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Proportional fair throughput allocation in multirate IEEE 802.11e wireless LANs

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Abstract Under heterogeneous radio conditions, Wireless LAN stations may use different modulation schemes, leading to a heterogeneity of bit rates. In such a situation, 802.11 DCF allocates the same throughput to all stations independently of their transmitting bit rate; as a result, the channel is used by low bit rate stations most of the time, and efficiency is low. In this paper, we propose a more efficient throughput allocation criterion based on proportional fairness. We find out that, in a proportional fair allocation, the same share of channel time is given to high and low bit rate stations, and, as a result, high bit rate stations obtain more throughput. We propose two schemes of the upcoming 802.11e standard to achieve this allocation, and compare their delay and throughput performance.

Keywords 802.11 · Wireless LAN · 802.11e · Throughput allocation · Proportional fairness · QoS · Heterogeneous radio conditions · Contention window · TXOP limit · Multirate

1. Introduction

This paper focuses on throughput allocation in IEEE 802.11 Wireless LANs (WLANs). The question of throughput allocation in such networks becomes increasingly important with the emergence of new bandwidth hungry applications, such as mobile information access, real-time multimedia, networked games, immersion worlds and cooperative work.

To satisfy the growing bandwidth demands in WLAN, the basic 802.11 standard of 2 Mbps capacity [1] has been extended to 11 Mbps nominal capacity, with 802.11b [2], and to 54 Mbps, with 802.11a/g [3, 4]. In this paper we assume 802.11b; however, our analyses apply equally to 802.11a/g. In parallel to these standards, QoS mechanisms for more efficient use of the WLAN capacity have been defined in the upcoming 802.11e standard [5].

Although DCF (Distributed Coordinated Function), the access method used in 802.11 WLANs, uses the CSMA/CA protocol to share radio resources in a fair way, some works in the literature [6, 7] have shown that, for 802.11b and a, respectively, this method results in a considerable performance degradation in some common situations in a wireless environment.

In a typical WLAN, some stations may be far away from their access point so that the quality of their radio transmission is low. In this case, the stations select a lower bit rate transmission mode, thus decreasing their bit rate from the nominal value to a smaller one. In fact, [7] shows that selecting a lower rate transmission mode under bad radio conditions is necessary in order to avoid a severe performance degradation due to transmission errors. Mode selection is not defined by standards but is implementation-dependent.[1]

If there is at least one station in the WLAN with a low bit rate, throughput is allocated in a way that [6] refers to as a *performance anomaly*: the throughput of all stations transmitting at a high bit rate is degraded to the level of the

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[1] [6] reports real-life experiments according to which current 802.11b products decrease their bit rate under bad radio conditions.

low bit rate station.[2] Such a behavior penalizes fast stations and privileges the slow one.

The reason for the above is that CSMA/CA guarantees that the long term channel access probability is equal for all stations. When one station captures the channel for a long time because its transmitting bit rate is low, it penalizes other stations that use a higher bit rate.

In this paper, we address the above described "performance anomaly" problem of DCF. We propose a throughput allocation criterion based on *proportional fairness* to solve this problem and study how this throughput allocation can be provided with different mechanisms of the upcoming 802.11e standard. While other papers in the literature [8–10] have proposed similar approaches, the fundamental difference between those papers and ours is that we address the problem from a formal viewpoint with a well defined performance criterion. In fact, it is interesting to observe that those papers, based on intuition, have reached similar conclusions to ours.

The paper is outlined as follows. In Section 2 we briefly review the DCF mechanism, and we illustrate its performance anomaly by means of simulation. In Section 3 we advocate the use of the proportional faimess criterion to deal with this performance anomaly. In Section 4 we present (and analyze mathematically) two schemes of 802.11e for throughput allocation: the Contention Window (CW) and the transmission length (TL) schemes. In Sections 5 and 6 we study the configuration of these schemes for proportional fairness. Results show that a necessary condition for achieving proportional fairness is that the channel time is equally shared among all stations, independently of their bit rate. Based on this result, we propose a centralized and a distributed configuration for each scheme. Throughput and delay performance of the two schemes is studied in Section 7. Results show that both offer an optimal tradeoff between delay and throughput performance. Concluding remarks are given in Section 8.

2. 802.11 DCF and performance anomaly

The DCF access method of the IEEE 802.11 standard is based on the CSMA/CA protocol. A station with a frame to transmit senses the channel and, if it remains free for a DIFS (Distributed Inter Frame Space) time, it transmits. If the channel is sensed busy, the station waits until the channel becomes idle for a DIFS time, after which it generates a random backoff time before transmitting.

The backoff time is chosen from a uniform distribution in the range $(0, CW - 1)$, where the CW value is called Contention Window, and depends on the number of failed transmissions for the frame. At the first transmission attempt, CW is set equal to a value CW_{min}, and is doubled after each unsuccessful transmission, up to a maximum value CW_{max}. In 802.11b, CW_{min} and CW_{max} are set equal to 32 and 1024, respectively.

The backoff time is decremented once every time slot σ for which the channel is detected idle, "frozen" when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for a DIFS time. The station transmits when the backoff time reaches zero.

If the frame is correctly received, the receiving station sends an ACK frame after a SIFS (Short Inter Frame Space) time. If the ACK frame is not received by the transmitting station, a collision is assumed to have occurred and the frame transmission is rescheduled according to the given backoff rules. If the ACK frame is correctly received, meaning that the frame has been correctly transmitted, the station resets the CW to its initial value and reenters the backoff process; before this ends, a new frame cannot be transmitted.

Figure 1 illustrates the above protocol operation. Two stations A and B share the wireless channel. At the end of a previous transmission, both stations A and B have new frames to transmit; they wait for a DIFS time and then choose a backoff time equal to 6 and 8, respectively. The transmission of station A occurs when the backoff value for station B is equal to 2. As a consequence of the channel being sensed busy, the backoff time of station B is frozen at this value and is only decremented again when the channel is sensed idle for a DIFS time. After transmitting, station A chooses a new backoff time equal to 7 and hence station B is the next to transmit.

The use of the Request to Send (RTS)/Clear to Send (CTS) mechanism is optional in 802.11. When this option is applied, upon the backoff counter reaching zero, the transmitting station sends an RTS frame instead of a data frame to the receiving station, which responds with a CTS frame. The data frame is then sent when the transmitting station receives the CTS. In this paper, we assume that the RTS/CTS option is turned off; however, following a similar reasoning to [11], our work here could easily be extended to the RTS/CTS case.

The time spent on a transmission depends on the frame size and the station's bit rate. 802.11b allows the following bit rate values: 11, 5.5, 2 and 1 Mbps.

To illustrate the *performance anomaly* in the throughput allocation of 802.11 DCF, we performed the following simulation (the details of the simulations are given in Section IV). In scenario *a*) we have two stations that share the channel, both transmitting at a bit rate of 11 Mbps; in scenario *b*), one station transmits at 11 Mbps and the other at 1 Mbps. Results are depicted in Fig. 2. It can be observed that the performance experienced by the fast station is severely degraded by the slow one.

[2] [7] shows that, in presence of transmission errors, low bit rate stations may even get a larger throughput than higher bit rate. In this paper we neglect the effects of transmission errors.

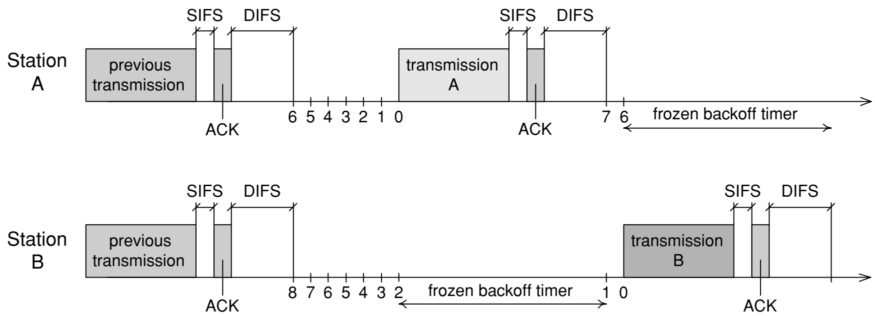

Fig. 1 DCF operation example

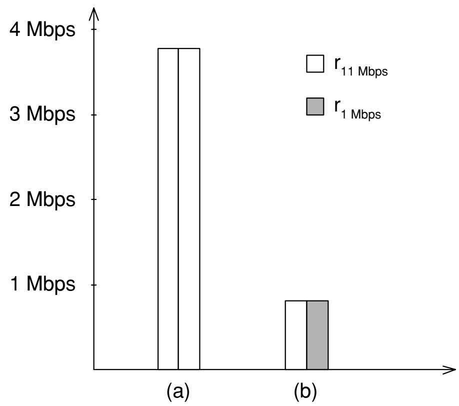

Fig. 2 DCF throughput allocation

3. The fairness criterion

From the above simulation, it can be seen that DCF does not make an optimal overall resource utilization, as it sharply degrades the performance of fast stations in order to provide slow stations with a marginal performance increase.

On the other hand, if only the optimization of the overall resource utilization was considered, this would lead to allocating the whole channel bandwidth to the fast stations, starving the slow ones. As this criterion is clearly not desirable either, we argue that a tradeoff in between the two extremes must be found.

In order to solve the above tradeoff, Kelly proposed the *proportional fairness* criterion [12]. A vector of throughput allocation $\{r_1, \ldots, r_n\}$ (where r_i is the throughput of station i) is proportionally fair if it is feasible, and for any other feasible allocation $\{r_1^*, \ldots, r_n^*\}$, the aggregate of the proportional changes is not positive:

$$\sum_i \frac{r_i^* - r_i}{r_i} \leq 0 \tag{1}$$

Note that, with the above definition, in a two station scenario the throughput of one station would be decreased by say 10% only as long as this allowed an increase in the throughput of the other station of more than 10%. This represents a balance between the two extreme allocations identified at the beginning of this section.

In this paper, we advocate using the above defined *proportional fairness* criterion to solve the fairness issue that arises in a WLAN in which the channel bandwidth is shared by a number of stations under heterogeneous radio conditions. This criterion was originally proposed in the context of wired networks and has been widely used to address a variety of fairness issues [13, 14] including other fairness problems of wireless packet networks [15].

To investigate the proportional fair allocation further, we consider a small feasible perturbation around the proportional fair allocation $r_i \rightarrow r_i + dr_i$. From Eq. (1)

$$\sum_i \frac{dr_i}{r_i} \leq 0 \tag{2}$$

which can be rewritten as

$$\sum_i (log(r_i))' dr_i \leq 0 \tag{3}$$

It follows from the above that the proportional fair allocation represents a local maximum of the function $\sum_i log(r_i)$. Since this is a concave function, it has only one maximum, and therefore the local maximum is also the global maximum.[3]

Following the above result, hereafter we look for the allocation that maximizes $\sum_i log(r_i)$ in order to find the proportional fair allocation.

4. Throughput allocation schemes

In order to implement the proportional fairness criterion proposed above, we need to allocate different throughputs to the various stations depending on their bit rate. In this section, we describe and analyze the schemes proposed in the upcoming IEEE 802.11e standard [5]. Specifically, three differentiation schemes are included in the EDCA mechanism of 802.11e: AIFS, Contention Window (CW) and Transmission Length (TL), the latter being based on the TXOP limit parameter of 802.11e. The first scheme (AIFS) is not appropriate for throughput allocation (see [17]) and is not further

[3] See [16], Theorem 1.2.3, for the complete and formal proof.

considered. The other two (CW and TL) are presented and subsequently analyzed.

The CW scheme is based on the CW_{min} and CW_{max} parameters, which are configurable in 802.11e. By setting these parameters appropriately, we can regulate the rate with which a station accesses the channel and as a result the throughput that the station obtains.

The TL scheme fixes the length of the data that a station transmits upon accessing the channel.[4] Given a certain access rate, this transmission length regulates the station's throughput. In 802.11e, the transmission length is given by the transmission opportunity limit parameter (*TXOP limit*), which limits the period of time a station is allowed to occupy the channel upon accessing it.

The rest of this section is devoted to an analysis of the resulting throughput allocation of the CW and TL schemes. Let CW^i_{min} and CW^i_{max} be the CW_{min} and CW_{max} of station i, and m_i the station's maximum backoff stage, defined as $CW^i_{max} = 2^{m_i} CW^i_{min}$. Let l_i be the length of the frame transmitted by the station when it accesses the channel,[5] R_i the station's bit rate and n the total number of stations in the WLAN.

In our analysis, as well as in the rest of the paper, we assume that all stations always have a frame to transmit. In fact, such a source model is the most commonly used to study throughput allocations in WLAN, and corresponds to greedy stations e.g. sending UDP CBR traffic at a rate equal to or greater than the station's allocated throughput. From our previous experience simulating WLANs (see [18–20]), we learned that using UDP ON/OFF and TCP source models results in similar throughput allocations, as long as the duration of the OFF periods is not too long and enough throughput is allocated for the TCP ACKs.

According to [11], the probability that a station under the above conditions transmits at a randomly chosen slot time[6] is equal to

$$\tau_i = \frac{2}{1 + CW^i_{min} + \sum_{j=0}^{m_i-1} (2p_i)^j} \tag{4}$$

where p_i is the probability that a transmission of the station results in a collision

$$p_i = 1 - \prod_{j\in\{1,\ldots,n\}\setminus i} (1-\tau_j) \tag{5}$$

[4] These data can be contained either in one frame or in several frames transmitted back-to-back, as allowed by the 802.11e standard draft.

[5] For simplicity we assume that all stations transmit a single frame upon accessing the channel. We note, however, that the analysis would be very similar in the case where some or all stations transmit several frames back-to-back upon accessing the channel [8].

[6] As in [11], "slot time" here refers to the variable time interval between two consecutive backoff time decrements.

The above constitutes a system of non-linear equations on τ_i and p_i that can be solved numerically. Then, the throughput experienced by station i, r_i, can be computed as the average amount of payload information transmitted by station i in a slot time divided by the average duration of a slot time

$$r_i = \frac{p_{s,i} l_i}{p_s T_s + p_c T_c + p_e \sigma} \tag{6}$$

where p_e, $p_{s,i}$, p_s and p_c correspond to the probability that a randomly chosen slot time is empty, contains a successful transmission of station i, a success of some station and a collision, respectively, and T_s and T_c are the average duration of a success and a collision.

$p_{s,i}$, p_s, p_c and p_e can be computed as follows

$$p_{s,i} = \tau_i \prod_{j\in\{1,\ldots,n\}\setminus i} (1-\tau_j) \tag{7}$$

$$p_s = \sum_{i=1}^{n} p_{s,i} \tag{8}$$

$$p_e = \prod_{i=1}^{n} (1-\tau_i) \tag{9}$$

$$p_c = 1 - p_s - p_e \tag{10}$$

The average duration of a success can be computed according to

$$T_s = \sum_{i=1}^{n} \frac{p_{s,i}}{p_s} T_s^i \tag{11}$$

where T_s^i is the duration of a success of station i.

To compute the average duration of a collision we need to account for the transmission length of all the stations involved, and take the length of the longest one. We proceed as follows. We index all the stations in the WLAN in order of increasing transmission duration, such that the duration of a transmission of station 1 is the shortest and the duration of a transmission of station n is the longest. Then,

$$T_c = \sum_{i=2}^{n} \frac{p_{c,i}}{p_c} T_c^i \tag{12}$$

where $p_{c,i}$ is the probability that a slot time contains a collision that involves station i and no station of higher index, and T_c^i is the duration of such a slot time.

The probability $p_{c,i}$ corresponds to the case in which station i transmits, no station of index higher than i transmits and at least some station of index lower than i transmits,

Table 1 802.11b system parameters

parameter	1 Mbps	2 Mbps	5.5 Mbps	11 Mbps
R	1 Mbps	2 Mbps	5.5 Mbp	11 Mbps
T_{PCLP}	192 μs	96 μs	96 μs	96 μs
H	34 bytes	34 bytes	34 bytes	34 bytes
ACK	14 bytes	14 bytes	14 bytes	14 bytes
σ	20 μs	20 μs	20 μs	20 μs
SIFS	10 μs	10 μs	10 μs	10 μs
DIFS	50 μs	50 μs	50 μs	50 μs

$$p_{c,i} = \tau_i \prod_{j=i+1}^{n} (1-\tau_j) \left(1 - \prod_{j=1}^{i-1}(1-\tau_j)\right) \tag{13}$$

The average duration of a successful transmission from station i is computed as follows,

$$T_s^i = T_{PCLP}^i + \frac{H+l_i}{R_i} + SIFS + T_{PCLP}^i + \frac{ACK}{R_i} + DIFS \tag{14}$$

where T_{PCLP}^i is the PLCP (Physical Layer Convergence Protocol) preamble transmission time of the station, R_i is the station's bit rate, H is the MAC header size and ACK is the size of the ACK frame.

Similarly, the average duration of a collision, station i being the station involved in the collision with the longest transmission duration, is computed as

$$T_c^i = T_{PCLP}^i + \frac{H+l_i}{R_i} + DIFS \tag{15}$$

To validate the model presented in this section, we have compared its results with a simulator developed by us. Ours is an event-driven simulator, written in C++, that closely follows the 802.11 DCF protocol details for each independently transmitting station. The system parameters used for the simulations are given in Table 1.

We first validate our model for the CW scheme. We consider four groups of stations, with bit rates of 11 Mbps, 5.5 Mbps, 2 Mbps and 1 Mbps, respectively, configured as follows. CW_{min}^{1Mbps} varies according to the value given in the x axis of the graphs, CW_{min}^{11Mbps} is set to 32, and the remaining CW_{min}^{i} are set to[7]

$$CW_{min}^{5.5Mbps} = \frac{1}{\frac{1}{CW_{min}^{11Mbps}} + \frac{1}{3}\left(\frac{1}{CW_{min}^{1Mbps}} - \frac{1}{CW_{min}^{11Mbps}}\right)} \tag{16}$$

[7] These CW values have been chosen so that the throughputs of different bit rate stations are equally spaced.

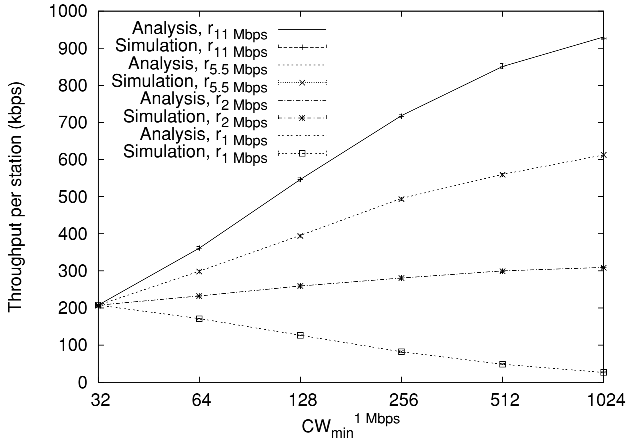

Fig. 3 CW scheme, 2 stations per group, $m_i = 5$

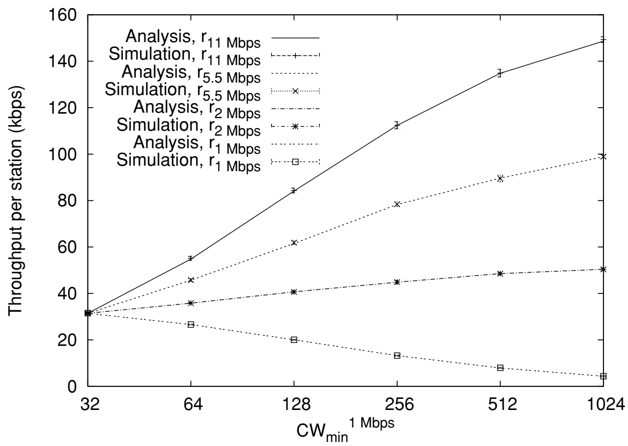

Fig. 4 CW scheme, 10 stations per group, $m_i = 5$

and

$$CW_{min}^{2Mbps} = \frac{1}{\frac{1}{CW_{min}^{11Mbps}} + \frac{2}{3}\left(\frac{1}{CW_{min}^{1Mbps}} - \frac{1}{CW_{min}^{11Mbps}}\right)} \tag{17}$$

Figures 3, 4 and 5 give the results for the above experiment with 2 stations per group and $m_i = 5\ \forall i$, 10 stations per group and $m_i = 5\ \forall i$, and 10 stations per group and $m_i = 0\ \forall i$, respectively. The transmission length is equal to 1500 bytes in all cases. Analytical results (lines) and simulations (points) are given; for the simulations, 95% confidence intervals are shown with error bars.

We next validate the model for the TL scheme. For this purpose, we consider 4 groups of stations, with bit rates of 11 Mbps, 5.5 Mbps, 2 Mbps and 1 Mbps, configured as follows. Upon accessing the channel, they transmit a frame of length 1500, 1500 - L, 1500 - 2L and 1500 - 3L, respectively, where the value of L is given by the x axis. All stations use the default CW values. Results are given in Fig. 6.

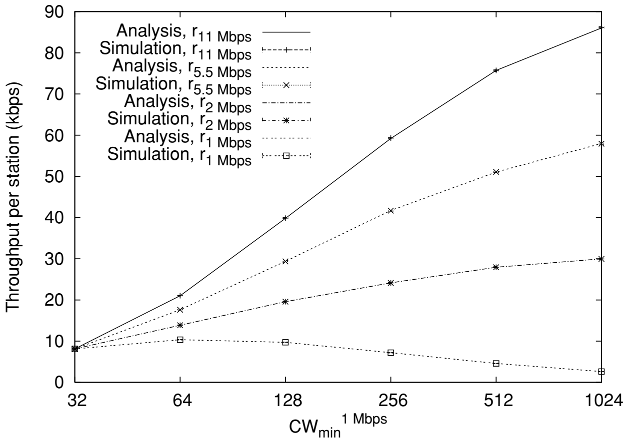

Fig. 5 CW scheme, 10 stations per group, $m_i = 0$

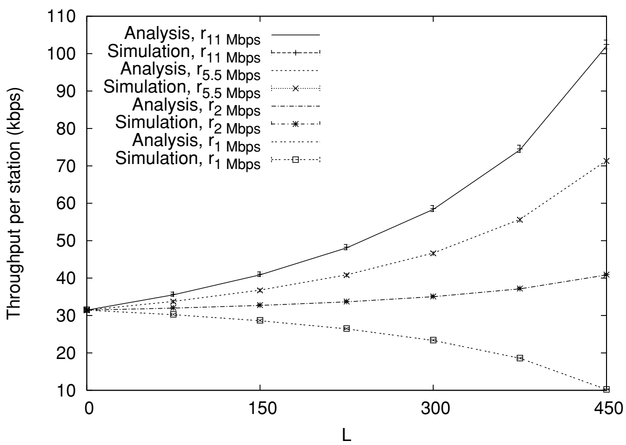

Fig. 6 TL scheme

As in all the above experiments analytical results practically coincide with the simulation results, we conclude that our analytical model is very accurate.

5. CW scheme configuration

The main challenge with the schemes analyzed above is to determine their configuration for providing a proportional fair allocation. In this section we focus on the CW scheme. We first show that a necessary condition for proportional fairness with this scheme is that its configuration is such that the channel time is equally shared by all the stations, independently of their transmitting bit rate. We then propose two approaches for throughput allocation that are based on this result.

Following Section 3, our goal for achieving proportional fairness is to find the configuration that leads to

$$max\left(\sum_{i=1}^{n} log(r_i)\right) \tag{18}$$

where r_i is the throughput allocated to station i.

The above constitutes an unconstrained optimization problem the solution of which can be derived from

$$\frac{\partial}{\partial \tau_j}\left(\sum_{i=1}^{n} log(r_i)\right) = 0 \quad \forall j \tag{19}$$

From Eq. (6) we have that r_i can be expressed as

$$r_i = \frac{p_{s,i} l}{E(T_{slot})} \tag{20}$$

where $E(T_{slot})$ is the expected duration of a slot time and l is the transmission length, which we take constant for all stations. Specifically, we take $l = l_{default}$, where $l_{default}$ is the transmission length used when all the stations transmit at the nominal bit rate.

Substituting the above into Eq. (19) and performing the derivative yields

$$\left(\frac{1}{\tau_j} - \sum_{i\in\{1,\ldots,n\}\setminus j} \frac{1}{1-\tau_i}\right) E(T_{slot}) - n\frac{\partial E(T_{slot})}{\partial \tau_j} = 0 \quad \forall j \tag{21}$$

where n is the total number of stations in the WLAN.

For $\tau_i \ll 1\ \forall i$ we can approximate the above by[8]

$$E(T_{slot}) - n\tau_j \frac{\partial E(T_{slot})}{\partial \tau_j} = 0\ \forall j \tag{22}$$

Taking the kth equation of the above system for some k, and adding it to the jth equation for all $j \neq k$, gives us the following necessary condition for the proportional fair allocation

$$n\tau_j \frac{\partial E(T_{slot})}{\partial \tau_j} - n\tau_k \frac{\partial E(T_{slot})}{\partial \tau_k} = 0 \quad \forall j \neq k \tag{23}$$

If we neglect the collisions of more than two stations, $E(T_{slot})$ can be expressed as

$$\begin{aligned} E(T_{slot}) = {} & \sum_{i=1}^{n} \tau_i \prod_{j\in\{1,\ldots,n\}\setminus i} (1-\tau_j) T_s^i \\ & + \prod_{i=1}^{n}(1-\tau_i)\sigma + \sum_{i=1}^{n}\sum_{j=i+1}^{n} \tau_i\tau_j \\ & \prod_{k\in\{1,\ldots,n\}\setminus i,j} (1-\tau_k) T_c^{i,j} \end{aligned} \tag{24}$$

[8] Note that the assumption $\tau_i \ll 1$ is reasonable, as large τ_i values would lead to a high collision probability and hence to an inefficient utilization of the WLAN bandwidth.

where $T_c^{i,j}$ is the duration of a collision between stations i and j.

If we neglect the terms of τ_i of order 2 and higher, $E(T_{slot})$ can be approximated by

$$E(T_{slot}) \approx \sum_{i=1}^{n} \tau_i T_s^i + \left(1 - \sum_{i=1}^{n} \tau_i\right) \sigma \tag{25}$$

Then,

$$\frac{\partial E(T_{slot})}{\partial \tau_i} = T_s^i - \sigma \approx T_s^i \tag{26}$$

Finally, substituting the above into Eq. (23) yields

$$\frac{\tau_i}{\tau_j} = \frac{T_s^j}{T_s^i} \tag{27}$$

which is approximately equivalent to

$$\frac{r_i}{r_j} = \frac{T_s^j}{T_s^i} \tag{28}$$

We conclude the above ratio among the allocated throughputs is a necessary condition for proportional fairness. This is the basis of the two alternative approaches we propose next.

Note that the above condition implies that the rate of successful transmissions experienced by a station is inversely proportional to their average duration. This leads to all stations receiving the same share of channel time.

5.1. Centralized approach

Our centralized approach requires a centralized entity, which we call the *Configuration Server*,[9] that needs to keep track, somehow, of the number of active stations in the WLAN and their bit rate. This can be achieved either by explicit signaling from the stations,[10] or by monitoring all channel transmissions in the WLAN to see which stations are actively sending at a given point in time (or within a certain time window) and their transmission rate[11]. The Configuration Server uses this information to compute the WLAN configuration (i.e. the CW_{min}^i and CW_{max}^i of each station), and then conveys the computed parameters to the stations.[12] Figure 7 illustrates these steps for the explicit signaling case.

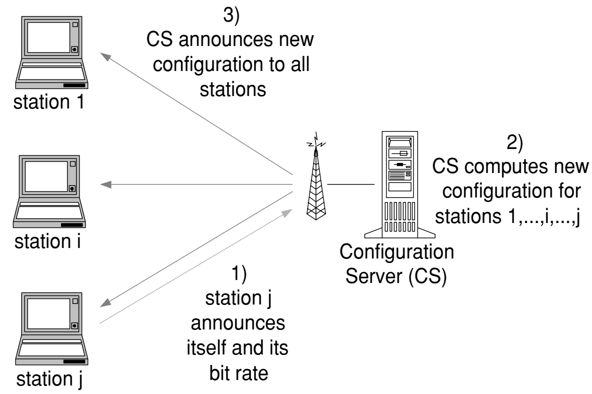

Fig. 7 Centralized approach message exchange

The remaining challenge for the above architecture is the computation by the Configuration Server of the CW_{min}^i and CW_{max}^i of all stations. Specifically, the goal is to compute these parameters such that the resulting allocation leads to

$$max\left(\sum_{i=1}^{n} log(r_i)\right) \tag{29}$$

With the restriction imposed by Eq. (28) we have

$$r_i = \frac{1/T_s^i}{\sum_{j=1}^{n} 1/T_s^j} r \tag{30}$$

where r is the total throughput in the WLAN.

With the above, and applying the product property of logarithms, our objective can be reformulated so as to maximize

$$\sum_{i=1}^{n} log\left(\frac{1/T_s^i}{\sum_{j=1}^{n} 1/T_s^j}\right) + \sum_{i=1}^{n} log(r) \tag{31}$$

subject to the condition of Eq. (28), which is equivalent to maximizing r subject to this condition.[13]

r can be expressed as

$$r = \frac{p_s l}{p_s T_s + p_c T_c + p_e \sigma} \tag{32}$$

[9] The Configuration Server could be located e.g. at the Access Point (AP).

[10] The upcoming 802.11e standard [5] considers a similar type of signaling from the stations to a centralized entity in its admission control functionality.

[11] A number of works in the literature propose algorithms to estimate the number of stations in a WLAN using only local information (see e.g. [21] and [22]). We note, however, that these algorithms cannot be used in our case, because (1) they assume that all stations have the same configuration (which does not hold in our approach), and (2) we not only require knowing the number of stations in the WLAN but also their bit rates.

[12] The upcoming 802.11e standard [5] specifies the signaling required to announce the WLAN configuration to the stations.

[13] In [17] we solve a similar problem for the case in which all stations transmit at the same bit rate.

From Eq. (27), we can express τ_i as a function of the τ of station 1, τ_1 (which we take as reference)

$$\tau_i = \frac{T_s^1}{T_s^i}\tau_1 = w_i \tau_1 \tag{33}$$

where we define w_i as T_s^1/T_s^i.

Substituting the above into Eq. (32) and assuming $\tau_1 \ll 1$, we can approximate r by

$$r \approx \frac{a\tau_1 - b\tau_1^2}{c\tau_1 + d} \tag{34}$$

with

$$a = \sum_{i=1}^{n} w_i \tag{35}$$

$$b = \sum_{i=1}^{n} \sum_{j \in \{i+1,\ldots,n\}} w_i w_j \tag{36}$$

$$c = \sum_{i=1}^{n} w_i \left(T_s^i - \sigma\right) \tag{37}$$

and

$$d = \sigma \tag{38}$$

The optimal τ_1, τ_1^*, that maximizes r can then be obtained by

$$\left.\frac{dr}{d\tau_1}\right|_{\tau_1=\tau_1^*} = 0$$

$$\Rightarrow bc\left(\tau_1^*\right)^2 + 2bd\tau_1^* - ad = 0$$

$$\Rightarrow \tau_1^* = \frac{\sqrt{(bd)^2 + abcd} - bd}{bc} \tag{39}$$

from which, following Eq. (33), the optimal τ_i of the remaining stations, τ_i^*, can be computed as $\tau_i^* = w_i \tau_1^*$.

The remaining step is to compute the CW_{min}^i and CW_{max}^i parameters that lead to these τ_i^* values. In DCF, after each unsuccessful transmission, the CW is doubled in order to reduce the probability of a new collision. However, this is not necessary in our centralized approach, since the Configuration Server can compute the CW values such that the resulting collision probability corresponds to optimal operation. Therefore, in the centralized approach we set $CW_{min}^i = CW_{max}^i$, i.e. $m_i = 0$. Then, Eq. (4) is simplified to

$$\tau_i = \frac{2}{1 + CW_i} \tag{40}$$

where $CW_i = CW_{min}^i = CW_{max}^i$.

Finally, isolating CW_i from the above, and accounting for the fact that contention windows must take integer values, we compute the optimal CW_i configuration, CW_i^*, as

$$CW_i^* = \text{round int}\left(\frac{2}{\tau_i^*} - 1\right) \tag{41}$$

Our centralized approach is based on configuring the WLAN stations with $CW_{min}^i = CW_{max}^i = CW_i^*$. We note that the computation of the CW_i^* values is very efficient, as it can be performed with a few basic (addition, product, square root) operations.

5.2. Distributed approach

The requirement of the centralized approach that the Configuration Server knows the number of active stations and their bit rates adds a significant level of complexity to the implementation. In this section we propose an alternative approach that avoids such complexity, at the price of a less optimized performance.

In our distributed approach, each station *i* sets its CW configuration (CW_{min}^i, CW_{max}^i) based only on local information, namely, the station's bit rate.

As the global WLAN information (i.e. the number of stations and their bit rates) is not available, the CW values cannot be adjusted such that the collision probability corresponds to optimal operation; therefore, we choose CW_{max}^i larger than CW_{min}^i, so that after a collision the CW is doubled, reducing the probability of a new collision. This binary exponential increase scheme ensures that the collision probability is kept low, and thus avoids wasting too much bandwidth on collisions. Following this reasoning, in our distributed approach we set $m_i = 5$ for all stations.

For the 11 Mbps bit rate stations, we choose the default CW_{min} value of 802.11b, i.e. $CW_{min}^{11Mbps} = 32$. If we assume the same collision probability for all stations, the throughput received by a station will be approximately inversely proportional to its CW_{min}^i. Then, in order to comply with the condition of Eq. (28), we set the CW_{min}^i of the remaining stations according to

$$CW_{min}^i = \frac{T_s^i}{T_s^{11Mbps}} CW_{min}^{11Mbps} \tag{42}$$

The above constitutes the configuration of the CW scheme for our distributed approach.

6. TL scheme configuration

We next address the configuration of the TL scheme to provide proportional fairness. Specifically, our goal is to find the transmission length values l_i that maximize $\sum_i log(r_i)$.

This is an unconstrained optimization problem the solution of which can be derived from

$$\frac{\partial}{\partial l_j}\left(\sum_{i=1}^{n} log(r_i)\right) = 0 \quad \forall j \tag{43}$$

From the above it follows,

$$\frac{1}{r_j}\frac{\partial r_j}{\partial l_j} + \sum_{i\in\{1,\ldots,n\}\setminus j} \frac{1}{r_i}\frac{\partial r_i}{\partial l_j} = 0 \quad \forall_j \tag{44}$$

r_i can be expressed as

$$r_i = \frac{p_{s,i} l_i}{E(T_{slot})} \tag{45}$$

which yields

$$\frac{\partial r_j}{\partial l_j} = \frac{p_{s,j} E(T_{slot}) - p_{s,j} l_j \frac{\partial E(T_{slot})}{\partial l_j}}{E(T_{slot})^2} \tag{46}$$

and

$$\frac{\partial r_i}{\partial l_j} = -\frac{p_{s,i} l_i}{E(T_{slot})^2}\frac{\partial E(T_{slot})}{\partial l_i} \tag{47}$$

$E(T_{slot})$ can be expressed as

$$E(T_{slot}) = \sum_{i=1}^{n} p_{s,i} T_s^i + p_c T_c + p_e T_e \tag{48}$$

where

$$T_{s,i} = K + \frac{l_i}{R_i} \tag{49}$$

where K is a constant term (see Eq. (14)).

Taking into account the above relationship between $T_{s,i}$ and l_i, and neglecting the term $p_c T_c$ of Eq. (48),[14] it follows

$$\frac{\partial E(T_{slot})}{\partial l_j} = \frac{p_{s,i}}{R_i} \tag{50}$$

Substituting Eqs. (46)–(50) into Eq. (44) we obtain

$$\frac{1}{r_j}E(T_{slot}) - \frac{1}{R_j}\sum_{\forall i}\frac{1}{r_i} p_{s,i} l_i = 0 \quad \forall j \tag{51}$$

[14] This approximation is analogous to the one of Section 5. In fact, for $\tau_i \ll 1$ the probability of collision is small and therefore this term can be neglected.

which yields

$$\frac{r_j}{R_j} = \frac{E(T_{slot})}{p_s \sum \frac{l_i}{r_i}} \quad \forall j \tag{52}$$

Since the right hand side of the above equation is a constant, it follows that one necessary condition for the optimal configuration is

$$\frac{r_i}{R_i} = \frac{r_j}{R_j} \quad \forall i, j \tag{53}$$

Since with the TL scheme the same CW configuration is taken for all stations, we have $p_{s,i} = p_{s,j}\ \forall i, j$, which, combined with Eq. (45), leads to

$$\frac{l_i}{l_j} = \frac{R_i}{R_j} \quad \forall i, j \tag{54}$$

Note that the above condition implies that the length of the transmissions of a station is inversely proportionally to the station's bit rate. This leads to all stations receiving approximately the same share of channel time. It is interesting to observe that we had reached the same conclusion in the analysis of the CW scheme configuration.

With the above, if the transmission length of a reference station is known, the transmission length of the other stations can be derived. However, the issue of fixing the transmission length of all the stations is still not closed.

Note that the choice of transmission lengths in WLAN is driven by a tradeoff between delay and throughput performance. Indeed, the longer the transmission length, the lower the overhead for each transmitted bit, which leads to better throughput performance. On the other hand, if stations hold the channel for a longer period every time they transmit, they incur larger delays on the packets awaiting transmission in other stations.

Taking into account the above consideration, we proceed as follows to set the transmission lengths. We consider that, when all the stations transmit at the nominal bit rate of 11 Mbps, their transmission length is set to a value, $l_{default}$, that provides an optimal tradeoff between throughput and delay performance. Our aim is to maintain this tradeoff when some stations decrease their bit rate. To achieve this, we keep the transmission length of 11 Mbps stations at the default value, while we set the transmission length of the other stations (following Eq. (54)) equal to $l_{default} R_i / 11 Mbps$. Note that, with this transmission length, the transmissions of the lower bit rate stations occupy the channel for the same period length as the 11 Mbps stations, and therefore delay performance is not degraded.

The remaining open issue is the configuration of the CW parameters. With the TL scheme we have that the CW_{min} and

CW_{max} parameters are set to the same values for all stations. To fix these values, we consider two approaches (like with the CW scheme): a distributed one and a centralized one. With the distributed approach, we set the CW_{min} and CW_{max} parameters of all the stations to their default values given by the 802.11b standard. With the centralized approach, we set them to their optimal value according to the formulae given in Section V-A, with $w_i = 1$ and $T_s^i = T_s \ \forall i$.

7. Performance evaluation

In this section we evaluate the performance of the four approaches proposed in this paper: CW distributed, CW centralized, TL distributed and TL centralized. We first study the throughput performance resulting from these four approaches and compare them against DCF. Next, we evaluate the delay performance of the approaches as compared to the case when all stations transmit at the nominal bit rate. Finally, we study whether there exists any configuration of the TL and CW schemes (or a combination of both) that outperforms our centralized approaches.

The performance evaluation results presented here are based on the analytical model of Section 4 for the CW and TL schemes, while simulations are not used. In fact, experiments VII-D and VII-E could not have been performed via simulation as this would have been practically unfeasible from a simulation time viewpoint. We argue that, as our model provides almost identical results to simulations, using analytical or simulation methods to evaluate performance will lead to very similar results. Both for the CW and TL schemes, the value of $l_{default}$ used is 1500 bytes. Average delays are obtained from the analysis of Section 4 following [23].

7.1. Throughput allocation

To illustrate the effect of the throughput allocation we propose, we repeat the experiment of Fig. 2 for the CW centralized approach (c), the CW distributed approach (d), the TL centralized approach (e) and the TL distributed approach (f). The results are shown in Fig. 8. We can observe that the four approaches proposed (c)–(f) provide roughly the same allocation. With all of them, fast stations are not significantly harmed with respect to the scenario in which all stations transmit at the nominal bit rate (a), in contrast to DCF (b). We conclude that with a proportional fair allocation, when a station decreases its transmission rate only the station's throughput is degraded, while the other stations keep approximately their original throughput. This holds independently of the mechanism used to provide proportional fairness.

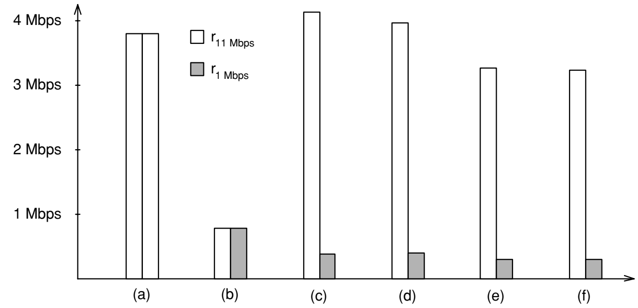

Fig. 8 Throughput allocation for different approaches

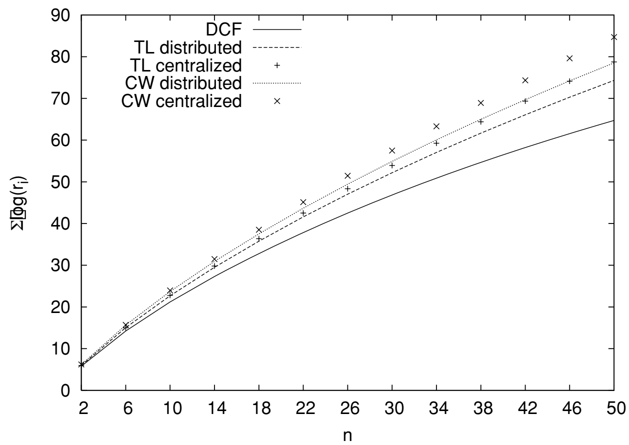

Fig. 9 Throughput performance evaluation, 2 bit rates

7.2. Throughput performance

From the definition of proportional fairness, it follows the performance of a throughput allocation is measured in terms of its $\sum_i log(r_i)$: the greater this value, the better the allocation. Accordingly, in the following we base our performance studies of throughput on this metric.

Figure 9 depicts the performance of the four approaches as a function of the total number of stations in the WLAN (n), when half of the stations transmit at 1 Mbps and the other half at 11 Mbps. The performance of these approaches is compared against DCF in order to evaluate the improvement resulting from the schemes and configurations proposed.

We can observe from the figure that all the approaches substantially outperform DCF. This shows the benefit derived from using the proposed schemes. Results also show that the centralized approaches perform better than the distributed ones. This is an expectable result since centralized configurations are computed taking into account additional data which allows an improved performance at the price of an increased complexity.

Another observation from Fig. 9 is that the centralized and distributed configurations of the CW scheme perform better in terms of throughput than the respective configurations of the TL scheme. These results, however, need to be contrasted

Table 2 Throughput performance evaluation, 4 bit rates, 5 stations per group

Approach	DCF	CW centralized	CW distributed	TL centralized	TL distributed
r_{11Mbps}(Kbps)	71.68	400.65	357.74	328.52	293.61
(CW_{min}, CW_{max})	(32,1024)	(213,213)	(32,1024)	(383,383)	(32,1024)
l (bytes)	1500	1500	1500	1500	1500
$r_{5.5Mbps}$ (Kbps)	71.68	201.27	185.34	164.26	146.81
(CW_{min}, CW_{max})	(32,1024)	(424,424)	(58,1856)	(383,383)	(32,1024)
l (bytes)	1500	1500	1500	750	750
r_{2Mbps} (Kbps)	71.68	78.01	70.17	59.79	53.44
(CW_{min}, CW_{max})	(32,1024)	(1094,1094)	(150,4800)	(383,383)	(32,1024)
l (bytes)	1500	1500	1500	273	273
r_{1Mpbs} (Kpbs)	71.68	42.90	35.09	29.79	26.62
(CW_{min}, CW_{max})	(32,1024)	(1989,1989)	(298,9536)	(383,383)	(32,1024)
l (bytes)	1500	1500	1500	136	136
$\sum_i log(r_i)$	37.11	42.16	41.06	39.91	38.94

against delay performance. A comparison of the CW and TL schemes that accounts for both throughput and delay is given in the following section.

Note that the distributed approaches perform almost as well as the centralized ones for small n, but worse when n increases. The reason for the decrease in performance is that the CW^i_{min} values chosen for the distributed approaches ($CW^i_{min} = 32$ for the TL scheme and $CW^i_{min} = 32T^i_s / T_s^{11Mbps}$ for the CW) are well adjusted for n small, but not for n large. DCF suffers from the same problem, which is inherently due to having the CW_{min} values statically set. A number of algorithms that adapt the CW based only on local information have been proposed to deal with this problem in DCF (see e.g. [19, 24, 25]); these algorithms could be adapted to our distributed approaches to improve its performance.

Table 2 shows the individual throughputs, configurations and $\sum_i log(r_i)$, when the channel is shared by 4 groups of 5 stations, the stations of each group transmitting at a different bit rate (1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps). Results lead to the same conclusions as those derived above for 2 different bit rates.

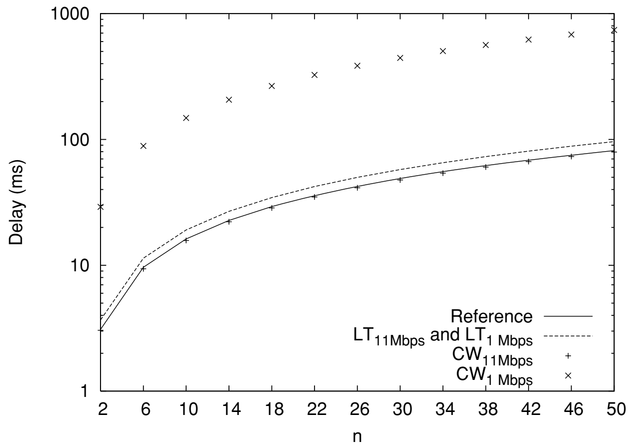

Fig. 10 Delay performance, centralized approaches

7.3. Delay performance

We next evaluate the performance of the approaches proposed in terms of delay. Following the considerations of Section 6, we take as reference (and compare our results against) the case when all the stations transmit at the nominal bit rate.

We first concentrate on the delay performance of the TL and CW centralized approaches. Figure 10 gives the delay results for the scenario of Fig. 9. Note that with the CW scheme, 1 Mbps and 11 Mbps stations experience different delays, while they experience the same delay with the TL scheme. The results are compared against the delay corresponding to the reference case, i.e. when all the stations transmit at the nominal rate.

We observe from the results that with the TL centralized scheme our goal (stated in Section 4) of not degrading the delay performance of the reference case is achieved. Indeed, with this scheme the delay experienced by both 1 Mbps and 11 Mbps stations (dotted line) is approximately equal to the delay of the reference case (straight line).

If we look at the delay behavior of the CW centralized approach, we find substantial differences. 11 Mbps stations experience a delay performance similar to the performance of the reference case. However, 1 Mbps stations suffer a considerable degradation. In particular, their delay is about 10 times higher.

From the above, we can see that, when some station in the WLAN reduces its bit rate from 11 Mbps to a lower rate, with the CW scheme both the throughput and the delay experienced by this station are degraded, while the other stations maintain (approximately) their original throughput

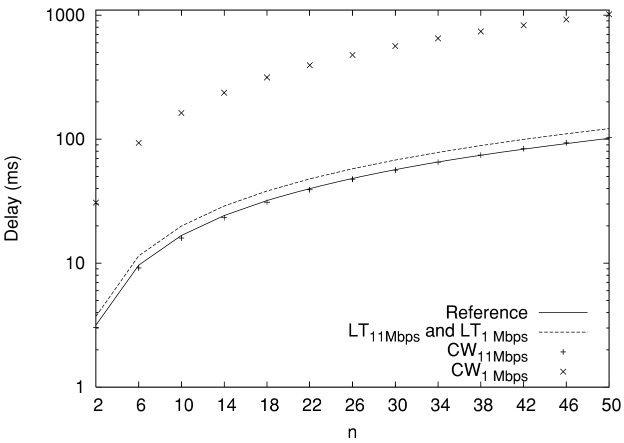

Fig. 11 Delay performance, distributed approaches

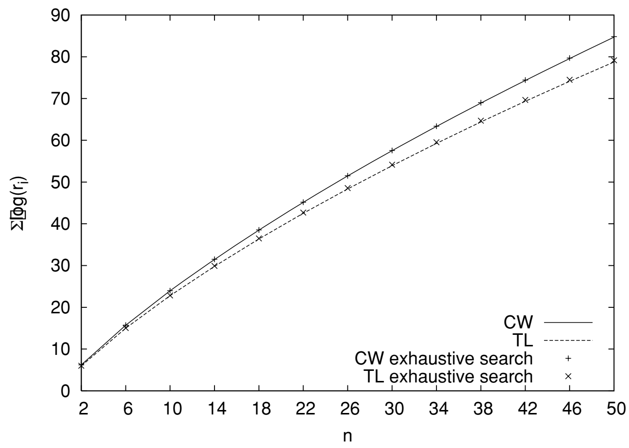

Fig. 12 Performance against exhaustive search

and delay performance. In contrast, the TL scheme degrades only the throughput of the station, and maintains the delay performance of *all* the stations (including the one that has decreased its bit rate). The price that the TL scheme pays for this is a lower overall throughput performance, as illustrated in the previous section.

From the above comparison between the TL and the CW schemes, we conclude that there is no clear winner among the two shemes. If we want to keep the delay of all stations to the reference value even when the throughput of some stations is decreased, this behavior is provided by the TL scheme. On the other hand, if we can accept that a station that sees its bit rate decreased sees not only its throughput but also its delay degraded, and want to preserve only the delay performance of the other stations, then the CW scheme is the better option, as it complies with these conditions and leads to a better throughput performance.

Figure 11 illustrates the delay performance of the CW and TL distributed approaches, compared against the reference case. We can observe that results follow the same trend as for the centralized case.

7.4. Optimality of the centralized configurations

The centralized approaches aim at finding the optimal configuration that provides the best possible performance. In order to understand if configurations better than the proposed ones exist, in this section we compare the performance of our approaches against the result of an exhaustive search over all possible configurations. Specifically, we perform a search over the entire configuration space (sweeping along the parameters of all the stations) and choose the configuration that provides the best performance. Note that this method is unfeasible for practical use, as it requires too much computational time and resources to find the optimal configuration; our intent here is rather to use it as a benchmark against which to assess the performance of our approaches.

First, for the CW approach we perform an exhaustive search over the CW^i_{min} and CW^i_{max} parameters of all stations and take the configuration that provides the best throughput performance (i.e. the greatest $\sum_i log(r_i)$) subject to the condition that the delay performance of the 11 Mbps stations is not degraded. Note that this condition ensures that the exhaustive search meets the objective of the CW scheme of maintaining the reference case delay performance for the 11 Mbps stations.[15]

Similarly, for the TL approach we perform an exhaustive search over the l_i, CW_{min} and CW_{max} parameters (the latter two set to the same value for all stations) and take the configuration that provides the best throughput performance subject to the condition that the delay performance of all stations is not degraded. This condition ensures that the objective of the TL scheme of maintaining the reference case delay performance for all stations is met by the exhaustive search.

Figure 12 shows the result of comparing the TL and CW centralized approaches ('CW' and 'TL') against the above exhaustive searches ('CW exhaustive search' and 'TL exhaustive search'). The results validate our optimal configurations. Indeed, they show that there exists no configuration of the CW and TL schemes that, while meeting the respective goals regarding delay performance, provides (significantly) better performance than our centralized configurations.

7.5. Combination of the CW and TL schemes

One of the restrictions upon which our work is based is that throughput differentiation is achieved by assigning either different CW's (the CW scheme) or different l_i's (the

[15] Specifically, the condition we impose in the exhaustive search is that delay of the 11 Mbps stations is not degraded as compared to the CW scheme. This condition ensures that the CW scheme and the exhaustive search meet the objective of maintaining the reference case delay performance for the 11 Mbps stations to the same degree.

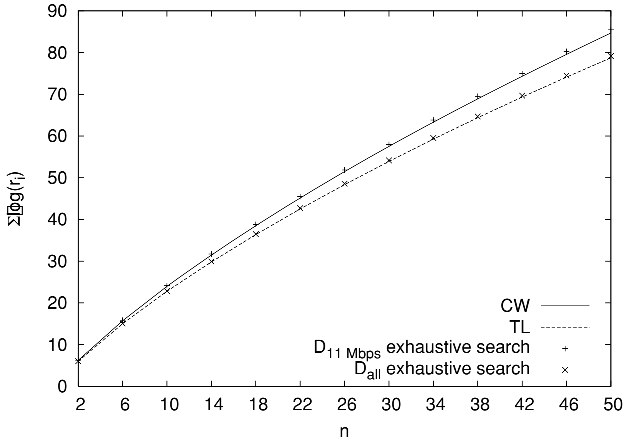

Fig. 13 Performance against combined CW-TL scheme

TL scheme) to different stations, but never both at the same time. In this clause we study if better performance could be achieved by combining both schemes, i.e. by assigning both different CW's and different l_i's to different stations.

In order to address the above issue, we proceed as follows. We perform an exhaustive search over all the parameters (CW^i_{min}, CW^i_{max} and l_i) of all stations subject to the delay performance objectives identified in Section 7.3: 1) the delay performance of the 11 Mbps stations shall not be degraded, and 2) the delay performance of all stations shall not be degraded.

Figure 13 illustrates the result of comparing the TL and CW centralized approaches ('CW' and 'TL') against the result of these exhaustive searches ('D_{11Mbps} exhaustive search' and 'D_{all} exhaustive search'). The results show that there exist no better configurations than the CW and TL ones in order to achieve the respective delay objectives.

From the above experiments, we conclude that, depending on the desired behavior with respect to delay, either the CW or the TL scheme should be used, and that the resulting performance cannot be (significantly) outperformed while satisfying the desired delay behavior, neither with a different configuration of the two schemes nor with a combination of both.

8. Conclusions

In this paper, we proposed a new paradigm for throughput allocation in WLAN; specifically, we advocated proportional fairness to deal with the fairness issue that arises under heterogeneous radio conditions. It is interesting to observe that based on intuition, other papers reached similar allocations to the one resulting from applying the proportional fairness criterion.

We proposed two schemes for this purpose, the Contention Window (CW) and the Transmission Length (TL) schemes. For both schemes, we proposed a centralized and a distributed configuration. The aim of the centralized approach is to achieve a more optimized performance at the cost of an increased complexity, while the distributed one involves minimal complexity.

We evaluated the four approaches proposed in terms of throughput and delay performance. Throughput performance was assessed according to the definition of proportional fairness. Delay performance was assessed against the reference scenario in which all stations transmit at the nominal bit rate. The performance evaluation was based on our analytical model, which, in turn, was validated via simulation.

Results showed that both the CW and TL schemes substantially outperform the legacy DCF. From the comparison of the CW scheme against the TL one there was no clear winner. Instead, results showed the two schemes respond to different delay paradigms. While with the TL scheme the delay of all stations is kept to the reference value when some stations decrease their bit rate, with the CW it is only the 11 Mbps stations that see their delay performance maintained. We concluded that the decision of using one or the other scheme depends on the preferred behavior with respect to delay.

In order to validate the optimal configuration computations performed for the centralized approaches, we compared them against the result of performing an exhaustive search over all possible configurations. Results validated the centralized configurations as they performed very closely to the "real" optimal derived from the exhaustive search.

The starting point of this paper was that different stations could be configured either with a different contention window or with a different transmission length, but not with both simultaneously. In order to assess whether a combination would result in an improved performance, we performed an exhaustive search over the two parameters. Results showed that, while meeting the respective delay objectives, the performance of the two schemes proposed in this paper cannot be improved by any combination.

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