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Location Enhancement to IEEE 802.11 DCF

Tamer Nadeem*, Lusheng Ji†, Ashok Agrawala*, Jonathan Agre‡
* Department of Computer Science
University of Maryland, College Park, MD 20742
{nadeem, agrawala}@cs.umd.edu
† AT&T Labs, – Research
180 Park Ave., Florham Park, NJ 07932
lji@research.att.com
‡ Fujitsu Labs of America
8400 Baltimore Ave., Suite 302, College Park, MD 20742
jagre@fla.fujitsu.com

***Abstract*— In this paper, we propose an enhancement to the existing IEEE 802.11 Distributed Coordination Function (DCF) MAC to improve channel spatial reuse efficiency, and thus improve overall network data throughput. Our modification, named the Location Enhanced DCF (LED) for IEEE 802.11, incorporates location information in DCF frame exchange sequences so that stations sharing the communication channel are able to make better interference predictions and blocking assessments. Utilizing an underlying physical layer design that supports frame capture, the LED enhanced interference estimation can increase overall network data throughput by permitting more concurrent transmissions. In this paper we also analytically study the potential performance enhancement of the LED over the original IEEE 802.11 DCF. The results are verified using the *ns-2* simulator, which shows that up to 35% of DCF blocking decisions are unnecessary and our LED method can achieve up to 22% more throughput than the original DCF.**

I. Introduction

The IEEE 802.11 [1] is the most popular standard for Wireless Local Area Networks (WLANs). The IEEE 802.11 Medium Access Control (MAC) specifies two different mechanisms: the mandatory contention-based Distributed Coordination Function (DCF) and the optional polling-based Point Coordination Function (PCF). At the present time, DCF is the dominant MAC mechanism implemented by the IEEE 802.11-compliant products.

Contention based MAC protocols are the mainstream for distributed and self-organized wireless networks since in such networks the infrastructure is usually not present and there is no clear separation between the roles of access points and client stations. The support of contention based DCF has also made IEEE 802.11 equipments popular choices for various wireless ad hoc networks.

The IEEE 802.11 DCF, just like most other contention based MAC protocols, are based on Carrier Sense Multiple Access (CSMA) mechanism. In CSMA, a station may transmit if and only if the medium is sensed to be idle. The purpose is to prevent any station from causing interference to an ongoing transmission occupying the medium. If a station does have data to transmit but a busy carrier has been detected, a certain blocking mechanism is then typically applied to postpone the station transmission. In addition to the common CSMA techniques, the DCF further reduces the possibility of collision and improves data delivery reliability by adding acknowledgement frames and optional channel reservation frames (Request-To-Send and Clear-To-Send) to its data delivery frame exchange sequences.

The IEEE 802.11 DCF has been discovered to be not efficient in shared channel use due to its overcautious approach towards assessing the possibility of causing interference. In particular, a station simply blocks its own transmission when it senses the medium busy or it receives a channel reservation frame sent by any other station. However in many cases this channel assessing station's own transmission may not introduce enough signal energy to disturb the ongoing transmission at its receiver.

Finer channel assessment schemes which do consider the above possibility are difficult to implement with information provided by the current IEEE 802.11 communication protocol. If more parameters regarding an ongoing transmission, such as locations of the transmitters and receivers and transmission power levels can be provided to the channel assessing stations, it is then possible for these stations to make better estimations to decide if indeed their transmissions will collide with the ongoing transmission. In this way, more concurrent transmissions in wireless networks can be conducted and the communication channel can be used more efficiently.

In this paper, we propose a novel contention-based distributed MAC scheme which assesses the channel condition more accurately and exploits radio signal capture phenomena to increase the simultaneity of data transmissions to enhance overall wireless network throughput. This scheme is designed as an enhancement to the DCF. In doing so, we will also develop a new MAC frame format in addition to the new MAC protocol to provide the additional information to help the stations in deciding whether to block their transmissions or not, when there are ongoing communications occurring in their vicinities.

II. Backgrounds and Related Works

A. IEEE 802.11 DCF Mode

Historically, the design of the IEEE 802.11 DCF is influenced by several other protocols. MACAW protocol [7], extending its predecessor Multiple Access Collision Avoidance (MACA) protocol [17], is based on the use of the Request-To-Send and Clear-To-Send (RTS/CTS) handshaking scheme. If a station has a packet to send, it firstly transmits a RTS packet to request the channel and the receiver replies with a CTS packet. After the sender receives the CTS packet successfully, it proceeds to transmit the actual data packet. Stations that overhear the RTS packet will defer transmission for a sufficiently long period of time to allow the transmitter to receive the CTS packet. Stations overhearing the CTS packet will back off for a period of time that is sufficiently long to allow the receiver to receive the entire data packet and acknowledge it. Sender stations using RTS/CTS do not use the carrier sense mechanism to assess the channel availability. An extended protocol named Floor Acquisition Multiple Access (FAMA) is proposed in [13]. FAMA bears significant resemblance to IEEE 802.11, employing both local carrier sensing, as well as the RTS/CTS collision avoidance exchange for data transmission.

The basic MAC method of IEEE 802.11, the DCF, is a Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism with a random back-off time window after sensing a busy medium. ACK frames are also used in the DCF for acknowledging the reception of unicast data frames.

The CSMA scheme of the DCF works as follows: Before a station transmits, it must sense the wireless channel to determine if any other stations are transmitting. The channel is assessed as busy if there are detected carrier signals or the energy level of the channel exceeds a threshold, or both, depending on each particular vendor's implementation. If the channel is assessed as busy, the station needs to wait until the carrier becomes idle and then wait more for a period known as the Distributed Inter-Frame Space (DIFS). After the DIFS period is passed, the station again waits for a random back-off interval and then transmits if the medium is still free.

After a directed transmission (unicast data frame) is correctly received, the receiving station sends an ACK frame back after a Short Inter-Frame Space (SIFS). The reception of an ACK frame following the transmission of a DATA frame notifies the transmitter that its data has been received by the receiver without error. If no ACK is received after the transmission of a data frame, the transmitter schedules the data frame for retransmission.

In addition to the above *basic* transmission mechanism, the DCF employs an optional reservation-based collision avoidance mechanism for unicast data frames. This option requires the sender and the receiver to exchange short Request-To-Send (RTS) and Clear-To-Send (CTS) control frames, respectively, prior to the actual data frame transmission to reserve the channel. Any stations which overhear either the RTS or the CTS block their own transmissions (if any) to yield to the communication between this sender and its receiver.

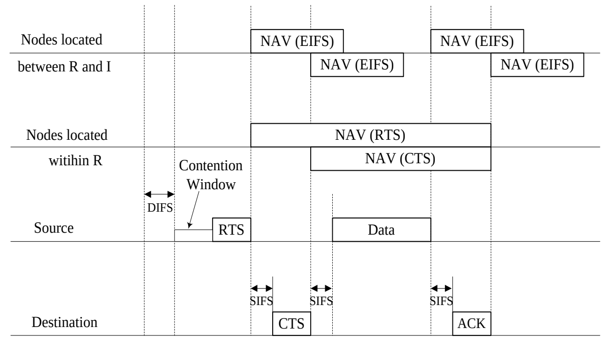

Fig. 1. IEEE 802.11 DCF mechanism

Each station maintains a timer called the Network Allocation Vector (NAV) which tracks the remaining time of any ongoing data transmission. After a station receives a RTS, CTS, DATA, or ACK frame not destined for itself, it sets its NAV according to the "Duration" field of the frame. The Duration field contains the frame sender's estimation for how long the whole data delivery frame exchange sequence (including all the SIFS waits and the acknowledgement) will take, or in other words, the reservation duration of this whole frame exchange sequence. After the NAV is set, it may be extended if a newly received frame contains a Duration field pointing to a later completion time. Figure 1 illustrates how stations set their NAVs during a RTS-CTS-DATA-ACK handshake. Checking its NAV before a station attempting to transmit is also known as "virtual carrier sensing". If the NAV is not zero, the station needs to block its own transmissions to yield to the ongoing data delivery.

In summary, a station blocks its own transmissions if either physical carrier sensing or virtual carrier sensing returns channel busy.

B. Capture Effect

When a frequency modulation scheme, such as the Direct Sequence Spread Spectrum (DSSS) used by most IEEE 802.11 and 802.11b physical layer (PHY) implementations, is used in wireless communication, an effect known as the "capture effect" [5], [24], [25], [20], [14] may occur. When two transmissions sent by two different transmitters at the same frequency overlap in time and they are received by the same receiver, the signals of the stronger transmission will capture the receiver modem, and signals of the weaker transmission will be rejected as noise.

Different works (e.g., [14], [9], [21], [28], [18]) have studied the analytical and simulation models for characterizing the capture effects. Among the results of these previous works, we adopt a simple yet widely accepted model to describe the capture effect. In our model, a receiver captures the signals of a particular transmission if the received energy P_r of this transmission sufficiently exceeds all other received energy P_i of *n* other concurrent interfering contenders combined by a

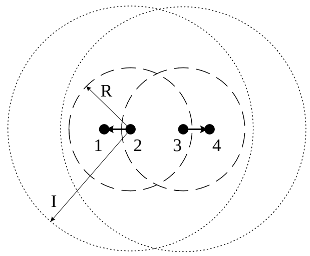

Fig. 2. Example of network with 4 stations, where R is transmission range and I is the carrier sense range

minimum ratio. That is, the capture occurs when:

$$P_r > \alpha \sum_{i=1, i\neq r}^{n} P_i \quad (1)$$

This minimum ratio α is called the capture ratio. The received signals are assumed to have phase terms varying quickly enough to allow incoherent addition of the received power of each frame.

Wireless communication technologies such as the IEEE 802.11 do not pay special attention to capture effects mainly to keep the design simple. Also the contention-based MAC protocol largely reduces the time and space overlapping of simultaneous transmissions. Nonetheless, the capture effect still exists in IEEE 802.11 DSSS networks and it has been confirmed by several published studies. Authors in [15], [29], [28], [18] have also studied the impact of capture effect on traffic fairness and throughput of UDP and TCP flows for both ad hoc and infrastructure modes of the IEEE 802.11 systems.

Another aspect, which has not been questioned by many of the previous works, that needs some discussion before we proceed further is the capturing of a *signal* versus capturing of a *frame*. We consider the case when the new (stronger) frame arrives after the receiver begins to receive the weaker frame. A receiver being able to capture a stronger signal does not necessarily mean it can capture the stronger frame. Whether a receiver can capture a stronger frame also depends on several other factors such as: the arrival moment of the beginning of the stronger frame, the current receiving state of the receiver, the capability of the receiver to realize that it is seeing the beginning of a new (stronger) frame, and capability of the receiver to jump to the appropriate receiving state for beginning to process the new frame. If the receiver is not able to realize that it has just seen the beginning of a new frame and reset its receiving state accordingly, the bits of the new frame may be interpreted as the bits of the weaker frame, which typically results in failure of the weaker frame's forward error checking and frame rejection.

We are interested in capture effect because we believe that they can be used to our advantage to improve channel sharing efficiency. Consider the following example as shown in Figure 2. Two concurrent connections share the same wireless communication channel. The first connection is from station 2 (source) to station 1 (destination) and the second is from station 3 to station 4. In the current IEEE 802.11 DCF, whichever connection acquires the channel first gets to complete its data frame delivery message exchange because stations of the other connection would have detected the carrier signals of this connection, or received reservation messages (RTS/CTS) of this connection, and remain blocked.

However, if the stations are positioned in such a way that the energy levels of stations 3 and 4's transmissions as measured at stations 1 and 2 are not strong enough that stations 1 and 2 can still capture each other's transmissions, stations of the second connection should be permitted to communicate, even after stations of the first connection have begun their frame transmissions Similarly stations 1 and 2 can do the same if stations 3 and 4 have acquired the channel first. One thing to note is that of course to do this the design of the station receivers must support the capture of stronger *frame*, regardless when it arrives.

C. Related Works

The IEEE 802.11 DCF uses a combination of physical/virtual carrier sensing and RTS/CTS channel reservation. While these mechanisms are generally effective in reducing frame collisions, the protocol is rather pessimistic and not very efficient in channel use because it does not encourage enough concurrent transmissions. Our observation concurs with the views of many other researchers, who have also proposed modifications to the DCF for the purpose of increasing the number of concurrent transmissions in the network.

Authors in [30] manipulate the timing of the original RTS-CTS-DATA-ACK frame sequence and attempts to synchronize the states among one hop neighbors so that if the receivers of two frames transmitted by two neighbors are far apart enough, these two transmissions are scheduled to occur concurrently. [4] observes that in an "overactive RTS/CTS" situation, in which the RTS/CTS exchange reserves way too much space than needed, just hearing RTS or CTS but not both does not justify for assessing the channel as busy. Thus a bystander to a pair of data transmitter and receiver should only block its own transmission if it receives both RTS and CTS. One issue with both approaches is that they do not fully address the complexity of capture effect. Thus the proposed solutions only work for certain scenarios.

The Interference Aware (IA) method proposed by [23] and [11] share the same philosophy as our proposal in the way that stations report channel condition by piggybacking condition information in the frame exchange sequence. In IA, a receiver of a RTS embeds the Signal to Interference Ratio (SIR) observed while receiving the RTS in its returning CTS frame. This way other stations, also taking into account the SIR observed while receiving the CTS frame, are able to calculate if their own transmissions may cause enough interference to the receiver in question. The approach makes assumptions about the participating stations such as same transmission power, same antenna characteristics, etc. The authors mainly rather keep their model simple than make their solution more generalized. In addition, the proposal only concerns about the receiver of RTS frame, not the sender of the RTS frame, which also is the receiver of the subsequent

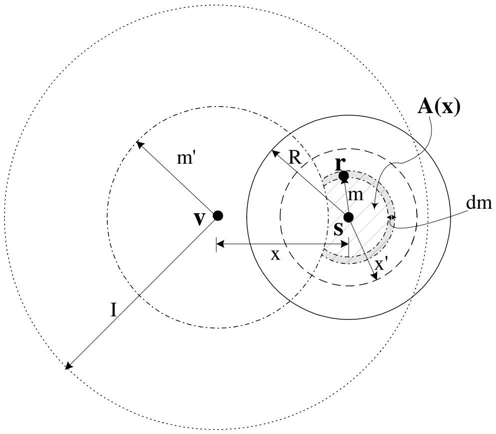

Fig. 3. Capture analysis where $x' = \frac{x}{\sqrt{\alpha}}$ and $m' = \sqrt{\alpha}m$

ACK frame. If a nearby station indeed decides not to block and its transmission collide with the ACK frame, the DATA frame transmission still needs to be rescheduled.

In addition to the above issues that are particular to each individual proposal, we have also noticed some rather common problems. The first is that these proposals rely on the RTS/CTS handshake. In reality the RTS/CTS handshake is turned off in most deployments, which makes these proposals inapplicable in such environments. The next issue is that these proposals do not take the aforementioned "capture frame" v.s. "capture signal" problem into consideration. As a result, many concurrent transmissions will not be received by their intended receivers, not because the signals are not strong enough, but because the received bits are cast into the wrong frame, the ongoing DATA frame that these receivers have already engaged in receiving.

It is the above stated observations and inspirations from various related works that leads us to our own modification to the IEEE 802.11 DCF protocol. We name the modification Location Enhanced DCF (LED).

III. Analysis of Blocking Probabilities with Capture Effect

In this section, we perform an analysis on the probabilities of successful transmission despite the presence of sensed signal(s). Using this probability, we illustrate the space for improvement to the original DCF in terms of overpessimistic blocking of transmissions.

We assume a free space omni-directional propagation channel model [27]. This is a model in which many channels, especially outdoor channels, have been found to fit in practice. In this propagation model, the received signal power, P_r, is calculated as follows:

$$P_r = \begin{cases} \frac{Pt*G_t*G_r*\lambda^2}{(4*\pi)^2*D^2*L} & D \leq D_{cross} \\ \frac{Pt*G_t*G_r*h_t^2*h_r^2}{D^4*L} & D > D_{cross} \end{cases} \quad (2)$$

where P_t is the transmission power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, D is the separation between the transmitter and the receiver, h_t is the transmitter elevation, h_r is the receiver elevation, L is the system loss factor not related to propagation (≥ 1), λ is the wavelength in meters, and D_{cross} is calculated as $D_{cross} = (4*\pi*h_r*h_t)/\lambda$. The first sub-model of Equation 2 is called the Friis free-space propagation model and only used when the distance between the transmitter and the receiver is small. The second sub-model is called the two-ray ground reflection model and used when the distance is large.

We assume that stations are uniformly distributed over an area with a density of δ. Each station has a transmission range R and a carrier sense range I. The former is the range within which frames sent by the station can be received and decoded, and the latter is the range within which transmissions of the station can be detected (channel busy). Both are under the condition that there is no other nearby transmission. For the ease of analysis, we assume that all stations have the same traffic model and all data packets are of the same length. Each packet requires transmission time τ, and is randomly destined to a 1-hop neighbor. One data packet is generated at a randomly selected time within every time interval T, where $T > \tau$. We also assume that all transmitters use the same transmission power and all antenna gains are the same.

We are concerned about the scenarios where a station v may cause interference to another station r which is receiving a data frame delivery from station s as shown in Figure 3. Station v transmits only if its transmission doesn't affect the reception of DATA frame at r and ACK frame at s. Using the Friis radio propagation model as in equation 2 and receiver capture model as in equation 1, to allow stations s and r to capture correctly each other's frames in the presence of any transmission from station v, the following should hold:

$$(\overline{v.s} > \sqrt{\alpha}\ \overline{s.r}) \text{ AND } (\overline{v.r} > \sqrt{\alpha}\ \overline{s.r}) \quad (3)$$

where $\overline{a.b}$ is the distance between station a and station b, and α is the capture ratio. We only use the Friis propagation model for the sake of analysis simplification.

Figure 3 illustrates the situations for both r to capture s' transmissions (DATA) and for s to capture r's transmissions (ACK) in the presence of v's transmission. For r to capture s' transmissions, given m being the distance between s and r, the distance between v and r must be greater than $\sqrt{\alpha}\ m$. For s to capture r's transmissions, given x being the distance between v and s, r must be within a circle of radius $min(R, \frac{x}{\sqrt{\alpha}})$. Considering both conditions, r must be located within the shaded area $A(x)$ in the figure. Hence, the probability that v's transmission *doesn't* corrupt the communication between s and r is:

$$P(B|x) = \frac{A(x)}{\pi R^2} \quad (4)$$

where the area $A(x)$ is calculated as follow:

$$A(x) = \int_0^{min(R, \frac{x}{\sqrt{\alpha}})} 2(\pi - \arccos(\frac{x - \frac{x^2 - m^2 + (\sqrt{\alpha}m)^2}{2x}}{m}))m\ dm \quad (5)$$

Since we only worry about potential interferers within the carrier sensing range, by unconditioning x we obtain:

$$P(B) = \int_0^I \frac{A(x)}{\pi R^2} \frac{2x}{I^2}\, dx \qquad (6)$$

Based on the traffic model, the probability that none of the stations within the carrier sensing range of a station will transmit is obtained by:

$$P_1 = [1 - \frac{\tau}{T}]^{\delta \pi I^2} \qquad (7)$$

and the probability that v's transmission will not interfere with other transmissions (if any) in the interference range is:

$$P_2 = [1 - \frac{\tau}{T} + \frac{\tau}{T} P(B)]^{\delta \pi I^2} \qquad (8)$$

Therefore, the probability P_b that v can transmit with the presence of a nearby transmission without corrupting this transmission is given by:

$$P_b = P_2 - P_1 \qquad (9)$$

Note that the calculated P_b is still conservative because of the following two assumptions:

1) Only the Friis propagation model is used in the analysis because we assume $I < D_{cross}$. However, in practice I may be greater than D_{cross} and thus the distance x could also be greater than D_{cross}. In this case, the two-ray ground model may be used instead, which further reduces the probability of the interference and consequently increases the P_b.
2) In the analysis, for simplicity we assume that all stations in the vicinity of v have the freedom of transmission. We do not take into account that some of these stations will have to block because of other ongoing transmissions in their vicinities. Accounting for these blocked stations would increase P_b.
3) In many other studies such as the [22], researchers have observed that in many scenarios, the propagation model for non-line-of-sight path has a path exponent factor greater than what the Friis model uses. This also reduces the probability of the interference and consequently increases the P_b.

We have verified our analytical results by generating random network topologies and traffic patterns and studying the interference situation in each case. We have also studied how our simplified assumptions stated in the previous paragraph affect our blocking probability estimation by relaxing them in simulation runs.

For constructing each random network, we place the v station at the center of an area of 1000×1000. Transmitter stations are distributed uniformly in this area. Each transmitter is paired with a corresponding receiver, whose location is randomly picked within a circular area which is centered at the transmitter and with radius R. Then each transmitter starts transmitting following the traffic model described before: all packets require transmission time τ and they are generated randomly at a constant rate: one packet every time interval

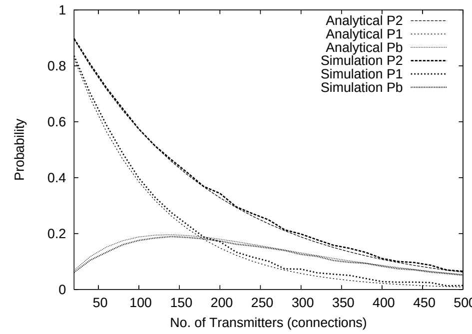

Fig. 4. The analytical and simulation values of the probabilities P_1, P_2, and P_b

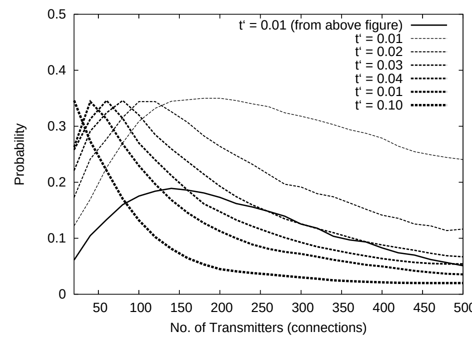

Fig. 5. The probability P_b with different load values t' where $t' = \tau / T$

T, where $T > \tau$. When v has a frame to send, we study if it will be blocked under the current IEEE 802.11 operations and when blocked if indeed v's transmission will harm other communications. The number of situations where unnecessary blocking is suggested by the IEEE 802.11 is then divided over the total number of simulated situations to derive the probability of unnecessary blocking, which is compared to the analytical result.

Figure 4 plots both the analytical and the simulated values of P_1, P_2, and P_b for R=250, I=550, α=5, τ / T=0.01, and different numbers of stations (thus varying the station density δ). As we can see, the simulation results closely match the analytical results which validates our analysis.

Figure 5 plots the simulation of P_b with the simplification assumptions relaxed. Also this figure plots P_b with different packet load values. The P_b plot with these assumptions, which is directly copied from Figure 4, is also included for easy comparison. The plots show that our analytical results are conservative.

As expected the probability analyzed above only takes into account whether the channel assessing station's transmission may corrupt other ongoing data deliveries. It does not address if this channel assessing stations' transmission will be received correctly by its own receiver. Such a transmission may still fail at its receiver if other ongoing data deliveries produce enough interfering energy there.

The above analysis shows that the unnecessary blocking probability of DCF is large enough (as high as 35%) to motivate us to consider modifying the MAC layer to exploit the capture phenomena of the physical layer. In the following section we will describe the newly proposed modification to the IEEE 802.11 DCF.

IV. Location Enhanced DCF for IEEE 802.11

In this section, we describe our Location Enhanced DCF (LED) for the IEEE 802.11 by first giving an overview of the LED mechanism. Then, we describe the design of the needed physical layer. Finally, we present the proposed modifications to IEEE 802.11 MAC with the details of LED mechanism. Before we introduce our approach of using location information and capture effect to improve channel efficiency, several terms which will be used during the description need to be clarified to avoid confusion.

In our description, we use the term "delivery" for the whole handshake procedure for delivering a unicast data frame. Depending on the frame size and network configuration, a "delivery" may involve the full RTS-CTS-DATA-ACK 4-way frame exchange sequence or just DATA-ACK 2-way exchange. A "source" is the station having data to send during a delivery. The "destination" of a delivery is the station to whom the source wishes to send data. While "source" and the "destination" regard data frames only, the terms "sender" and "receiver" on the other hand refer to the sender and the receiver of *any* individual frame, RTS, CTS, DATA, or ACK. So for instance the senders of CTS and ACK frames are actually the destinations. In addition to the above, "transmitter" is used interchangeably with "sender", and "connection" is used to refer to both the source and destination stations collectively.

A. Protocol Overview

Our approach is simple: to include more information about each transmission in the transmission itself so that any other stations overhearing the transmission are able to better assess whether their own transmissions may harm this ongoing delivery. Among various relevant parameters, the locations of the transmitters and receivers are the most important. We assume that each station is capable of acquiring its own location, e.g. by GPS [12] or other RF based localization methods [6], [19]. A station can retrieve other communication parameters regarding its own transmitter/receiver easily as they are typically configuration parameters.

When the above parameters are included in each transmission, an overhearing station of a data delivery can compute the received energy level of the frames belonging to the same data delivery at their receivers, using a propagation model suited for the surrounding environment. Then if the capture ratio of the receiver is also known, knowing its own location, antenna gain, and transmission power, this station can make a prediction of whether its own transmission may affect this ongoing data delivery. If the result is negative, this station should not block its own transmissions, if any, despite the presence of the ongoing data delivery. This is the core of the LED mechanism. When the LED predictions are accurate, each transmissions will not affect the correct receptions of others at their corresponding receivers if these receivers are capable of frame capture. Network wide, more concurrent transmissions are permitted by LED and the overall network throughput can be improved.

The use of propagation model to predict interference may introduce certain limitations on how LED can be applied in real world applications. For instance, as [22] points out, path-loss in in-door environments tends to be very dependent on building structure and construction. Thus a propagation model, no matter how well it may work for one deployment, may not be a good choice for other deployments. Although the problem of "what propagation model to use for a particular deployment" is out of the scope of this paper, we would like to point out that the protocol operations of LED are not affected by the choice of underlying propagation model. Thus, a LED-based system design may wish to build in the flexibility of plugging in different propagation models under different operation environments. Additional measurement-based control mechanisms may also be included in such a system in an open-loop fashion so that the prediction model can be better "tuned" for non-distance induced fading conditions.

This is a rather simplified estimation model as each channel assessing station only considers the effects from its own potential transmission. It may occur that several stations simultaneously predict that their own transmissions will not cause collision to the ongoing delivery. In this event, the aggregated energy from all these side transmissions may actually change the result of the capture effect and cause enough interference with the ongoing delivery. We slightly addressed this issue at the performance evaluation section. However, we postpone further studies for this issue to future works.

One particular issue we should point out is that in the current model, a station is only concerned if its own transmission will affect any ongoing deliveries. The prediction model does not consider if the station's own transmissions can be received correctly by the intended receivers. This optimistic approach is largely for keeping the model simple at its current stage. Also from MAC perspective, a station can always learn if its data frames have been received correctly by observing the reception of ACK frames.

B. Physical Layer Design

As we have pointed out, the current IEEE 802.11 standard does not require a receiver modem to be able to capture a new (stronger) frame after the receiver has been tuned to receive another frame, even if the signals of the new frame are strong enough to be captured. As we explained before, unless the frame capture capability is specifically designed into the receivers, they usually are not able to correctly capture the new frame. This may cause problems in our approach. If a station decides to transmit after it estimates that its own transmission will not interfere with an ongoing delivery, it will begin to send its own frame. However, chances are that the intended receiver of this frame is already engaged in receiving another frame, one of the frames of the ongoing delivery. As a result, this

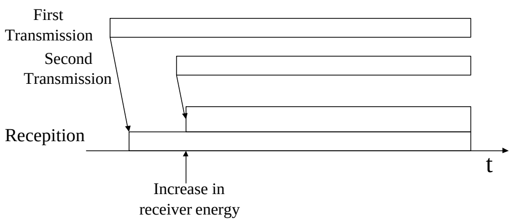

Fig. 6. Message-In-A-Message

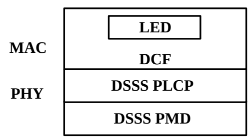

Fig. 7. PHY-MAC layer structure

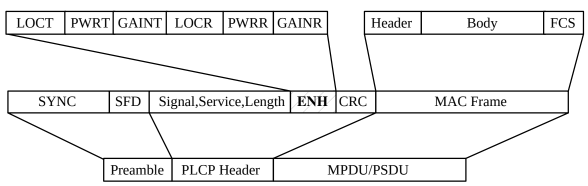

Fig. 8. Frame structure

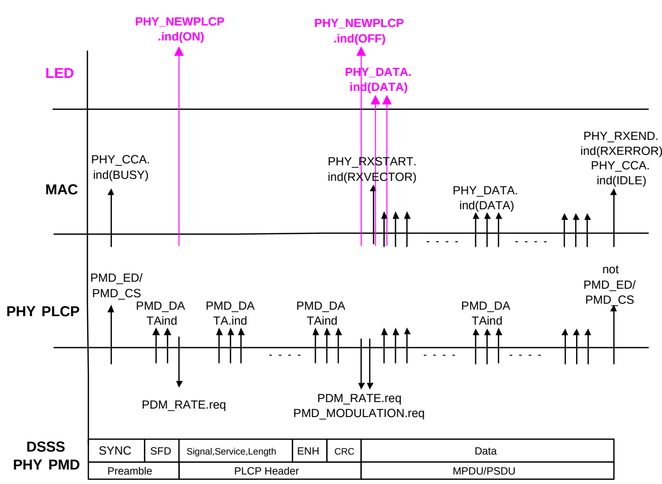

Fig. 9. PHY-MAC interactions

receiver will not receive and interpret the new frame correctly even if the signals are strong enough.

Fortunately, receiver designs which do support the capture of a new frame after the receiver has already begun to receive another frame do exist. One example of such a receiver physical Layer (PHY) design is Lucent's PHY design with "Message-In-A-Message" (MIM) support [8]. In this design, the newly arrived frame is referred to as the "(new) message in the (current) message".

A MIM receiver is very similar to normal IEEE 802.11 PHY designs except that it continues to monitor the received signal strength after the PHY transits from receiver training state to data reception state. If the received signal strength increases significantly during the reception of a frame, as shown in Figure 6, the receiver considers that it may have detected the beginning of a MIM frame and hence switches to a special MIM state to handle the new frame.

While under the MIM state, the receiver tries to detect a carrier for a new frame. If the carrier signal is detected, the receiver begins to decode the initial portion of the new frame and retrains to synchronize with the new transmission. If no carrier, preamble, or frame delimiter is detected, which indicates that the energy increase is likely caused by noise, the PHY will remain in this MIM state until either a carrier is detected or the scheduled reception termination time for the first frame is reached.

With a MIM-capable design, a receiver is able to correctly detect and capture a strong frame regardless of the current state of the receiver, unlike regular IEEE 802.11 PHY designs where the strong frame can only be correctly captured while the PHY is under certain (i.e. receiver training) states during its reception of a weak frame.

C. MAC Layer Design

Our enhanced design for a DCF MAC stands atop a MIM-capable PHY. Figure 7 illustrates the layered structure of the relevant entities. The IEEE 802.11 Physical Medium Dependent (PMD) layer performs wireless medium transmission and receiving services. The Physical Layer Convergence Protocol (PLCP) layer adapts the raw services of PMD to PHY-MAC data and control interface. The new LED is a part of the MAC layer function. Figure 8 shows the frame format to support the enhanced functionalities of the new MAC.

We propose to insert a block of information called ENH ("Enhanced") to provide the additional information needed for the LED. Since the earlier the ENH block is received, the sooner the receiver can decide if it needs to block its own transmission, the ENH block should be inserted before the true MAC data section, also known as the PLCP Service Data Unit (PSDU). In the current design, we have the ENH as part of the PLCP header instead of at the beginning of PSDU mainly due to two reasons. Firstly the PLCP header has its own CRC field so the contents of the ENH block can immediately be verified and utilized. Secondly all stations within the service set can understand the ENH block since the PLCP header is transmitted at a base rate.

The ENH block is further divided into six fields. The LOCT field contains the location of the frame transmitter, the PWRT field describes the transmission power of the transmitter, and the GAINT field specifies the transmission antenna gain. The LOCR, PWRR, and GAINR fields contain the same pieces of information for the receiver.

If RTS/CTS exchange is needed for a data delivery, a source starts its unicast data delivery by sending out an RTS frame to reserve the channel. In the ENH block of this frame, the source fills the LOCT, PWRT, and GAINT fields with its own parameters, and the LOCR, PWRR, and GAINR with the destination's parameters, if known. Any unknown parameters are set to NULL. Upon receiving the RTS, the destination of the data delivery copies the LOCT, PWRT, and GAINT fields into the corresponding fields of its CTS frame. It also fills or updates the LOCR, PWRR, and GAINR fields of the CTS frame with its own parameters. In subsequent DATA and ACK frames, full descriptions of both the source and the destination are included. In case of the frame size being less than the RTS/CTS threshold and no RTS/CTS handshake being conducted, the DATA frame will have its fields set in the same fashion as the RTS frame, and the ACK frame is filled the same way as the CTS frame.

A parameter cache may be maintained by stations to store the location, power, and antenna information of already known stations. This way when sending data to a station in cache, the cached parameters may be used in the corresponding fields of the ENH block instead of NULL values. Cache entries are updated if newer information is received from their corresponding stations. Cache entries are removed after the expiration time.

In the standard IEEE 802.11, normally the PHY (PLCP in particular) will signal three evens to the MAC layer during frame reception: carrier busy, begin receiving PSDU, and end receiving PSDU. It does not deliver any data bits to the MAC layer until the PSDU reception has begun. Then the receiver will proceed until the end of the frame (unless interrupted by carrier loss in the middle of the reception). Received bits are passed to the MAC layer as they are decoded and assembled into the MAC frame. At the end of the PSDU is a forward error detection CRC block called Frame Check Sequence (FCS). If the MAC frame passes the CRC check, it is accepted and passed up for further 802.11 MAC processing. If the CRC fails, the frame is dropped.

In addition to the above interactions, the LED defines two new mechanisms for the PLCP layer to interact with the LED. They are illustrated by Figure 9. The first is an indicator called PHY_NEWPLCP. This indicator is turned on by the PLCP layer after it finishes receiving the Start Frame Delimiter (SFD) field of a frame's Preamble section. The meaning of this indicator is that the PHY is affirmative that it has begun receiving a new frame, and the next thing it expects is the PLCP header of the frame. Upon receiving this indicator, the LED needs to block transmission so the PLCP header can be received without interruption. The PHY_NEWPLCP indicator will be turned off by the PLCP layer after it finishes receiving the CRC field of the PLCP header. The second mechanism is for the PLCP layer to pass up the PLCP header contents to the LED, as soon as the PLCP is verified to be correct by CRC checking. After receiving the PLCP header from the PLCP layer, the LED will make a decision if the physical layer should block its own transmission.

During the blocking decision making process, a non-receiver station (denoted as station i) of the frame calculates if its own transmissions will cause enough interference to interrupt the data delivery to which the just received frame belongs. The station needs to calculate the power level of its own transmission at both the source, denoted as P_i^s, and the destination, denoted as P_i^d, of the ongoing data delivery using an appropriate propagation model (i.e. Equation 2). The station also needs to calculate the received power level of the destination station's transmission at the source, denoted as P_d^s, and that of the source transmission measured at the destination, P_s^d. If $(P_d^s > \alpha P_i^s)$ and $(P_s^d > \alpha P_i^d)$, the station should not block its own transmissions. Otherwise, it should block its transmissions. In the case that the communication parameters of either the source or the destination are unknown, the assessing station assumes the worst and blocks its own transmission.

If the station decides to block its own transmission due to worries that the transmission may affect the correct reception of some frames of the ongoing data delivery, it remains in receiving state and continues the receiving procedure as specified by the standard. It disables any transmission request from upper layer, and sets its NAV value according to the Duration field of the frame, which is set to the time required for the full data delivery frame exchange sequence to finish. One thing to note is that on the intended receiver of the frame, the blocking estimation implicitly will always produce positive result.

On the other hand, if the station decides not to block, the receiving may still continue but upper layer transmission requests are not disabled. No NAV is set in this case either. If there is indeed any outgoing frame ready, the modem can accept the request by switching to transmission state and starting the transmission. A PHY reset signal is needed in this case to force the PHY to leave the receiving state and enable PHY_TXSTART signal when the MAC has a frame to send.

If the LED decides not to block, the handling of the physical carrier sensing mechanism, i.e. the Clear Channel Assessment (CCA) indicator produced by the physical layer, requires careful consideration. CCA is set to busy when there is carrier being detected. Since the frame is still being transmitted in the air, the CCA will remain busy. It needs to be temporarily ignored. The overriding of CCA in LED layer is accomplished by proposing a new vector called CCA-Suppression Vector (CSV), which is a suppression timer. CSV is set to the end of reception of the current frame, calculated based on the length field contained in the received PLCP header of the frame.

During the reception of a frame, if a new stronger frame arrives and captures the receiver, the PHY will again pass up the PLCP header to the LED upon successfully verifying the CRC. The LED will estimate interference again using the new PLCP header. If the LED decides to block transmission for this new data delivery, NAV is set to the end of *this* new delivery, if it is later than the current NAV expiration time. Start-to-transmit requests are disabled as well. If the LED decides not to block for this new delivery, the NAV value is not changed but the CSV expiration time remains or set to the end of the new frame, whichever is later.

At the source or the destination station of the ongoing delivery, according to the IEEE 802.11 standard, the NAV is not set for the duration of the delivery. In LED, this specification is still followed. However, in LED the source and the destination stations of a data delivery do need to set their CSV's to the estimated end of the delivery. The reason is as follows. LED permits concurrent transmissions by other stations as long as they do not produce enough interference to disturb the ongoing delivery. If any other station indeed decides to transmit, the energy of the transmission may cause the source and the destination of the ongoing data delivery to sense that CCA is busy and thus abort the data delivery frame sequence. Hence, the CCA should be suppressed on the source and destination stations till the end of the data delivery.

In total, a LED station has four indicators related to the transmission blocking estimation. The CCA is the physical carrier indicator. It is "TRUE" when the PHY layer detects carrier (or energy exceeding threshold, or both, depending on equipment vendor implementation). The NAV indicator is the virtual carrier indicator. It is "TRUE" when there is a channel reservation which needs to be honored. That is, if this station transmits, then the transmission will interfere with the ongoing delivery. The PHY_NEWPLCP indicator is on while a PLCP header is being received. Finally, the CSV indicator tells the station if it should ignore the physical layer CCA. It is "TRUE" when the suppression timer is running. More precisely, the decision of whether this station should block its own transmission or not is made as follow:

if (PHY_NEWPLCP *or* ((CCA *and* (*not* CSV)) *or* NAV)) *then* BLOCK

Another issue occurs if a channel-assessing station only detects carrier but can not decode the frame. In this case, a station is not able to estimate whether its transmission will affect this ongoing transmission. Either an aggressive approach or a conservative approach can be taken. In the aggressive approach this station will not block its own transmission in the event of "detecting a carrier but not being able to decode the frame", while in the conservative approach this station will block its own transmission.

V. Performance Evaluation

In this section, we present extensive simulation-based studies on the performance of the LED mechanism. The performance comparisons are done using the *ns-2* simulator [3], enhanced with the CMU-wireless extensions [2]. The underlying link layer is IEEE 802.11 with 11 Mbps data rate. In doing this, we have extended ns-2 as follows:

- We have modified the capture model to allow receivers to capture the stronger packet out of the weaker packet(s), as in Equation 1, if the stronger packet comes after the weaker to reflect the MIM PHY design as discussed in the previous section.
- Current implementation of ns-2 allows the stations to compare the newly-arriving packet only with the one it is receiving. In order to implement the capture Equation 1, we extended the PHY layer in ns-2 to allow each station to keep track of all its incoming packets and the aggregated background signals. Also in order to create a more realistic environment, we allow each station to aggregate the signals that have lower values than the CSThresh_ [1] used by ns-2.
- We have enhanced the IEEE 802.11 MAC layer by extending it with the implementation of our LED mechanism.

Each of our simulated networks consists of a set of connections which are constructed as pairs of stationary sender and receiver stations. The senders and receivers are placed in a $1000m \times 1000m$ area in the same fashion as the simulations described before in Section III. We assume that each sender has already cached the location of its corresponding receiver. Other parameters such as transmission power levels and antenna gains are also assumed to be fixed and known to all stations therefore not included in simulation. In simulation, the ENH header only contains LOCT and LOCR fields of 32 bits each.

In ns-2, we adopted the propagation channel model described in Equation 2. With such model, the transmission power P_t is set to 0.282W while $RXThresh\_$ [2] and $CSThresh\_$ are set to configure the transmission radius R of a station to 250m and the interference radius to 550m. Each connection is a flow of UDP packets which are 1000 bytes in size and transmitted at 11Mbps. To simplify the simulation implementation, base rate is also set to 11Mbps. Such a simplification should not affect the correctness of the evaluation method since we are more interested in relative performance improvement. Each simulation is run for a fixed duration of 50 seconds. Each point on the curves to be presented is an average of 5 simulation runs.

We have not been able to find any IEEE 802.11 equipment specification with capture ratio information. The capture ratio used in simulation is derived by the following method. To achieve a specific Bit Error Rate (BER) the required Signal to Noise Ratio (SNR) for a particular modulation technique can be calculated. In the case of 11Mbps CCK modulation, according to calculations described by [27], it can be determined that 18dB of SNR is needed to achieve 10^{-8} BER, as specified by Orinoco wireless cards. The 11 Mbps CCK uses 8 chip/symbol, which is 9dB spreading gain. In addition, CCK coding provides about 2dB additional coding gain. All together the processing gain is 11dB. When only considering signals before receiver processing, the SNR requirement is 7dB. Roughly, this maps to 5 times of signal power over interference. We adopt the same number as the capture ratio. In our model, when a station is in the middle of receiving frame A and frame B arrives, one of the following will happen. If the received power of frame A, P_A, is more than 5 times of P_B, the receiver continuously receives frame A. If P_B is more than 5 times of P_A, the receiver drops frame A and begins receiving frame B. In all other situations, packets collide and no frame is received correctly.

[1] CSThresh_ is the power value of a transmitted signal measured at the boundary of its interference range I

[2] RXThresh_ is the power value of a transmitted signal measured at the boundary of its transmission range R

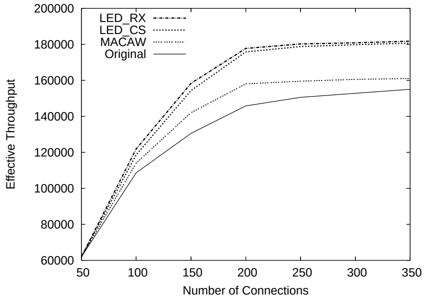

Fig. 10. Effective throughput versus node density

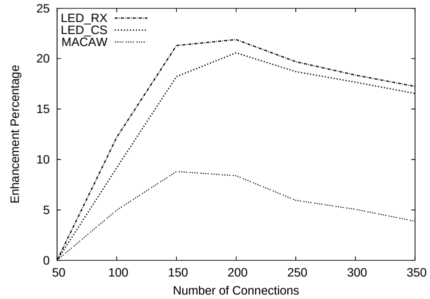

Fig. 11. Throughput enhancement over Original mechanism versus node density

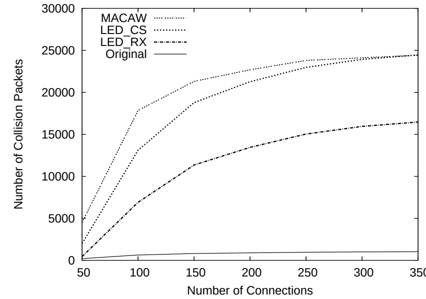

Fig. 12. Packet collisions versus node density

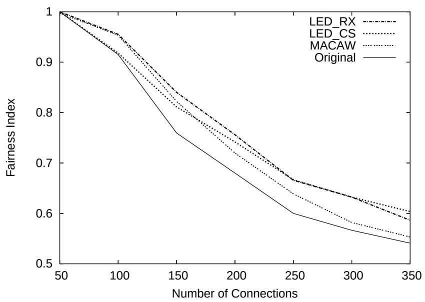

Fig. 13. Fairness index versus node density

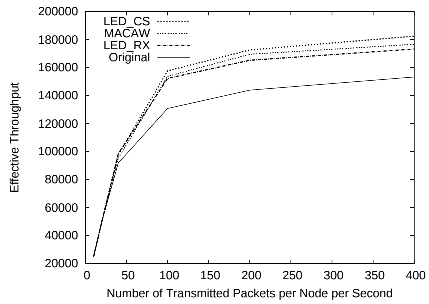

Fig. 14. Effective throughput versus network load

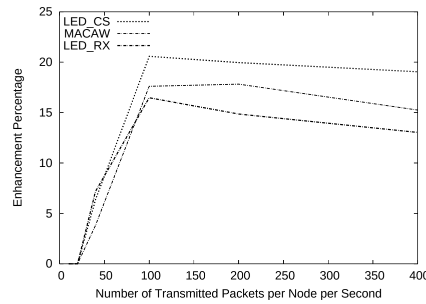

Fig. 15. Throughput enhancement over Original mechanism versus network load

We have modelled various scenarios of different station densities, work loads, transmission and interference ranges (transmission power levels), and errors in location estimation and their effects on performance. To study the performance of our suggested schemes, we compare our LED with both the ***Original*** IEEE 802.11 DCF and ***MACAW*** mechanisms[3]. The reason for using MACAW is that comparing to the schemes in [23] and [11] MACAW is less restrictive when making blocking decisions, and consequently the MACAW scheme outperforms the two aforementioned schemes. As described in Section IV, we experiment with two different flavors of LED: ***LED_CS*** and ***LED_RX***. LED_CS mechanism is an aggressive (optimistic) version of LED mechanism in which when a station receiving a frame it cannot decode [4], it simply assumes that its transmission will not interfere with that ongoing data delivery and therefore should not block. On the other hand, LED_RX is a conservative (pessimistic) version of LED in which a station assumes its transmission will interfere with the ongoing data delivery under the same situation.

During the simulation runs, we take the following measurements:

1) **Effective Throughput:** This counts the total number of data received by all the receiver stations over the simulation period.
2) **Collision Packets:** This counts the total number of observed collisions that involve data and ACK packets by all the attempted deliveries over the simulation period.
3) **Fairness Index:** To measure the bandwidth sharing of the connections under different mechanisms, we use Jain's fairness index [10], [16] which is defined as follows:
$$F = \frac{(\sum_{i=1}^{N} \gamma_i)^2}{N \sum_{i=1}^{N} \gamma_i^2} \tag{10}$$
where N is the number of connections and γ_i is the number of received packets for connection i.

We have experimented both with and without RTS/CTS prior to data. Due to space constrain of this paper, we limit our discussion here to the RTS/CTS case. One interesting finding regarding RTS/CTS is that forcing the stations to be blocked during the whole RTS/CTS period of other deliveries will actually increase the network throughput. The reason for this is more related to the particular ns-2 implementation of the physical layer thus we omit the details here. For more details about this particular issue, and experiment results of the non-RTS/CTS configuration, which show similar results as we report in the rest of this section, the readers may refer to [26].

Figure 10 shows the effective throughput of the networks with different numbers of connections. The data traffic between each pair of source and destination is a constant bit rate (CBR) UDP flow at a rate of 20 packets per second. As shown, the LED_CS, LED_RX, and MACAW mechanisms

[3]Both Original and MACAW mechanisms use the extended ns-2 capture model as described earlier.

[4]In ns-2 this is the situation where the received signal level is lower than the RXThresh_.

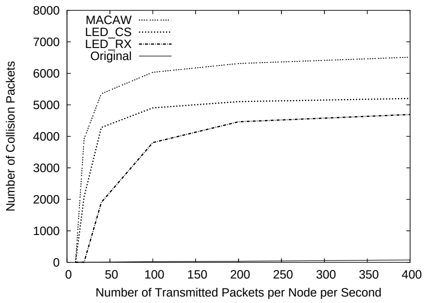

Fig. 16. Collision packets versus network load

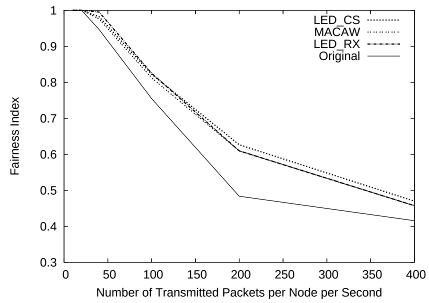

Fig. 17. Fairness index versus network load

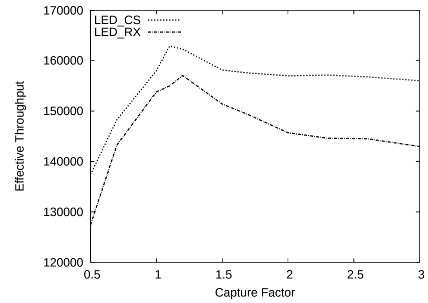

Fig. 18. Effective throughput versus capture factor (β).

all have higher data throughput than the Original mechanism. Figure 11 further illustrates the improvements by showing the percentage throughput gain of using the LED_CS, LED_RX, and MACAW over the Original. At their peaks, the LED_CS could achieve about 20% more throughput than the Original and the LED_RX could reach 22% higher throughput while the MACAW could see 8% throughput gain. The LED_RX yields higher throughput than the LED_CS for because of its aggressive nature. Figure 12 shows the total number of collisions that occur in the networks occurred at intended frame receivers, as an indication of the level of transmission concurrency within the network. Since the LED_CS is more aggressive than the LED_RX, as expected its collision count is higher. However, simply trying harder may not help in this case because more transmissions may result in more collisions at frame receivers, which actually brings the throughput down.

Lacking more detailed knowledged regarding the ongoing transmissions, the MACAW does not spatially reuse the channel as intelligently as the LED mechanisms. A station using the MACAW blocks it transmission only if it overhears CTS frames. As the simulations show, oftentimes such an assessment is incorrect. Although the MACAW tries very hard, as indicated by the high number of collisions in Figure 12, its throughput does not increase as hoped. As the station density increases, the MACAW performance approaches Original since the CTS frames will cover most of the network area, just like the RTS and CTS frames of the Original. Figure 13 shows the fairness index of different mechanisms. The LED_CS, LED_RX, and MACAW However the newly proposed mechanisms of the LED have better fairness levels than the Original. An explanation for this is that the LED mechanisms reduce the well-known "exposed node" problem in the Original mechanism which is one of the major sources for the unfairness.

Next, we experiment with different network packet loads to see their effects on performance. We fix the number of connections in the network to 50 and vary the packet generation rate at each source station between 10 packets per second to 400 packets per second. Figures 14 and 15 show the effective throughput and the relative enhancement of each mechanism over the Original respectively. As shown, different from the previous results, the LED_CS has the highest throughput over the LED_RX and the MACAW. The LED_RX performs not as well as the LED_CS and the MACAW under high packet loads. With high packet loads, the chance that there are some frames being transmitted nearby increases. Thus it is more likely for the LED_RX to decide to block. This is opposite to the LED_CS which takes advantage of its aggressive mechanism to squeeze in more transmissions.

The packet collisions for the different mechanisms are shown in Figure 16. MACAW mechanism has the highest number of packet collisions because of its high aggressiveness as described earlier. Comparing the aggressive LED_CS with the conservative LED_RX, the LED_CS mechanism experiences more packet collisions than the LED_RX mechanism. However, the aggressiveness of the LED_CS in networks with small number nodes is justified by the significant large number of successful transmissions in comparison to the number of collisions. Therefore, the LED_CS mechanism has higher total throughput than the LED_RX mechanism as shown in Figure 14.

Figure 17 shows the fairness index of all the mechanisms under different packet loads. The LED_CS, LED_RX, and MACAW mechanisms have similar fairness index measurements which are higher than the Original mechanism. An explanation for this is that these mechanisms reduce the well-known "exposed node" problem in the Original mechanism which is one of the major sources for the unfairness.

As pointed out earlier, it may occur that several stations simultaneously predict that their own transmissions will not cause interference to the ongoing delivery and hence start their own transmissions. In this event, the aggregated energy from all these side transmissions may change the result of capture effect and cause interference with the ongoing delivery. To further study this problem, we multiply the capture ratio α used in

Equation 1 by capture factor β. By increasing β value over 1, we decrease the chance that the aggregated energy from all these side transmissions would interfere with the ongoing transmission. At the same time, increasing β has the same effect of increasing the capture ratio in reducing the network throughput. Figure 18 shows the LED_CS and LED_RX performance over different values of β for 50 connections with CBR traffic of 100 packets per second.

Setting β to values less than 1 degrades the performance of both mechanisms since there are more chances for channel

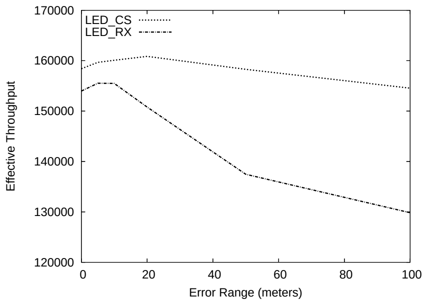

Fig. 19. Effective throughput versus error range.

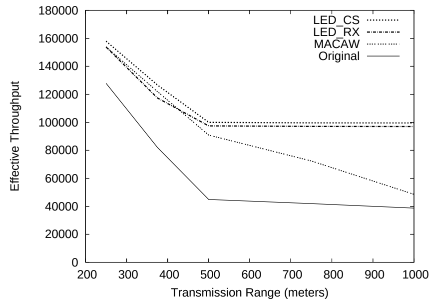

Fig. 20. Effective throughput versus transmission range.

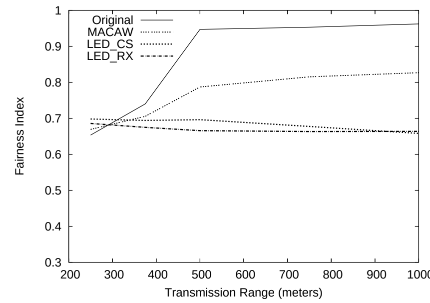

Fig. 21. Fairness index versus transmission range

Transmission Power	*Transmission Range (R)*	*Carrier Sense Range (I)*
0.282W	250m	550m
1.427W	375m	825m
4.510W	500m	1100m
22.829W	750m	1650m
72.151W	1000m	2200m

TABLE I

DIFFERENT TRANSMISSION POWERS AND THEIR CORRESPONDING RANGES USED BY NS-2.

competing stations to decide to transmit and result in frame collision at receiver. As β increases over 1, the throughput increases since we reduce the number of interferences caused by the aggregated signals. However, increasing β to large values has a negative effect on the throughput since it under-utilizes the capture mechanism. What is more interesting is that for our experiment configurations, using $\beta = 1.2$ results in the optimal performance.

Next, we study the effect of errors in station locations due to the inaccuracy of the location estimation systems. We again experiment with network configuration of 50 connections with CBR traffic of 100 packets per second. Each station adds an error, selected randomly from the range $[-Err, Err]$, to the X and Y position of the station. We test using different values of Err as shown in Figure 19. Surprisingly, the effective throughput increases with small values of Err. This could be explained as using small random errors emulates the effect of using the capture factor β as described earlier in reducing the interference possibility. However, just like β, with high errors the performance of the LED mechanisms degrades. The performance degradation of the LED_RX is higher than that of the LED_CS since the LED_RX effectively depends on the location information only in deciding of the blocking status while LED_CS depends on the signal energy in addition to the location information.

All the mechanisms under consideration are based on the transmission and the interference ranges in the network. To examine the performance of those mechanisms under different ranges, we fix the maximum distance for a connection to be within 250m while changing the station transmission power. Table I shows the used transmission powers and their corresponding transmission and interference ranges used in our ns-2 experiments using the propagations channel model defined by Equation 2. Figure 20 shows the effective throughput of the network versus the transmission ranges for network configuration of 50 connections with CBR of 100 packets per second. Although in addition to transmission range, performance of the LED mechanism depends on the network topology and station locations, the effective throughput of LED_CS decreases as the transmission range increases because of the following: 1) with large ranges, more stations hear the transmission and have to block during the RTS/CTS exchange, and 2) as the transmission range increases, many of the unblocked stations which were not able to decode the transmission frames before become able to decode those frames now and may find that they have to block during those transmissions. On the other hand, increasing the number of decoded frames in LED_RX mechanism results in many unblocked stations that formerly would block unnecessarily because of their inability to decode frames. However, increasing the transmission power still reduces the LED_RX throughput as shown in the figures because of: 1) similarly, using large transmission ranges force more stations to hear the transmission and to block during the RTS/CTS exchange, and 2) as the transmission power increases, the interference range increase and additional stations become able to hear the transmission but unable to decrypt it and hence force the stations to block. As the transmission range increases, the area where the stations are unable to decode the frames becomes smaller since we conduct experiments within a fixed square region and hence the performance of LED_RX becomes similar to the LED_CS performance. On the other hand, the performance of Original and MACAW keep degrading as the transmission range increases because now a single RTS/CTS frame exchange will block more stations. For Original, more stations will also be blocked because they sense the carrier as busy. As shown in the figure, when the transmission range is large, the performance of LED mechanisms is superior to the Original and MACAW mechanisms.

Figure 21 shows the effect of transmission ranges on fairness index. LED mechanisms experience fixed fairness index over the different transmission ranges while both Original and MACAW mechanisms have increase in their fairness index as the transmission range increases since the hidden and exposed station problems are reduced.

VI. Conclusion and Future Works

In this paper we have introduced an enhancement of the IEEE 802.11 DCF. This enhancement, known as the Location Enhanced DCF, includes communication parameters especially the locations of transmitters and receivers in each frame. These parameters may assist stations to better assess the channel condition. We have shown that the 802.11 DCF is conservative in terms of collision estimation, with as much as 35% of unnecessary blocking assessments. On the other hand, our LED may improve throughput as much as 22% over DCF with better fairness at the same time.

It should be noted that although the LED achieves better throughput, it is at the cost of trying harder with more transmissions. This is indicated by the higher collision counts compared to the original IEEE 802.11 DCF as shown in Section V. We suspect these excessive collisions are mostly resulted from the following two reasons: 1) a station is only concerned if its own transmission will affect an ongoing delivery and consequently it does not consider if its own transmission can be received correctly by its destination, and 2) the aggregated interference energy changes receiver capture results, caused by transmissions from multiple stations which simultaneously make negative collision estimation because each station only considers how its own transmission may affect the ongoing delivery and not leave space for other channel assessing stations to make the same decision.

The design decisions behind these two reasons are largely made for keeping the model simple at its current stage. As part of the future works, we plan to investigate the issues further and enhance the LED mechanism to address the above two points. As for the first point, we will refine the station's channel assessment algorithm to consider the success of its own transmission and then study the impact of this refinement on the LED performance. As for the second point, we plan to extend our works regarding the β capture factor. Additional radio resource management techniques such as dynamic transmission power control may also be included to improve communication channel spacial reuse, and thus enhance performance of the LED mechanism.

Acknowledgements

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