Optimizing Network-Assisted WLAN Systems with Aggressive Channel Utilization

Aleksandr Ometov[1(✉)], Sergey Andreev[1], Alla Levina[2], and Sergey Bezzateev[3]

[1] Tampere University of Technology, Korkeakoulunkatu 1, 33720 Tampere, Finland
`{aleksandr.ometov,sergey.andreev}@tut.fi`
[2] Saint Petersburg National Research University of Information Technologies, Mechanics and Optics (ITMO University),
Lomonosova St., 9, 191002 St. Petersburg, Russia
`levina@cit.ifmo.ru`
[3] Saint Petersburg University of Aerospace Instrumentation,
Bolshaya Morskaya St., 67, 190000 St. Petersburg, Russia
`bsv@aanet.ru`

Abstract. Cellular network assistance over unlicensed spectrum technologies is a promising approach to improve the average system throughput and achieve better trade-off between latency and energy-efficiency in Wireless Local Area Networks (WLANs). However, the extent of ultimate user gains under network-assisted WLAN operation has not been explored sufficiently. In this paper, an analytical model for user-centric performance evaluation in such a system is presented. The model captures the throughput, energy efficiency, and access delay assuming aggressive WLAN channel utilization. In the second part of the paper, our formulations are validated with system-level simulations. Finally, the cases of possible unfair spectrum use are also discussed.

1 Introduction and Motivation

Today, modern Wireless Local Area Networks (WLANs) are widely utilized all over the world. This is due to their low deployment and service costs, relatively simple channel access protocols, and ubiquitous availability of radio interfaces on most of the contemporary user devices. Being a major technology trend, IEEE 802.11 (WiFi) took its niche as one of the most popular wireless communication solutions [1]. It utilizes unlicensed bands (2.4, 5 GHz), thus allowing for unrestricted high-speed connectivity between users and network infrastructure. Based on its previous editions, the current protocol version [2] introduces advanced Medium Access Control (MAC) mechanisms built over a wide range of Physical (PHY)-layer features that altogether support the steadily growing numbers of networked devices[1].

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[1] See Ericsson mobility report: On the pulse of the Networked Society, http://www.ericsson.com/mobility-report.

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On the other hand, cellular network operators are increasingly willing to offload their excess traffic demand onto unlicensed bands[2] by e.g., leveraging direct connectivity between user devices in license-exempt spectrum. With such cellular network assistance, there exists an opportunity to manage and improve performance of the conventional WLAN deployments [3,4]. Similar approaches have been investigated from various perspectives and shown to offer throughput and energy efficiency benefits [5]. However, we believe that the ultimate capabilities of network-assisted WLAN operation have not been studied conclusively. For instance, the potential of novel MAC algorithms and "adaptive scheduling" [6] remains largely unexplored in this context.

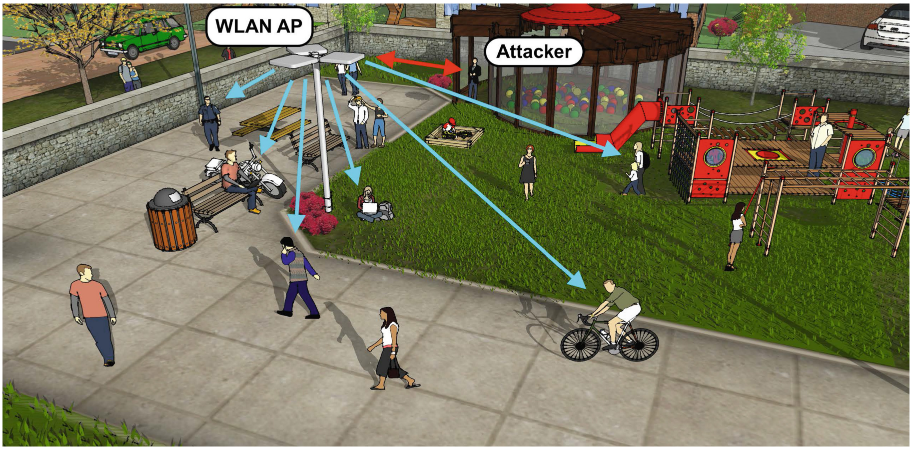

Fig. 1. Topology of the considered scenario

More specifically, the tentative performance gains with network-assisted traffic offloading have been considered in the past by relying on WiFi-Direct connectivity [7], as well as employing anchor access points as part of the cellular infrastructure [8]. We expect that the practical advantages of integrating the WLAN connectivity with system-wide cellular network management would grow further over the following years [9,10]. This should result in generally improved levels of performance that current IEEE 802.11 system deployments would gain with added cellular network assistance.

The above considerations call for revisiting the existing WiFi-specific performance evaluation models to determine the optimal network-assisted operation of real-life WLANs. In this work, a model for aggressive channel utilization based on regenerative analysis is discussed. It allows to quantify system performance with high scalability by operating with only a small number of parameters and thus may be preferred over traditional Markov chain based approaches [11,12].

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[2] See Cisco Visual Networking Index: Global Mobile Data Traffic Forecast, http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html.

To illustrate its capabilities, we model the network operation for static and dynamic user arrivals. Finally, we overview our developed technology prototype that continues the authors' previous work in [13]. The described demonstrator features a conventional Linux laptop with a custom-compiled kernel WiFi module and a traffic generation software in order to mimic the case of aggressive channel utilization, as it is demonstrated in Fig. 1.

The rest of this text is organized as following. In the following section, the WiFi-specific Binary Exponential Backoff protocol operation and the corresponding analytical model are briefly reviewed. The numerical results and the model validation are elaborated in Sect. 3. The final section summarizes the work-in-progress and concludes this paper.

2 Case Description and Analysis

In this work, we consider the conventional IEEE 802.11n MAC operation, which utilizes the so-called Distributed Coordination Function (DCF) based on Binary Exponential Backoff (BEB) protocol for collision resolution and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism [14] operating in the Request-To-Send/Clear-To-Send (RTS/CTS) mode.

For the sake of simplicity, we consider a single Access Point (AP) in our network together with M stationary devices connected to it. We also assume that all of the WiFi devices are operating in the "aggressive" saturation mode, that is, their traffic queues are always full whenever they initiate a transmission. Another important assumption is that the co-located cellular network always has an up-to-date knowledge on the number of devices connected to the AP or residing in its range, since we only consider multi-radio devices with two radio interfaces, WLAN and cellular.

The RTS/CTS based channel reservation mechanism – employed whenever a particular device seizes a channel for transmission – operates as a four-way handshake. The system in question is primarily controlled by three parameters: the initial backoff window W_0, the backoff stage m, and the retransmission counter K. If the channel is not reserved during the Arbitration Inter-Frame Spacing ($AIFS$) interval, the tagged device is applying a backoff procedure before commencing its data transmission attempt.

Hence, the Backoff Counter (BC) value is selected uniformly from the interval 0 to $W_0 - 1$, and the current contention window value is denoted as W_i. After each idle slot, the BC value is decremented. Whenever it reaches zero, a transmission attempt is initiated. In case there are two or more simultaneously transmitting users, a *collision* is detected at the AP side. As long as the packet is not discarded (K still allows to retransmit), the CW is doubled ($W_i = 2W_i - 1$) to reduce the collision probability and the BC is generated again.

It is important to note that equipment vendors set the maximum limit for the CW as $CW_{max} = W_0^m$. However, if there have been more than K unsuccessful transmissions of one packet, it is discarded and the corresponding data is lost. A diversity of WiFi chipsets available on the market calls for harmonization of the utilized BEB parameters to achieve efficient and fair medium access. To this end, our considered analytical model may be applied to select the corresponding set of MAC parameters in a close-to-optimal manner.

Over the recent years, multiple research papers use Markov chain based techniques to analyze the BEB scheme [15,16]. However, it may be difficult to scale such models to study all the system parameters of interest due to the fast state space growth. Fortunately, there are alternative analytical approaches to evaluate the performance indicators in case of saturation, which are based on regenerative analysis. We believe the latter may be scaled better and capture the system behavior more efficiently [17,18].

In what follows, we discuss an analytical model to optimize the BEB parameters for network-assisted WLAN operation with aggressive channel utilization. First, we characterize the number of successful transmissions and the corresponding transmission attempts. Accordingly, the well-known collision probability expression can be written as follows

$$p_c = 1 - (1 - p_t)^{M-1}, \tag{1}$$

where $M-1$ is the number of contending devices that may collide with the tagged user during a time slot and p_t is the transmission probability for a device, i.e., the probability for a user to start its transmission in a randomly chosen time slot. This value may be obtained as

$$p_t = \lim_{n\to\infty} \frac{\sum\limits_{i=1}^{n} B^{(i)}}{\sum\limits_{i=1}^{n} D^{(i)}} = \frac{E[B]}{E[D]}, \tag{2}$$

where $B^{(i)}$ is the number of packet transmission attempts for a given regeneration cycle i^{th} related to the duration of the i^{th} cycle in slots $D^{(i)}$.

Therefore, the probability of a successful transmission can be derived as

$$p_s = \frac{Mp_t(1-p_t)^{M-1}}{1-(1-p_t)^M}. \tag{3}$$

Further, we may develop the discussed analytical approach for a case when some of the packets may be discarded based on the number of retransmission attempts K and the backoff stage value m. In order to produce the respective transmission probabilities, we need to evaluate the average number of transmission attempts $E[B]$ during the i^{th} cycle as

$$E[B] = \sum_{i=1}^{K+1} i \Pr\{B=i\} = (1-p_c)\sum_{i=1}^{K+1} ip_c^{i-1} + (K+1)p_c^{K+1} = \tfrac{1-p_c^{K+1}}{1-p_c}. \tag{4}$$

Additionally, we have to take into account the number of transmission attempts $E[D^{1,2}]$ as

$$\begin{cases} E[D^1] = & (1-p_c)\left[\sum\limits_{i=1}^{K+1}\left(2^{i-1}W_0 - \frac{W_0-i}{2}\right)p_c^{i-1}\right] + \\ & +p_c^{K+1}\left(2^K W_0 - \frac{W_0-(K+1)}{2}\right), \\ E[D^2] = & (1-p_c)\left[\sum\limits_{i=1}^{m+1}\left(2^{i-1}W_0 - \frac{W_0-i}{2}\right)p_c^{i-1} + \right. \\ & \left. + \sum\limits_{i=m+2}^{K+1}\left(2^{m-1}W_0(i-m+1) - \frac{W_0-i}{2}\right)p_c^{i-1}\right] + \\ & +p_c^{K+1}\left(2^{m-1}W_0(K-m+2) - \frac{W_0-(K+1)}{2}\right). \end{cases} \tag{5}$$

Finally, we determine the sought transmission probabilities by calculating (4) for both (5) and (2). After straightforward technical transformations, we arrive at

$$\begin{cases} p_t^1 = \frac{2(1-2p_c)(1-p_c^{K+1})}{W_0(1-p_c)(1-(2p_c)^{K+1})+(1-2p_c)(1-p_c^{K+1})}, \\ p_t^2 = \frac{2(1-2p_c)(1-p_c^{K+1})}{(1-2p_c)(W_0(1-2^m p_c^{K+1})+(1-p_c^{K+1}))+p_c W_0(1-(2p_c)^m)}, \end{cases} \tag{6}$$

where p_t^1 is for the case when $K \leq m$ and p_t^2 stands for $K > m$. As the last step, by taking into account the results from (6), we produce the probability of a successful transmission with (3).

3 Numerical Results

In this section, we evaluate the considered analytical approach by utilizing a simple MAC-layer WiFi simulator. Correspondingly, the main operating parameters are summarized in Table 1. Our subsequent results are divided into two groups: the overview of possible BEB optimization opportunities for network-assisted WLAN deployments; and the case when the number of saturated multi-radio devices varies uniformly.

Table 1. Core system parameters

Parameter	Value
Packet size	1500 bytes
PHY data rate	65.0 Mbps
Number of users	5 to 100
Initial backoff window W_0	2 to 1024
Backoff stage R	2 to 14
Short retry limit K	7, ∞
Maximum simulation duration	30 min or 10^6 slots

Based on a live trial reported in [19] and executed in Mountain View, California, the average number of devices connected to one AP is fluctuating below 5 during the day. In this work, as the worst case, we assume 5 times more devices that have an active saturated connection to a single AP. Along these lines, we study a set of cases in order to obtain insights into the best initial Contention Window and Retransmission Counter values based on the successful transmission probability. Accordingly, we estimate the probability that a packet has been successfully delivered if its transmission is attempted by the tagged user.

The results for the actual average number of devices is shown in Fig. 2(a). Here, the horizontal line represents a suboptimal algorithm based on the approach from a well-known work in [20]. In this case, the system has knowledge of the total number of users (via the cellular network assistance) and each of the user devices is only allowed to utilize the corresponding channel access probability (which can be easily recalculated into the initial CW and RC values).

Further, our simulation tool was calibrated with the discussed analytical framework and the example for $W_0 = 16$, $R = 6$, and $K = 7$ is shown in Table 2. However, Jain's Fairness Index ($J = (\sum_{i=1}^{n} x_i)^2 / n \sum_{i=1}^{n} {x_j}^2$) [21] demonstrates that the numbers of successful transmissions across the users are not equal. This crucial BEB operation feature is related to the Channel Capture Effect issues [22].

Table 2. Calibration between simulation and analysis

Number of users	p_s, analysis	p_s, simulation	Jain's index
10	0.32792	0.32563	0.90665
20	0.35368	0.35822	0.94976
30	0.36366	0.36833	0.96009
50	0.37025	0.37706	0.97315

As shown in Fig. 2(a), there is only one optimal point (see the peak in the plot) with the backoff parameters of $W_0 = 5$ and $R = 2$. In order to optimize the system operation, the values need to be updated accordingly for each of the devices through the AP and in coordination with the cellular network assistance function. The step-wise behavior in the right side of the plot is due to a decreased saturation in the channel, i.e., the initial contention builds up as the channel access time increases.

The corresponding results for 10 users are illustrated in Fig. 2(b). Clearly, there is more than one peak, that is, the best successful transmission probability may be achieved in a number of ways by selecting the alternative pairs of BEB parameters. Here, to consider only one of those, the middle part of this cluster of points may become an adequate option ($W_0 = 4, R = 4$). This is due to a lower influence of the capture effect, and the initial CW value does not affect the operation in terms of the initial transmission delay either.

Finally, we increase the number of contending devices to a larger value of 100 in Fig. 2(c). We see that the number of peaks also increases and make a similar decision as in the case for 10 users to choose the suboptimal operating point. Therefore, for 100 devices, the BEB parameters may be chosen as $W_0 = 4$ and $R = 4$.

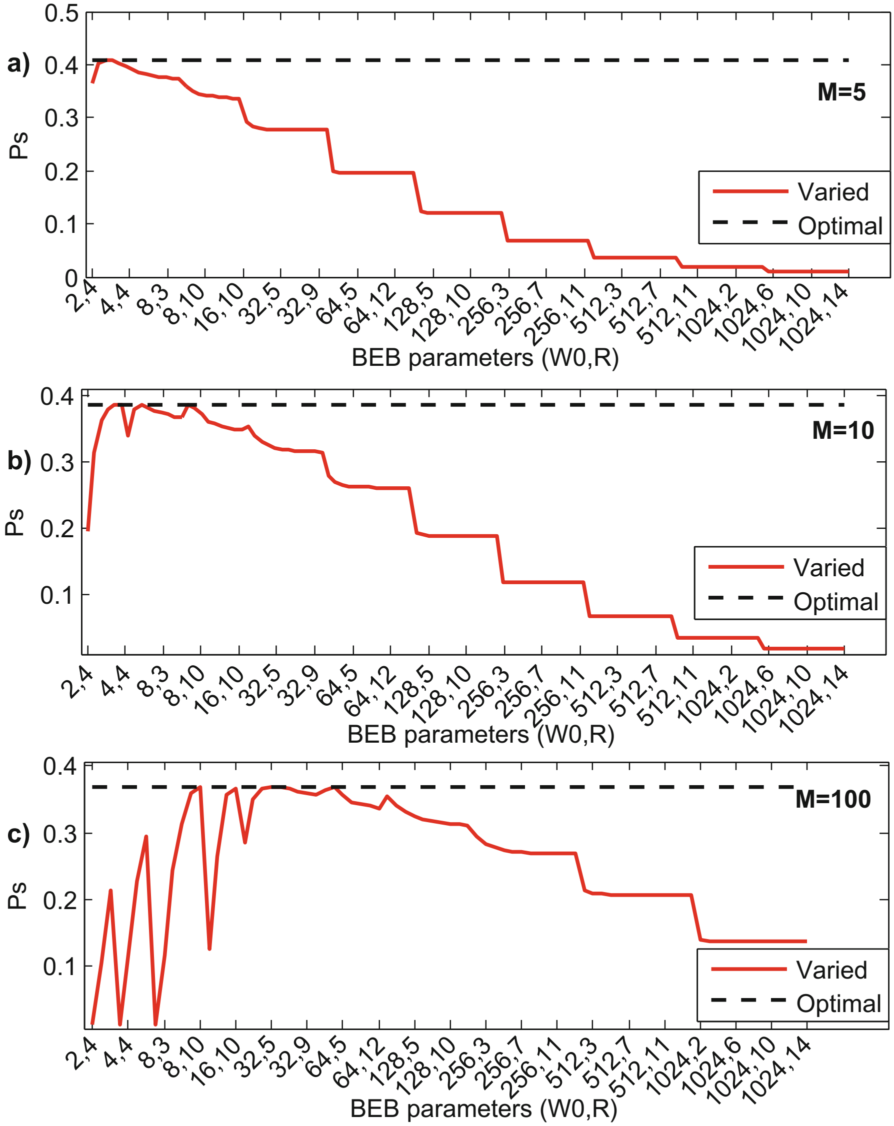

Fig. 2. Successful transmission probability for different numbers of users

We continue by modeling dynamic user arrivals and thus utilize the following setup. The devices attempt to access the channel over an interval of time equal to 5, 000 slots. The randomly chosen 10 % of the maximum number of users are inactive, while others keep transmitting or activate. If a user was applying the backoff procedure in the previous operating interval, the BEB parameters remain the same in the current one. In case a device has just activated, the BEB parameters are set to the initial values.

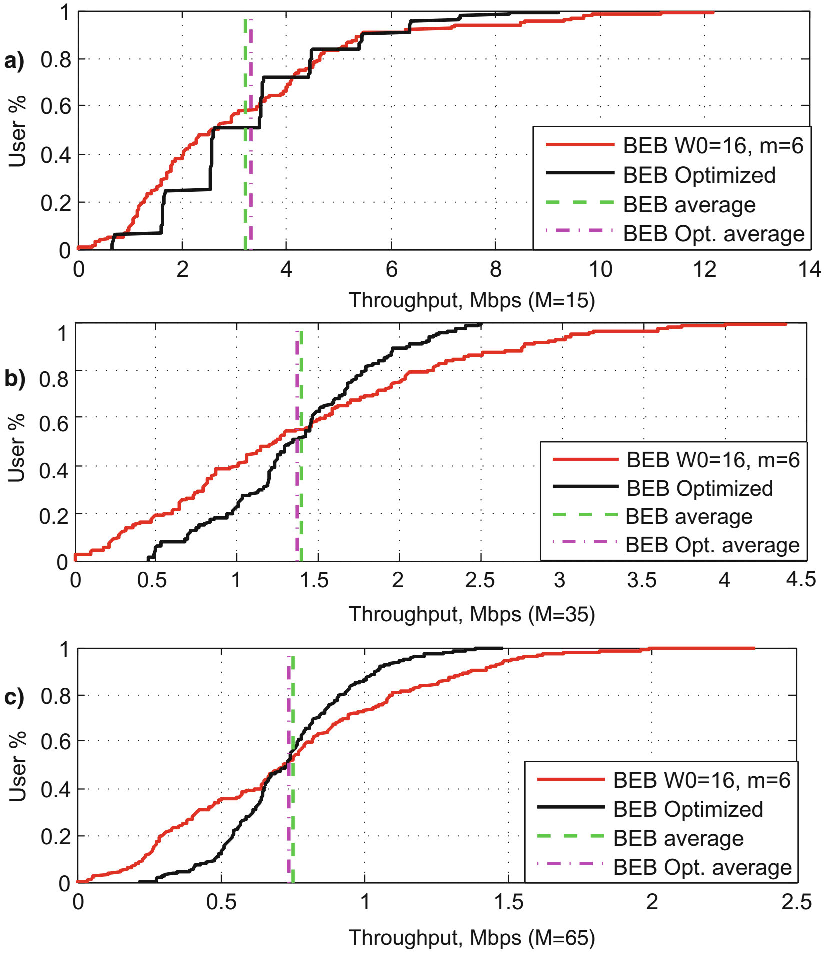

Fig. 3. System throughput

The BEB setup for this experiment was configured according to the widely-used *MadWifi* driver[3] as $W_0 = 16$, $R = 6$, and $K = 7$. All of the users are operating in the "lossy" mode [23], that is, packet drops are possible according to the Short Retry Limit value. The results for the system throughput (Fig. 3) fully support our previous discussion by indicating the same average throughput value for all the algorithms, while fairness may be optimized for higher numbers of devices.

The system operation from the delay perspective is illustrated in Fig. 4. The optimized solution shows better results even for the small number of devices (Fig. 4(a)). This is generally due to shorter channel access times. The standard

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[3] See ath9k, https://wireless.kernel.org/en/users/Drivers/ath9k/.

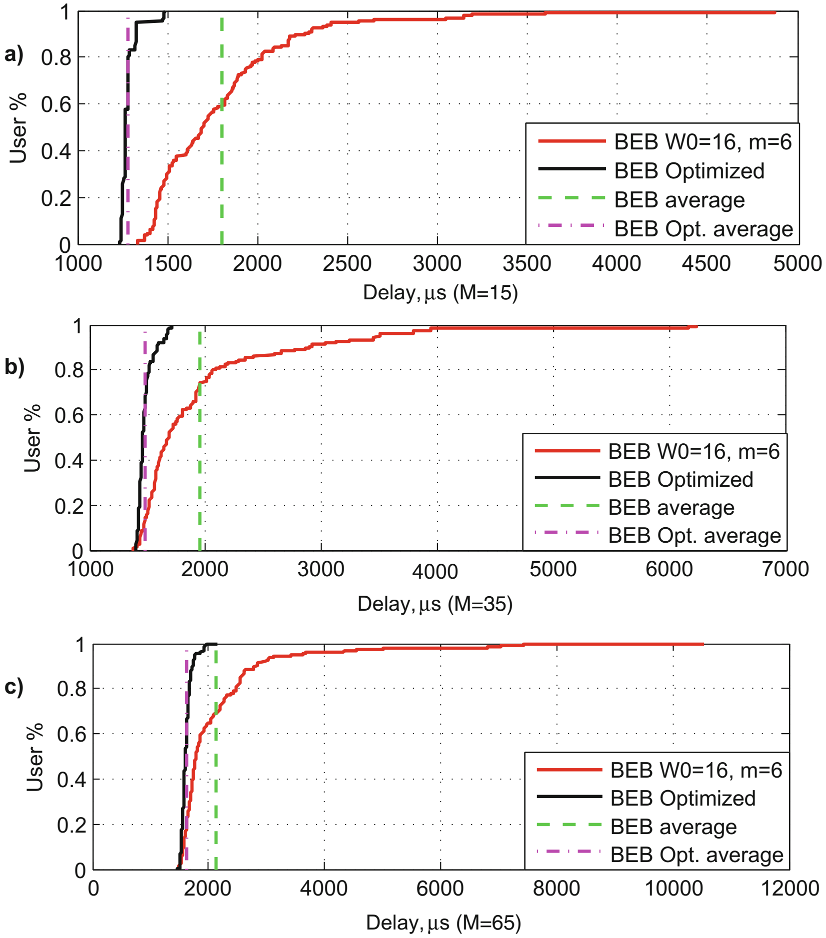

Fig. 4. Packet transmission delay

backoff procedure with the RTS/CTS mechanism requires each device to wait for at least the first *CW* interval that may be significantly longer than the one with the optimized BEB parameters. Additionally, the default parameters have more impact on collision resolution time in case of higher numbers of users (Fig. 4(b) and (c)).

The delay performance is directly connected to that of energy efficiency [24], which is shown in Fig. 5. We quantify the energy efficiency based on 100 mW idling power, 200 mW RX, and constant 100 mW + the transmit power for TX [7]. The optimized solution enjoys faster collision resolution and thus the users are attempting to transmit more frequently when their number is low (Fig. 5(a)). On the contrary, as the number of devices grows, the optimized parameters make users backoff for longer time intervals (Fig. 5(b) and (c)).

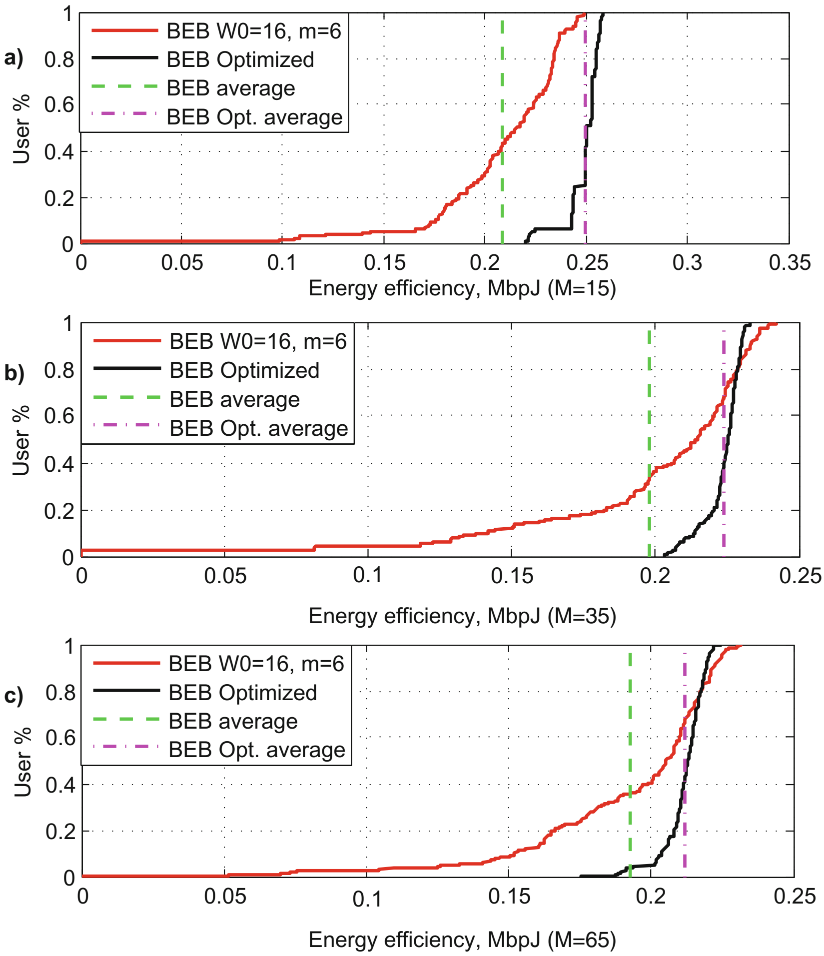

Fig. 5. Energy efficiency

Due to a lower impact of idling and RX power, the reduced collision rate leads to smaller energy consumption.

Summarizing the above, we verified our custom-made modeling tool with the developed analytical model in the saturation regime. Further, we studied the dynamics of user arrivals in the network-assisted WLAN system and can conclude that cellular assistance may bring significant benefits for all the considered performance indicators.

4 Current Work and Conclusions

In this section, we briefly discuss the system prototype under development and the available options for software-based traffic load generators. In a nutshell, our prototype operates by utilizing a conventional Linux laptop equipped with an open-source WiFi driver. It is running an *iperf server*[4] in order to mimic the intended aggressive channel utilization. The main feature of this testbed is in its ability to generate *artificial load*, i.e., it is possible to emulate the needed number of users by only modifying the BEB operation of one user. We note that more expensive APs on the market can also update the MAC parameters on the devices dynamically.

Importantly, as Linux systems allow their users to recompile the core modules, a malicious person may modify the BEB parameters in an offensive way, e.g., by setting CW, BC, and K to near-zero values. Should such a person be located in a public hot-spot (see Fig. 1), the attacker's device would transmit almost immediately without the initial channel sensing and/or waiting intervals used by others. Said attacker would then achieve a better channel utilization, while the remaining "fair" users would continue resolving their increased collisions as it was shown in the previous section. Preventive measures may thus be necessary to detect and protect from this and similar types of attacks.

Summarizing, in this work we studied the relations between the number of devices, the backoff parameters, the access delay, and the energy efficiency for cellular-assisted IEEE 802.11-based networks. Our results were obtained for both static and dynamic user arrival models. The considered optimization procedure was shown to provide improved system-wide fairness as well as generally better performance. Finally, we presented a capable testbed that may be employed to study more subtle real-world effects of network-assisted WLAN operation.

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[4] See iperf3: A TCP, UDP, and SCTP network bandwidth measurement tool, https://github.com/esnet/iperf/.

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