits, *i.e.*, 144-bit preamble, 48-bit PLCP header and 84-byte payload.)

Third, once BER is obtained, *frame error rate* (*FER*) can be calculated, which determines the percentage that a frame is received correctly. For example, given α-bit preamble, β-bit PLCP header and γ-bit payload with BER of p_a, p_b and p_c, respectively, FER is obtained by $1 - (1 - p_a)^{\alpha}(1 - p_b)^{\beta}(1 - p_c)^{\gamma}$. As shown in Fig. 5(b), FER without cooperation is much higher than that with cooperative diversity and that's how cooperative communication improves the reliability of a wireless link. For comparison, Fig. 5(b) also shows the FER curve used in unmodified ns-2. As discussed earlier in this section, if SNIR is larger than CPThresh (the default value used in ns-2 is 10 dB as in Fig. 5(b)), the frame succeeds (FER = 0.0). Otherwise, it fails (FER = 1.0). In summary, FER is not deterministically but probabilistically determined based on SNIR in our simulation, making our evaluation more realistic.

B. Simulation Environment

It is assumed that 50 mobile nodes move over a square area of 300 × 1500m^2. Each run has been executed for 900 *sec* of simulation time. The propagation channel of *two-ray ground reflection model* is assumed with a data rate of 2 Mbps. The environment noise level of -83 or -90 dBm modeled as a Gaussian random variable with the standard deviation of 1 dB.

[2] Note that the BER-E_b/N_0 curve given in [36] is simply converted into the BER-SNIR curve since SNIR = $E_b/N_0 \times R/B_T$, where E_b is energy required per bit of information, N_0 is noise (plus interference) in 1 Hz of bandwidth, R is system data rate, and B_T is system bandwidth that is given by $B_T = R$ for QPSK in the Intersil chipset [37].

Noise level of -90 dBm is considered ignorable and interference from other transmitters dominates (see the SNIR equation in Section IV.A). On the other hand, noise level of -83 dBm is used to simulate a harsh communication environment.

Four constant bit rate (CBR) sources transmit UDP-based traffic at 2 packets per second and the data payload of each packet is 512 bytes long. Source-destination pairs are randomly selected. Mobile nodes are assumed to move randomly according to the *random waypoint model* [27] with the node speed of 0 ~ 5 *m/sec*. Pause time between moves varies from 0 to 900 seconds. Since simulation time is 900 seconds, the pause time of 900 seconds means a static network. And, the pause time of 0 second simulates a constant moving, high mobility scenario. *Ad-hoc On-demand Distance Vector* (AODV) [24] routing protocol is used to discover a routing path for a given source-destination pair.

Performance metrics are *packet delivery ratio*, *average end-to-end delay*, *route discovery frequency* and *cooperation ratio*. The packet delivery ratio is the ratio of the number of data packets successfully delivered to the destination over the number of data packets send by the source. The average end-to-end delay is the averaged end-to-end data packet delay including all possible delays caused by buffering during route discovery, queuing delay at the interface, retransmission delays at MAC, propagation and transfer times. The route discovery frequency indirectly refers to the number of route failures because a source node is supposed to discover a new routing path if an existing one does not work. This happens when any one of the links of a multi-hop path breaks. Links breaks caused by node mobility are not unavoidable but those due to reliable communication environment can be overcome, which is in fact the main theme of this paper. Finally, the cooperation ratio refers to how often nodes cooperatively transmit packets in CD-MAC. Since CD-MAC attempts to use the original DCF whenever possible, it is interesting to know how often it succeeds and how often it resorts to cooperative communication.

C. Simulation Results and Discussion

This subsection presents simulation results comparing DCF and CD-MAC. Fig. 6 shows the packet delivery ratio of DCF and CD-MAC with two environment noise levels of -90 and -83 dBm. As shown in the figure, CD-MAC consistently outperforms DCF regardless the mobility but the gap becomes more significant (53~73% increases) when the environment noise is high (-83 dBm). This is because noisy environment makes wireless links more unreliable and cooperative diversity is usefully exploited in CD-MAC in this case. As the node mobility decreases, the packet delivery ratio improves slightly except for very high mobility.

Fig. 7 shows the corresponding average end-to-end delay with DCF and CD-MAC. Due to the cooperative relaying, CD-MAC increases per-hop communication time, leading to higher end-to-end packet delay (see Section III.A and Fig. 3). Unfortunately, it is more than double in the case of pause time of 300 seconds and noise level of -90 dBm. We suspect this is the result of bad selection of a relay node. When the channel between the sender and the relay is not reliable enough, cooperative communication would not bring in performance improvement while increasing the overhead. It requires further investigation, which comprises one of our future works. However, it does not overshadow the benefits of CD-MAC in terms of packet delivery capability as already seen in Fig. 6.

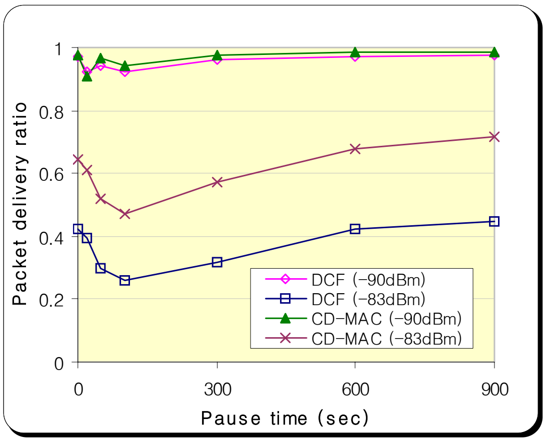


Fig. 6. Packet delivery ratio.

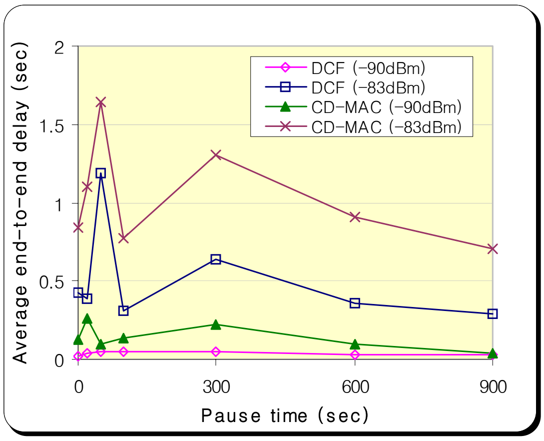


Fig. 7. Average end-to-end delay.

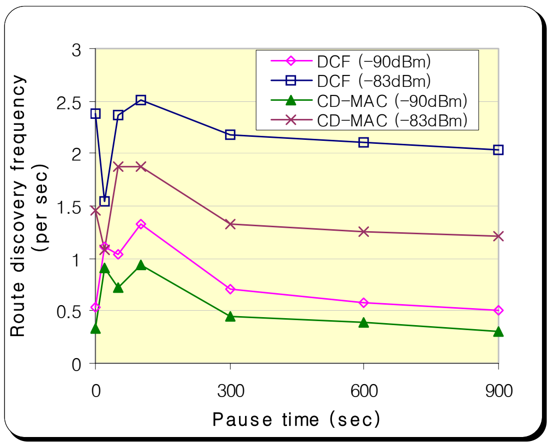


Fig. 8. Route discovery frequency.

Fig. 8 compares the route discovery frequency. Thanks to the cooperative diversity the route discovery frequency with CD-MAC is less than that with DCF. It is reduced 22~50% and 35~69% with the noise level of -90 and -83 dBm, respectively. This clearly tells that the path or link reliability is improved significantly with CD-MAC. Note the case when the pause time is 900 seconds. Since it is a static scenario as explained earlier in Section IV.A, there must not be route failures once a route is discovered for a source-destination pair. CD-MAC eliminates around half of the false alarms and thus helps reduce the control overhead for finding new routing paths.

Fig. 9 shows how often nodes cooperate in CD-MAC. When the environment noise level is high (-83 dBm), the cooperation happens more frequently to survive the harsh communication environment. As the node mobility deceases, the cooperation ratio is also decreased thanks to less unstable links. Note that the cooperation ratio is about 20% even if the environment noise is low (-90 dBm) and there is no mobility (900 seconds of pause time). This is because there still exist a number of unreliable links in the network due to, for example, inter-node interference.

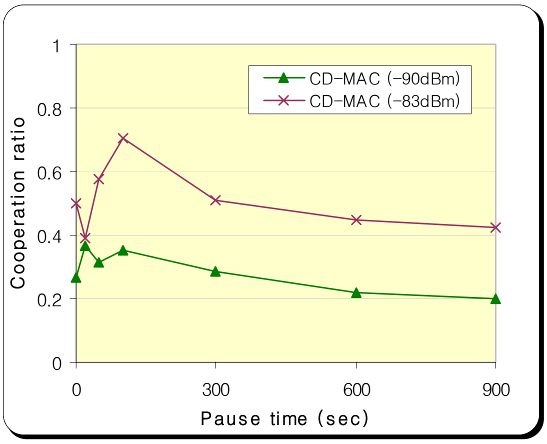


Fig. 9. Cooperation ratio.

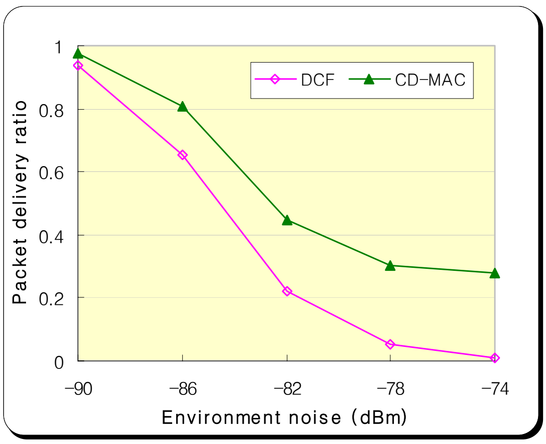


Fig. 10. Impact of environment noise.

To see the impact of environment noise in more detail, the packet delivery ratio with the different environment noise levels of -90 ~ -74 dBm is shown in Fig. 10. While the performance decreases sharply in noisier environment, CD-MAC always performs better than DCF and the gap is larger as the environment noise increases. In noisy and unreliable communication environment, CD-MAC is very promising.

V. Conclusions

This paper proposes *cooperative diversity MAC* (*CD-MAC*) and discusses design issues and performance benefits in wireless ad hoc networks. When a communication link is unreliable, a sender transmits its signal together with its relay delivering the signal more reliably. In order to select a relay, each node monitors its neighbors with respect to link quality by receiving periodic hello packets and overhearing ongoing communications. The proposed CD-MAC is designed based on the IEEE 802.11 standards and does not require any changes in frame formats, making it amenable to immediate implementation. For accurate performance study, we developed a realistic reception model based on BER and FER, which are derived from Intersil radio hardware specification. According to the system-level simulation results, CD-MAC significantly outperforms the conventional DCF of the original IEEE 802.11 standards while increasing end-to-end packet delay.

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