Characterizing the Effect of Packet Losses in Current WLAN Deployments

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***Abstract*—In this paper, we consider a contemporary short-range technology, IEEE 802.11-2012 a.k.a. WiFi, to enable high-speed wireless communication and thus facilitate ubiquitous Wireless Local Area Network (WLAN) connectivity. In particular, we detail our integrated simulation-analytical framework to characterize full-buffer WLAN deployments revealing the impact of many important performance factors, such as user density, radio channel properties, access protocol settings, and others. By contrast to existing saturated models typically applying Markov chains, our approach is based on regenerative analysis and thus remains scalable even when the number of parameters of interest is large. We specifically emphasize that a user might wish to limit the number of attempts to transmit a single packet and discard packets if the maximum number of retransmissions is reached. Accounting for packet losses, we arrive at a new analytical model, extending the previous models, and verify it with extensive simulations of the current IEEE 802.11-2012 protocol.**

***Keywords*—short-range communications, full-buffer traffic, saturated system, number of retransmissions, packet losses, regenerative analysis, WLAN, IEEE 802.11-2012.**

I. INTRODUCTION AND BACKGROUND

Today, the deployments of Wireless Local Area Networks (WLANs) are nearly ubiquitous. Due to lower equipment costs as well as simpler access protocols, IEEE 802.11 (or WiFi) has become a predominant short-range wireless technology to enable high-speed wireless communication and thus facilitate robust WLAN connectivity in interference-prone unlicensed bands. Building upon a series of successful previous editions, the current WiFi technology standard, IEEE 802.11-2012, offers a rich set of Physical (PHY) layer features supported by advanced Medium Access Control (MAC) mechanisms.

It thus comes as no surprise that performance evaluation of various flavors of WLAN technology constitutes a well-established research area with a wide variety of comprehensive results, ranging from analytical frameworks and associated simulation models, to testbed implementations and field trials. Consequently, many aspects of contemporary WiFi networks have been thoroughly investigated, including expected user quality-of-service (QoS) experience for realistic traffic arrival patterns [1], asymptotic throughput prediction in saturated regime [2], energy efficient operation of battery-driven user devices employing IEEE 802.11 equipment [3], and others. As the result, considerable knowledge has accumulated on the *individual* performance of this popular short-range technology.

However, with increasing demand from mobile network operators to improve the capacity of their existing cellular deployments (by leveraging unlicensed spectrum), current WLANs experience a renewed surge of attention. Indeed, by seamlessly offloading some of the mobile data traffic onto unlicensed-band connections, with and without the involvement of the WiFi infrastructure, significant performance gains are observed in user throughput, energy efficiency, and even MAC transfer delay at no extra cost associated with the deployment of additional network equipment. We have recently addressed the research challenges and related performance benefits of network-assisted traffic offloading onto infrastructureless WiFi links (employing WiFi Direct connectivity) [4] as well as those of leveraging infrastructure-based WLAN deployments (relying on anchor access points) as part of cellular architecture [**?**].

These recent findings confirm the practical benefits of integrating current WLAN connectivity with existing (as well as next-generation) cellular networks and we expect this important trend to continue over the following years. Given that contemporary user devices are already capable of establishing concurrent cellular and WLAN connections, we envision significant network capacity and user connectivity improvements even with moderate degrees of network assistance. Industry is becoming increasingly interested in this topic with several ongoing activities on cellular/WLAN interworking. This should result in higher degrees of control over otherwise uncoordianted WiFi operation employing random-access protocols. However, it also brings potential extra complexity in characterizing evolved IEEE 802.11 technology taking advantage of network assistance and thus dependent on more parameters and factors than ever before.

All the above calls for revisiting the past WiFi performance evaluation models with a target to identify a powerful methodology which would be able to efficiently capture existing and novel parameters of integrated IEEE 802.11 deployments. Even though a plethora of special-case models exists, there is currently a lack of unified frameworks having the potential to scale with respect to the anticipated complexity boost of evolved WLANs. In this work, we detail our integrated simulation-analytical framework to characterize *full-buffer* WLAN deployments thus revealing the impact of many important performance factors, such as user density, radio channel properties, access protocol settings, and others. By contrast to existing saturated models typically applying Markov chains [2], [5], [6], our approach is based on regenerative analysis and thus remains scalable even when the number of parameters of interest is large.

Our previous research in [7] has already focused on investigation of heterogeneity, as well as coexistence between unicast and broadcast traffic, in the context of the legacy WiFi technology. In this paper, we concentrate on the up-to-date WLAN specifications and particularly emphasize that a user might wish to limit the number of attempts to transmit a single packet by discarding packets if the maximum number of retransmissions is reached. Accounting for packet losses, we arrive at a new analytical model, extending the previous models, and verify it with extensive simulations of the current IEEE 802.11-2012 protocol. In Sections II and III, we introduce our system model and then detail the proposed regenerative analysis of the *lossy* WiFi system, respectively. Further, in Section IV, we summarize our numerical results, both for the saturation throughput and the proportion of discarded packets, based on the *calibrated* simulations of IEEE 802.11-2012 technology. We conclude that our model remains very accurate for a wide range of practical protocol settings.

II. Our system model

We consider a static WLAN *cluster* of M users (without any hidden terminals), as shown in Figure 1, residing in unlicensed bands and employing random-access protocol to send their uplink data on the wireless channel. Specifically, a *collision* arises whenever there are two or more users transmitting their packets to the Access Point (AP) in the same *slot* by contrast to *success* when there is exactly one transmitting user (and the channel conditions are favorable) or *idle* if there has been no transmission. All users are assumed to have saturated queues of packets or to have a packet ready for transmission whenever such opportunity arises. Full-buffer traffic allows recreating the conditions of the worst-case load on a WLAN system thus predicting its achievable saturation throughput S.

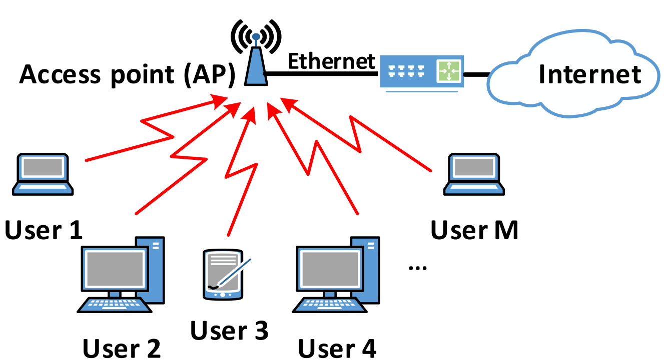

Fig. 1. Considered WLAN topology

According to the IEEE 802.11 standard [?], collision resolution process is based on the so-called Binary Exponential Backoff (BEB) protocol which has been subject to numerous past research works. By contrast to most previous literature, here we account for the fact that every user has a retransmission counter (RC) associated with it. Every time a packet transmission fails (due to a collision, channel noise, etc.), the value of this counter is decremented by one. If the RC reaches zero, the currently transmitted packet is *discarded* by the user (this way, e.g. the maximum MAC transfer time could be controlled). The counter resets to its default value K after a packet discard or its successful transmission, so that it would not affect subsequent packets.

Our model accounts for two alternative channel access mechanisms according to the IEEE 802.11 specifications. In the Basic access scheme (see Figure 2(a)), a data packet or an aggregated block of packets with the same preamble (P) is transmitted immediately after waiting for the specified Arbitration Inter-Frame Spacing (AIFS) time and the random BackOff Time (BOT). Successful packet(s) are acknowledged by a dedicated individual or Block Acknowledgment (BA), depending on whether packet aggregation is enabled. The Request-To-Send / Clear-To-Send (RTS/CTS) access scheme (see Figure 2(b)) employs 4-way handshake when, prior to sending their packet(s), the communicating users implicitly reserve the channel by exchanging two short signaling frames.

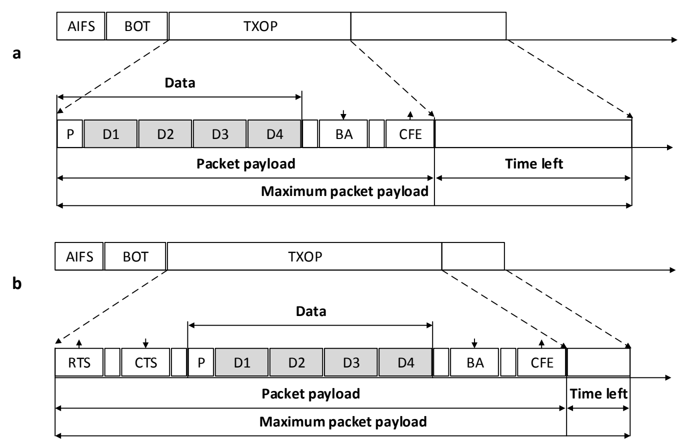

Fig. 2. Basic and RTS/CTS channel access mechanisms

Owing to packet aggregation mechanisms at the PHY layer of IEEE 802.11, the impact of the signaling overhead may be reduced even for higher data rates and thus we consider such aggregation in this work. After aggregation, the overall transmission by a user should not exceed the Transmit Opportunity (TXOP) time including the required Short Inter-Frame Spacings (SIFSs), the acknowledgment, and (optionally) the RTS/CTS frames. If necessary, a user may also release the unused TXOP time by explicitly sending the Contention-Free End (CFE) frame. One important note here is that for longer TXOP values the use of RTS/CTS may be preferred as otherwise the collision could affect the entire aggregated data block.

According to the standard, after the first AIFS time, a Backoff Counter (BC) value is chosen as a uniform random variable in the range between 0 and $W_0 - 1$, where W_i is the so-called Contention Window (CW). The BC is decremented by one after every idle slot (given that AIFS time has elapsed previously). Whenever the BC reaches zero, the corresponding user attempts its transmission (according to Basic or RTS/CTS access scheme). Two or more simultaneously attempting users will produce a collision at the AP and would need to retransmit if their RCs permit it. In case of a retransmission, the value of the CW is doubled ($W_i = 2W_{i-1}$) to reduce the chances of further collisions and the BC is sampled again. However, the growth of the CW is also limited by its maximum value (W_{max}), but the user may still continue its retransmission attempts if the RC is greater than zero. At every packet success or discard, the CW is reset to its initial value W_0. Clearly, $W_{max} = 2^m W_0$, where m is often named the backoff stage.

In summary, the BEB protocol operation is fully determined by its two parameters, the initial backoff window size W_0 and the backoff stage m. Further, the RC value corresponds to the Short Retry Limit (for an RTS packet) or to the Long Retry Limit (for a data packet) as defined by a particular WLAN implementation. Assuming idealistic (noiseless) channel conditions here, the value of the RC only decrements in case of collisions. Hence, a user attempts its packet (RTS frame) transmission if the medium is idle for at least AIFS, the BC is zero, and the RC is non-zero. Consequently, for the RTS/CTS-based channel access, the packet transmission is guaranteed to be successful in our model whenever there has been no RTS collision. This leads to an optimistic estimate of the resulting saturation throughput. Finally, all users are assumed homogeneous by transmitting packets of identical size and using single channel access mechanism (either Basic or RTS/CTS) throughout the entire cluster.

III. Proposed regenerative analysis

In what follows, we detail our approach to the analysis of lossy saturated BEB-operated system described above. As in [2], it is based on two probabilities, transmission probability p_t by a user in a slot and conditional collision probability p_c (conditioning on the fact that the user has transmitted), which are assumed *constant* throughout the system operation. In essence, the consideration of the entire multi-user random-access cluster is thus simplified by concentrating on a single (tagged) user in this system, whereas other users are only accounted for through the value of p_c. Importantly, such replacement is only accurate when the random-access system is *fair*, that is, all the users have (approximately) equal chances to transmit on the channel [8], [9].

However, for smaller initial backoff window sizes W_0 and/or larger numbers of users M, the BEB protocol operation may become unfair and some users could *capture* the channel probabilistically by actually having higher transmission probabilities p_t. Naturally, in a practical WLAN, the backoff parameters W_0 and m should be controlled so that channel access would remain fair. Therefore, we expect our model to be well-suited for real-world WiFi deployments. Similar (but less detailed and powerful) models have already been shown to agree well with field trials and measurements [10].

A. General concepts and lossless system

We base our model, exemplified in Figure 3, on the concept of a *regeneration cycle*. For simplicity, this figure shows equal time slots where every packet transmission attempt is synchronized with the slot borders and takes exactly one slot. Such simplified models are very typical to investigate random-access protocols [11] and could easily scale with respect to the required protocol timings, as we demonstrate later. We note that a typical (tagged) user in this abstract model has the following probability to collide with any other remaining user in a given slot:

$$p_c = 1 - (1 - p_t)^{M-1}. \quad (1)$$

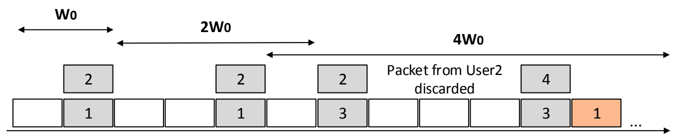

Fig. 3. Simplified example of BEB protocol operation

More interestingly, transmission probability for this tagged user may be obtained as the number of its packet transmission attempts $B^{(i)}$ in a given regeneration cycle i related to the duration of this cycle in slots $D^{(i)}$:

$$p_t = \lim_{n\to\infty} \frac{\sum_{i=1}^{n} B^{(i)}}{\sum_{i=1}^{n} D^{(i)}} = \frac{E[B]}{E[D]}. \quad (2)$$

Firstly, assuming *lossless* system operation ($K \to \infty$) under saturated load, we can easily calculate the value of $B^{(i)}$ as:

$$E[B] = \sum_{i=1}^{\infty} i \Pr\{B = i\} = (1 - p_c) \sum_{i=1}^{\infty} i p_c^{i-1} = \frac{1}{1 - p_c}. \quad (3)$$

For $D^{(i)}$, the corresponding expression can be obtained similarly (see [7] for details):

$$E[D] = \sum_{i=1}^{\infty} D(i) \Pr\{D = i\} = (1 - p_c) \sum_{i=1}^{\infty} D(i) p_c^{i-1}, \quad (4)$$

where $D(i)$ is the length of the regeneration cycle (in slots) given that exactly i transmission attempts have been made. Depending on the mutual relationship of i and m, it can be shown that the value of $D(i)$ may be given by:

$$D(i) = \begin{cases} 2^{i-1}W_0 - \frac{W_0 - i}{2}, & \text{if } 1 \le i \le m+1, \\ 2^{m-1}W_0(i - m + 1) - \frac{W_0 - i}{2}, & \text{if } i > m+1. \end{cases} \quad (5)$$

After plugging (5) into (4) and some near-trivial transformations, we arrive at:

$$E[D] = \frac{(1 - 2p_c)(W_0 + 1) + p_c W_0 (1 - (2p_c)^m)}{2(1 - 2p_c)(1 - p_c)}. \quad (6)$$

Substituting (3) and (6) into (2), we thus conclude that:

$$p_t = \frac{2(1-2p_c)}{(1-2p_c)(W_0+1)+p_cW_0(1-(2p_c)^m)}. \quad (7)$$

Noteworthy, the above expression constitutes the main result of the seminal work in [2] (see formula (7) therein) being reproduced here using a far simpler technique, which remains applicable even when additional system parameters need to be accounted for. By contrast, the research in [2] suggests analysis based on a (bidimensional) Markov chain, which does not scale as easily. The expressions (1) and (7) constitute a system of two non-linear equations with two unknowns, p_c and p_t, which can be solved numerically. This solution has been shown to be unique in [2] and, as we demonstrate below, the resulting transmission probability p_t is a necessary component to obtain e.g. the saturation throughput of the system.

B. Lossy system and protocol signaling

We continue by addressing the lossy system with the finite number of packet *retransmission* attempts K. To calculate p_t in this system, we consider $E[B]$ and $E[D]$ as in (2), but now the expression for the mean number of transmission attempts $E[B]$ in a regeneration cycle is modified as:

$$E[B] = \sum_{i=1}^{K+1} i \Pr\{B=i\} = (1-p_c)\sum_{i=1}^{K+1} i p_c^{i-1} + (K+1)p_c^{K+1} = \frac{1-p_c^{K+1}}{1-p_c}. \quad (8)$$

Further, we obtain the average duration of a regeneration cycle with i packet transmission attempts $E[D]$ as:

$$E[D] = \sum_{i=1}^{K+1} D(i)\Pr\{D=i\} = (1-p_c)\sum_{i=1}^{K+1} D(i)p_c^{i-1} + p_c^{K+1}D(K+1). \quad (9)$$

Further, we differentiate between two options with respect to mutual relationship of m and K in our system: $K \leq m$ and $K > m$. For the first option, our approach gives us:

$$E[D'] = (1-p_c)\left[\sum_{i=1}^{K+1}\left(2^{i-1}W_0 - \frac{W_0-i}{2}\right)p_c^{i-1}\right] + p_c^{K+1}\left(2^K W_0 - \frac{W_0-(K+1)}{2}\right). \quad (10)$$

The corresponding transmission probability p_t' for this case is delivered by (2) after substituting the value of $E[B]$ from (8) and the value of $E[D]$ (in this case, $E[D']$) from (10):

$$p_t' = \frac{2(1-2p_c)(1-p_c^{K+1})}{W_0(1-p_c)(1-(2p_c)^{K+1})+(1-2p_c)(1-p_c^{K+1})}. \quad (11)$$

To characterize the second option, that is, $K > m$, we first need to calculate the corresponding $E[D'']$ as:

$$E[D''] = (1-p_c)\left[\sum_{i=1}^{m+1}\left(2^{i-1}W_0 - \frac{W_0-i}{2}\right)p_c^{i-1} + \sum_{i=m+2}^{K+1}\left(2^{m-1}W_0(i-m+1) - \frac{W_0-i}{2}\right)p_c^{i-1}\right] + p_c^{K+1}\left(2^{m-1}W_0(K-m+2) - \frac{W_0-(K+1)}{2}\right). \quad (12)$$

Similarly, the transmission probability p_t'' in this case can again be produced by (2) after substituting the value of $E[B]$ from (8) and the value of $E[D]$ (in this case, $E[D'']$) from (12):

$$p_t'' = \frac{2(1-2p_c)(1-p_c^{K+1})}{(1-2p_c)(W_0(1-2^m p_c^{K+1})+(1-p_c^{K+1}))+p_cW_0(1-(2p_c)^m)}. \quad (13)$$

Combining the above, the transmission probability p_t in the lossy system may be calculated as p_t' from (11) or as p_t'' from (13) depending on whether $K \leq m$ or not. Solving the non-linear system of two equations, (8) and the appropriate one for p_t, we establish the corresponding value of p_t.

The last remaining step is to account for actual WiFi signaling in the calculation of the saturation throughput, which can be done similarly to [2] and numerous other works. In this research, we employ the practical (non-equal) slot lengths according to the recent IEEE 802.11-2012 standard. More specifically, we illustrate our calculations for the RTS/CTS access scheme, but respective derivations for the Basic access scheme may be completed similarly. In particular, the idle slot duration corresponds to the corresponding IEEE 802.11 parameter σ (see Table I), whereas the durations of the successful slot T_s and the collision slot T_c may be given as:

$$\begin{cases} T_s = RTS + SIFS + CTS + SIFS + H + E[P] + \\ \qquad + SIFS + BA + AIFS \\ T_c = RTS + AIFS. \end{cases} \quad (14)$$

Finally, given the appropriate slot lengths, the average payload per aggregated data block $E[P]$, and several system-wide probabilities, we may derive the saturation throughput S of the multi-access system as:

$$S = \frac{P_tP_sE[P]}{(1-P_t)\sigma + P_tP_sT_s + P_t(1-P_s)T_c}, \quad (15)$$

where $P_t = 1-(1-p_t)^M$ is the (system-wide) probability that there is at least one transmission in a slot, $P_s = Mp_t(1-p_t)^{M-1}P_t^{-1}$ is the conditional success probability in a slot (conditioning on the fact that at least one user transmitted), and the remaining standardized parameters are detailed in Table I.

Finally, in the lossy system, we can explicitly estimate the packet discard probability for a user (after K packet retransmission attempts have been wasted due to repetitive collisions) as $p_d = p_c^{K+1}$.

TABLE I. CORE SYSTEM PARAMETERS

Parameter	Value
Packet size	1500 bytes
Maximum TXOP duration	1300 μs
MAC header size H	244 bits
PHY data rate	1.0, 65.0 Mbps
Number of users	5 to 50
Initial backoff window size W_0	16, 32, 64, 128
Backoff stage m	3, 5
Short retry limit K	∞, 3
Simulation run duration	30 min
Idle slot duration σ	9 μs
Arbitration Inter-Frame Spacing (AIFS)	20 μs
Short Inter-Frame Spacing (SIFS)	16 μs
Block acknowledgment (BA) frame duration	48 μs
Request-To-Send (RTS) frame duration	48 μs
Clear-To-Send (CTS) frame duration	44 μs
Contention-Free End (CFE) frame duration	44 μs

IV. SOME NUMERICAL RESULTS AND CONCLUSIONS

In this section, we verify the above analytical approach with extensive simulations of the current IEEE 802.11-2012 protocol. Our simulator is a flexible tool that captures the essential features of WiFi operation, including the required number of users, necessary BEB features, and system parameters. First and foremost, we calibrate our simulator with the results reported in [2] (dependence of the saturation throughput S on the number of users M). For that matter, we reproduce Figure 6 therein by directly digitizing it from the paper and overlay our corresponding simulation results in Figure 4.

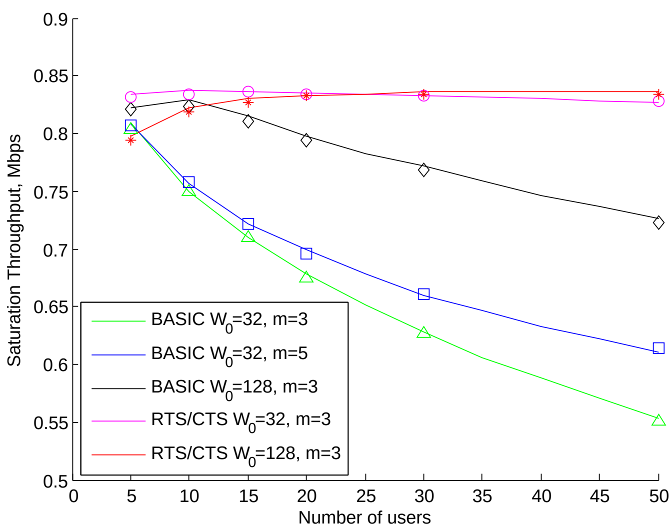

Fig. 4. Saturation throughput at 1 Mbps and $K \to \infty$, calibration

We notice that our results and those form [2] agree exceptionally well in the *legacy* IEEE 802.11 scenario with the maximum data rate of 1 Mbps (lossless system). Hence, our simulator demonstrates similar performance in the trusted test scenario and is this *calibrated*.

Second, we look at the operation of the same saturated cluster of M users with the contemporary WiFi signaling as per IEEE 802.11-2012 specifications. Therefore, we set the maximum data rate as 65 Mbps and compare our analysis (solid lines) against the simulation results (symbols) in Figure 5.

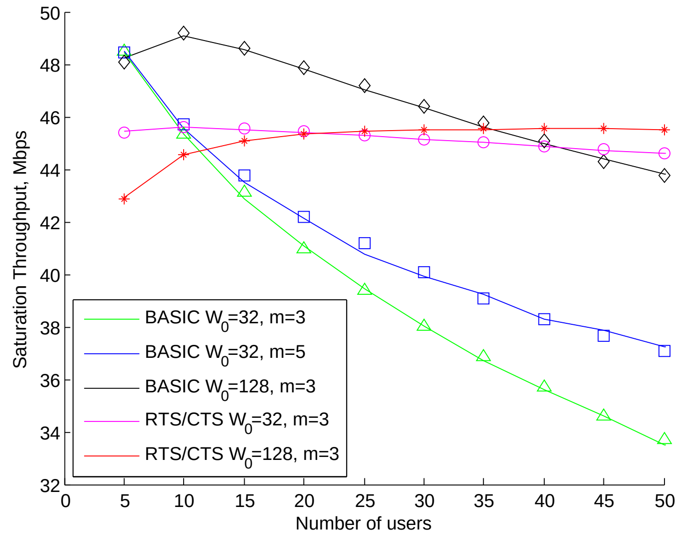

Fig. 5. Saturation throughput at 65 Mbps and $K \to \infty$

We emphasize that Figure 5 also focuses the lossless system operation when the number of packet retransmission attempts is unbounded. We recreate conditions where M users send their full-buffer traffic to the AP and study their achievable throughput levels with our approach. The used system parameters are summarized in Table I. Generally, the trends in Figure 5 are similar to those in Figure 4, but the values of the saturation throughput are naturally higher. We also note that our analytical approach agrees well with simulation data.

We continue by investigating the throughput performance of the BEB protocol in the lossy system, when the maximum number of packet retransmission attempts K is limited. For the sake of example, we set $K = 3$ in Figure 6 and continue to look at the cluster of M users in saturation sending their data at 65 Mbps. Furthermore, we only concentrate on the RTS/CTS channel access scheme as it is beneficial for longer TXOP durations.

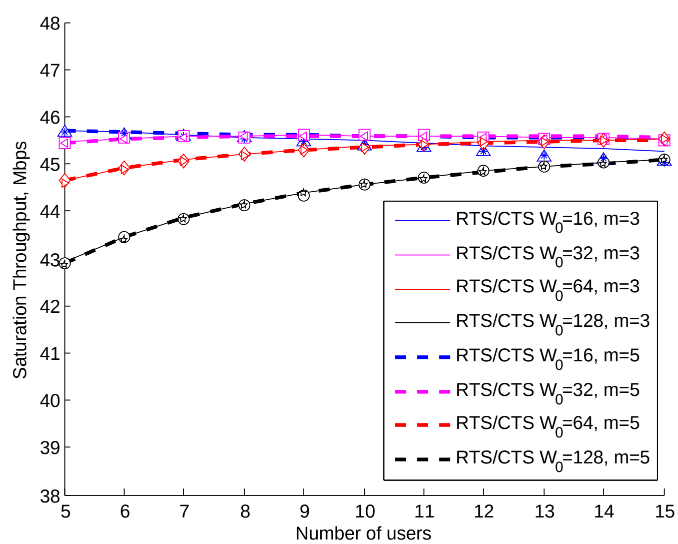

Fig. 6. Saturation throughput at 65 Mbps and $K = 3$

Figure 6 considers a range BEB parameters W_0 and m partly borrowed from [12] and confirms that our analytical approach remains accurate even for the realistic IEEE 802.11-2012 settings. Generally, we see that the throughput levels are not very sensitive to the employed BEB parameters, which is the joint effect of RTS/CTS and packet aggregation.

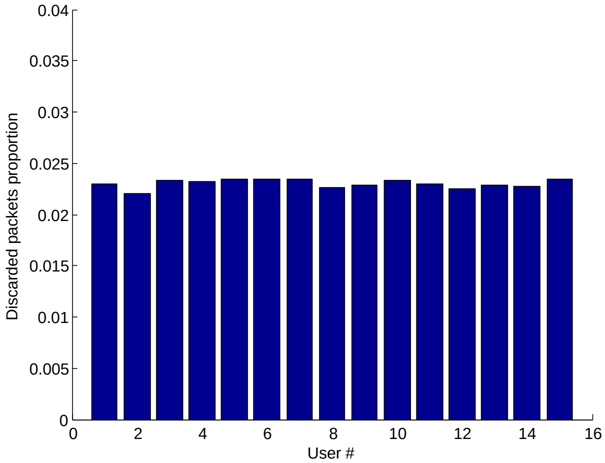

Fig. 7. Proportion of discarded packets per user, $M = 15$

Interestingly, for lower values of the initial contention window size (e.g., $W_0 = 16$) the analytical prediction begins to slightly diverge with simulation for larger numbers of users. This is due to the capture effect discussed in the beginning of Section III when some users have better channel access probabilities than the others. As the result, the simple analysis based on the typical (tagged) user behavior may not be accurate and more complex approaches could be required. Nevertheless, practical systems should avoid such unfairness and control BEB parameters to eliminate channel capture. Therefore, already for $W_0 = 32$ the system becomes fair and we confirm that in Figure 7.

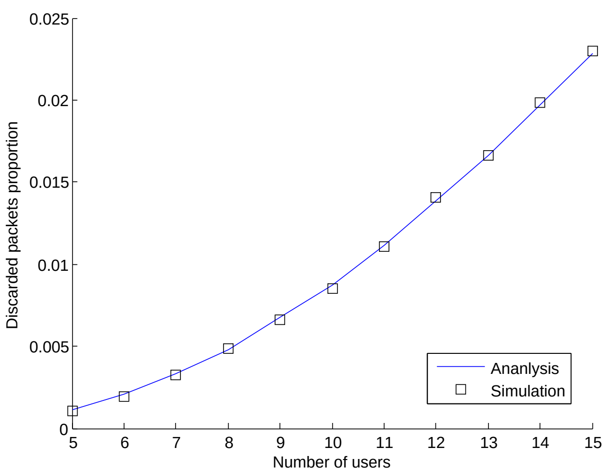

Fig. 8. Proportion of discarded packets, variable number of users

Figure 7 reports simulation data for the proportion of dropped packets when $M = 15$, $W_0 = 32$, $m = 5$, and $K = 3$. We see that packet discard probabilities are similar across all users, which only happens in the fair system. As the conclusion, we highlight that our analysis is applicable for practical BEB systems which enforce fairness of their users. Finally, we also plot the packet discard probabilities for the variable number of users and compare these with our analytical prediction in Figure 8.

In summary, this paper details an integrated simulation-analytical framework for the performance evaluation of IEEE 802.11 protocols which is based on the calibrated baseline and remains accurate for realistic parameters and system settings. Our methodology is a simple and powerful tool to characterize the effects of many practical factors that impact WLAN deployments and we expect it to be useful in the future with the proliferation of WiFi-based wireless networks.

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