Fairness Characterization in Contemporary IEEE 802.11 Deployments with Saturated Traffic Load

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***Abstract*—This paper studies a widely used wireless technology (IEEE 802.11-2014) and the simulation establishment of the efficient Wireless Local Area Network (WLAN) in modern environment. However, currently used saturation based analysis may be applied only for fair systems, hence, the question arises which system may be considered as fair. Mostly used metric for such an analysis (Jain's Fairness Index) does not apply for 802.11-2014 standard in a particular case of a small number of users. So, we propose a novel metric to define fairness.**

I. INTRODUCTION

The technology currently wide distributed and based on IEEE 802.11 standard [1], a.k.a WiFi, enables high-speed wireless connectivity in an unlicensed band. It took its place mainly due to low costs, simple access protocols and wide implementation. Additionally, the current standard is improved by its early versions [2], [3], [4].

However, currently used saturated analytical models based on well known Bianchi's work [5] stand only for a fair system analysis with the definition that all the users obtain the same amount of channel resources during the system operation. Unfortunately, 802.11 protocol interacts in such a way that one user may take over the channel for a long time, whereas other users might stay in backoff during a collision resolving procedure. However, as proposed analysis is assumed as applicable for a fair system its definition should be reconsidered.

Moreover, many groups all over the world are currently working on the improvement of such a technology so it seems that WLAN performance analysis in addition to simulation based tools are highly required nowadays. The previous research [6] has already focused on the fair system analysis, as well as it implements calibration with Bianchi's results in the context of WiFi technology. In this paper, we use modern WLAN specification and simulate both *lossy* and *lossless* systems to analyze the influence of the proposed metric to system throughput and delay outcomes. Accounting the transmission attempt vector (order of the attempts by users), we arrive at an improved approach, extending the previous model, and verifying it with extensive simulations.

II. SYSTEM MODEL

A WLAN deployment of M stationary users in a cluster with one Access Point (AP) is assumed. Moreover, we propose that all the users are synchronized, use the same channel to communicate, there are no hidden terminals, the channel is noise free, every user have a saturated queue (full buffer) with a packet ready for transmission and an unlicensed band based on 802.11-2014 is used. However, we focus on the uplink and during the transmission from a single user to AP there may appear three events: *Collision* - when there are two or more simultaneously transmitting users at the same *slot*; *Success* - when the transmission is performed exactly by one user; *Idle* - if there are no currently transmitting users. Furthermore, a saturated model offers us to analyze a *worst* situation [7] and allows to obtain a Saturation Throughput S.

Collision resolution process in 802.11-2014 is based on the Binary Exponential Backoff (BEB) algorithm which was widely studied in numerous works [8],[9]. Somehow, our implementation of this protocol takes in account that every user has a Retransmission Counter (RC), that is decremented by one every time a packet transmission fails. In case if counter reaches zero, a packet is considered as *discarded* by the user to stabilize system actuality and decrease its load. After a packet is discarded or sent successfully, the counter is set to its initial value K.

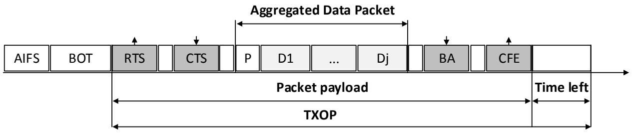

Fig. 1. RTS/CTS channel access mechanism

In this paper we account an Request-To-Send / Clear-To-Send (RTS/CTS) access mechanism mainly relied on the wide use in modern WLAN deployments because of the packet aggregation [10]. This RTS/CTS mechanism shown in Fig. 1 has an implementation of 4-way handshake, which is supported by the data packet(s) exchanging procedure, the communicating users (or AP and a user in a classical model) can capture the channel for the whole needed transmission time with the use of RTS and CTS frames. Anyhow, it complements to a packet of data (or a group of packets) which is sent after Arbitration Inter-Frame Spacing (AIFS) and the random BackOff Time

(BOT). Based on our assumption of the noiseless channel, a collision may appear only during RTS/CTS frames. On the other hand, if data was successfully transmitted it is followed by Block Acknowledgment (BA), and Contention-Free End (CFE) frame. Anyway, total transmission time for a user might apply to the Transmit Opportunity (TXOP) duration with RTS/CTS frames, aggregated data duration, required Short Inter-Frame Spacings (SIFSs) and BA. CFE frame may be sent to release the unused TXOP time.

According to 802.11-2014 standard, for a specific user a Backoff Counter (BC) value uniformly chosen in the range between 0 and $W_0 - 1$, where W_i is the supposed to be called Contention Window (CW). After each idle slot the BC is decremented by one. If it reaches zero, the user tries to start his transmission. However, if there were more than one user attempting to transmit at the same slot, a collision would be detected at the AP, thus there would appear a need for them to retransmit if RC would allow to do it. In that case, CW value would be multiplied by two ($W_i = 2W_{i-1}$) to reduce the chances of future collisions and the BC is sampled again. Anyhow, CW growth is limited by its maximum value (W_{max}). However, a user can continue retransmission attempts if the RC allows him to being not equal to zero. It is also defined during the initialization phase and so-called K. If a packet is either successfully transmitted or discarded, the CW is reset to its initial value W_0, so $W_{max} = 2^m W_0$, where m is the backoff stage.

BEB protocol operation is fully determined by its three parameters: initial backoff window W_0, backoff stage m and retransmission counter K. According to the standard, RC can be selected in two different ways: the Short Retry Limit is chosen to be used in case of the failure that is connected to a collision; the Long Retry Limit if there was an error during data transmission. As noiseless conditions were assumed, the value of the RC only decrements in case of collision. As a result, specific user tries to transmit for at least after AIFS, if the BC is zero and the RC is not equal to zero. So, the saturation throughput calculation seems to be valid and trustworthy for a fair system. Moreover, all the users have aggregated data packets of the same size.

III. SYSTEM DESCRIPTION AND ANALYSIS IMPROVEMENT

In the following, we firstly focus to the lossless system and secondly to the analysis of the lossy one. Based on [5], the system can be observed and described by transmission probability p_t in a slot by a specific user and conditional collision probability p_c which is taking in account that the user was transmitting, which are assumed *constant* during the whole system functioning. However, the system can be analyzed from the point of view of this *marked* user, while all the others are only accounted for through the value of p_c. This assumption may take place only when the system is *fair*. Precisely, when all the users have equal chances to transmit on the channel [11].

The analytical model (see [6]) is based on the concept of a *regeneration cycle* which is presented in Fig. 2, which shows a simplified understanding of the functionality for both lossy ($K \to \infty$) and lossless ($K = const$) systems. Such simplified models with equal slots are time-based scalable and very common to investigate random-access protocols [12]. The expression expression (4) was also estimated in the fundamental work [5]. However, Markov chains based Bianchi's analysis is hardly scalable in contrast to our proposal. This two equations system with two unkowns, p_c and p_t, which can be solved numerically, are required to estimate throughput in saturation scenario.

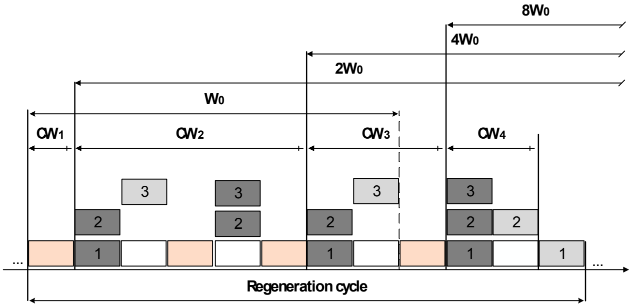

Fig. 2. Explanation of the Regeneration Cycle Concept

$$\begin{cases} p_c = 1 - (1 - p_t)^{M-1} \\ p_t = \frac{2(1-2p_c)}{(1-2p_c)(W_0+1)+p_c W_0(1-(2p_c)^m)} \end{cases} \quad (1)$$

In addition, the main assumption stands for the system to function stable and it is reachable only with some specific parameters. And thus to be analyzed from saturated analysis point of view it should be determined as fair. Since saturation throughput is widely used as a main quality assessment, a fairness index is calculated for those values. Unfortunately, with small initial backoff window W_0 or large numbers of users M, random clients would *capture* the channel resource by obtaining better transmission probability and therefore higher saturation throughput level.

TABLE I. MEDIUM ACESS PARAMETERS

Parameter	Value
Idle slot, σ	9 μs
AIFS	20 μs
SIFS	16 μs
BA	48 μs
RTS	48 μs
CTS	44 μs
CFE	44 μs
Packet size	1500 bytes
Max TXOP duration	1300 μs
MAC header H	244 bits
Data rate	65.0 Mbps
Number of users M	2 to 30
Initial backoff window size W_0	16, $2M + 1$
Backoff stage m	6
Short retry limit K	7,∞
Simulation run duration	70.000 slots

Currently wide used metrics to analyze system's allocation of resources is *Jain's Fairness Index* [13] that can be estimated as:

$$J(P_{s1}, P_{s2}, .., P_{sn}) = \frac{(\sum_{i=1}^{n} P_{si})^2}{n \sum_{i=1}^{n} {P_{si}}^2}, \qquad (2)$$

where P_{si} is a probability that specific i^{th} user would have a successful transmission if he was attempting a transmission in a single slot (which is proportional for user throughput), n is a number of users.

To the surprise, it was established that Jain's Fairness Index does not apply for some specific channel situations as small initial backoff window or small number of users. Such an effect due to the capture effect during the channel access. So, that one user successfully transmits while others start resolving their collisions by increasing contention window and thus their delay[14], [15]. However, this fortunate user stays as a transmitting one repeatedly until another one does not take over the channel.

To gain sight of such a capture effect a novel metrics called Soft Capture Index is proposed. Basically, we are estimating the ratio of the *in a row* transmissions number by all the users to the number of the transmission attempts to estimate system fairness:

$$F_{sc} = \frac{\sum_{i=1}^{n} R_i}{\sum_{i=1}^{n} (S_i + C_i)}, \qquad (3)$$

where R_i is a number of the successful transmissions in a row for i^{th} user, S_i is a number of successful transmissions and C_i is a number of collisions. In that case, we can determine that as R_i increases but transmission attempts number for the system stays the same, so F_{sc} would also show its growth. Thus, we can classify system as unfair even if Jain's Fairness Index tends to one.

IV. NUMERICAL RESULTS

The verification of the purposed approach with currently implemented simulator of the IEEE 802.11-2014 RTS/CTS medium access control mechanism is shown in this section. All the needed parameters to manipulate BEB parameters, channel errors and user congestion can also be setup easily. In our previous paper [6] this tool was precisely calibrated with the results obtained from well-known work [5] (S and P_s). Someway, results are presented in Table II to verify system functionality for the parameters based according to ones implemented in a really existing *ath9k* driver [16], the number of users $M = 30$ and the ratio of $65Mbps$: $W_0 = 16$, $m = 6$, $K = 7$.

TABLE II. ANALYTICAL AND SIMULATION RESULTS

Parameter	Analysis	Simulation
Conditional collision probability, p_c	0.53675	0.51495
Conditional success probability, p_s	0.36714	0.36366
Transmission probability, P_t	0.02532	0.024914

However, during the analytical results validation it was obtained that randomly the simulation successful transmission probability p_s stays much more than the analytical one for a small number of users. Thus there came an notion that the channel medium is shared between users not equally. So, Jain's Fairness Index was calculated based on the formula (2) for different number of users in the system, the results are shown in Fig. 3. Whence, for any number of users and based on the results during all the system function it seems fair.

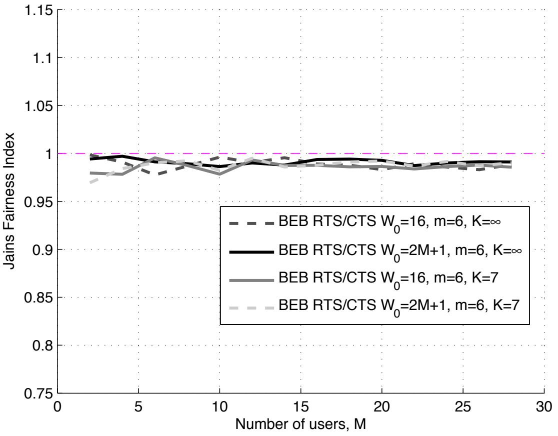

Fig. 3. Jain's Fairness Index estimation

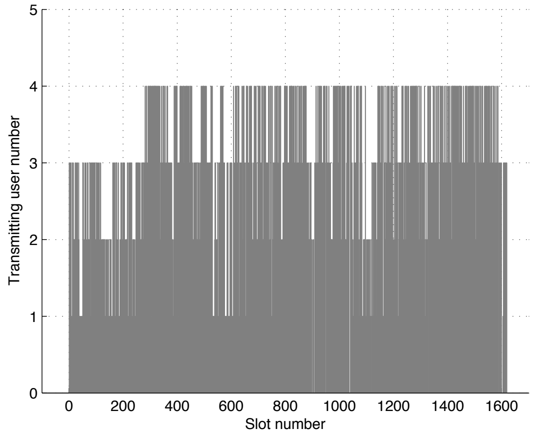

Fig. 4. Transmitting users bar during the simulation

Afterward, we focused on the low number of users $M = 5$ and tracked the order of their channel access. The results of such an observation are shown in Fig. 4. Surprisingly, it is obvious to estimate that a user took over a channel for some period of time and then the baton passed to another one. On the other hand, in this case and for a continuous simulation time all the users obtain almost equal system resources and Jain's Fairness Index can not determine such an unfairness in some concrete period of the simulation. In addition, scenario with an initial contention window chosen as $W_0 = 2M + 1$ is used to analyze optimal parameter setting when a system has static number of users [17], [18].

Additionally, saturation throughput empirical cumulative

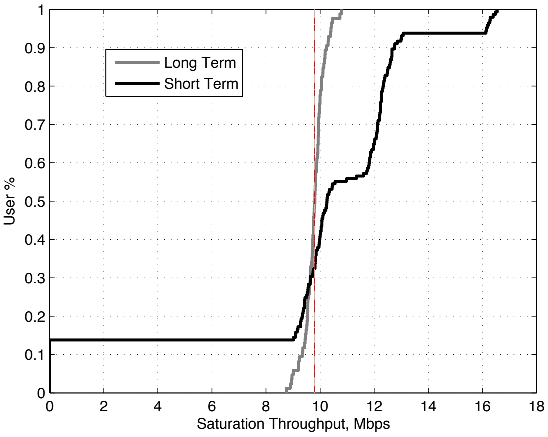

Fig. 5. Saturated Throughput Distribution for $M = 5$

distribution function was calculated for a system with fixed number of users $M = 5$ (see Fig. 4). For this estimation simulations with the same parameters were performed for two simultaneously running processes: when a system functioning case stays fair (*Long Term*) and the opposite one (*Short Term*). However, it is evident that for some cases system stays unfair and it can not be detected mainly because of the simulation duration. Also it is notable, that average saturation throughput is equal and not dependent on system fairness. Moreover, number of successful transmissions for each user during Short and Long Terms shown in Fig. 7) also demonstrates that in average all the users would get almost equal performance results.

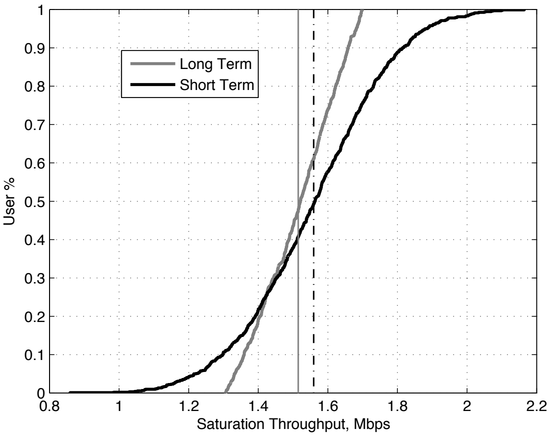

Fig. 6. Saturated Throughput Distribution for $M = 30$

Furthermore, it should be mentioned that for the higher number of users a competition for the channel is more concentrated during all the system functioning time so average channel saturation throughput is more similar for both Short Term and Long Term scenarios (see Fig. 6). Also, it is significant to note that fairness for all the users in a such a system is less efficient which can be captured by Jain's Fairness estimation.

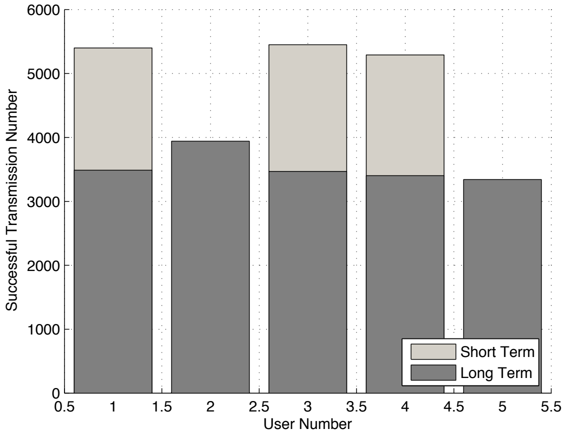

Fig. 7. Number of Successful Transmission for User, $M = 5$

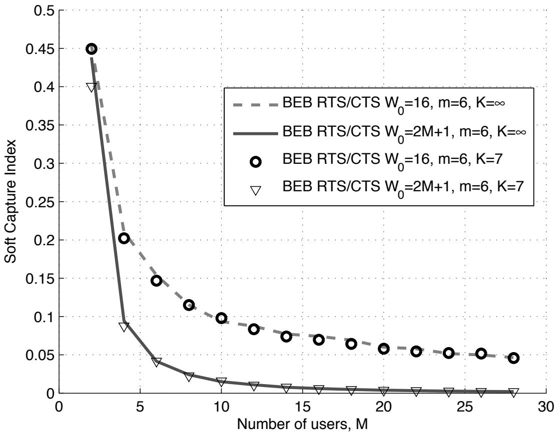

Fig. 8. Soft Fairness Index simulation results for various number of users in the system

To solve a fairness estimation issue for a small number of users, Soft Fairness Index was evaluated and results are shown in Fig. 8. There the phenomenon of the index growth due to repeating capture effect by different users during the simulation process can be observed. We propose our metrics to be used for the time span analysis and estimating system fairness in the conditions of a small number of users (M) on a short initialization contention window (W_0). Moreover, it can detect channel capture even for small number of users in addition to long simulation time. Nevertheless, Soft Fairness Index can improve fairness detection in addition to Jain's Fairness estimation simultaneously. Interestingly, during the Short Term some users did not get an access to the channel at all, but during the Long Term all of them still have almost equal saturation throughput. Entertaining, that the number of *stairs* on the Short Term plot is based on the quantity of users repeatedly taking over the channel during the simulation in different segments.

In addition, the *MAC delay* is also evaluated based on the previous simulation model as follows:

$$\theta = \frac{T_s + T_c + \sigma}{St_i} \tag{4}$$

where T_s is a duration of a successful transmission one, T_c is a duration of a collision (see (5)), σ, accordingly, of an idle slot, St_i is a number of successful transmission for i^{th} user. All the need parameters could be found in Table I. Anyhow, the actual meaning of MAC delay is a time a marked packet stays in a buffer until it is successfully transmitted of discarded.

$$\begin{cases} T_s = RTS + SIFS + CTS + SIFS + \\ \qquad +H + E[P] + SIFS + BA + AIFS \\ T_c = RTS + AIFS \end{cases} \tag{5}$$

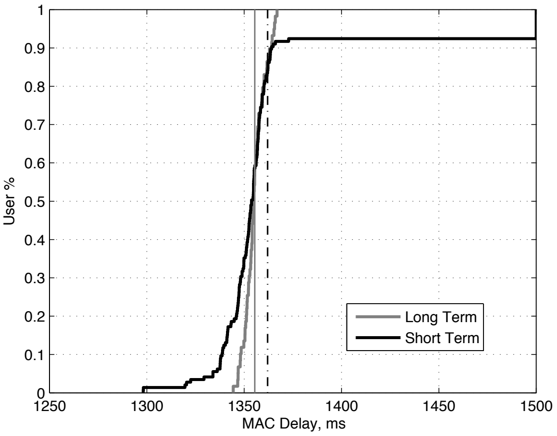

Fig. 9. Channel Access Delay for $M = 5$

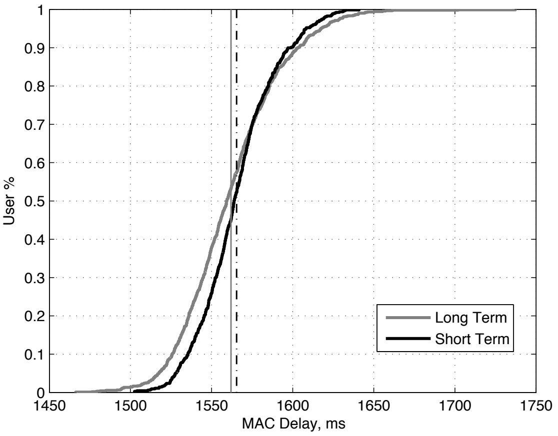

Fig. 10. Channel Access Delay for $M = 30$

However, the results are presented in Fig. 9 and we can observe an effect similar to one shown in Fig. 5. Though, for a small number of users and for a Short Term some abonents basically do not get any access to the channel. In contrast, for the whole system all of the messages in each users buffer have almost equal waiting before discarding or successful transmission time. Besides, delay empirical cumulative distribution function for a large number of users $M = 30$, shown in Fig. 10, results in a way that a small percentage of users might still be served unequal in comparison to the most part of the cluster ones but it would not affect the saturation throughput in general.

V. CONCLUSION AND FUTURE WORK

In general, a combination of an analytical approach supplemented by a calibrated simulator is considered for current version of IEEE 802.11 standard. In particular, the main result of this paper is characterization of fairness criteria and conclusion that the system remains accurate for realistic system settings in a saturated conditions and also followed by the implementation of novel analytical metric to infer is a system is fair or, in other words, applicable for the use of the analytical tool. Which in turn entails that it can be applied for the system with additional knowledge and AP assistance for example as a dynamic BEB parameters distribution based on any metrics fairness. However, a future work is mainly focused on the analysis of the energy efficiency gain in such an assisted fairness deployments in comparison to classical ones, so that may be used for the Internet of Things concept.

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