An Accurate Model for Energy Efficiency in IEEE 802.11 WLANs

Eleni-Constantina Davri†‡, Emmanouil Kafetzakis†, Kimon Kontovasilis†, Charalabos Skianis‡

National Centre for Scientific Research “Demokritos”, Athens, Greece
University of Aegean, Samos, Greece

Email: {davri, mkafetz, kkont}@iit.demokritos.gr, cskianis@aegean.gr

Abstract—A critical restriction in using mobile electronic devices is the limited battery autonomy. This paper focuses on the energy efficiency of IEEE 802.11 network interface. It proposes an energy consumption model that reflects accurately the backoff window dynamics under saturation conditions. In addition, all power state levels used by the IEEE 802.11 standard are considered in the analysis. Numerical and simulation results demonstrate that the proposed IEEE 802.11 energy model is more accurate than previous approaches, and it overcomes the modeling limitations of previous works which are becoming more significant in newer versions of IEEE 802.11 standard. Finally, by providing a clearer insight into the backoff factors, the proposed model lends itself to the use of arbitrary (generic) backoff window schemes, allowing the comparison of the energy efficiency of various alternatives for the backoff window growth.

I. INTRODUCTION

Mobile electronic devices, particularly smart phones, are powered from batteries with limited size and thus, limited capacity and autonomy. Therefore, it is of vital importance to establish accurate analytical models that assess energy consumption and provide insights on the management of energy. In this paper, we study the energy efficiency of IEEE 802.11 component that exists in almost every mobile device. Although WiFi is not the module with the greatest energy consumption (measurements have shown that GSM, CPU, and graphics modules spend more energy in comparison to WiFi [1]), our model highlights that when IEEE 802.11 network interface is on WiFi (with a typical use of all other hardware modules), the fraction that cannot be ignored.

As a concrete example elaborating on this last point, one of the premium smart phones in the market today is equipped with a battery at 3.8 V-1440 mAh, 5472 mWh [2]. In a typical setting of having to compete with nine other IEEE 802.11g devices, our model shows that the energy suffices for around 40 hours if all energy is dedicated to the WiFi module. The manufacturer declares that the mobile use is up to 10 hours on WiFi (with a typical use of all other hardware modules), therefore about one quarter of total power is dedicated to IEEE 802.11.

Assessing the energy efficiency of WiFi requires a careful consideration of relevant IEEE 802.11 functions. Due to its popularity, IEEE 802.11 standard [3] has been studied extensively, particularly with respect to the throughput that can be achieved, under various wireless channel conditions and traffic loads. Reference [4] has served as a starting point for many subsequent studies; it was the first one that modeled the IEEE 802.11 Distributed Coordination Function (DCF) using a two-dimensional Markov chain to characterize the backoff dynamics of each station under saturated conditions. The model was based on the assumption of a constant and independent collision probability for each packet transmitted by a station, regardless of the number of retransmissions that the packet had already suffered. Despite the success of this assumption, the model neglects the advantage of a station on regaining access to the channel, at the moment just after the station has successfully transmitted [5]. In recognition of this fact, a relevant argument has been originally expressed in renewal-theoretic terms in [6] and later has been extended into Discrete Markovian/Semi-Markovian framework in [7], incorporating the effect of repeated successful transmissions.

Despite the significant amount of work on throughput analysis, energy aspects of IEEE 802.11 standard have not been adequately addressed. Energy consumption of IEEE 802.11 DCF under saturation was analysed in [8] through estimating the average service time that a station waits to transmit a packet successfully, based on the channel state probabilities of [4]. Subsequently, a refined energy model for IEEE 802.11 DCF access mechanism that considers the carrier sensing, the collisions and the freezing mechanism in backoff was proposed in [9]. Both studies adopt a limited number of power state levels (i.e., transmission and reception power levels), ignoring the carrier sensing power state level. Moreover, they are restricted due the modeling limitations of [4] previously mentioned.

The model proposed here adopts the extension of [7] and it provides an energy consumption model for IEEE 802.11 DCF that reflects accurately the backoff window dynamics under saturation. In this direction, it associates all the power levels used by the IEEE 802.11 standard in contrast to previous attempts, such as [8] and [9]. Providing a clearer insight into the backoff factors, it allows the use of arbitrary (generic) backoff window growth schemes and the comparison of the energy efficiency of various alternatives for the backoff window growth (e.g., window sizes with polynomial and linear growth [10], besides the binary exponential growth form foreseen by the standard).

The energy model proposed here has been validated through experiments into ns-2 simulator (version 2.35) [11]. Simulation results have been based directly on the energy consumption implementation for IEEE 802.11 protocol [12], and no other intermediate quantities have been used to estimate energy efficiency. The results demonstrate that our...
IEEE 802.11 energy model is more accurate than previous approaches and that the impact of the geometric number of transmissions after a successful packet transmission by the same IEEE 802.11 station is increasing in newer versions of IEEE 802.11 standard with smaller initial backoff window values [13].

The rest of the paper is organized as follows: Section II briefly presents the Semi-Markovian model that will be enhanced to yield the energy efficiency of IEEE 802.11 standard. Section III calculates the different energies with all necessary details, taking into account all different power levels, and derives the energy efficiency of IEEE 802.11 standard. Afterwards, Section IV discusses the numerical results. Finally, conclusions and future work are given in Section V.

II. MODELING FOUNDATIONS FOR IEEE 802.11 DCF AND THROUGHPUT CALCULATION

The seminal work in [4] was the first to model the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) access algorithm used by the IEEE 802.11 protocol as a Discrete Markov Chain (DMC). Taking into account the refinements of [6], a Semi-Markovian Chain that expands the DMC has been proposed in [7], incorporating the packet transmission details and including relevant timing information. The reduced four-state Semi-Markovian model, depicted in Fig. 1, will be enhanced to yield the energy efficiency of individual IEEE 802.11 stations under saturated traffic conditions. This section reviews background material (mainly from [7]).

Note that the Semi-Markovian model allows the use of arbitrary backoff counter probability distributions and captures the phenomenon of potentially multiple successful packet transmissions by a station just after having transmitted successfully. The impact of these properties on performance metrics is becoming important in the newer versions of IEEE 802.11 standard.

In Fig. 1, State $ov$ corresponds to the signaling/overhead transmissions before and after a data packet transmission, plus the transmission dedicated to the packet’s MAC header. State $tr$ corresponds to the successful transmission of the packet’s payload, while State $dc$ to the constant shortest system time-slot, required for the initial decrement of the backoff counter, before the backoff is entered after a successful transmission (State $bc$). Note that, by virtue of the IEEE 802.11 MAC layer attributes, only one of the competing stations may reside in one of the States $ov$, $tr$, $dc$; all the other must necessarily be in backoff mode.

With respect to the transition probabilities, the overhead and payload data transmissions always occur in pairs, thus the transitions from State $ov$ to State $tr$ occur with probability one. After a successful payload transmission, State $ov$ is visited again with probability $B_0$ (probability that the value of the backoff counter drawn at the $0^{th}$ backoff stage is zero) so the station transmits successfully one more time, while with probability $1 - B_0$ the station enters the backoff procedure after the backoff counter has been decreased by one (State $dc$).

The Semi-Markovian model is constructed in such a way that during the sojourn time at each of its states a constant server rate is maintained. This rate is $\hat{r}$ (the WLAN’s nominal peak rate) for State $tr$ and zero for all other states. For State $ov$, corresponding to the signaling/overhead before and after payload transmission, including packet’s header transmission, we assign a service rate equal to zero even though the station actually transmits signaling data and/or the packet header. This choice is in line with the intention of computing the station’s server rate available to the higher layers of the protocol stack.

The sojourn times in States $ov$, $dc$ are constant for RTS/CTS access and are equal to:

$$T_{ov} \triangleq (RTS + CTS + PHY_{hdr} + ACK)/r_{signal} + MAC_{hdr}/\hat{r} + 3SIFS + DIFS,$$

$$T_{dc} \triangleq t_{slot}.$$

The quantities $RTS$, $CTS$, $SIFS$, $DIFS$, $ACK$, $MAC_{hdr}$, $PHY_{hdr}$ denote respectively the RTS packet size, the CTS packet size, the SIFS time interval, the DIFS time interval, the ACK packet size, the MAC header and the PHY header. The quantity $r_{signal}$ is the transmission rate used for signaling operations, while $t_{slot}$ stands for the duration of the shortest system-slot.

The mean value of the sojourn time in State $tr$ (i.e., payload transmission time) is

$$E[T_{tr}] = E[L]/\hat{r},$$

where $L$ denotes the data packet’s payload length. If $L$ is constant, the transmission time is deterministic.

The sojourn time $T_{dc}$ in State $bc$ is described in terms of the random variable $T_s$, the time required for decreasing the value of the backoff counter by one for a station backing off. Since the channel can be sensed busy (due to transmission or collision) or idle (due to an empty channel), $T_s$ can take only one of the following distinct values per case: (a) the duration of a collision plus the duration of the shortest system-slot; (b) the duration of a successful transmission plus the duration of the shortest system-slot; (c) the duration of the shortest system-slot. The shortest system-slot included in each possible duration is necessary for the decrement of the backoff counter of the listening stations. Note that the deterministic duration of a packet collision $t_{coll}$ is equal to

$$t_{coll} \triangleq RTS/r_{signal} + EIFS + t_{slot};$$

because collided $RTS$ messages are followed by an $EIFS$ time interval plus the duration of the shortest system-slot. Based on the above,

$$E[T_s] = P_{coll}t_{coll} + P_{empty}t_{slot} + P_{succ}E[t_{succ}]$$
where
\[ P_{\text{succ}} = (n - 1)\tau(1 - \tau)^{n-2}, \]
\[ P_{\text{empty}} = (1 - \tau)^{n-1}, \]
\[ P_{\text{coll}} = 1 - P_{\text{succ}} - P_{\text{empty}}, \]  
(5)

are the probabilities of a successful transmission, an empty slot and a collision respectively, observed by a station backing-off (which observes \( n - 1 \) other independent stations). The mean time for a successful transmission is
\[ E[t_{\text{succ}}] = \frac{E[T_{u}] + T_{ov} + t_{\text{slot}}}{1 - B_{0}}. \]  
(6)

The first term in (6) expresses the fact that the total duration of a successful transmission results from a geometric series of individual transmissions by the station not backing-off, with probability \( B_{0} \), the probability that a backoff counter sampled at the \( 0^{th} \) backoff stage has zero value. The quantity \( \tau \) in (5), called transmission probability, denotes the probability that a station attempts transmission in a random model time-slot. The value of \( \tau \) is obtained by solving numerically the system of equations
\[
1 - p = (1 - \tau)^{n-1}, \\
\tau = \left[ 1 + (1 - p) \left( \frac{E[W_{0}]}{1 - B_{0}} - 1 + \sum_{i=1}^{\infty} p^{i}E[W_{i}] \right) \right]^{-1}.
\]  
(7)

for the conditional collision probability \( p \) and the transmission probability \( \tau \) [4], [7]. \( E[W_{i}] \) denotes the mean backoff window at the \( i^{th} \) stage, \( i \geq 0 \).

The average number of backoff decrements during \( T_{bc} \) can be found equal to
\[ E[N_{bc}] = \frac{E[W_{0}]}{1 - B_{0}} - 1 + \sum_{i=1}^{\infty} p^{i}E[W_{i}]. \]  
(8)

The sojourn time \( T_{bc} \) includes, not only the time spent in decrementing backoff counters, but also the time to resolve the collisions experienced before a successful transmission, therefore
\[ E[T_{bc}] = \frac{p}{1 - p}t_{\text{coll}} + E[N_{bc}]E[T_{s}]. \]  
(9)

To find out the throughput of an IEEE 802.11 station, we refer to the simple transmission diagram between the States: tr, ov, dc, and bc, as depicted in the Semi-Markov model of Fig. 1. The stationary probabilities associated with those States can be expressed in terms of the stationary probability of State tr, \( \pi_{tr} \), as follows:
\[ \pi_{ov} = \pi_{tr}, \quad \pi_{dc} = (1 - B_{0})\pi_{tr}, \quad \pi_{bc} = (1 - B_{0})\pi_{tr}. \]  
(10)

From standard Markov Renewal theory and by recalling that the only non-zero data transmission rate occurs in State tr, the node’s throughput \( S \) is seen equal to
\[ S = \frac{\pi_{tr}E[T_{u}]}{\pi_{tr}E[T_{tr}] + \pi_{ov}T_{ov} + \pi_{dc}T_{dc} + \pi_{bc}E[T_{bc}]} \]  
(11)

By replacing the stationary probabilities from (10) to (11) and by using (2), the throughput becomes
\[ S = \frac{E[L]}{E[L]/\hat{f} + T_{ov} + (1 - B_{0})(E[T_{bc}] + t_{\text{slot}})}. \]  
(12)

It is noted that the values of \( p \) and \( \tau \) (as computed by (7)) depend only on the number of competing stations \( n \), the mean backoff windows \( E[W_{i}], i \geq 0 \), and the probability \( B_{0} \) of selecting zero backoff value at the \( 0^{th} \) stage. Therefore, arbitrary counter probability distributions can be adopted for the backoff stages.

III. EXPANDING SEMI-MARKOVIAN MODEL FOR ENERGY EFFICIENCY ASSESSMENT

The way to derive the energy efficiency of IEEE 802.11 DCF is analogous to the methodology already presented for throughput computation, with some additional refinements to accommodate the mean times spent in various power levels. This is required because the mean energies depend on the various power levels employed and the mean times in each power level.

More specifically, energy efficiency can be defined as the ratio of the payload to the energy needed for the successful transmission of one data packet. In this view, given the mean energy consumed during a sojourn time in each state of the Semi-Markov chain of Fig. 1 (i.e., \( E_{tr}, E_{ov}, E_{dc}, E_{bc} \), the overall energy efficiency \( \eta_{T} \) can be expressed in a form analogous to the throughput expression (12), as
\[ \eta_{T} = \frac{E[L]}{E_{tr} + E_{ov} + (1 - B_{0})(E_{dc} + E_{bc})}. \]  
(13)

In the following, we calculate the energy factors of the denominator of (13) with all necessary details and taking into account all different power levels.

Three different power levels are involved under saturation conditions: one on transmission mode \( U_{tr} \), one on reception mode \( U_{rcv} \), and one on sensing mode \( U_{sens} \). The typical relation between transmission, reception, and sensing power level modes is \( U_{tr} > U_{rcv} > U_{sens} \), but this is not a necessary condition posed by the IEEE 802.11 standard or assumed by the model discussed here.

On State ov (i.e., the transmission of signaling information except payload), the sojourn time is divided into three parts, to account for the corresponding power levels involved, i.e.,
\[ E_{ov} = \left( \frac{RTS + PHY_{\text{hdr}}}{r_{\text{signal}}} + \frac{MAC_{\text{hdr}}}{\hat{f}} \right)U_{tr} + \left( \frac{CTS + ACK}{r_{\text{signal}}} \right)U_{rcv} + (3\text{IFS} + \text{DIFS})U_{sens}. \]  
(14)

On the State dc, the sojourn time corresponds just to the sensing power level. Therefore,
\[ E_{dc} = E_{\text{slot}} = t_{\text{slot}}U_{sens}. \]  
(15)

Similarly, during State tr, the payload is transmitted with power \( U_{tr} \), and
\[ E_{tr} = \frac{E[L]}{\hat{f}}U_{tr}. \]  
(16)

The energy consumed during the backoff procedure \( E_{bc} \) is the sum of the mean energies spent for all the number of the back off counter decrements and the energy spent for resolving
the collisions experienced in unsuccessful attempts to transmit. With $E[N_{bc}]$ as given in (8),

$$E_{bc} = \frac{p}{1 - p} E_{coll} + E[N_{bc}] E_s. \quad (17)$$

Here, $E_s$ denotes the average energy spent by a station in backoff mode to decrement its backoff counter once. $E_{coll}$ is the energy consumed by a station participating in one packet collision, i.e.,

$$E_{coll} = \frac{RTS}{r_{signal}} U_{tr} + (EIFS + t_{slot}) U_{rcv}. \quad (18)$$

The expression $p/(1 - p)$ in (17) is due to the fact that the number of collisions suffered is geometrically distributed with parameter $p$.

The mean energy for one backoff counter decrement can be determined by a reasoning analogous to the one leading to (4) as

$$E_s = P_{succ} E_{succ} + P_{coll} E_{coll,l} + P_{empty} E_{empty}.$$

The probabilities, $P_{succ}, P_{coll}, P_{empty}$ are as in (5), so one just needs to calculate the corresponding mean energies. The energies $E_{succ}, E_{coll,l}, E_{empty}$ refer to the energy required for a backoff station to sense the channel in three different states: a) busy due to a successful transmission, b) busy due to a collision and c) idle due to an empty slot, respectively. By breaking up the time (6) into parts corresponding to the different power levels employed, the energy that a station needs to listen the whole successful transmission of a packet is

$$E_{succ} = \frac{1}{(1 - B_0)} \left[ \left( \frac{RTS + PHY_{hdr} + CTS + ACK}{r_{signal}} U_{tr} + \frac{E[L] + MAC_{hdr}}{r_{signal}} U_{rcv} + (3EIFS + DIFS) U_{sense} \right) + E_{slot}. \right]$$

Similarly, by breaking the time expressed by (3) into parts, a backoff station requires a mean amount of energy to listen to a collision on the channel equal to

$$E_{coll,l} = \frac{RTS}{r_{signal}} U_{tr} + (EIFS + t_{slot}) U_{sense}.$$

It can be observed that in the equation above, reception and sensing powers are used, instead of transmission and reception powers used in (18).

Finally, the energy to sense an empty channel involves only the sensing power level, so

$$E_{empty} = t_{slot} U_{sense}.$$  

Note that $E_{empty} = E_{dc} = E_{slot}$. At this point, one can insert the energies in (13) to assess the energy efficiency.

### IV. Numerical Results and Discussion

In this section, the proposed energy assessment framework is validated and compared to other existing modeling approaches. Our model is of high accuracy, even for the latest amendments of IEEE 802.11 standard. Furthermore, we are able to provide numerical results for non-standardized backoff window growth schemes too, showing that those schemes are also beneficial in terms of energy efficiency.

The IEEE 802.11 energy efficiency model has been validated by comparing analytical with simulation results. The simulation results were obtained with the help of ns-2 simulator [11], by exploiting a full detailed energy consumption implementation for IEEE 802.11 protocol [12].

The parameter values used in the simulations appear in Table I. These values correspond to IEEE 802.11g WLAN, in Direct-Sequence Spread Spectrum (DSSS) – Orthogonal Frequency-Division Multiplexing (OFDM) short preamble mode. Parameters for IEEE 802.11n (one spatial stream, with OFDM guard interval equal to 400 ns and data rate equal to 144 Mbps) are also provided inside parentheses, whenever their values differ. The power levels employed are those for the device [14]. While a multitude of devices exist, this choice facilitates the comparison with the numerical results of many other works.

FIG. 2. IEEE 802.11g energy efficiency vs. number of contending stations.

Fig. 2 demonstrates a perfect coincidence of analytical with simulation results for the IEEE 802.11 energy efficiency. Our model matches more closely the simulation results (cross marks) compared to the model proposed in [9]. This fact indicates the importance of considering the sensing power level (see Section III) and the consecutive successful transmissions from an IEEE 802.11 station. Sensing the shared channel during idle periods requires less power than in reception mode, as regarded in [9].

In energy efficiency, our model differs from the model in [9] up to 27%. To investigate which of the two factors is of
greater importance, in Fig. 3, we present the throughput derived from our model (which takes into account the geometric number of successful transmissions) and the throughput from the model in [4] (also used in [9]). Since the distance between the results of the two models is relatively small, we conclude that the introduction of the sensing power is the critical factor that attributes in the model accuracy for this setting.

The importance of the other factor is highlighted in IEEE 802.11n setting, where smaller initial backoff windows are used, increasing the probability of consecutive successful transmissions. Indeed, there is a greater mismatching on IEEE 802.11n throughput values between our model and the one in [4] (see Fig. 4). This mismatching has a more intensive impact on the corresponding energy efficiency in Fig. 5.

Finally, our model can be applied to investigate the effect of alternative backoff window growth schemes on the energy efficiency. More specifically, two different (linear with $\beta = 2$ and polynomial with $\beta = 1.8$ [10]) backoff growth mechanisms have been compared to the standardized binary window expansion. From Table II, we observe that the two alternative window growth schemes perform both better in throughput and energy efficiency.

<table>
<thead>
<tr>
<th>$n$</th>
<th>Throughput (Mbps)</th>
<th>Energy Efficiency (Mb/J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Linear</td>
<td>Polynomial</td>
</tr>
<tr>
<td>20</td>
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<td>0.345 (2.985%)</td>
</tr>
<tr>
<td>40</td>
<td>0.159</td>
<td>0.166 (4.033%)</td>
</tr>
<tr>
<td>60</td>
<td>0.102</td>
<td>0.107 (4.02%)</td>
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V. CONCLUSIONS AND FUTURE WORK

We have presented an analytical model for the IEEE 802.11 DCF energy consumption under saturation conditions. The model associates all the power state levels used by IEEE 802.11 standard and reflects accurately the energy expenditure during the backoff period. The numerical results demonstrate the accuracy and the universality of the methodology by adopting various backoff window growths.

As future work, the general principles of the methodology here (i.e., considering all power level states and the detailed backoff dynamics) will be applied in the context of non-saturated WLANs. This is not a simple task as the IEEE 802.11 station may have no data packets to transmit, therefore there is a need for an additional sleep power level.

REFERENCES