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RESEARCH ARTICLE

Energy efficiency and quality of service optimization for constant bit rate real-time applications in 802.11 networks

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ABSTRACT

In this paper, we propose a quality of service (QoS)-sensitive energy efficiency optimization mechanism for 802.11 networks on the basis of the dynamic and simultaneous adjustment of the content window (W) and retry attempts limit (r) of the media access control (MAC) sublayer. The use of both operational variables let us not only find the optimum operational point regarding energy efficiency but also attain a positive impact on the QoS, which improves the results obtained with current single-variable optimization strategies. The model under consideration includes external noise and does not impose the saturation condition in stations and as such is well suited for real-time industrial applications under noisy channels. Results obtained from simulation confirm the advantages of adjusting simultaneously W and r versus adjusting either one separately, obtaining a slight improvement in energy efficiency and resulting in less loss and delay at the MAC sublayer. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
802.11; QoS; energy; WiFi; retry limit

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1. INTRODUCTION

IEEE 802.11 wireless networks are experiencing widespread adoption far beyond consumer electronics, in industrial applications such as wireless networked control systems or sensor networks, where soft real-time applications such as event registration, measurement, slow control loop and multimedia are increasingly extended [1].

One of the main challenges to be faced when transmitting real-time data over WiFi is the provision of quality of service (QoS) and bandwidth guarantees. Current IEEE 802.11 standards cope with this, allowing the use of prioritized output queues that enable the protection of real-time traffic against background traffic, making current WiFi networks suitable for real-time applications such as VoIP [2,3] or non-critical control [4,5].

In addition to QoS, the other major challenge of WiFi communications is to prolong the battery life of the devices (e.g., sensors and smart phones) through efficient usage of the energy at the WiFi interface. In this respect, a number of energy saving techniques have been proposed in literature, including alternating between different radio interfaces [6], application-dependent cross-layer approaches for the power saving mode (PSM) [7] and, most notably, finding the best value of a media access control (MAC) sublayer operational variable (e.g., contention window size W or maximum retry attempts r) that maximizes energy efficiency. Interestingly, the use of MAC operational variables has also been independently suggested in the QoS-dimensioning research field to optimize bandwidth efficiency while meeting the QoS requirements of different real-time applications, most notably, delay in VoIP. Although QoS, bandwidth and energy efficiency are not independent, they have been traditionally studied as such, thereby failing to take advantage of the synergies of a common optimization strategy.

In this paper, we focus on the optimization of energy efficiency by adjusting the MAC operational variables in a scenario where stations generate periodic real-time constant bit rate uplink traffic via a noisy WLAN. The maximization of energy efficiency through the adjustment of either W or r has been addressed in literature over the past years. Most studies utilize Markov chains based models (e.g., Bianchi [8]) to obtain the probability of transmission in the channel τ, used afterward to develop an analytical expression for the energy efficiency that is subjected to optimization. Because both W and r have an impact on τ, state-of-the-art proposals have been focused on finding the best value of one of these parameters (normally the contention window W) that optimizes energy efficiency, whereas the other parameter is left at its default value [9–11]. Ideal channel and saturated traffic conditions are commonly assumed, facilitating mathematical tractability. However, these assumptions limit the applicability in more realistic scenarios where noise is likely to be present in the radio channel, and stations running real-time applications do not necessarily meet the saturation condition.

Similar but independent research efforts have been made in the QoS-bandwidth efficiency field, where either W ([12–18]) or r ([19]) has been used to find the value of τ that yields the maximum bandwidth efficiency in specific scenarios. Note that τ values leading to optimum bandwidth efficiency are close but not coincident to τ values that leads to optimum energy efficiency.

Because both W and r have influence on τ and on the QoS (e.g., longer W should increase the delay, whereas smaller r should increase the losses), we believe that the simultaneous use of both variables would provide us with an extra degree of freedom that will let us not only maximize energy efficiency but also minimize the negative impact of these parameters on the QoS.

We propose the use of a dynamic centralized algorithm that finds the W and r values that maximize energy efficiency while also seeking to minimize the negative impact on the QoS (e.g., delay and loss). Our proposal can be applied to industrial applications that collect information from WiFi sensors, soft control loops and unidirectional multimedia sessions such as surveillance monitoring or push-to-talk services. The main differences between our proposal and the state-of-the-art related research can be summarized as follows:

- Both energy efficiency and QoS are addressed in the optimization algorithm. Instead of finding the optimal value for only one MAC operational parameter (W or r), we find the combination of both (W and r) that maximizes energy efficiency and also has the most positive influence in the QoS.
- We consider a complex scenario that includes external noise dynamically changing and non-saturated traffic in the stations. In addition, we also include the use of PSM in our analysis.

2. SCENARIO UNDER STUDY

The scenario under consideration is composed by a set of n homogeneous stations sending real-time traffic via a noisy channel WLAN (Figure 1). Each station periodically generates packets of size $E[P]$ with frequency f_s to an access point (AP). The AP is a sink station that executes an algorithm that periodically estimates the probabilities of corruption, collision and packet error and finds the best values for all stations' MAC parameters W and r that represent the maximum energy efficiency and the best QoS possible at the same time. Both W and r are conveyed periodically to the stations, which adjust their MAC operational parameters accordingly. In order to work with prompt information, as required in control-related applications, we will assume a small buffer size in the stations. Note that we do not impose any restriction over the traffic generated by the stations (i.e., non-saturated condition) except for the AP that will generate occasional control packets whose effect can be neglected in our traffic model.

We will also consider that stations can use PSM to save energy. Finally, we will assume a small data packet size, which is likely to be the case in real-time applications and, as shown in [20], justifies the use of the basic rejection mode instead of the Request-to-Send/Clear-to-Send mode.

3. WIFI ANALYTICAL MODEL

This section is devoted to obtain analytical expressions for energy efficiency, delay and loss that are related with our control variables W and r via the probability of transmission in the channel τ. Our model will include the presence of external noise, stations using PSM and non-saturated condition.

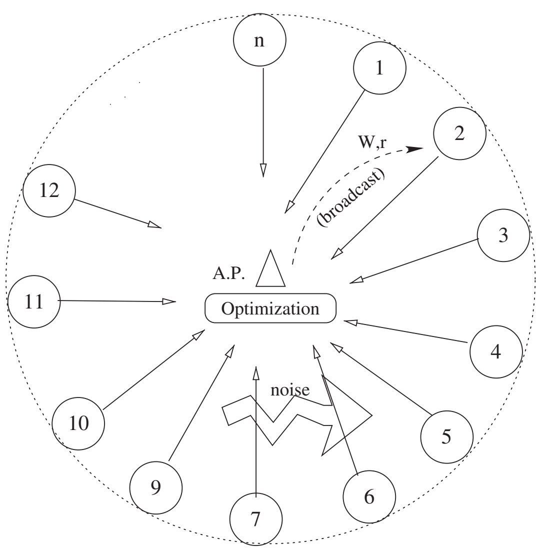

Figure 1. Scenario under study.

3.1. Transmission probability and slot duration

Bianchi in his seminar paper [8] defines a Markov chain based analytical expression for τ, which is refined in subsequent works to include effects such as noise and finite retry limit. In this paper, we adopt as primary τ expression the one in [21] that includes the existence of external noise, non-saturated condition (i.e., limited load) and finite number of retry attempts. For the sake of clarity, we reproduce this expression in Equation (1). The notation and the definition of the terms used follow.

$$\tau = \frac{2q(1-p_{\mathrm{eq}}^{r+1})(1-2p_{\mathrm{eq}})}{qW(1-p_{\mathrm{eq}})\left(1-(2p_{\mathrm{eq}})^{m+1}\right)+q(1-2p_{\mathrm{eq}})(1-p_{\mathrm{eq}}^{m+1})+qp_{\mathrm{eq}}^{m+1}(1-2p_{\mathrm{eq}})(2^mW+1)(1-p_{\mathrm{eq}}^{r-m}) \atop +2(1-p_{\mathrm{eq}})(1-2p_{\mathrm{eq}})(1-q)(1-p_{\mathrm{eq}}^{r})+2p_{\mathrm{eq}}^{r}(1-p_{\mathrm{eq}})(1-2p_{\mathrm{eq}})(1-q)} \tag{1}$$

p_{eq}: probability of error due to packet collision or corruption

$$p_{\mathrm{eq}} = p_{\mathrm{c}} + p_{\mathrm{e}} - p_{\mathrm{c}}p_{\mathrm{e}} \tag{2}$$

p_{e}: probability of packet corrupted due to channel errors
p_{c}: probability of packet collision

$$p_{\mathrm{c}} = 1-(1-\tau)^{n-1} \tag{3}$$

p_{t}: probability that at least one station is transmitting

$$p_{\mathrm{t}} = 1-(1-\tau)^{n} \tag{4}$$

p_{s}: probability of one successful transmission (i.e., only one station is using the channel)

$$p_{\mathrm{s}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{5}$$

W: minimum contention window size
r: maximum retry attempts
m: times that the contention window can be doubled
q: probability that one station has not an empty buffer; for small buffers, we can use the expression from Malone [22] (note that f_{s} is the packet generation frequency)

$$q = f_{\mathrm{s}}E[S_{\mathrm{ts}}] \tag{6}$$

The average slot duration $E[S_{\mathrm{ts}}]$ over which τ is estimated can be defined as

$$E[S_{\mathrm{ts}}] = (1-p_{\mathrm{t}})\sigma + p_{\mathrm{t}}(1-p_{\mathrm{s}})T_{\mathrm{c}} + p_{\mathrm{t}}p_{\mathrm{s}}(1-p_{\mathrm{e}})T_{\mathrm{s}} + p_{\mathrm{t}}p_{\mathrm{s}}p_{\mathrm{e}}T_{\mathrm{e}} \tag{7}$$

where σ is the slot time, T_{c}, T_{e} and T_{s} are the average times that the channel is sensed busy because of a collision, error-affected data frame transmission time and successful data frame transmission time, respectively, as in [23].

Finally, as carried out in [24,25], we will assume a constant window size (i.e., the window size is not duplicated after collisions) because the number of stations n is known and fixed. Consequently, for the remainder of this paper, the τ expression in Equation (1) will be simplified as follows:

$$\tau = \frac{2}{W+1+\frac{(1-q)(1-p_{\mathrm{eq}})}{q(1-p_{\mathrm{eq}}^{r+1})}} \tag{8}$$

3.2. Power consumption and energy efficiency

Analytical expressions of the energy efficiency can be profusely found in the literature. However, to the best of our knowledge, none of them are directly applicable to our scenario because of assumption mismatches such as saturation condition (i.e., $q = 1$) and/or ideal channels [26–32]. Thus, we have extended the expressions from [31] to include errors in the channel as well as limited load. In [31] the authors define the energy consumption of a station l for each of the following time slot types:

(1) idle, with probability $\tau(1-\tau)^n$
(2) successful reception of a packet destined to l, with probability $(1-p_{\mathrm{e}})\tau(1-\tau)^{n-1}$
(3) successful reception of a packet not destined to l, with probability $(1-p_{\mathrm{e}})(n-2)\tau(1-\tau)^{n-1}$
(4) reception of a collided packet, with probability $(1-\tau)(p_{\mathrm{c}}-(n-1)\tau(1-\tau)^{n-2})$
(5) successful transmission of a packet originated in l, with probability $(1-p_{\mathrm{e}})\tau(1-p_{\mathrm{c}})$
(6) colliding transmission of a packet originated in l, with probability τp_{c}

We have added the following types of time slot to include the effect of channel noise in the energy consumption:

(7) transmission of a packet originated in l that suffers corruption, with probability $p_{\mathrm{e}}\tau(1-p_{\mathrm{c}})$
(8) reception of a corrupted packet, with probability $p_{\mathrm{e}}\tau(n-1)(1-\tau)^{n-1}$

The new expression for the average energy consumption per average slot time $E[J_{\mathrm{st}}]$ is given by Equation (9), where J_σ, $J_{\mathrm{s}}^{\mathrm{rx}}(l)$, $J_{\mathrm{s}}^{\mathrm{rx}}(\sim l)$,$J_{\mathrm{c}}^{\mathrm{rx}}$, $J_{\mathrm{s}}^{\mathrm{tx}}$, $J_{\mathrm{c}}^{\mathrm{tx}}$, $J_{\mathrm{e}}^{\mathrm{tx}}$ and $J_{\mathrm{e}}^{\mathrm{rx}}$ represent the energy consumption associated to the possible aforementioned events that can happen during a slot duration (see Equation (7)) and are defined in Equation (10). Observe that ρ_σ, ρ_{rx} and ρ_{tx} are the hardware-dependent power coefficient in the transmission, idle, reception and transmission states, respectively; T_{DATA} represents the transmission time of a data packet; T_{ACK} the transmission time of an ACK frame and δ stands for the propagation delay whose values are copied from [31].

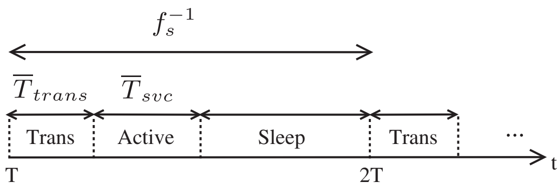

Figure 2. Power saving mode consumption diagram.

$$
\begin{aligned}
E[J_{\text{ts}}] = {} & (1-\tau)^n J_\sigma + (1-p_{\text{e}})\tau(1-\tau)^{n-1} J_{\text{s}}^{\text{rx}}(l) + (1-p_{\text{e}})(n-2)\tau(1-\tau)^{n-1} J_{\text{s}}^{\text{rx}}(\sim l) \\
& + p_{\text{e}}(n-1)\tau(1-\tau)^{n-1} J_{\text{e}}^{\text{rx}} + (1-\tau)(p_{\text{c}} - (n-1)\tau(1-\tau)^{n-2}) J_{\text{c}}^{\text{rx}} + (1-p_{\text{e}})\tau(1-p_{\text{c}}) J_{\text{s}}^{\text{tx}} \\
& + p_{\text{e}}\tau(1-p_{\text{c}}) J_{\text{e}}^{\text{tx}} + \tau p_{\text{c}} J_{\text{c}}^{\text{tx}}
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
J_\sigma &= \rho_\sigma \text{SLOT} \\
J_{\text{s}}^{\text{rx}}(l) &= \rho_{\text{rx}} T_{\text{DATA}} + \rho_\sigma(\text{SIFS} + \delta) \\
&\quad + \rho_{\text{tx}} T_{\text{ACK}} + \rho_\sigma(\delta + \text{DIFS}) \\
J_{\text{s}}^{\text{rx}}(\sim l) &= \rho_{\text{rx}} T_{\text{DATA}} + \rho_\sigma(\text{SIFS} + \delta) \\
&\quad + \rho_{\text{rx}} T_{\text{ACK}} + \rho_\sigma(\delta + \text{DIFS}) \\
J_{\text{c}}^{\text{rx}} &= \rho_{\text{rx}} T_{\text{DATA}} + \rho_\sigma(\text{EIFS} + \delta) \\
J_{\text{s}}^{\text{tx}} &= \rho_{\text{tx}} T_{\text{DATA}} + \rho_\sigma(\text{SIFS} + \delta) \\
&\quad + \rho_{\text{rx}} T_{\text{ACK}} + \rho_\sigma(\delta + \text{DIFS}) \\
J_{\text{c}}^{\text{tx}} &= \rho_{\text{tx}} T_{\text{DATA}} + \rho_\sigma(\text{EIFS} + \delta) \\
J_{\text{e}}^{\text{tx}} &= J_{\text{c}}^{\text{tx}} \\
J_{\text{e}}^{\text{rx}} &= J_{\text{c}}^{\text{rx}}
\end{aligned} \tag{10}
$$

Expressions for the energy consumption either in active mode or the PSM can be obtained using the newly defined $E[J_{\text{st}}]$ as follows.

Average power consumption in active mode: It can be defined as the energy consumption carried out by the WiFi card by time unit. Using the average power consumption by time slot (Equation (9)) and the average slot duration (Equation (7)), we obtain

$$\overline{P} = \frac{E[J_{\text{ts}}]}{E[S_{\text{ts}}]} \tag{11}$$

Average power consumption in power saving mode: We assume that stations only wake up when a new package is received from the upper layer and go back to sleep after the packet is successfully transmitted (ACK is received) or discarded (ACK timeout). Because packets are periodically generated, we can analyze a basic transmission cycle such as the one illustrated in Figure 2. Each cycle can be broken down into three phases: sleep-to-active transition, active and sleep.[†] The transition phase duration $\overline{T}_{\text{trans}}$ and its associated power consumption ρ_{trans} have been studied in [34], and we adopt its duration and power values. The average time in active state $\overline{T}_{\text{svc}}$ (average service time) can be expressed as

$$
\begin{aligned}
\overline{T}_{\text{svc}} = {} & \left\{ \sum_{i=0}^{r} p_{\text{eq}}^{i} \left(i T_{\text{c}} + \sum_{j=0}^{i} \overline{W}_j E[S_{\text{ts}}] + T_{\text{s}} \right) \right. \\
& \left. + p_{\text{eq}}^{r+1} \left[(r+1) T_{\text{c}} + \sum_{j=0}^{r} \overline{W}_j E[S_{\text{ts}}] \right] \right\} \\
& \Big/ \sum_{j=0}^{r+1} p_{\text{eq}}^{j}
\end{aligned} \tag{12}
$$

where the time until ACK reception or timeout has been included. After the active stage, the station will be in sleep mode for the rest of the time left in this cyclic period (i.e., $f_{\text{s}}^{-1} - \overline{T}_{\text{trans}} - \overline{T}_{\text{svc}}$). The power consumption associated to the sleep mode will be notated by ρ_{sleep}.

Consequently, we can express the average power as

$$
\begin{aligned}
\overline{P}^{\text{psm}} = {} & \overline{P} \cdot f_{\text{s}} \overline{T}_{\text{svc}} + (\rho_{\text{trans}} - \rho_{\text{sleep}}) f_{\text{s}} \overline{T}_{\text{trans}} \\
& + \rho_{\text{sleep}} (1 - f_{\text{s}} \overline{T}_{\text{svc}})
\end{aligned} \tag{13}
$$

It is also useful to re-write the expression of $E[J_{\text{st}}]$ for the PSM case. Using Equations (7) and (13), we obtain

$$
\begin{aligned}
E[J_{\text{ts}}]^{\text{psm}} = {} & E[J_{\text{ts}}] \cdot f_{\text{s}} \overline{T}_{\text{svc}} + E[S_{\text{ts}}](\rho_{\text{trans}} - \rho_{\text{sleep}}) \\
& \cdot f_{\text{s}} \overline{T}_{\text{trans}} + \rho_{\text{sleep}} E[S_{\text{ts}}](1 - f_{\text{s}} \overline{T}_{\text{svc}})
\end{aligned} \tag{14}
$$

Energy efficiency: Energy efficiency can be defined as the number of bits successfully sent by energy unit per station. Accordingly, we can define it as

$$E_{\text{ef}} = \frac{p_{\text{t}} p_{\text{s}} (1 - p_{\text{e}}) E[P]}{E[J_{\text{ts}}] \cdot n} \tag{15}$$

When PSM is used, we can re-write the previous expression as

$$E_{\text{ef}}^{\text{psm}} = \frac{p_{\text{t}} p_{\text{s}} (1 - p_{\text{e}}) E[P]}{E[J_{\text{ts}}]^{\text{psm}} \cdot n} \tag{16}$$

[†]The active to sleep transition will not be considered because its impact on the energy consumption is negligible as shown in [33].

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3.2.1. Quality of service metrics: delay and loss in the media access control sublayer

Delay and loss are important in the context of real-time applications. Both QoS parameters can be related to the previous analytical expressions as follows:

Average delay: The average access delay can be related to the service time defined in Equation (12). In fact, we can identify two terms in that expression: the time spent transmitting packets that successfully arrive at their destination and the time spent transmitting packets that end up discarded. The average delay can then be obtained accounting only the first term as follows:

$$\overline{D} = \frac{\sum_{i=0}^{r} p_{\mathrm{eq}}^{i}\left(iT_{\mathrm{c}} + \sum_{j=0}^{i} \overline{W}_j E[S_{\mathrm{ts}}] + T_{\mathrm{s}}\right)}{\sum_{j=0}^{r+1} p_{\mathrm{eq}}^{j}} \quad (17)$$

where $\overline{W}_j$ stands for the average window size, which in our case (i.e., $m = 0$) is

$$\overline{W}_j = \frac{W-1}{2} \quad (18)$$

Packet loss: The loss probability can be defined as the ratio between the number of packets unreceived and the total number of packets generated as

$$P_{\mathrm{loss}} = 1 - \frac{S}{nf_{\mathrm{s}}E[P]} \quad (19)$$

where $E[P]$ is the average packet size and S stands for the throughput, which basically depends on τ and can be expressed as

$$S = \frac{p_{\mathrm{t}}p_{\mathrm{s}}(1-p_{\mathrm{e}})E[P]}{(1-p_{\mathrm{t}})\sigma + p_{\mathrm{t}}(1-p_{\mathrm{s}})T_{\mathrm{c}} + p_{\mathrm{t}}p_{\mathrm{s}}(1-p_{\mathrm{e}})T_{\mathrm{s}} + p_{\mathrm{t}}p_{\mathrm{s}}p_{\mathrm{e}}T_{\mathrm{e}}} \quad (20)$$

To conclude this section, we recap on the analytical expressions presented and their relationship with τ in Figure 3. It can be observed that our control variables W and r both have influence on τ, which in turn has a decisive impact on the energy efficiency, losses and delay in the MAC sublayer.

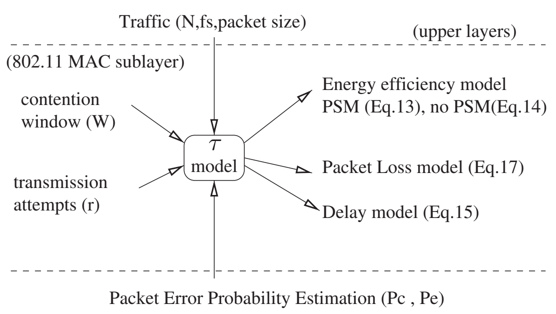

Figure 3. Relationship map between the control variables W and r and the analytical models used.

4. ALGORITHM FOR OPTIMIZATION

Before describing our optimization strategy, it is worthy to have a look at Figure 4, which is a sketch of the curve that relates energy efficiency and τ. Energy efficiency optimization problems seek the obtention of the τ value that yields the peak of energy efficiency ($\tau_{\mathrm{opt}}^{\mathrm{e}}$) by setting one MAC control variable, usually W, to an optimum value, while the other variable, r, is left at its default value [9]. We also address this maximum energy efficiency problem, but our goal also includes attaining the most positive influence possible in QoS.

Observe that reaching $\tau_{\mathrm{opt}}^{\mathrm{e}}$ is not always possible because τ also depends on the traffic load (see Equation (1) and Figure 3) which in turn, is related to the inter-packet generation rate f_{s} of the stations.[‡] Thus, as shown in Figure 4, there will be a minimum threshold for f_{s}, namely f_0, that will determine whether $\tau_{\mathrm{opt}}^{\mathrm{e}}$ is attainable by at least one combination of W and r values. This fact led us to consider two different optimization strategies accordingly:

- *Low-load* conditions ($f_{\mathrm{s}} < f_0$). In this case, τ will always be less than $\tau_{\mathrm{opt}}^{\mathrm{e}}$; therefore, the maximum energy efficiency is not reachable. Our strategy will be increasing τ to obtain as close as possible to the maximum value of energy efficiency. We will do this by reducing W to the minimum possible and increasing r as long as it is helpful to reduce the packet error probability. Because under low-load conditions delay is small, our QoS goal will be to reduce the losses attributable mainly to the external noise by increasing r.
- *Medium/high load* conditions ($f_{\mathrm{s}} \geq f_0$). In this case, it is always possible to find at least one combination of W and r that yields $\tau = \tau_{\mathrm{opt}}^{\mathrm{e}}$. Out of all the possible W and r combinations that yield $\tau = \tau_{\mathrm{opt}}^{\mathrm{e}}$, we will have the one with lower r value, for it will also provide less delay, which will be our QoS goal.

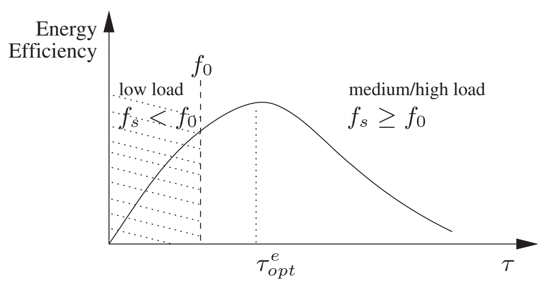

Figure 4. Sketch of the energy efficiency as a function of τ.

[‡]Note that our scenario assumes that stations are registered in the AP and thereby, parameters such as f_{s}, N and packet size $E[P]$ are constant and inputs to our algorithm.

Note that τ also depends on the packet error probability $p_{\rm eq}$, which in turn depends on $p_{\rm e}$ (i.e., corruption probability due to external noise) and $p_{\rm c}$ (i.e., collision probability). Because noise dynamically changes, $p_{\rm eq}$ has to be periodically inferred as indicated in Figure 5, and consequently, our algorithm will have to be periodically executed. A new estimation cycle starts each time that $N_{\rm samples}$ frames have traversed the AP.

4.1. Algorithm

As shown in Figure 5, our algorithm exhibits two sequential phases: (i) $p_{\rm eq}$ *estimation* for the present cycle and (ii) *W&r calculation*. The first phase will use the observation of the traffic that traversed the AP in the past cycle to obtain an estimation of $p_{\rm eq}$ valid for the current cycle. The second phase uses the newly updated value of $p_{\rm eq}$ to update the value of f_0 and find the optima values of W and r according to our optimization strategy. The main steps of the algorithm can be expressed through the flow diagram shown in Figure 6.

In the first time the algorithm is executed, it starts with an initiation phase where some constants used afterward will be calculated. Then, the two aforementioned phases are executed. The algorithm finishes broadcasting the resulting W and r values to stations. It follows a detailed description of each step of the algorithm.

4.1.1. Initialization

The algorithm takes a number of constant values that will not change between executions. Most of these values are known such as the number of stations n, the station's packet generation rate $f_{\rm s}$ or some administratively defined values such as the minimum window size ($W_{\rm min}$), minimum value for the retry limit (r_0),[§] or the limit of valuable improvement in the packet loss $\Delta_{\rm min}$.

Calculation of $\tau_{\rm opt}^{\rm e}$. One key value that will also remain constant is the τ value that maximizes the energy efficiency $\tau_{\rm opt}^{\rm e}$. We have developed a new analytical expression for $\tau_{\rm opt}^{\rm e}$ that extends the one in [9] to noisy channels and finite buffers. To obtain $\tau_{\rm opt}^{\rm e}$, we simply solve $\mathrm{d}E_{\rm ef}/\mathrm{d}\tau = 0$ using the expression of $E[J_{\rm ts}]$ shown in Equation (9). After setting the first derivative equal to zero, we obtain

$$(p_{\rm e}-1)E[P](1-\tau)^n\Big[-J_\sigma(1-\tau)^n + J_{\rm c}^{\rm tx}(n-1)\tau^2 + J_{\rm c}^{\rm rx}(-1+(1-\tau)^n - n(\tau-1)\tau+\tau^2)\Big] = 0 \qquad (21)$$

Observe that $p_{\rm e}$ can be suppressed from the previous expression ($E[P]$ could also be suppressed, albeit it is

§These values can be readily calculated if the number of stations is known.

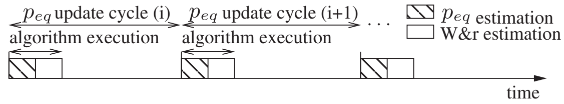

Figure 5. Periodic execution of the algorithm in the access point.

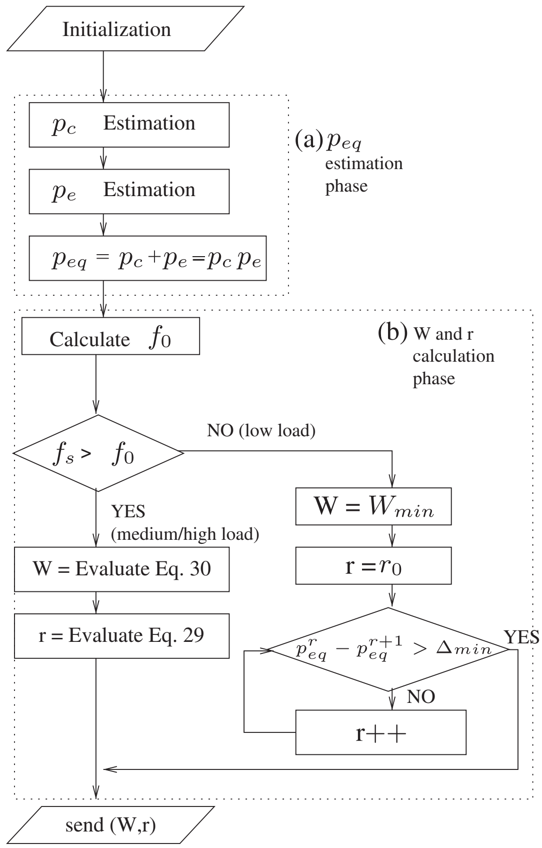

Figure 6. Proposed optimization algorithm.

included in the expression of the consumption). Those terms of τ of order higher than 2 can be considered negligible because $\tau \ll 1$, obtaining the following expression:

$$\frac{1}{2}\Big[-2J_{\rm c}^{\rm tx} + J_{\rm c}^{\rm rx}(n-2)(n-1) + 2n(J_{\rm c}^{\rm tx} + J_\sigma - 2J_\sigma n)\Big]\tau^2 + 2n\tau J_\sigma - J_\sigma = 0 \qquad (22)$$

Solving the previous equation and re-arranging, we obtain

$$\tau_{\rm opt}^{\rm e} = \frac{1}{n + \frac{\sqrt{J_\sigma(n-1)(2J_{\rm c}^{\rm tx}+(n-2)J_{\rm c}^{\rm rx}-2nJ_\sigma)}}{\sqrt{2}J_\sigma}} \qquad (23)$$

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Note that the previous expression does not depend on the error probability, and hence, $\tau_{\text{opt}}^{\text{e}}$ will remain constant along subsequent executions of the algorithm.

4.1.2. p_{eq} Estimation phase

The algorithm starts with a phase that estimates p_{eq} or, equivalently, p_{c} and p_{e}, by inspecting the traffic that has traversed the AP during the last estimation interval. The estimation of the p_{eq} components is as follows:

- The collision probability (p_{c}) depends on the number of stations n and the transmission probability τ (see Equation (3)). The latter can be directly estimated by monitoring the number of consecutive idle slots (n_{idle}) between packet transmissions as indicated in [35]:

$$\tau = 1 - \left(\frac{\overline{n}_{\text{idle}}}{1+\overline{n}_{\text{idle}}}\right)^{1/n} \tag{24}$$

Substituting the previous expression in Equation (3), we obtain

$$p_{\text{c}} = 1 - \left(\frac{\overline{n}_{\text{idle}}}{1+\overline{n}_{\text{idle}}}\right)^{\frac{n-1}{n}} \tag{25}$$

- The packet error probability p_{e} depends on τ (which is known) and the throughput S (see Equation (17)). The latter can be readily measured by counting the bytes that traverse the AP during a period of observation. Consequently, re-arranging the expression of Equation (17), we have

$$p_{\text{e}} = \frac{(1-p_{\text{t}})\sigma + p_{\text{t}}(1-p_{\text{s}})T_{\text{c}} + p_{\text{t}}p_{\text{s}}\left(T_{\text{s}} - E[P]/S\right)}{p_{\text{t}}p_{\text{s}}\left(T_{\text{s}} - T_{\text{e}} - E[P]/S\right)} \tag{26}$$

We assume that the values measured for $\widehat{n}_{\text{idle}}$ and $\widehat{S}$ after the end of an estimation interval (i) will be repeated in the next interval ($i+1$) with a correction given by an exponential smoothing filter with parameter α as follows:

$$\begin{cases} \widehat{n}_{\text{idle}}(i+1) &= \alpha\widehat{n}_{\text{idle}}(i) + (1-\alpha)\tilde{n}_{\text{idle}}(i) \\ \widehat{S}(i+1) &= \alpha\widehat{S}(i) + (1-\alpha)\tilde{S}(i) \end{cases} \tag{27}$$

Finally, we use p_{c} and p_{e} to compute the probability p_{eq} by using Equation (2). Figure 7 shows a simulation of the p_{eq} estimator performance under time-varying packet error probability (three steps at 0, 10 and 20 s) for a scenario with 10 stations and $f_{\text{s}} = 50$ packets/s. The smoothing factor used is $\alpha = 0.999$, and the number of samples per interval is set to 100. As shown in the figure, our proposed estimator for p_{eq} follows closely theoretical noise dynamic set in the simulation.

4.1.3. W&r calculation phase

As stated earlier, the optimization strategy followed depends on the relationship between f_{s} and f_0. Hence, this phase starts updating the value of the threshold frequency f_0. To do this, we can substitute f_{s} from Equation (6) in our simplified τ expression (see Equation (8)). Then, the maximum τ value (i.e., using the maximum r possible and minimum W possible) that yields $\tau_{\text{opt}}^{\text{e}}$ would be given by the frequency:

$$f_0 = \frac{2(1-p_{\text{eq}})}{E[S_{\text{ts}}]\cdot\left(\left(1-p_{\text{eq}}^{r_{\max}+1}\right)\left(2\tau_{\text{opt}}^{-1} - W_{\min} - 1\right) + 2(1-p_{\text{eq}})\right)} \tag{28}$$

If $f_{\text{s}} \geq f_0$, then it is possible to find a combination of W and r that yields $\tau_{\text{opt}}^{\text{e}}$ (i.e., medium/high load conditions); otherwise, $\tau_{\text{opt}}^{\text{e}}$ will not be reachable (i.e., low-load conditions).

Medium/high load case. Out of all the possible combinations of W and r that yield $\tau_{\text{opt}}^{\text{e}}$, we will select the one that exhibits the lowest limit of retransmission attempts

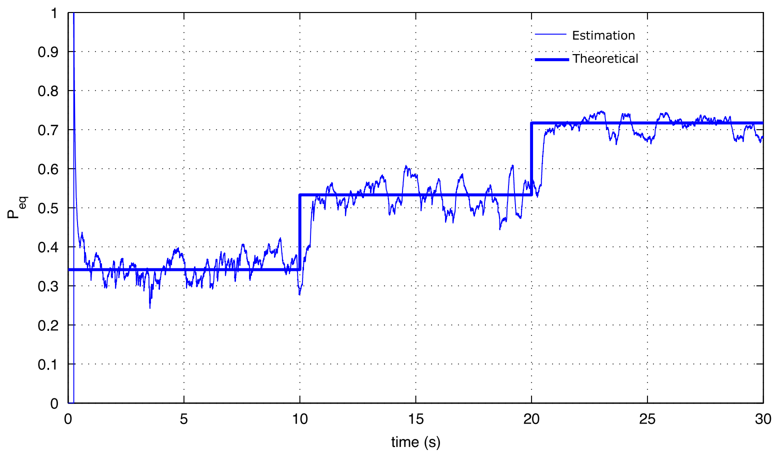

Figure 7. Run time exponential smoothing estimate of the equivalent packet error probability p_{eq}.

($r_{\min}$) for it will also minimize the delay. Because $W_{\min}$ would provide us with the maximum τ value possible, the minimum r that allows to obtain $\tau_{\mathrm{opt}}^{\mathrm{e}}$ can be found from Equation (8) as

$$r_{\min} = \left\lceil \frac{\ln\left(1 - \frac{2(1-f_{\mathrm{s}}\cdot E[S_{\mathrm{ts}}])(1-p_{\mathrm{eq}})}{f_{\mathrm{s}}\cdot E[S_{\mathrm{ts}}](2\tau_{\mathrm{opt}}^{-1}-W_{\min}-1)}\right)}{\ln(p_{\mathrm{eq}})} - 1 \right\rceil \quad (29)$$

Once we have set r, the W value that yields $\tau_{\mathrm{opt}}^{\mathrm{e}}$ can be readily obtained from Equation (8) as

$$W_{\mathrm{opt}} = \max\left(W_{\min}, \frac{2}{\tau_{\mathrm{opt}}} - 1 - \frac{2(1-q)(1-p_{\mathrm{eq}})}{q(1-p_{\mathrm{eq}}^{r_{\min}+1})}\right) \quad (30)$$

Thus, the values $W = W_{\mathrm{opt}}$ and $r = r_{\min}$ will be sent to the stations.

Low-load case. Under low-load conditions, delay is small, and losses are mainly because of external noise. In this case, the traffic generated is insufficient to attain $\tau_{\mathrm{opt}}^{\mathrm{e}}$. Observe that τ increases as W decreases and/or r increases. Thus, we will try to increase τ as much as possible toward $\tau_{\mathrm{opt}}^{\mathrm{e}}$ by means of setting W to the minimum window size possible $W_{\min}$ and increasing r as long as it is helpful to reduce the losses due to noise. The increasing process will stop when the difference between p_{eq}^{r} and p_{eq}^{r+1} reaches a threshold $\Delta_{\min}$ (i.e., $\Delta = p_{\mathrm{eq}}^{r} - p_{\mathrm{eq}}^{r+1}$), increasing r by one as long as $\Delta > \Delta_{\min}$.

Therefore, r will be set to the resultant value from the previous procedure, and W will be set to $W_{\min}$.

4.2. Algorithm complexity

The time-complexity of our algorithm is determined by the p_{eq} estimation phase, where up to N_{samples} observations have to be evaluated for each p_{eq} component (i.e., p_{c} and p_{e}). This same complexity of $O(c N_{\mathrm{samples}})$ is exhibited by related works when c variables are dynamically estimated (e.g., $c = 2$ [14,16,23], $c = 1$ [19,24,36]). The computation of W and r offers a constant complexity, and the actual execution time will depend on the expressions evaluated. Evaluating r in addition to W only requires the evaluation of Equation (29) or the loop that increases r until the error probability improvement is small enough. However, the latter loop can be considered to have an upper limit of 10 in practice.

As shown in Figure 5, the algorithm is re-executed periodically after each p_{eq} update cycle. One key aspect for the feasibility of the implementation is that the algorithm execution time is significantly shorter than any update interval (e.g., $N_{\mathrm{samples}}/(f_{\mathrm{s}}\cdot n)$ in the shortest case). We have tested this by running our algorithm written in C language in a DELL Vostro 1000 laptop (CPU Athlon 64 X2, 1.7 GHz) (Dell Inc., One Dell Way, Round Rock, Texas 78682 USA), obtaining an execution time 10^4 times shorter than the shortest cycle duration, which offers a significant margin for APs with a slower processor.

5. NUMERICAL RESULTS

This section compares the results obtained with our optimization algorithm (W&r optimization) versus the energy efficiency optimization in [9] (W-only optimization) and the 802.11 standard default values for W and r. Observe that W-only optimization [9] assumes saturated condition in stations and absence of noise (i.e., f_{s} and p_{eq} are ignored).

5.1. Simulation scenario

Results have been obtained with Opnet simulator (v14.5) (OPNET Technologies, Inc. 7255 Woodmont Avenue Bethesda, MD 20814) complemented with the following modules:

- A new module for energy measurement has been created and connected to the physical layer of the stations. This module accounts for the time spent on each possible state of the WiFi card (e.g., tx, rx, idle or sleep for PSM) and the corresponding transitions. The collected statistics are later multiplied by the respective power coefficients to obtain the energy consumption of the station.
- The MAC sublayer of the AP node has been connected to a new module that implements noise estimation such as that described in the previous section. The output of this noise estimator (i.e., p_{c} and p_{e}) is in turn connected to another module that implements the optimization algorithm under study. The output of the optimization algorithm will be automatically read by all stations that will adjust their operational parameters W and r accordingly.

The scenario of the simulation is described in Figure 1 where n stations periodically send packets to a central AP. The traffic generation parameters used in stations are shown in Table I and represent a traffic pattern likely found in real-applications (e.g., 80 B every 40 ms) such as state monitoring in a sensor network. For the noise estimation module, the smoothing factor used is $\alpha = 0.999$ and the number of samples per estimation interval (N_{samples}) is set to 100. The duration of simulations was 300 s, and results presented represent average values. The scenario and the new modules implemented can be downloaded from [37].

5.2. Simulation results

Because the accuracy of our algorithm relies on the proper estimation of p_{c} and p_{e}, we would like to start with results related to the performance of the noise estimator. Figures 8(a) and 8(b) show the values of p_{e} and p_{c} obtained by our estimator module in a 20-station simulation scenario arranged with different values of corruption probability due to channel errors. It can be observed that the estimated p_{e} is very close to the value set in the simulation scenario, and the estimated p_{c} also follows closely

Table I. Network parameters for simulation of IEEE 802.11b standard.

Parameter	Value
Packet size	80 B
Buffer size	1
f_s	25 pkt/s
R_b	1 Mbit/s
PHY	192 μs
MAC	28 B
ACK	14 B
SLOT	20 μs
DIFS	50 μs
SIFS	10 μs
EIFS	364 μs
ρ_σ, ρ_{rx}, ρ_{tx} and ρ_{psm}	0.11, 0.9, 2.5 and 0.02 W
CW_{min}	32
CW_{max}	1024
r	5
m	5

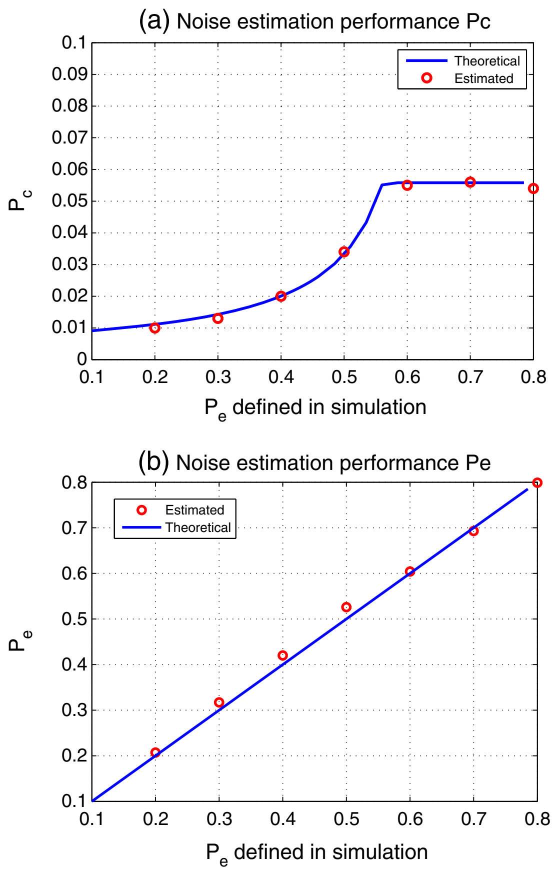

Figure 8. Performance of the noise estimator module.

the theoretical value. This let us conclude that our noise estimator module is accurate.

Figure 9 shows the energy efficiency obtained by 20 stations with (a) and without (b) PSM for different probabilities of corruption due to external noise (p_e). It can be noticed that our $W\&r$ optimization proposal attains always higher efficiency than either the W-only optimization or 802.11 standard default values. The differences are more noticeable when PSM is used, for the lower MAC sublayer delay achieved by our proposal produced more time spent in sleep state. The worst results are obtained by the W optimization, which can be attributed to its noise insensitiveness, utilizing in all cases the W value that yields τ^e_{opt} and assuming saturation condition in stations, which give rise to high W values.

Figure 10 shows the QoS performance obtained by each approach. The packet loss displayed in Figure 10(a) shows that our $W\&r$ proposal exhibits similar results than the 802.11 standard default values but better than the W-only. The default W and r values from the 802.11 standard exhibit a small improvement in packet loss for $p_e = 0.2$ than our proposal. This can be traced back to the fact that τ is set to reach the maximum throughput possible that is slightly bigger than τ^e_{opt}. After that point, both approaches exhibit very similar results. Nevertheless, as shown in Figure 10(b), our $W\&r$ proposal exhibits lower delay than either W-only or default values approaches in every range of p_e. This is well suited for real-time multimedia or control applications, which are very sensitive to delay. Moreover, as suggested earlier, lower delay implies that stations can go to sleep earlier and save energy. In addition, real-time applications need a fast convergence with changes in external noise. Figure 11 illustrates how delay and energy efficiency adapt to changes produced by a step in p_e (from 0.3 to 0.5 between simulation times 50 and 100 s) in a 20-station scenario. It can be observed that our $W\&r$ proposal reacts to a quick change in p_e, and the degradation suffered in both delay and energy efficiency is smaller than in the other two approaches. Also, it can be observed that our two-variable control proposal achieves more stability (i.e., less variability from the average) than the rest, which is also positive for meeting QoS guarantees in real-time communications.

Finally, Figure 12 shows how energy efficiency (a),(b); loss (c); and delay (d) vary with the number of stations (n) for $p_e = 0.5$. Observe that again our proposed $W\&r$ algorithm exhibits higher efficiency and better QoS behavior than the rest for all n. Note that, as expected, delay and loss increase with the number of stations. However, the energy efficiency decreases with n, which can be attributed to an increment in the collision probability (p_c) with the number of stations n.

6. CONCLUSIONS

We have presented a new strategy for IEEE 802.11 energy efficiency optimization that dynamically adjusts the values of W and r in the stations to optimize the energy efficiency while minimizing the negative impact on the QoS. The extra degree of freedom offered by simultaneously using both W and r offers better performance than other approaches such as W-only or using the 802.11 default values.

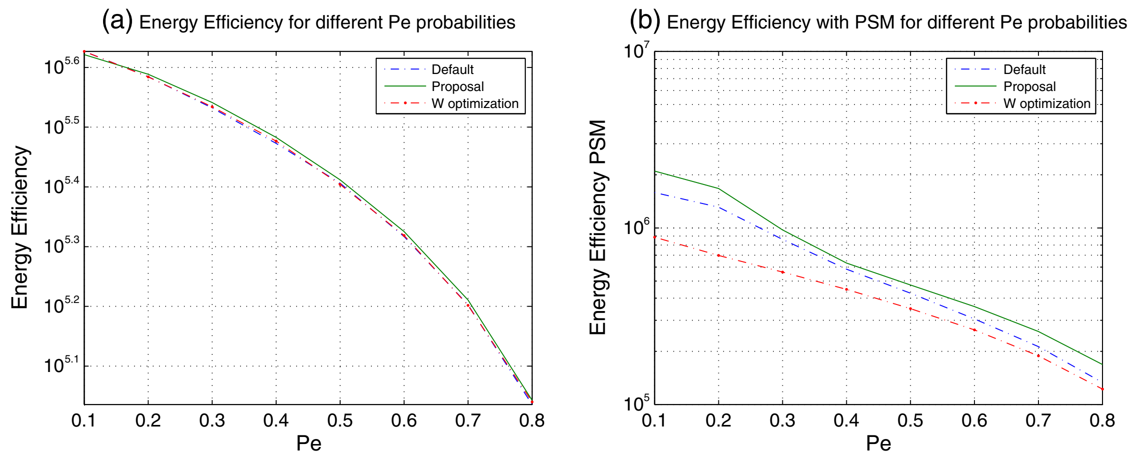

Figure 9. Variation of energy efficiency with (a) and without PSM (b) with the external noise (P_e) for $n = 20$.

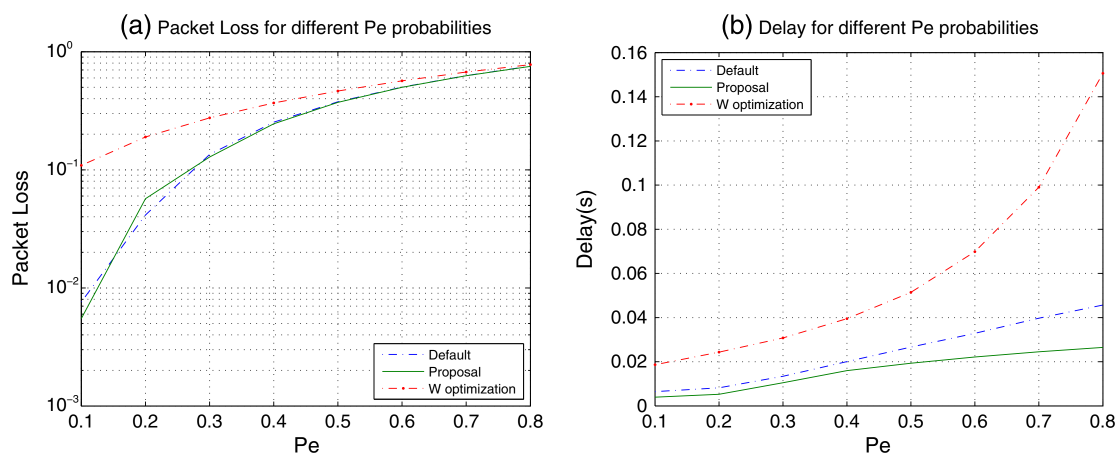

Figure 10. Variation of loss (a) and delay (b) with the external noise (P_e) for $n = 20$.

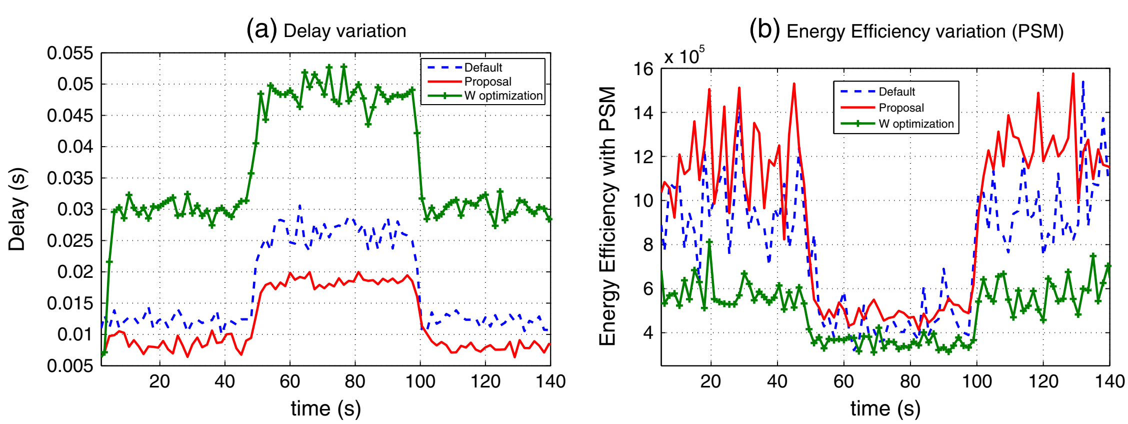

Figure 11. Variation of delay (a) and energy efficiency (b) obtained throughout the simulation.

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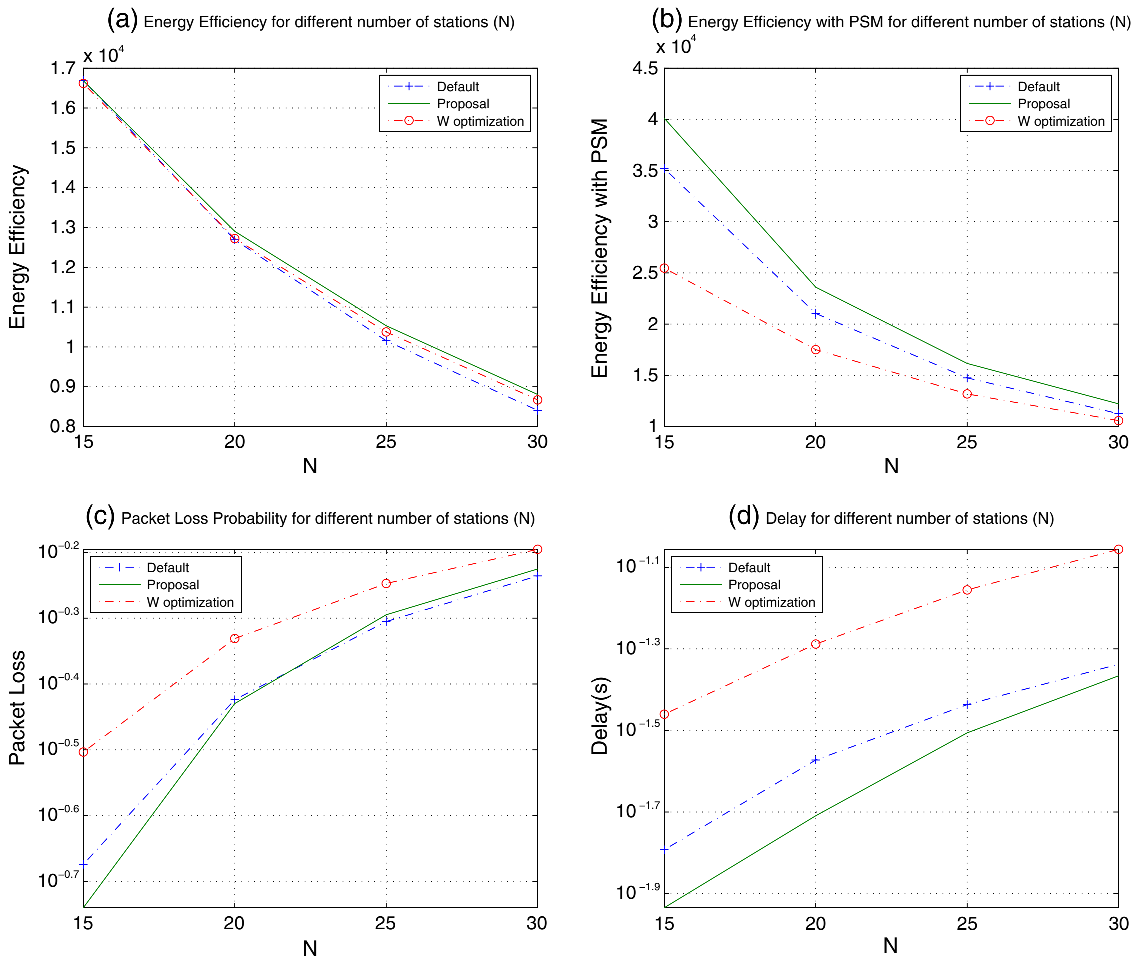

Figure 12. Variation of energy efficiency with (a) and without PSM (b) and loss (c) and delay (d) with the number of stations n for $p_e = 0.5$.

The scenario of application includes noisy channel and non-saturation, which is well suited for industrial real-time applications where external noise is typically present and stations are not necessarily in saturated conditions. Further work includes the extension of our scenario to include background traffic, bidirectional traffic or heterogeneous terminals.

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REFERENCES

1. Willig A, Matheus K, Wolisz A. Wireless technology in industrial networks. *Proceedings of the IEEE* 2005; **93**(6): 1130–1151.
2. Shin S, Schulzrinne H. Measurement and analysis of the VoIP capacity in IEEE 802.11 WLAN. *IEEE Transactions on Mobile Computing* 2009; **8**(9): 1265–1279. DOI: 10.1109/TMC.2009.49.
3. Havinga PJM, Smit GJM. Energy-efficient wireless networking for multimedia applications. *Wireless Communications and Mobile Computing* 2001; **1**(2): 165–184.
4. Cena G, Bertolotti I, Valenzano A, Zunino, C. Evaluation of response times in industrial WLANs. *IEEE Transactions on Industrial Informatics* 2007; **3**(3): 191–201. DOI: 10.1109/TII.2007.903219.
5. Boggia G, Camarda P, Grieco L, Zacheo G. Toward wireless networked control systems: an experimental study on real-time communications in 802.11 WLANs, In *IEEE International Workshop on Factory Communication Systems, 2008. WFCS 2008*, Dresden, Germany, 2008; 149–155, DOI: 10.1109/WFCS.2008.4638711.

6. Pering TGR, Agarwal Y. CoolSpots: reducing the power consumption of wireless mobile devices with multiple radio interfaces, In *4th International Conference on Mobile Systems, Applications, and Services*, Uppsala, Sweden, 2006; 220–232, DOI: 10.1109/ICC.2007.73.
7. Tsao SL, Huang CH. An energy-efficient transmission mechanism for VoIP over IEEE 802.11 WLAN. *Wireless Communications & Mobile Computing* 2009; **9**: 1629–1644. DOI: 10.1002/wcm.v9:12.
8. Bianchi G. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE Journal on Selected Areas in Communications* 2000; **18**(3): 535–547.
9. Serrano P, Garcia-Saavedra A, Hollick M, Banchs A. On the energy efficiency of IEEE 802.11 WLANs, In *2010 European Wireless Conference (EW)*, Lucca, Italy, 2010; 932–939.
10. Liu J, Yuan D, Ci S, Zhong Y. Nonlinear optimization for energy efficiency in IEEE 802.11a wireless LANs. *Computer Communications* 2006; **29**(17): 3455–3466.
11. Wang X, Agrawal DP. Analysis and optimization of energy efficiency in 802.11 distributed coordination function, In *IEEE International Conference on Performance, Computing, and Communications 2004*, 2004; 707–712.
12. Hegde N, Proutiere A, Roberts J. Evaluating the voice capacity of 802.11 WLAN under distributed control, In *The 14th IEEE Workshop on Local and Metropolitan Area Networks, 2005. LANMAN 2005*, Chania, Greece, 2005; p. 6, DOI: 10.1109/LANMAN.2005.1541525.
13. Calì F, Conti M, Gregori E. Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit. *IEEE/ACM Transactions on Networking* 2000; **8**(6): 785–799.
14. Bononi L, Conti M, Gregori E. Runtime optimization of IEEE 802.11 wireless LANs performance. *IEEE Transactions on Parallel and Distributed Systems* 2004; **15**(1): 66–80.
15. Wang C, Tang W. A probability-based algorithm to adjust contention window in IEEE 802.11 DCF. In *2004 International Conference on Communications, Circuits and System*, Vol. 1, 2004; 418–422.
16. Deng DJ, Ke CH, Chen H, Huang YM. Contention window optimization for IEEE 802.11 DCF access control. *IEEE Transactions on Wireless Communications* 2008; **7**(12): 5129–5135.
17. Toledo AL, Vercauteren T, Wang X. Adaptive optimization of IEEE 802.11 DCF based on Bayesian estimation of the number of competing terminals. *IEEE Transactions on Mobile Computing* 2006; **5**(9): 1283–1296.
18. Wang X, Yin J, Agrawal DP. Impact of channel conditions on the throughput optimization in 802.11 DCF. *Wireless Communications and Mobile Computing* 2005; **5**(1): 113–122.
19. Li Q, Schaar MVD. Providing adaptive QoS to layered video over wireless local area networks through real-time retry limit adaptation. *IEEE Transactions on Multimedia* 2004; **6**(2): 278–290.
20. Chatzimisios P, Vitsas V, Boucouvalas AC. Throughput and delay analysis of IEEE 802.11 protocol, In *2002 IEEE 5th International Workshop on Networked Appliances, 2002. Liverpool. Proceedings*, England, 2002; 168–174.
21. Siddique MAR, Kamruzzaman J. Performance analysis m-retry BEB based DCF under unsaturated traffic condition, In *IEEE Wireless Communications and Networking Conference, WCNC*, Sydney, Australia, 2010.
22. Malone D, Duffy K, Leith D. Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions. *IEEE/ACM Transactions on Networking* 2007; **15**(1): 159–172.
23. Daneshgaran F, Laddomada M, Mesiti F, Mondin M. Unsaturated throughput analysis of IEEE 802.11 in presence of non ideal transmission channel and capture effects. *IEEE Transactions on Wireless Communications* april 2008; **7**(4): 1276–1286. DOI: 10.1109/TWC.2008.060859.
24. Patras P, Banchs A, Serrano P. A control theoretic approach for throughput optimization in IEEE 802.11e EDCA WLANs. *Mobile Networks and Applications* 2009; **14**(6): 697–708.
25. Serrano P, Banchs A, Patras P, Azcorra A. Optimal configuration of 802.11e EDCA for real-time and data traffic. *IEEE Transactions on Vehicular Technology* 2010; **PP**(99): 1–1.
26. Carvalho MM, Margi CB, Obraczka K, Garcia-Luna-Aceves JJ. Modeling energy consumption in single-hop IEEE 802.11 ad hoc networks, In *13th International Conference on Computer Communications and Networks (ICCCN 2004)*, Chicago, (IL) USA, 2004; 367–372.
27. Hoefel RPF. A MAC and PHY analytical cross-layer model for energy consumption in IEEE 802.11 networks, In *2006 International Telecommunications Symposium*, Fortaleza, (Ceara) Brazil, 2006; 237–242.
28. Chan DS, Berger T, Bridgelall R. Energy efficiency of CSMA protocols for wireless packet switched networks. In *IEEE Wireless Communications and Networking Conference (WCNC 2004)*, Vol. 1, 2004; 447–452.
29. Zanella A, Pellegrini F. Mathematical analysis of IEEE 802.11 energy efficiency, In *Proc. WPMC*, Sept 2004.

30. Yin J, Wang X, Agrawal DP. Energy efficiency evaluation of wireless LAN over bursty error channel. In *IEEE Global Telecommunications Conference, 2005. GLOBECOM '05*, Vol. 6: Padova, Italy, 2005; 5 pp. - 3632.
31. Ergen M, Varaiya P. Decomposition of energy consumption in IEEE 802.11, In *IEEE International Conference on Communications, 2007. ICC '07*, Glasgow, Scotland, 2007; 403–408.
32. Sakakibara K, Nakagawa H, Yamakita J. Analysis of energy consumption of IEEE 802.11 DCF under non-saturation conditions, In *1st International Symposium on Wireless Pervasive Computing*, Phuket, Thailand, 2006; 6.
33. Havinga P, Smit G. Energy-efficient TDMA medium access control protocol scheduling, In *Asian International Mobile Computing Conference (AMOC 2000)*, 2000; 1–9.
34. Jung ES, Vaidya NH. Improving IEEE 802.11 power saving mechanism. *Wireless Networks* 2008; **14**(3): 375–391.
35. Heusse M, Rousseau F, Guillier R, Duda A. Idle sense: an optimal access method for high throughput and fairness in rate diverse wireless LANs. In *Computer Communication Review*, Vol. 35, 2005; 121–132.
36. Xia Q, Hamdi M. Contention window adjustment for IEEE 802.11 WLANs: a control-theoretic approach. *Proceedings of the IEEE ICCC 2006* 2006; **9**: 3923–3928.
37. Jimenez J. Opnet contributed models. model id: 971. https://enterprise1.opnet.com/tsts/4dcgi/MODELS_FullDescription?ModelID=971.

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