Protocol Modifications for Improved Co-Channel Wireless LAN Goodput in Partitioned Spaces

Raymond J. Jayabal, Chiew Tong Lau

Abstract—Partitions can play a significant role in minimising co-channel interference of Wireless LANs by attenuating signals across room boundaries. This could pave the way towards higher density deployments in home and office environments through spatial channel reuse. Yet, due to protocol limitations, the latest incantation of IEEE 802.11 standard is still unable to take advantage of this fact: Despite having clearly adequate Signal to Interference Ratio (SIR) over co-channel neighbouring networks in other rooms, its goodput falls significantly lower than its maximum in the absence of co-channel interferers. In this paper, we describe how this situation can be remedied via modest modifications to the standard.

Keywords——IEEE 802.11 Wireless LAN, spatial channel re-use, physical layer capture.

I. Introduction

$\mathbf{T}$ILL today, the IEEE 802.11 Wireless LAN remains the most popular wireless data communications technology in the unlicensed band. Though not exclusive to indoor environments, it enjoys widespread deployment particularly in home and office environments.

Despite its evident popularity, the IEEE 802.11 Wireless LAN exhibits poor spatial reuseability: when more than one network is deployed using the same channel within signal detection range of each other, a significant drop in goodput occurs even though the signal attenuation caused by partitions between them is theoretically sufficient for error-free operation if transmissions were allowed to take place concurrently.

This performance degradation is due to a limitation in the protocol which our work attempts to solve. We shall present it in the following order: In section II, we review background information such as path loss, radio capture and related past works. In section III, we present our own scheme. In section IV, we explain how the efficiency of our proposed modifications are evaluated. In section V, we present the performance improvements obtained. Finally in section VI, we conclude by summarising our work and speculating on further improvements.

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II. Background Information

A. Effects of Path Loss, Radio Capture and Partition Attenuation Factor on Spatial Channel Re-Use.

Based on [1], the path loss between any transmit-receive (T-R) pair in a network is given by,

$$PL(d) = PL(d_0) + 10 n_{sf} \log\left(\frac{d}{d_0}\right) + \sum PAF \tag{1}$$

where $PL(d)$ is the path loss measured in dB at a T-R distance of d meters, d_0 the *close-in* reference distance at which the transmitter's transmission power is measured, n_{sf} the path loss exponent value measured in the same floor with little to no clutter in the T-R line-of-sight (LOS), *PAF* (partition attenuation factors) the loss (dB) caused by each partition crossed by straight line drawn between the T-R pair.

Based on [2][3], Physical Layer (PHY) capture in IEEE 802.11 networks occurs when,

$$P_i > 10^{0.1\alpha} \sum P_j, \left| T_i - T_j \right| < T_{pre}, j \neq i \tag{2}$$

where T_{pre} is the duration of the preamble, P_n and T_n the received power and arrival time of the nth packet, and α the minimum multi-user Signal to Interference Ratio (SIR) in dBm for capture to occur.

Consider now general scenario of two co-channel networks deployed in separate rooms, where the maximum distance between transmit-receive (T-R) pairs within a room is d_c while the minimum distance between nodes in different rooms are d_i. Ideally, d_i should be as small as possible compared to d_c without any goodput impairment. In this case, the deployment can be so dense that co-channel networks can be in adjacent rooms! The possibility of such a high level of spatial channel re-use can be very advantageous especially in classrooms, internet cafés or LAN gaming establishments.

Using equations (1) and (2), the following relationship between d_i and d_c can be derived:

$$\frac{d_i}{d_c} > 10^{\frac{\alpha - \sum PAF}{10 n_{sf}}} \tag{3}$$

Since n_{sf} is limited to the range of 1.6-3.3 in indoor environments in the 0.9-4.0 GHz frequency range, Eq.(3) tells us that d_i can indeed be smaller than d_c if *PAF* is larger than α. Since *PAF* can be an construction engineering choice through selection of materials of concrete, aluminium, metal, and

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commercial absorbers with the range of 8-47dB for in the 0.815–9.6 GHz range [1][1], while the multi-user SIR keeps improving with newer PHY modulation and antenna diversity techniques, this desireable situation is not difficult to achieve at all! Yet, this not the case for reasons that are explained in the following section.

B. Limitations in the PLCP-MAC Protocol Interactions

Consider the typical interactions between the PHY Convergence Layer Protocol (PLCP) and the Medium Access Control (MAC) during the reception of the PLCP Protocol Data Unit (PPDU) [4] (see Fig. 1). When the Received Signal Strength Index (RSSI) rises above the Energy Detection Threshold (ED_THRESH) and the code-lock quality measured over the preamble sustains above a certain level for a time shorter than the Clear Channel Assessment (CCA) Time (aCCATime), the PLCP will signal to MAC the PHY-CCA.indicate primitive indicating that the medium is busy. After the Start Frame Delimiter (SFD) is encountered, the overall mode of the receiver changes from that of signal detection and synchronisation to data reception. This is marked by the consecutive issuance of PHY-RXSTART.indicate, a string of PHY-DATA.indicate PHY-RXEND.indicate and another PHY-CCA.indicate to signal that the medium had returned to idle.

Because of the mode change after the SFD and the slotted nature of the MAC protocol, capture only occurs when a collision occurs. When the slot is seized by the interfering BSS however, time equivalent to the reception period of the entire PPDU (which is to be discarded anyway) is wasted when it could have been better spent to backoff or transmit, and the two networks thus behave as a single double-sized network, or a less larger one with capture and/or hidden node effects. In the light of this latter case, the minimum non-interfering distance is in fact not quite *MAI-limited* as expressed by Eq.(3), but is rather *ambient noise and receiver sensitivity limited*. This distance is not at all related to the maximum distance of T-R pairs within the same network:

$$d_{i,pre}^{n_{sf}} > \frac{P_t G_t G_r}{L}\left(\frac{\lambda}{4\pi}\right)^2 10^{\frac{-(\alpha_{pre}+\sum PAF+n_0)}{10}} \qquad (4)$$

where $P_t, G_t, G_r, L, \lambda$, are the transmit power (in mW), transmitter gain, receiver gain, system loss and transmit wavelength parameters associated with the Friis equation, α_{pre} the minimum SNR required for good code-lock and n_0 the receiver/ambient noise floor.

Eq.(3) however is still relevant: because capture does not guarantee successful demodulation and decoding of the payload it can be used to determine the minimum interference distance for successful *retention* of the payload ($d_{i,sdu}$) when the transmissions of the two networks are colliding or overlapping by substituting α with α_{sdu}, i.e. minimum SIR requirement for the payload.

Dividing Eq.(4) with Eq.(3) and substituting $P_t, G_t, G_r, L, \lambda$, α_{pre}, α_{sdu} and n_0 with typical values (see TABLE 1) will show

that the former will always yield a higher minimum distance requirement. This is most unfortunate as it means that spatial reuseability is being limited by and large by the smaller, control overhead of the PPDU (i.e., the preamble and header), rather than its larger payload.

This is where our work fits in: while there may be many possible methods to circumvent this issue this with perhaps even more profound performance improvements, our work can be distinguished as one which is implementable by just the addition or modification of a few lines of codes in existing MAC/PLCP protocol implementations, is backward compatible, and most importantly, imposes no additional feature or timing requirements on the PHY Medium Dependent (PMD) software or hardware, yet is able to produce significant results.
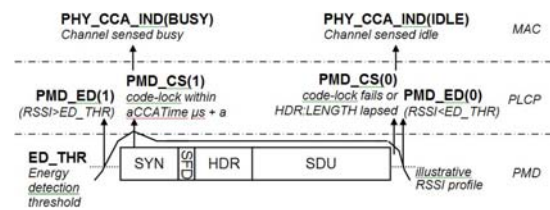

Fig. 1 PPDU Format & Primitives Exchanged between PLCP-MAC During its Normal Reception

C. Related Work

The problem of improving the spatial reuse of IEEE 802.11 Wireless LANs in the general sense is not a new one: various schemes have been proposed before. In [5], Muqattash and Krunz employed schemes where nodes calculate tolerable interference levels based on overheard RTS/CTS exchanges and tune their transmit power accordingly. In [6][11], Zhu et al. introduced algorithms that dynamically adjusts the energy detection threshold. In [8], a scheme which dynamically varies the sensing threshold was described by Vasan et al. for 802.11-based hotspots.

In [9], Fuemmeler et al. presented combined transmit power and sensing threshold control to reduce collisions. In [10], Kim et al. proposed a transmit power and date rate control algorithm to for high data rate transmission while minimising interference to neighbouring transmissions. In [7][12][13], Yang and Vaidya utilized consecutive failure/success statistics of transmissions to control both sensing threshold and data rate to limit the interference range of transmissions. In [14], Akella et al. presented auto-fallback mechanisms for transmit power and data rate for over-populated wireless hotspots. In [15], Sadeghi et al. proposed a rate adaptation scheme based on channel conditions.

In [16], a scheme involving imbedding channel condition information in the RTS/CTS frames for other nodes to determine if they can use the NAV time for their own transmissions was suggested by Cessana et al. In [17], Nadeem et al. proposed imbedding transmit and receiver powers, gains and transmitter and receiver location information into frame headers so that nodes can determine if their transmissions would interfere, based on in-built propagation models.

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However, all of these methods exhibit two or more of the following shortcomings: a) new operational features such as granular transmit power control, support for different spreading codes, GPS/RF-based localisation support, Message-in-Message (MIM) receiver, etc., are required in the PMD which necessitates a hardware upgrade; b) reliance on the accuracy and stability of the receiver's SNR measurements and Variable Gain Control (VGC) mechanisms, and/or use of algorithms with unrealistic a priori knowledge of path loss distribution; c) drastic changes in the syntax and semantics of the MAC-PLCP protocol and frame formats, and d) based on simulations which do not take into consideration the actual MAC-PLCP interactions as stipulated in the standards specification.

In contrast, our scheme does not require additional operational features in the PMD, and is not susceptible to SNR measurement or transmit power control inaccuracies. Based on actual PLCP-MAC interactions, it is also completely faithful to the framework of the original PLCP/MAC protocol, i.e., the procedures, state machines, intra-layer primitives, peer-to-peer frames syntax and exchange sequences, etc., and is easily added to existing MAC and PLCP software.

III. PARTITIONED-DCF

A. DCF Partition Identifier (DPI)

The application of our scheme is limited to the mandatory Distributed Coordinating Function (DCF) basic access method, and arbitrarily call it the "Partitioned-DCF" (P-DCF) mode of operation to distinguish it from the normal operation. It hinges on the use of up to 3 of the remaining reserved bits of the SERVICE field in the PLCP header [4] to carry a parameter which we arbitrarily term as the "DCF Partition Identifier" (DPI) as shown in Fig. 2.

The purpose of the DPI is to allow two or more DCFs within preamble code-locking distance to decide whether they should behave as a single DCF or as separate DCFs each selectively retaining its own payload and making use of the other's payload period to engage their backoff and transmission procedures. This value, which is to be configured to the AP via the AP-configuration software by the network administrator while taking into account possible isolation from other co-channel neighbourhood networks during initial layout-planning and deployment of the WLAN, is to be communicated between MAC and PLCP through the SERVICE field of the RXVECTOR and TXVECTOR parameter block already born by the PHY-RXSTART.indicate and PHY-TXSTART.request primitives, respectively.

B. Method of Operation

Whenever a STA receives a PPDU from the AP, it discerns the DPI; if it is all zero, then the P-DCF mechanism is disengaged, ensuring backward compatibility with APs and STAs not having the P-DCF feature. If, however, it is non-zero, then the STA will start to discriminate signals arriving from neighbouring APs or STAs associated with neighbour APs based on this value. Regardless of the value of the DPI,
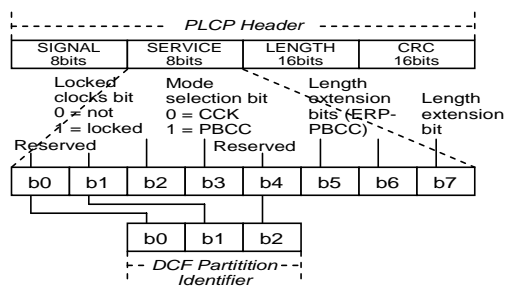

Fig. 2 Proposed "DCF Partition Identifier" field in the SERVICE field of the PLCP Header

STAs will use the same value in its transmissions to its serving AP, which the AP will discriminate likewise.

At some regular interval (e.g., 30 minutes), the AP attempts to run the P-DCF mode, failing which it reverts to the original mode. The criteria for failure of the P-DCF mode is as follows: the track record of its total retry attempts per T-R pair over some observation window is checked against expected values (Fig. 3) for the same number of nodes as have associated with it in the BSS including itself; if this value significantly greater than an administrator-controlled margin (e.g. 10% more), the P-DCF mode has failed and the AP will disengage it, which in turn will cause its served STAs to follow suite, thereby defaulting to the original protocol. Meanwhile, each STA will also keep track of its total retry attempts in similar fashion and set the DPI field to zero for subsequent transmissions if it exceeds the limit; on persistently receiving zero for the DPI from STAs, AP will also disengage the P-DCF mode.

When the P-DCF scheme is engaged, the following simple change is enabled in the original DCF protocol: on the transmitting node, in the primitive PHY-TXSTART.request to PLCP requesting transmission of a MAC frame, the DPI value in the TXVECTOR parameter block is set to the local DPI value. On the receiving node, on receipt of PHY-RXSTART.indicate primitive, MAC checks the DPI value
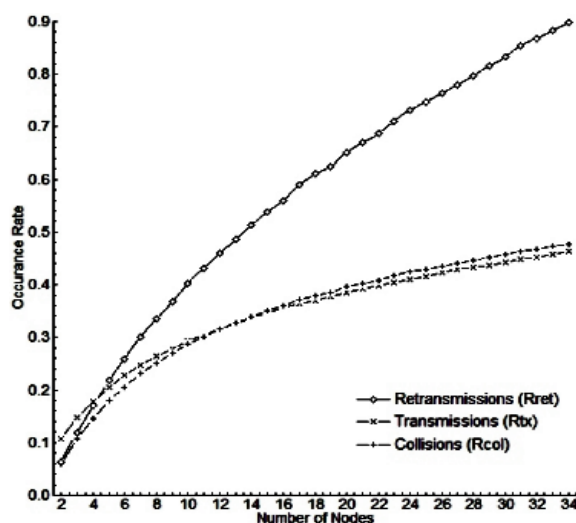

Fig. 3 Average transmissions, collisions and retry rates as a function of nodes for a 7 stage Truncated Binary Exponential Backoff access scheme with window range (32,1024)

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contained in the RXVECTOR parameter; if it is equal to zero or equal to the local DPI value, MAC proceeds to receive the PHY payload up to the issuance of the PHY-RXEND.indicate primitive as per the original protocol; if it is nonzero and not equal to the local DPI value, then MAC sends PHY-CCARESET.request forcing PLCP to abandon the current reception procedure, to reset its state to idle and to start the CCA procedure. Meanwhile, MAC's channel assessment procedure returns to the IDLE state, thereby allowing the backoff procedure to resume counting and the transmission procedure to be engaged when the count reaches zero or when the LLC requests for a data transmission.

When the P-DCF scheme is not engaged, on the transmitting node, a DPI value of zero is used in the TXVECTOR parameter block accompanying the PHY-TXSTART.request so that the transmitted PPDU contains the same value in its DPI field; on the receiving node, if a non-zero DPI is being reported in the RXVECTOR accompanying the PHY-RXSTART.indicate primitive, it is ignored and the original PLCP receive procedure is obeyed.

IV. EVALUATION APPROACH

For the purpose of evaluation, our scheme was implemented in ns2 [18] using the 2.4GHz DSSS as the PHY layer model as it was the most studied PHY with complete empirical data regarding its transmission characteristics such as capture and BER vs. SINR performance.

Fig. 4 shows the topology used in simulating the effects of the proposed modification. Here, 2 rooms are being served by 2 APs each mounted at the centre of each room. Each room is divided into 4, 9 and 16 cubicles containing a STA each. Effects of soft partitions and general clutter are glossed over by a path loss index of 2.5 used in the propagation model.

Between the two rooms, a hard partition exists which *PAF* value is varied in the range of 0-58dB in steps of 1dB.

Other parameters of the simulation are listed in TABLE 1. Of particular note are the choice of values for the capture and retention parameters: to this date no empirical or analytical information is available for this ratio, but as interfering frames are highly unlikely to coincide *exactly* at both the modulation symbol interval *and* the PN code interval, they are unlikely to present themselves as other than noise as far as the despreading process is concerned. Furthermore, no distinction is made in the the minimum SIR/SNR required for good code-lock and errorless reception of the PLCP header and set it to 2dB based on the BER-E_b/N_0 curves of a popular chipset [19] at 1% allowable false detection and/or header error, which
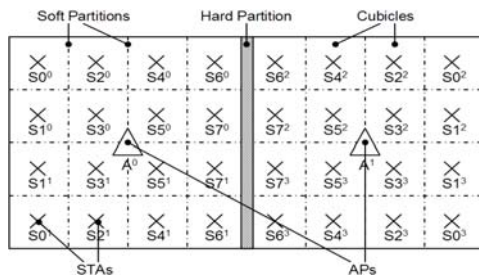
TABLE 1
SIMULATION PARAMETERS

Parameter	Value
Number of Rooms/APs	2
Room size (A)	16 x 16 m^2
AP position	Room centre
STAs per room, evenly distributed (N_{sta})	4,9,16
Propagation model	See Eq(1)
Path loss index (n_{sf})	2.5
Partition attenuation factor (*PAF*)	0-58 dB
Propagation delay	2 μs
Ambient noise (n_0)	-96 dBm
Antenna type	Omnidirectional
Transmit (Gt) receive (Gr) and system loss (L)	1,1,1
AP-STA antenna height difference	2.5m
AP/STA operating frequency (3e+8/λ)	2.472 GHz
AP/STA transmit power (Pt)	15 dBm
Energy detection threshold (*ED_THRESH*)	-95 dBm
CCA time (aCCATime)	15 μs
PLCP preamble and header length ($T_{pre+hdr}$)	56+16+48 bits (96 μs)
SNR/SIR for errorless preamble/header (α_{pre})	2 dB
SIR for errorless payload (α_{sdu})	12.5 dB
Slot time (aSlotTime) (σ)	20 μs
Short Interframe Space (SIFS)	10 μs
DCF Interframe Space (DIFS)	50 μs
Extended Interframe Space (EIFS)	1005.6 μs
ACK payload length (at 11Mbps)	14 bytes (10.2 μs)
DATA payload length (at 11Mbps) (L_{payl})	1034 bytes (752 μs)
ACK timeout (ACKTimeout)	120.2 μs
Min. contention window length (aCWMin+1)	32
Max. contention window length (aCWMax+1)	1024
STA Short retry limit	7
Traffic model	Poisson/Exponential
Packet size	1000 bytes
Uplink/downlink ratio	N_{sta}:1
Offered load per AP	33 Mbps (Saturation)
Simulation period (per *PAF* value)	10 minutes (1-2 million transmissions)

roughly works out to 1e-4 BER over the 120 bits (0.01/120 = 8.3e-5); for the 11Mbps payload, the minimum SIR for successful retention is assumed to be 12.5dB based on a BER cut-off of 1e-5 drawn from the maximum Frame Error Rate of 8% that PHY is allowed to present to MAC for a payload size of 1034 bytes (0.08/(1034x8) = 9.7e-6) specified in the 802.11b standard.

V. RESULTS

Fig. 5 – Fig. 8 show the uplink and downlink goodput and delay graphs for the original DCsasdqweqw ueqw9 wq9ueq9w qwe 9qweu q9weu9 que9qw ue9wqu 9ewqu e9wqu 9qweu 9qweu 9qweu qw9eu qw9eu qweuqw9euqw9euqw9euqw9eu q9weFig. 5 – Fig. 8 show the uplink and downlink goodput and delay graphs for the original DCF (O-DCF) versus the P-DCF with a 10% retransmission cap, as well as their associated fairness indices [20] as a function of the *PAF* for the lowest and highest STA densities simulated, which yields the best and worst performance depending on the proximity of interfering STAs (e.g., S6^0 to S6^2 in Fig. 3). Retransmission plots are also

Fig. 4 Simulation topology

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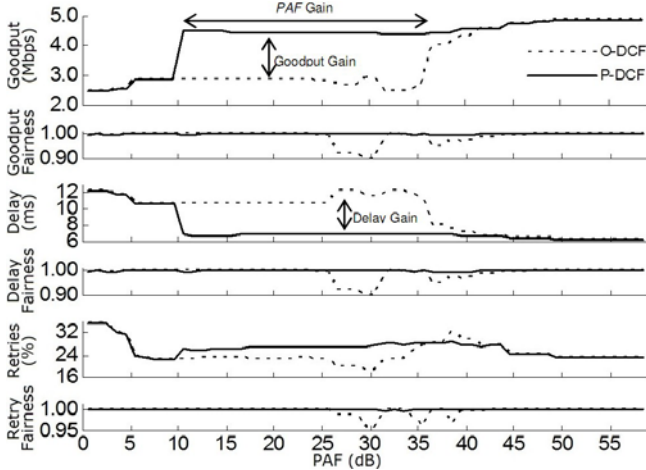Vol:4, No:12, 2010

Fig. 5 Uplink Goodput, Delay and Retries as a Function of *PAF*, along with Fairness Indices for N_{sta}=4.
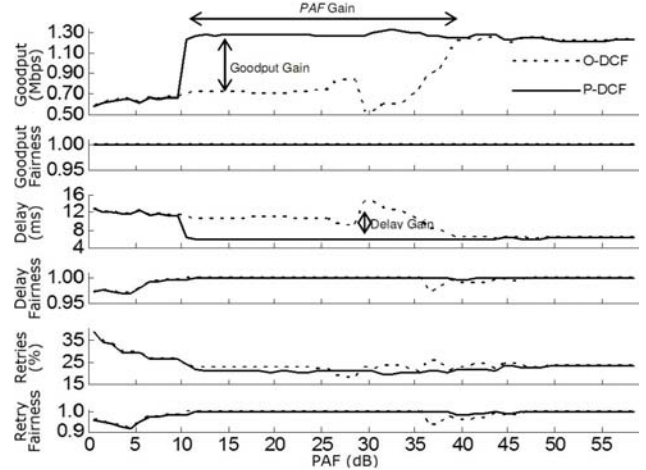

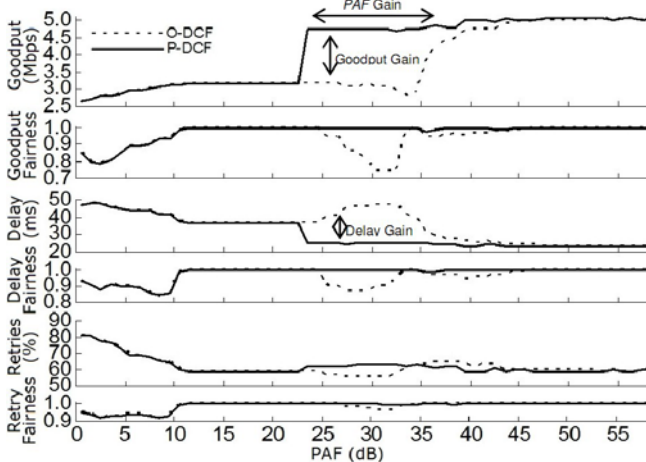Fig. 6 Downlink Goodput, Delay and Retries as a Function of PAF, along with Fairness Indices for Nsta=4.

Fig. 7 Uplink Goodput, Delay and Retries as a Function of *PAF*, along with Fairness Indices for N_{sta}=16.
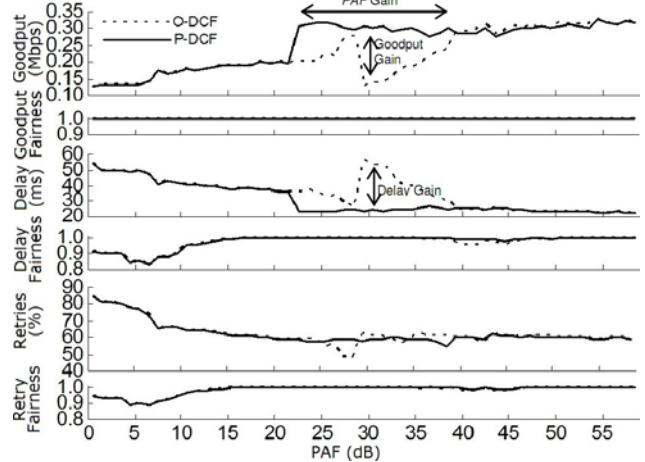

Fig. 8 Downlink Goodput, Delay and Retries as a Function of *PAF*, along with Fairness Indices for N_{sta}=16.

provided as an indication of the frame-drop propensity of the system.

A quick review of these graphs reveals the following advantages the P-DCF exhibits over the original DCF:

First and most importantly, the cut-off *PAF* is reduced significantly; in the general case, the *absolute* cut-off *PAF*s of the original and partitioned DCF by can be obtained by rearranging Eqs.(3) and (4) and substituting d_c and/or d_i with the appropriate values (e.g, for the given simulation, d_c is the distance of the AP to its furthest corner STA and d_i the distance of between STAs on opposing sides of the partition which are $(A/2)^{1/2}$ - $(A/2N_{sta})^{1/2}$ and $(A/N_{sta})^{1/2}$, respectively):

$$PAF_{cut-off,o-dcf} = 10\log\left(\frac{PtGtGr}{L}\left(\frac{\lambda}{4\pi}\right)^2\right) - 10n_{sf}\log(d_i) - \alpha_{pre} - n_o \quad (5)$$

$$PAF_{cut-off,p-dcf} = 10n_{sf}\log\left(\frac{d_c}{d_i}\right) + \alpha_{SDU} \quad (6)$$

Secondly, after the cut-off *PAF* is reached, the P-DCF achieves 90% of the goodput of an isolated DCF (e.g, at *PAF* > 55dB) obtainable from the following equation [21] by substituting r_{tx} and r_{col} for values at $N=N_{sta}+1$ given by Fig. 4:

$$S = \frac{r_{tx}(1-r_{col})L_{payl}}{(1-r_{tx})\sigma + r_{tx}(1-r_{col})T_{suc} + r_{tx}r_{col}T_{col}} \quad (7)$$

where T_{suc} is the sum of the time periods DATA+SIF+ACK+DIF and T_{col} the sum of time periods DATA+DIF. At the same time, goodput fairness, delay and delay fairness performances comparable to that of an isolated DCF are also retained, while its retry-based mode-switching keeps the retry and retry fairness also fairly close.

Thirdly, in the region of between the cut-off *PAF* of the P-DCF and the O-DCF (obtainable via Eqs. (5) and (6)) where the original DCF shows erratic performance due to varying fraction of STAs becoming hidden or experiencing EIFS cycles due to errornous reception of the payload part of frames from the interfering DCF, the P-DCF is impervious to them and maintains a steady performance throughout due to its selective payload-retention capability.

VI. CONCLUSION AND FUTURE WORK

In this paper we have presented a method for improving goodput of the IEEE 802.11-based Wireless LANs in

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partitioned indoor environment without modification to the MAC and PLCP protocol framework (i.e., intra-layer primitives and and peer-to-peer frame formats) or additional feature or timing requirements for the PMD.

By means of the ns2 MAC 802.11 simulator which we had modified to reflect actual MAC-PLCP interactions and timings, we have illustrated that by just the use of the reserved bits in the SERVICE field of the PCLP header and slight changes to the DCF behaviour with respect to these bits, we are able to significantly reduce the *PAF* requirements for effective isolation of two DCFs in separate rooms with negligible impact to the throughput, delay, retransmission probability and fairness statistics compared to the original DCF; to boot, at certain *PAF* values, goodput, delay and fairness values are even improved when our scheme is in place.

However, our work does not stop here; our next step would be to quantify the differences observed between the goodput and retransmission performances of the P-DCF after its cut-off *PAF* and of the original DCF after its cut-off *PAF*. Also, we intend to extend and validate our scheme to cater to more than just 2 neighbouring DCFs – a development which would yield even greater spatial reuseability. Another area which we are interested to work on is the quantitative characterisation of the behaviour of the original DCF in the region where its throughput, delay and fairness varies oddly, i.e., in between the two cut-off *PAF*s

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