IEEE 802.11 DCF Location Aware

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***Abstract*— In this paper, we proposed an enhancement to the existing IEEE 802.11 DCF MAC function named the Location Enhanced DCF (LED) for IEEE 802.11, which incorporates location information in the RTS-CTS-Data-ACK handshakes of the IEEE 802.11 DCF so that other stations sharing the channel are able to make better interference predictions and blocking assessments and thus improves channel spatial reuse efficiency and data throughput. We study how LED may improve channel efficiency in normal ad hoc networks as well as its effectiveness in the newly emerging application of mesh networking.**

I. Introduction

The IEEE 802.11 [1] is the most popular standard for Wireless Local-Area Networks (WLANs). The mandatory contention-based Distributed Coordination Function (DCF) is the dominant MAC mechanism implemented by IEEE 802.11-compliant products. The support of contention based DCF has also made IEEE 802.11 equipments popular choices for various wireless ad hoc networks.

Like most of the contention based MAC protocols, the IEEE 802.11 DCF is based on Carrier Sense Multiple Access (CSMA). In CSMA, a station may transmit if and only if the medium is sensed to be idle. In addition to basic CSMA, the DCF incorporates acknowledgement signals and a back-off mechanism when the medium is assessed as busy. An optional channel reservation mechanism known as the "Collision Avoidance" is also include in the DCF.

The IEEE 802.11 DCF is not efficient in shared channel use due to its over-cautious approach towards assessing the possibility of causing interference. In particular, a station simply blocks its own transmission when it senses the medium is busy, or there exists active channel reservation. However in many cases this station's own transmission, if executed, may not introduce enough signal energy to disturb the receiving of the on-going transmission by its intended receiver.

In this paper, we proposed 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 wireless network performance. This scheme is designed as an enhancement to the DCF and named the "Location Enhanced DCF" (LED). We will introduce the enhancement, and study its performance improvements for ad hoc wireless networks as well as its effectiveness in the newly emerging application of mesh networking.

II. Backgrounds and Related Works

Historically, the design of the IEEE 802.11 DCF is influenced by several other protocols. MACAW protocol [4], extending the predecessor Multiple Access Collision Avoidance (MACA) protocol [13], is based on the use of the Request-to-send and Clear-to-Send (RTS/CTS) handshaking scheme. In MACAW, sender nodes do not use the carrier sense mechanism to assess the channel availability. An extended protocol named Floor Acquisition Multiple Access (FAMA) [8] bears significant resemblance to IEEE 802.11, employing both local carrier sense, as well as the RTS/CTS collision avoidance exchange for data transmission.

In brief, the CSMA scheme of the IEEE 802.11 DCF works as follows. Before a station transmits, it must sense the wireless channel to determine if any other stations are transmitting. If the carrier is assessed as busy, the station needs to wait for a random back-off interval after a fixed inter-frame waiting period before it attempts to transmit again. After any directed (unicast) transmission is correctly received, the receiving station sends an ACK frame back. 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 packets. 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 till the end of the whole RTS-CTS-DATA-ACK sequence. Any stations which hear either the RTS or the CTS block their own transmissions (if any) to yield to the communication between this sender and its receiver. The reservation scheme is implemented via a timer called the Network Allocation Vector (NAV) which tracks the remaining time of any on-going transmissions of other stations. Checking NAV before a station attempting to transmit is also known as "virtual carrier sensing".

In summary, a node blocks its own transmissions if either physical carrier sensing or virtual carrier sensing returns channel busy. Although this scheme is generally effective in reducing collisions, it is often unnecessarily pessimistic because it blocks transmissions which will not in fact collide with on going transmissions. The reason is that because of a phenomena known as the "capture effect" [3], [15], [16], [14], [9], – as long as the intended signal is significantly stronger than the sum of all noise signals the intended signal can still be "captured" in presence of noise signals. This effect occurs when a frequency modulation scheme is used in wireless communication.

Different works (e.g., [9], [6], [20], [19]) studied the analytical and simulation models for characterizing the capture effects. A simple yet widely accepted model to describe the when an intended signal can be captured is stated as:

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

where P_r being the received energy of the intended signal and P_i being received energy of the $i-th$ noise signal. The ratio α is called the capture ratio.

With improved receiver design such as the "Message-In-A-Message" (MIM) support [5] which supports the capturing of strong frame regardless if the receiver has already engaged in receiving a weak frame, the following concurrent transmission scenario becomes possible. Consider the example as shown in 1 whereas two concurrent connections share the same wireless communication channel. If the stations are positioned in such a way that the energy levels of station 3 and 4's transmissions as measured at station 1 and 2 are not strong enough that station 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 exchange. Similarly station 1 and 2 can do the same if station 3 and 4 have acquired the channel first. Without taking advantage of the capturing capability, IEEE 802.11 DCF's combined physical and virtual carrier sensing mechanism prevents concurrent station 1-2 and station 3-4 communications.

The newly emerging IEEE 802.11 application of "mesh networking" may also benefit from the capture effect. The ongoing works of the IEEE 802.11s task group specify mesh networking in detail. While purely ad hoc wireless networks are formed by store-and-forward nodes, mesh networks are formed by establishing peer-to-peer wireless links between Access Points (AP). Thus, mesh networks are formed with two classes of wireless nodes, APs and clients. Only APs store and forward packets on behave of other APs and clients. Since a typical AP only has one wireless communication interface, AP-to-AP links will share channel with AP-to-client links. Because of the channel sharing, mesh network data throughput may also be improved by schemes which increase concurrent communication.

Other researchers [10], [2], [12] have also noticed the rather pessimistic approach of 802.11 DCF to channel spacial reuse and proposed their manipulations of the functionality of RTS/CTS in order to enhance network performance. However, capture effect was not usually considered in these approaches. It is the above stated observations and inspirations from various related works which lead us to our own modification to the IEEE 802.11 DCF protocol. We name the modification Location Enhanced DCF (LED).

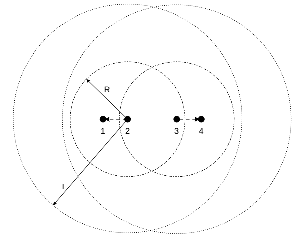

Fig. 1. Network with 4 nodes, (R: transmission range, I: carrier sense range

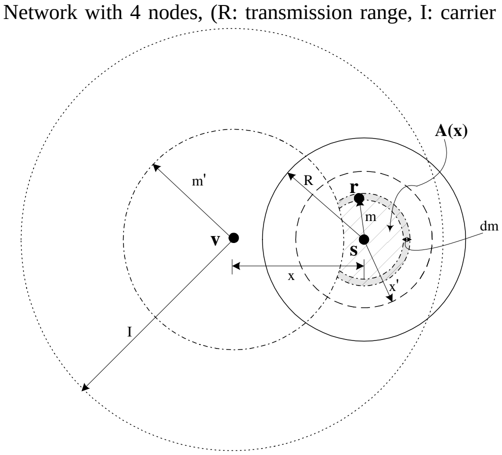

Fig. 2. Capture analysis where $x' = \frac{x}{\sqrt{\alpha}}$ and $m' = \sqrt{\alpha}m$

III. Motivation

Exactly how much overly pessimistic the current IEEE 802.11 scheme is in terms unnecessary blocking transmission can be mathematically analyzed. We assume that stations are uniformly distributed over an area with a density of δ. Each station has a transmission range R within which its transmissions can be received, and a carrier sense range I within which its transmissions can be detected (carrier busy). For the ease of analysis, we assume that all stations have the same traffic model. All data packets are of the same length. Each packet requires transmission time τ, and is randomly destined to a local neighborhood node. 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.

Using the Friis radio propagation[1],

$$Pr = \frac{Pt * G_t * G_r * \lambda^2}{(4 * \pi)^2 * D^2 * L} \tag{2}$$

, and receiver capture model as in equation 1, to allow nodes s and r to capture correctly each other's packets in the presence of any transmission from v, the following should hold:

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

where $\overline{a.b}$ is the distance between node a and node b, and α is the capture ratio.

We are concerned about the scenarios where a node v's transmission may change the capture result of another node r

[1]The parameters are: Pt being the transmission power, Gt and Gr being the antenna gains, D being the separation between transmitter and receiver, L being the system loss factor, and λ being the wavelength in meters.

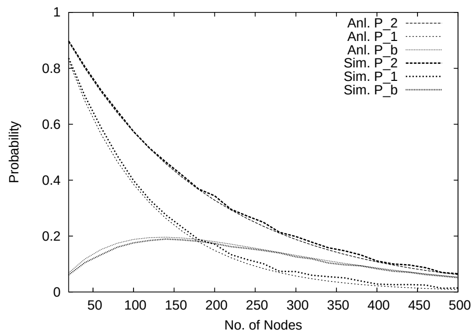

Fig. 3. Blocking Probability

which is receiving a data packet delivery from node s as shown in Figure 2. 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 $\sqrt{\alpha}m$. Symmetrically, since the CTS and ACK frames are from for r to s, 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 communication between s and r is:

$$P(B) = \int_0^I \frac{A(x)}{\pi R^2}\frac{2x}{I^2}\ dx \tag{4}$$

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

$$P_1 = [1 - \frac{\tau}{T}]^{\delta \pi I^2} \tag{5}$$

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

$$P_2 = [1 - \frac{\tau}{T} + \frac{\tau}{T}P(B)]^{\delta \pi I^2} \tag{6}$$

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

$$P_b = P_2 - P_1 \tag{7}$$

. This probability is plotted by 3. The analysis is also verified by simulations during which random network and traffic situations are generated and their interference results are verified to produce the corresponding P_1, P_2, and P_b.

The above unnecessary blocking analysis above is still conservative because of the following two assumptions. First, only the Friis propagation model is used in analysis. As pointed out by [18] Friis model is better suited for short distance propagation and the Two Ray Ground Reflect model should be used for longer distance propagation, which further reduces the probability of the interference and consequently increases the P_b. Second, in above analysis, for simplicity, we assume that all nodes in the vicinity of v have the freedom of transmission. We do not take into accounts that some of these nodes will have to block because of other ongoing transmissions in their own vicinities. Accounting for these blocked nodes would reduce P_1 and hence increase P_b. Simulations with these two conditions relaxed verified the conservativeness of the above analysis by showing a higher P_b. More details can be found in **[?]**.

The probability analyzed above only takes into account whether the channel assessing node's own transmission may corrupt other ongoing data deliveries. It does not address if this channel assessing nodes' transmission will be received correctly by its 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 to motivate us to consider modifying the MAC layer to exploit the capture phenomena of the physical layer.

IV. Location Enhanced DCF for IEEE 802.11

In this section, we describe our Location Enhanced DCF (LED) for IEEE 802.11. In our description, we use the term "delivery" for the whole handshake procedure for delivering a unicast packet. Depending on the packet size, a "delivery" may involve the full RTS-CTS-DATA-ACK 4-way message 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. The "sender" and "receiver" are the sender and receiver of individual RTS, CTS, DATA, or ACK frame. "Transmitter" is used interchangeably with "sender". "Connection" is used to refer to both the source and destination stations collectively.

The approach is simple: to include more information about each transmission in the transmission itself so that any other stations hearing the transmission are able to better assess whether their own transmissions may collide with this transmission. Among various transmission related parameters, the locations of the transmitters and receivers are the most important. We assume that each node is capable of acquiring its own location, e.g. by GPS or other RF based localization methods. Other parameters include the antenna gain and transmission power. A station can these parameters regarding itself easily as they are typically configuration parameters. In addition, capture ratio is assumed to be the same for all stations and known.

At a given station, for a particular on-going delivery that does not involve itself, if these communication parameters of the source and destination stations are known, using a radio propagation model which is suitable for the deployment environment, this station can compute the received energy level of the frames of the data delivery at their intended receivers. Then knowing the capture ratio of the stations of the on-going data delivery, its own location, antenna gain, and transmission power, this station can make a prediction of whether its own transmission may interfere this on-going data delivery.

Figure 4 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 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, or the PLCP (Physical Layer Convergence

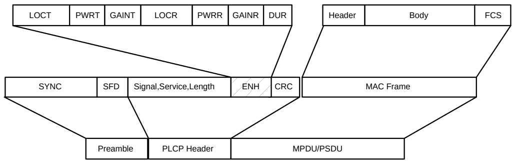

Fig. 4. Frame Structure

Protocol) Service Data Unit (PSDU). In current design, we have the ENH as part of the PLCP header mainly due to the fact that firstly the PLCP header has its own CRC field so the contents of the ENH block can immediately be verified and utilized, and secondly all stations within the service set can understand the ENH block since the PLCP header is transmitted at the base rate.

The ENH block is further divided into seven 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. The DUR field is a copy of the Duration field of a RTS, CTS, DATA, or ACK message MAC format, except that it is in PLCP header instead of PSDU.

When a source has a unicast data packet to send, it starts by sending out an RTS message to reserve the channel. In this message, 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 the parameters regarding the destination are not known at that time, they are set to NIL. Upon receiving the RTS, the destination of the data delivery copies the LOCT, PWRT, and GAINT fields into the corresponding fields of its CTS message. It also fills the LOCR, PWRR, and GAINR fields of the CTS message with its own parameters. In subsequent DATA and ACK messages, 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 message will have its fields set in the same fashion as the RTS message, and the ACK message is filled the same way as the CTS message.

In the standard IEEE 802.11, the PHY (PLCP in particular) does not deliver any data bits to the MAC layer until the PSDU reception has begun. Then the receiver will proceed all the way till the end of the message (unless the carrier is lost in the middle of the reception). Received bits are passed to the MAC layer as they are decoded for being assembled into the MAC frame. At the end of the PSDU is a forward error detection CRC block called 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 LED, because of the ENH block's location, additional data namely the ENH block needs to be passed from the PLCP layer to the LED part of the MAC layer for processing.

Upon receiving a frame with ENH block, a station other than the intended receiver of the frame begins interference estimation. The station needs to calculate the power level of its own transmission at both the source P_i^s and destination P_i^d of the ongoing data delivery using the designated propagation model. The station also needs to calculate the received power level of the destination at the source P_d^s and that of the source 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 does not block its own transmissions. Otherwise, it blocks its transmissions. In the case that the communication parameters of either the source or the destination are unknown, the assessing node assumes the worst and blocks its own transmission.

Normally, after a station other than the intended receiver of the frame receives a RTS, CTS , DATA, or ACK message, it needs to set its NAV value according to the Duration field of the message, which is set to the time required for the full RTS-CTS-DATA-ACK message exchange to finish. In LED, a non-receiver station will only set the NAV according to the standard when it determines that its own transmission will interfere with this on-going delivery. Otherwise, the NAV is not set.

In addition, if the non-receiver station determines that it does not need to block it own transmission to yield to the on-going delivery, it also needs to set a special vector called CCA-Suppression Vector (CSV). The CSV is also a timer. It is set according to the Duration field of the received RTS, CTS , DATA, or ACK message, which means the timer will run till the whole on-going delivery is completed. Together with an active CSV each station needs to remember the source and destination stations of the delivery the CSV is referring to so that this station will block its own transmissions addressed for either. Just like NAV, if a later message prolongs the duration of the delivery, the CSV can also be extended. Once the CSV counts down to zero, a CCAReset signal is issued to the PHY layer so the CCA mechanism will retest the carrier and report the result. Upon receiving a busy CCA indicator, the station will block until either the carrier is idle again, or another frame is captured.

On the source or destination station of the on-going delivery, according to the standard, the NAV is not set for the duration of the delivery. In LED, this specification is still followed. However, a LED receiver does set its CSV to the end of the delivery. The reason is that since LED permits concurrent transmissions by other stations as long as they do not produce enough energy to disturb the on-going delivery. Thus, if any other station is indeed transmitting, their carrier may cause the source and destination of the on-going delivery to abort their RTS-CTS-DATA-ACK handshake. Thus, the CCA should be suppressed on the source and destination stations till the end of their delivery.

In total, a LED station has three indicators related to the channel estimation. The CCA is the physical carrier indicator, the NAV indicator is the virtual carrier indicator, and the CSV indicator tells if the station should ignore the CCA. The decision of whether this station should block its own transmission is made as follows.

$$\text{if ((CCA AND (NOT CSV)) OR NAV) then BLOCK} \tag{8}$$

Another issue occurs if a channel assessing node only detects carrier but can not decode the frame. In this case this node is not able to estimate whether its transmission will affect this on-going transmission. Either an aggressive approach (no blocking) or a conservative approach (blocking) can be taken.

A tricky issue requiring more discussion is for a station to receive messages from more than one delivery. We refer to this situation as the "stacked delivery". Simple stacking situations can be handled by using CSV and NAV together. If the first delivery does not require this station to block its own transmission (non-blocking delivery), the NAV is not set and the CSV is set till the end of this delivery. Now the second delivery is started and it is a blocking delivery. In this case, the NAV is set immediately to the end of the second delivery, and the CSV is not changed. The overall result is the station will block from the moment the first frame of the second delivery is received till the completion of the second delivery. The opposite case is that the first delivery is a blocking delivery and the second is non-blocking. Now the NAV is set for the first delivery and the CSV is set for the second. Overall, the station only blocks till the end of the first delivery when the NAV is cleared. More complex stacking situations are left for future works.

V. Performance Evaluation

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

- We 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 PHY design as discussed in the previous section.
- Current implementation of ns-2 allows the node to compare the newly coming 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 node 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 node to aggregate the signals that have lower values than the CSThresh_ [2] used by ns-2.
- We enhanced the IEEE 802.11 MAC layer by extending it with the implementation of our LED mechanism.

In our evaluation we used two different network configurations: single-hop ad-hoc network, and 802.11s mesh network which will be described below. 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.

The transmission radius R of a node is selected to be 250m while the interference radius is 550m. Each connection is a UDP flow with packets of 1000 bytes which are transmitted at 11Mbps. To simplify the simulation implementation, all RTS and CTS messages, as well as the PLCP headers, are also sent as 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.

IEEE 802.11 equipment does not come with capture ratio specifications. The capture ratio used in simulation is derived by the following method. Given a specific Bit Error Rate (BER) the theoretical 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 [18], it can be determined that 18dB of SNR is needed to achieve 10^{-8} BER, as specified by Orinoco's WLAN 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 signal power over interference. We adopt the same number as the capture ratio. In our model, when a station is receiving frame A and frame B arrives, if the received power of frame A, P_A, is more than 5 times P_B, the receiver captures A and continuously receives frame A; if P_B is more than 5 times of P_A, the receiver captures B and drops A; and in all other situations, packets collide and no frame is received.

We modeled various scenarios of different node 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 and **MACAW** protocols[3]. 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 a node receiving a frame with signal level lower than RXThresh_ [4], from an on going transmission, assumes its transmission will not interfere with that ongoing transmission and therefore should not block. On the other hand, LED_RX is a conservative (pessimistic) version of LED in which a node assumes its transmission will interfere with the ongoing transmission of a frame with a signal lower than RXThresh_.

We use *Effective Throughput* and *Fairness Index* as performance evaluation metrics. Effective throughput counts the total number of packets received by all the receiver nodes over the simulation period. Fairness index measures the bandwidth sharing of nodes under different mechanisms, we use Jain's fairness index [7], [11] which is defined as the following:

$$F = \frac{(\sum_{i=1}^{N} \gamma_i)^2}{N \sum_{i=1}^{N} \gamma_i^2} \tag{9}$$

where N is the number of nodes and γ_i is the number of transmitted packets by node i.

We have experimented both with and without RTS/CTS prior to data. Due to space constrains of this paper, we limit our discussion here to the RTS/CTS case. Although the LED mechanism

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

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

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

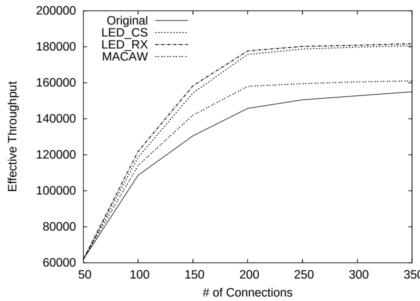

Fig. 5. Effective throughput versus node density

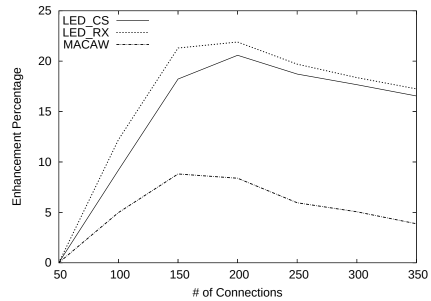

Fig. 6. Throughput enhancement over Original protocol versus node density

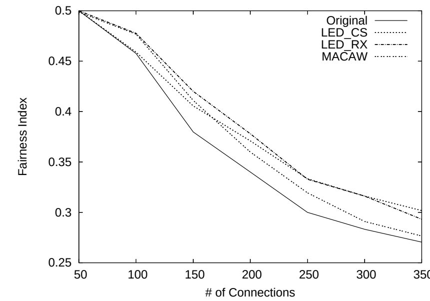

Fig. 7. Fairness index versus node density

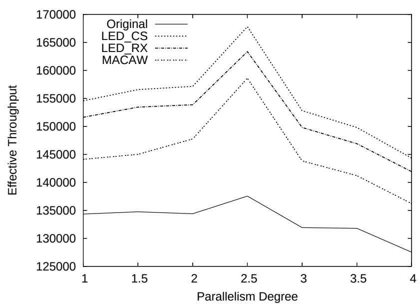

Fig. 8. Effective throughput versus parallelism degree

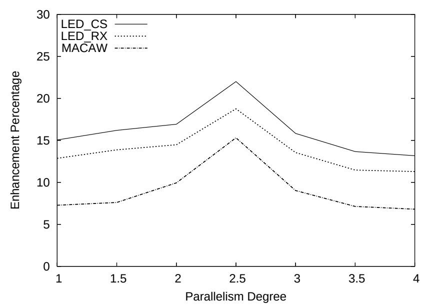

Fig. 9. Throughput enhancement over Original protocol versus parallelism degree

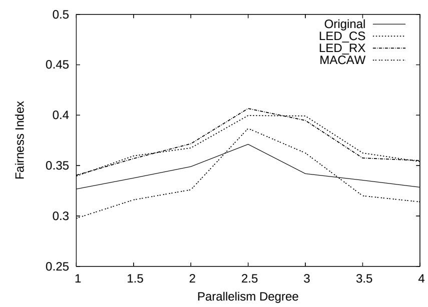

Fig. 10. Fairness index versus parallelism degree

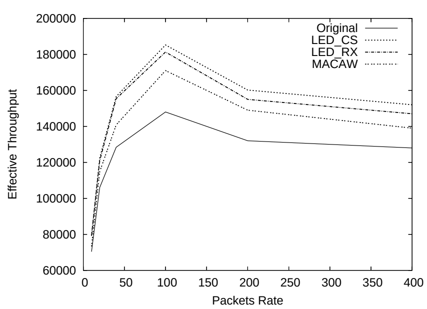

Fig. 11. Effective throughput of 802.11s configuration versus packet rate

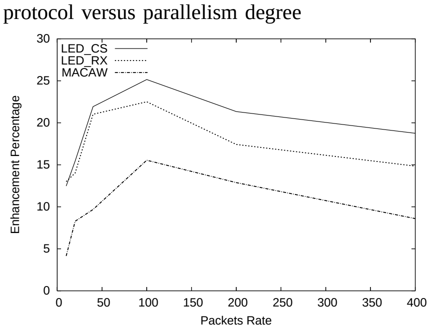

Fig. 12. Throughput enhancement over Original protocol of 802.11s configuration versus packet rate

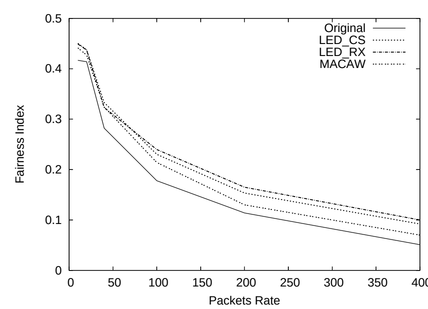

Fig. 13. Fairness index of 802.11s configuration versus packet rate

forces each node to be blocked during the ENH header of each received frame, we found that forcing the node to be blocked during the RTS/CTS period of the other connections will increase the network throughput. The reason for this is more related to the particular ns2 implementation of the physical layer. More details can be found in [17].

We first present the results of the single-hop ad-hoc networks. Single-hop ad-hoc network consists of a set of connections which are constructed as pairs of stationary sender and receiver nodes. Sender nodes are placed randomly in a $1000m \times 1000m$ area while each corresponding receiver node is placed randomly within the transmission range of its sender. Figure 5 shows the effective throughput of the networks with different numbers of connections. The UDP flows are constant bit rate (CBR) at a rate of 20 packets per second. LED_CS, LED_RX, MACAW have higher throughput than the original IEEE 802.11 DCF. Figure 6 further illustrates the improvements by showing the percentage throughput gain of LED_CS, LED_RX, and MACAW over Original. At their peaks, LED_CS could reach about 20% more than the Original amd LED_RX could reach to 22% higher throughput than Original while MACAW could reach to 8%. LED_RX experiences higher throughput than LED_CS for scenarios especially with the number of connections is large because of the aggressive nature of the LED_CS mechanism, which also leads to high number of collisions and retransmissions. On the other hand, MACAW does not utilize the spatial reuse as LED mechanisms. For example, a node using MACAW blocks it transmission once it hears CTS packet regardless if its own transmission will interfere with others or not. Therefore as the node density increases, MACAW performance approach Original since CTS packets will cover most of the network area. Another reason for low performance of MACAW is due to its high aggressiveness. A node hearing RTS packet but not CTS packet will assume its transmission will not interfere with others and start to transmit its packet. Since such node decision may be incorrect, large number of collisions happen. Figure 7 shows the fairness index for the different mechanisms. Using the extended capture model increases the unfairness in the network, however the newly proposed mechanisms have better fairness levels than the Original. An explanation for this is the LED mechanisms reduce the well-known "exposed node" problem in IEEE 802.11 DCF which is one of the sources for unfairness.

Next, we experiment with connection parallelism degree to study their effect on the protocol performance. We measure the parallelism degree by the average number of ongoing and outgoing links per node. For example, when the parallelism degree is 1, it means that each node has one line either outgoing (sender) or ingoing (receiver). We use 50 connection pairs in a network of 100 nodes as the basic configuration with parallelism degree of 1. For higher parallelism degree, we add additional connections to the original connections. To add a new connection, a node is selected randomly as the sender side of the connection while the receiver side node is selected randomly from the neighbor node set of the sender node. In this experiment we fix the packet transmission rate on each connection to be 100 packets per second. Figures 8 and 9 show the effective throughput and the relative enhancements of each mechanism over the Original respectively. As shown, LED_CS has the highest throughput over LED_RX and MACAW. LED_RX performs not as well as LED_CS since it is a conservative mechanism and with small number of nodes as in our experiment (100 nodes), a node will block long period of times while it can transmit within such period with no interference with other transmissions. This is opposite to LED_CS which takes an advantage of its aggressive mechanism and avoid such blocking periods. Figure 10 shows the fairness index of all the mechanisms. LED_CS and LED_RX protocols have similar fairness index measurements which are higher than the Original and MACAW protocols since both LED_CS and LED_RX try to resolve the exposed node problem.

Next we present the result for the 802.11s network configuration mentioned above. In such configuration we placed 10 access points (APs) randomly in the $1000m \times 1000m$ area in which each AP has 20 clients placed randomly within the transmission range. For each AP, half of its clients are transmitting flows to the AP while the other half are receiving flows from the AP. Bi-direction flows are established for any two APs in the transmission range of each other. Note that all the APs and the clients have identical transmission and interference ranges in addition to use the same data packet transmission rate varying from 10 packets per second to 400 packets per second. Figures 11 and 12 show the effective throughput and the relative enhancements of each mechanism over the Original respectively. As expected, LED_CS has the highest throughput over LED_RX and MACAW. The low performance of the LED_RX in comparison with LED_CS could be traced to its conservative nature as explained above in the parallelism degree experiments. Figure 13 shows the fairness index of all the mechanisms. Similarly, LED_CS and LED_RXprotocols have similar fairness index measurements which are higher than the Original and MACAW.

VI. Conclusion and Future Works

In this paper we have introduced an enhancement of the IEEE 802.11 DCF (LED). This enhancement, known as the Location Enhanced DCF, includes more communication parameters especially the locations of transmitters and receivers than the original 802.11 DCF frames. These parameters may assist stations to better assess the channel condition. We have shown that the 802.11 DCF is conservative in terms of channel assessment, causing as much as 35% of unnecessary blocking. 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 (or blocking less). This is indicated by the higher collision counts compared to the original DCF. Although many of these collisions occur at other nearby nodes rather than the packet destinations, they do increase overall network energy expenditure, which may become an issue when applying LED to energy constrained network applications such as sensor networks.

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