Mathematical Analysis of IEEE 802.11 Energy Efficiency

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***Abstract*— Mobility and portability are the major advantages that IEEE 802.11 wireless networks offer over their traditional counterparts, i.e. wired Ethernet networks. However, when nodes are mobile or portable units, power consumption becomes a primary issue since terminals are usually battery driven. In this paper we propose an analytical framework to investigate the energetic cost of communicating in a cluster of IEEE 802.11 DCF terminals. We propose a linear model describing all the different phases that a node goes through during its active period. Under independence hypothesis, we provide the complete statistical description of the power consumption process through a moment generating function. By this means, we can evaluate the average life of a terminal, that is the maximum number of packets which can be transmitted by a terminal competing in a cluster of n nodes. Using our model, we develop a case study and provide interesting indications to mitigate the power consumption of IEEE 802.11 terminals.**

***Keywords*— IEEE 802.11, energy efficiency, statistical analysis**

I. Introduction

In IEEE 802.11 networks, channel access is ruled by the CSMA/CA (Carrier-Sense Multiple Access with Collision Avoidance) medium access control algorithm. Compared to a pure random access protocol, CSMA/CA reduces the collision probability by forcing each station to sense the channel before transmitting. Such strategy is enforced by the use of a classical random backoff scheme. Channel sensing, however, is an energy–demanding process, and previous research [1–3] ascribed the high energy cost of communication in IEEE802.11 Networks to the collision avoidance technique.

In this paper, we give a mathematical formulation to describe the power consumption of IEEE802.11 stations, and we derive practical guidelines for the design of energy aware algorithms and devices.

Our network model is a cluster of n IEEE 802.11 terminals using the Distributed Coordination Function (DCF), which is the native ad–hoc mode used, in practice, by all commercial wireless devices. Such n terminals share the same radio channel, i.e. there is no hidden or exposed node [4; 5]. We further assume that the cluster is under heavy traffic conditions, so that at each instant we have exactly n *active* packets: under this assumption, in fact, each node in the cluster is either performing the exponential backoff procedure or transmitting a packet. In the following we make a standard hypothesis [4] and assume that the probability that a transmitted packet collides at a given time slot is a constant p, independent of the transmission history of the cluster.

The energy model relies on a few parameters and it is aimed to represent the energy required to transmit with success a packet from source to destination according to [6].

The problem, in modeling the energy consumption of such an ad–hoc network is that, due to the channel sensing procedure, nodes are constantly either transmitting, or listening to the channel. This implies that even all receiving operations should be accounted in order to quantify the energy consumption of a transmitting station. Also, it is known from previous work [1; 3] that the energy cost to receive is close to the cost of transmission. This clearly affects the energy required to transmit a packet, since during the backoff procedure, all alien (non–destination) packets must be discarded. Furthermore, sensing the channel has a cost as well and must be taken into account.

Hence, to the aim of deriving a complete statistical description of the energy spent by a node, we will list in detail each of the operations for packet transmission and reception, including carrier sensing and backoff delaying.

Using our model, we developed a case study to explore how a careful sensing policy could improve the overall power consumption. In particular, we investigated a potential energy saving strategy, assuming that nodes are able to temporary switch receiving devices to a low–power consumption mode. As reported in [1], such a energy saving technique may be feasible at 2Mbps but the same scheme may bring no benefit at higher rates (i.e. 11Mbps). Power consumption, in fact, strongly depends on the technology adopted and on several physical parameters. Thus, a detailed analytical model, as the one provided in this work, is necessary to design effective energy saving techniques for IEEE802.11 devices.

The paper is organized as follows. In Section II we describe previous related work, in Section III we detail the network model and in Section IV we introduce our linear model for the energy consumption. In Section V we derive the energy consumption statistics and in Section VI we present analytical results.

II. Contribution and Related Work

The problem of power consumption of IEEE802.11 cards emerged early as a major drawback of the CSMA/CA technique. In [3], in particular, the authors showed through measurements that the most power drawn from batteries by such devices is by far due to the sensing mechanism (idle mode). Later, a detailed set of testbed measurements were reported in [1]. From such measurements, the power consumed during receiving/sensing confirmed to be of the same order of magnitude of the power needed for transmitting. The authors showed also that non destination hosts spend a significant amount of energy in discarding traffic.

In [7], using renewal arguments, a general comparison of battery power consumption is provided, in terms of average values and for different wireless access protocols. In [8], the authors introduce a detailed analysis of the average performance for the energy consumption and channel utilization of CSMA/CA MAC protocols in WLANs, adopting a p–persistent random backoff procedure. Finally, in [2], the native power saving mode implemented by the IEEE 802.11 standard, using beacons and sleep mode, was evaluated when using the DCF mode.

In this paper, we are interested in energy consumption when all terminals are active, and thus, they cannot be put to sleep. Nevertheless, the energy saving scheme we will analyze later is suitable to be used together with sleep/active mode managing.

To the authors knowledge, the literature still lacks a complete statistical characterization of the energy consumption of the IEEE 802.11 systems, which represents the main contribution of our paper. As a side–effect of our analysis, we could quantify the energy spent in backoff compared to the overall energy consumption. Thus, we confirmed that the sensing/discarding policy of CSMA/CA has a major impact on the energy required to transmit a packet.

This work was supported by the Italian Ministry of University and Research (MIUR) within the framework of the PRIMO project FIRB RBNE018RFY, information available at http://primo.ismb.it/firb/index.jsp.

III. ENERGY MODEL

In the following, we make use of standard notation to introduce our energy analysis. The statistical expectation operator is denoted by $\mathrm{E}[\cdot]$. For a given random variable X, $p_X(\cdot)$ is the probability density (or mass) function, whereas $p_X(\cdot|e)$ is the conditional probability given the event e. Furthermore, we denote by $G_X(z) = \mathrm{E}\left[z^X\right]$ the probability generating function associated to a discrete random variable X, whereas the notation $H_Y(s) = \mathrm{E}\left[e^{sY}\right]$ is the moment generating function of a continuous random variable Y.

The overall energy required for a node to transmit a packet with success, E, can be broken down according to

$$E = E_T + E_{T_c} + E_B = E_T + \sum_{j=1}^{n_c} E_{T_c,j} + E_B \qquad (1)$$

where E_T is the energy required for a successful transmission and E_{T_c} is the energy wasted into collisions, respectively. Integer random variable n_c represents the number of collisions which the packet incurs before success, whereas $E_{T_c,j}$ is the energy spent at j–th collision. Notice that, a key role is played by E_B, which carries the overall energy spent due to the backoff procedure.

In order to derive a complete statistical description, we make some independence assumptions. In particular $\{E_{T_c,j}\}$ are assumed i.i.d., and independent of E_T; with the latter hypothesis, we neglect the dependency between the duration of a collision and the packet length distribution.

Since we assume a collision occurs with probability p, the number of collisions a packet undergoes before success can be modeled as a geometric random variable with average $p/(1-p)$ and probability mass function given by

$$p_{n_c}(r) = (1-p)p^r \ , \quad r = 0, 1, \dots \ , \qquad (2)$$

where p can be calculated as shown in [4]. In the following, we will assume that, if a collision occurs, all packets transmitted during overlapping time intervals cannot be decoded correctly and can be considered collided packets as well.

The IEEE802.11 standard [6], defines a physical and a virtual carrier-sense mechanism. The former provides indications to the MAC layer whether the channel is free or busy (for example in the case of DSSS mode used by WiFi cards, this is done either measuring the *energy* of some ongoing communication on the channel or detecting a *PN* sequence). The virtual carrier-sense mechanism, on the other hand, uses the network allocation vector (NAV)[6], which maintains a prediction of future traffic on the medium, based on duration information of discarding traffic (packet header or RTS/CTS of non–destination hosts). Basically, the NAV is counter, counting down to zero at a uniform rate. When the counter is zero, the virtual carrier–sense indicates that the medium is idle; when nonzero, the indication is busy.

We will introduce shortly the main parameters of our model and give a brief explanation of their meaning. We denote by α the power required to *transmit* (we implicitly assume that all stations adopt the same power level). The power spent to *decode* an incoming signal is β_R and the power required to *sense* the media is β_S. Furthermore, we assume that it is possible to switch a receiver into a low–power consumption mode, spending β_0 in such condition. Thus, the information stored in the NAV can be fruitfully used to trigger terminals which are in backoff and switch them into low–power consumption mode. In particular two opposite situations are possible: in the first case we assume terminals can switch into a low power consumption mode until the NAV register counts down to zero ($\beta_0 = 0$), while in the opposite situation regular sensing is performed irrespective of the NAV state ($\beta_0 = \beta_S$). As discussed in the following, the virtual carrier sense may prove critical to improve the energy efficiency of IEEE802.11 terminals.

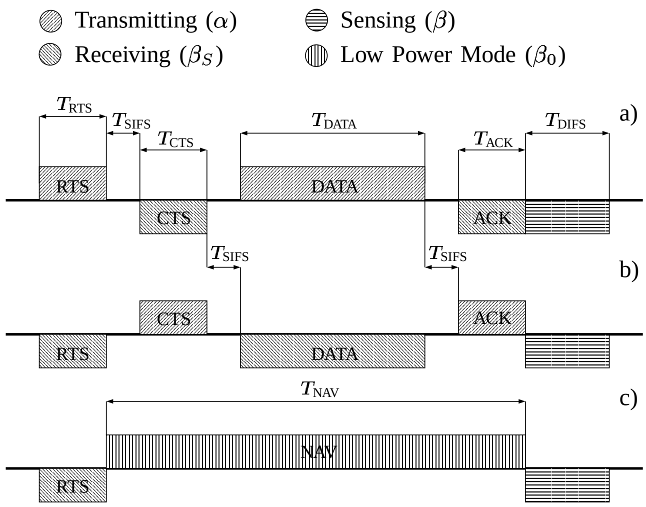

Fig. 1. Energetic costs for the successful delivery of a packet using RTS/CTS; a) transmitting station b) receiving station c) other stations.

In Fig.1 we depicted the contribution to power consumption in the cluster during the transmission of a packet from transmitter to receiver. In the following, we describe each contribution that is involved when transmitting a packet, due to various operations of a cluster of terminals. The major distinction is made between receiving and transmitting operations; thereafter, we will apply a simple linear reasoning to detail each contribution.

For each case, we will specialize to the basic access mode, denoted as case (a), and the RTS/CTS access mode, denoted as case (b), following the method adopted in [4].

For the simplicity's sake, SIFS intervals are spent entirely to switch from receiving to transmitting mode and viceversa, with no additional power consumption.

A. Receiving power

We distinguish three major cases for the energy consumed by a station in receiving mode: (i) *reception* of a packet intended to the receiving station, (ii) *dropping* a packet not intended for the receiving station and (iii) handling a packet jammed due to collisions.

When a packet is received (i) the amount of energy required (Fig.1b) is given by

$$E_R = \begin{cases} \beta_R T_{\mathrm{D}} + \alpha T_{\mathrm{ACK}} + \beta_S T_{\mathrm{DIFS}} & \text{(a)} \\ \beta_R (T_{\mathrm{RTS}} + T_{\mathrm{D}}) + \alpha (T_{\mathrm{CTS}} + T_{\mathrm{ACK}}) + \beta_S T_{\mathrm{DIFS}} & \text{(b)} \end{cases} \qquad (3)$$

where T_{D},T_{ACK},T_{RTS} and T_{CTS} are the duration of a data packets, ACK packets, RTS and CTS packets respectively. Notice that, as anticipated, SIFS contributions have been neglected, while sensing is mandatory to resume the backoff procedure.

In case (ii), a packet may be discarded by stations listening to the channel (Fig.1c) at cost

$$E_D = \begin{cases} \beta_R T_H + \beta_S T_{\mathrm{DIFS}} + \beta_0 T_{\mathrm{NAV}} & \text{(a)} \\ \beta_R T_{\mathrm{RTS}} + \beta_S T_{\mathrm{DIFS}} + \beta_0 T_{\mathrm{NAV}}. & \text{(b)} \end{cases} \qquad (4)$$

where $T_{\mathrm{NAV}} = T_{\mathrm{D}} + T_{\mathrm{ACK}}$ for the RTS/CTS mode, $T_{\mathrm{NAV}} = T_{\mathrm{D}} + T_{\mathrm{ACK}} - T_H$ in the basic access mode and T_H is the duration of the packet header.

Finally, in case (iii) the power consumption can be modeled as

$$E_{R_c} = \begin{cases} \alpha T_H + \beta_S (T_c - T_H + T_{\mathrm{DIFS}}) & \text{(a)} \\ \alpha T_H + \beta_S (T_{\mathrm{DIFS}} + T_{\mathrm{RTS}}) & \text{(b)} \end{cases} \qquad (5)$$

where T_c is the duration of a collision in the basic access mode and we assume a station gives up decoding after detecting a jammed header. Notice that, in the RTS/CTS mode, collisions involve RTS packets only.

B. Transmitting power

The transmission of a packet, in case of *success*, requires the following energy

$$E_T = \begin{cases} \alpha T_{\text{D}} + \beta_R T_{\text{ACK}} + \beta_S T_{\text{DIFS}} & \text{(b)} \\ \alpha(T_{\text{RTS}} + T_{\text{D}}) + \beta_R(T_{\text{CTS}} + T_{\text{ACK}}) + \beta_S T_{\text{DIFS}}\,, & \text{(a)} \end{cases} \quad (6)$$

whereas a *collision* [1] has an overall transmitting cost

$$E_{T_c} = \begin{cases} \alpha T_{\text{D}} + \beta_S(T_{\text{ACK}} + T_{\text{DIFS}}) & \text{(a)} \\ \alpha T_{\text{RTS}} + \beta_S(T_{\text{CTS}} + T_{\text{DIFS}}) & \text{(b).} \end{cases} \quad (7)$$

In the following we will use this linear model to provide a general description of the power consumption of a node.

IV. POWER CONSUMPTION MODELING

The main output of our analysis is the moment generating function for the energy spent to transmit a packet E, that is $H_E(s) = \mathrm{E}\left[e^{sE}\right]$. Replacing equation (1), we obtain

$$\begin{aligned} H_E(s) &= \mathrm{E}\left[e^{sE_T}\right] \sum_{r=0}^{+\infty} p_{n_c}(r) \mathrm{E}\left[e^{s(rE_{j,T_c}+E_B)} | \, n_c = r\right] \\ &= (1-p) H_{E_T}(s) \sum_{r=0}^{+\infty} \left(p\, H_{E_{T_c}}(s)\right)^r \mathrm{E}\left[e^{sE_B(r)}\right]; \end{aligned} \quad (8)$$

where we have denoted by $E_B(r)$ the overall energy spent during the backoff time given that the packet incurs in r collisions before successful transmission. Let us denote by ξ the energy spent during a *tick period*. A tick period is defined as the time between two successive decrements of the backoff counters. Hence, we have

$$E_B(r) = \sum_{j=0}^{W_r} \xi_j \;; \quad (9)$$

where W_r is the number of tick periods that a node waits before attempting the $r+1$ packet retransmission, given that the first r attempts resolve into collisions. Again, we make an independence assumption, and let the energies $\{\xi_j\}$ spent at each tick–time i.i.d., with moment generating function $H_\xi(s)$. Thus, putting (9) into (8), we get

$$\begin{aligned} H_E(s) &= (1-p) H_{E_T}(s) \sum_{r=0}^{+\infty} (p\, H_{E_C}(s))^r \, \mathrm{E}\left[e^{s\sum_{j=0}^{W_r}\xi_j}\right] \\ &= (1-p) H_{E_T}(s) \sum_{r=0}^{+\infty} (p\, H_{E_C}(s))^r \sum_{k=0}^{+\infty} p_{W_r}(k) \left(H_\xi(s)\right)^k \\ &= (1-p) H_{E_T}(s) \sum_{r=0}^{+\infty} \left(p\, H_{E_{T_c}}(s)\right)^r G_{W_r}\left(H_\xi(s)\right). \end{aligned}$$

Next, we will determine the expression of $H_\xi(s)$ and $G_{W_r}(z)$.

A. Tick Period Energy Statistics

As previously stated, the energy spent during the tick period, ξ, collects the overall energy consumption spent between two successive decrements of a node backoff counter. The tick period resembles the *slot period* defined in [4]. However, in our analysis, we consider the tick periods perceived by a node that is currently in backoff and, hence, is not allowed to transmit. Hence, the statistic of the tick period energy is evaluated assuming $n-1$ potential transmitting nodes instead of n. As long as no node attempts a transmission, backoff counters are decremented by 1 per time slot σ, at fixed cost $\beta_s\sigma$ required to sense the channel. Whenever the channel is sensed busy, the backoff countdowns are suspended till the channel becomes available again for transmissions.

Hence, the energy spent during a tick period is be expressed as

$$\xi = \beta_s\sigma(1-\chi_{T_c}-\chi_{T_s}) + \chi_{T_s}\chi_R E_R + \chi_{T_s}(1-\chi_R) E_D + \chi_{T_c} E_{R_c} \;; \quad (10)$$

where χ_{T_s} (χ_{T_c}) is a pseudo–random variable that takes the value 1 if a packet transmission (collision) occurs at a given instant, and the value 0 otherwise. Pseudo–random variable χ_R takes value 1 if the packet is intended to the receiving station, 0 otherwise (discarding).

According to [4], we denote by τ the probability that a node transmits at a given tick time. Hence, for $n-1$ potential transmitting nodes, we obtain (with a self–explanatory notation)

$$\begin{aligned} p_{1,0} &= p_{\chi_{T_s}\chi_{T_c}}(1,0) = (n-1)\tau(1-\tau)^{n-2} \;; \\ p_{0,1} &= 1 - (1-\tau)^{n-1} - (n-1)\tau(1-\tau)^{n-2}; \\ p_{0,0} &= (1-\tau)^{n-1}. \end{aligned} \quad (11)$$

Hence, the moment generating function of ξ, turns out to be

$$\begin{aligned} H_\xi(s) &= p_{1,0}(p_R H_R(s) + (1-p_R) H_D(s)) \\ &\quad + p_{0,1} H_{R_c}(s) + p_{0,0} e^{s\sigma\beta_S} \end{aligned} \quad (12)$$

where we let $p_{\chi_R}(1) = p_R$, whereas $H_R(s), H_D(s)$ and $H_{T_c}(s)$ are the moment generating functions of E_C, E_R and E_{R_c} respectively. Hence, the average energy spent during a tick time results

$$m_\xi = \sigma\beta_S + p_{1,0}(p_R m_{E_R} + (1-p_R) m_{E_D}) + p_{0,1} m_{E_{R_c}}. \quad (13)$$

B. Backoff Statistics

To determine the statistic of the number W_r of tick periods a node spends in backoff, we need to introduce some further notations.

Let $s(i)$ denote the backoff stage after i collisions, and CW_i be the backoff window at the stage $s(i)$, so that:

$$s(i) = \begin{cases} i, & \text{if } i < m\,; \\ m, & \text{if } i \geq m\,. \end{cases} \quad (14)$$

and $CW_i = CW_0\, 2^{s(i)}$. Moreover, let x_i be the number of tick periods a node spends in backoff stage $s(i)$. Since the backoff time counter takes any of the values in the backoff window $[0, \ldots, CW_i - 1]$ with probability $1/CW_i$, we have

$$G_{x_i}(z) = \sum_{k=0}^{CW_i-1} \frac{z^k}{CW_i} = \frac{1 - z^{CW_i}}{(1-z)CW_i}. \quad (15)$$

Therefore, we can express the random variable W_r as $W_r = \sum_{i=0}^{r} x_i$ from which, assuming x_i are independent random variables, we have

$$G_{W_r}(z) = \prod_{i=0}^{r} G_{x_i}(z)\,. \quad (16)$$

Expression (16) can be further simplified by distinguishing the cases $r \leq m$ and $r > m$. For $r \leq m$ we have

$$G_{W_r}(z) = \prod_{i=0}^{r} \frac{1 - z^{CW_0 2^i}}{(1-z)CW_0 2^i} = \frac{\prod_{i=0}^{r}\left(1 - z^{CW_0 2^i}\right)}{\left[CW_0(1-z)2^{\frac{r}{2}}\right]^{r+1}}\,. \quad (17)$$

For $r > m$, (16) turns out to be

$$\begin{aligned} G_{W_r}(z) &= G_{W_m}(z) G_{x_m}(z)^{r-m} \\ &= \frac{\left(1 - z^{W_0 2^m}\right)^{r-m} \prod_{i=0}^{r}\left(1 - z^{W_0 2^i}\right)}{[W_0(1-z)]^{r+1}\, 2^{\frac{m(2r-m+1)}{2}}}\,. \end{aligned} \quad (18)$$

[1] The term $T_{\text{ACK}} + T_{\text{DIFS}}$ which appears in (7) corresponds to the $EIFS$ interval defined in [6].

C. Power Consumption Statistics

At this point, we can further specify (10). Replacing (17) and (18) into (10), and using, for easy of reading, $\mathcal{E}$ instead of $H_\xi(s)$, we get

$$\begin{aligned} H_E(s) &= (1-p)H_{E_T}(s)\left\{\sum_{r=0}^{m}\left(p\,H_{E_{T_c}}(s)\right)^r G_{W_r}(\mathcal{E})+\right.\\ &\left.+\sum_{r=m+1}^{+\infty}\left(p\,H_{E_{T_c}}(s)\right)^r G_{W_m}(\mathcal{E})G_{x_m}(\mathcal{E})^{r-m}\right\}\\ &= (1-p)H_{E_T}(s)\left\{\sum_{r=0}^{m}\left(p\,H_{E_{T_c}}(s)\right)^r G_{W_r}(\mathcal{E})+\right.\\ &\left.+\left(p\,H_{E_{T_c}}(s)\right)^m G_{W_m}(\mathcal{E})\sum_{k=1}^{+\infty}\left[p\,H_{E_{T_c}}(s)G_{x_m}(\mathcal{E})\right]^k\right\} \quad (19)\\ H_E(s) &= (1-p)H_{E_T}(s)\left\{\sum_{r=0}^{m}\left(p\,H_{E_{T_c}}(s)\right)^r G_{W_r}(\mathcal{E})+\right.\\ &\left.+\left(p\,H_{E_{T_c}}(s)\right)^m G_{W_m}(\mathcal{E})\frac{pH_{E_{T_c}}(s)G_{x_m}(\mathcal{E})}{1-pH_{E_{T_c}}(s)G_{x_m}(\mathcal{E})}\right\}. \end{aligned}$$

Using the above analysis we obtain the average energy consumption of station in the cluster

$$m_E = \frac{d}{ds}H_E(s)\bigg|_{s=0} = m_{E_T} + (1-p)\sum_{r=0}^{+\infty}p^r\phi'_r(0) \quad (20)$$

where $\phi_r(s) = (H_{E_{T_c}}(s))^r G_{W_r}(H_\xi(s))$, so that

$$\phi'_r(0) = r\,m_{E_{T_c}} + m_{W_r}m_\xi. \quad (21)$$

After some algebra, the average energy consumption results

$$\begin{aligned} m_E &= m_{E_T} + \frac{p}{1-p}m_{E_{T_c}} + (1-p)m_\xi\sum_{r=0}^{+\infty}p^r m_{W_r}\\ &= m_{E_T} + \frac{p}{1-p}m_{E_{T_c}} + (1-p)m_\xi\sum_{r=0}^{+\infty}p^r\,\frac{\tilde{W}_r-1}{2}\\ &= m_{E_T} + \frac{p}{1-p}m_{E_{T_c}} + \frac{1}{2}m_\xi\left[\sum_{r=0}^{+\infty}(1-p)p^r\tilde{W}_r - 1\right] \quad (22) \end{aligned}$$

where $\tilde{W}_r = W_i$ for $i = 0, 1, \ldots, m-1$ and $\tilde{W}_r = W_m$ for $r \geq m$. Finally, replacing the actual window size at each backoff stage,

$$m_E = m_{E_T} + \frac{p}{1-p}m_{E_{T_c}} + R(p)\,m_\xi \quad (23)$$

where $R(p) = \left[W_0\frac{(1-p)-p(2p)^m}{1-2p} - 1\right]$. Notice that, for a given access mode, $R(p)$ depends on the number of terminals n only.

D. Life of a terminal

A central question is the maximum amount of information which can be exchanged by a station of the cluster before exhausting its battery charge. Given an initial battery charge B_0, we define *life* of a terminal the integer random variable N representing the maximum number of packets which can be transmitted by a station. In particular it holds

$$P_r\{N \geq k\} = P_r\left\{\sum_{j=1}^{k}E_j \leq B_0\right\}.$$

where E_j is the energy spent by a node to transmit a packet.

The distribution of N, $F_N(B_0)$, in principle can be derived via IFFT from the moment generating function of the sum the E_j, that is $\{H_E(e^{j2\pi f B_0})\}^k$. In practice, however, such method is feasible only for small values of k. Hence, we resort to an alternative description obtained under the simplifying hypothesis that the sequence of random variables $\{E_k\}$ is i.i.d. Thus, we let $N(e)$ be the number of transmitted packets when the expended energy is e, so that the energy consumed transmitting $N(e)$ packets is $\sum_{k=1}^{N(e)} E_k$. Using the basic renewal theorem we can write the statement

$$\lim_{e\to\infty} \mathrm{E}\left[N(e)\right]/e = 1/m_E. \quad (24)$$

We will use (24) to evaluate the average life of a terminal, under the hypothesis of *large* batteries. In particular, we assume that the charge stored in each battery is large enough to neglect transitory effects, so that the average life of the terminal can be approximated as $N = B_0/m_E$.

In the next section, we will examine two limit cases, that is the case that the energy spent during the NAV period is negligible ($\beta_0 = 0$), and the case that regular sensing is performed throughout the overall NAV period ($\beta_0 = \beta_S$).

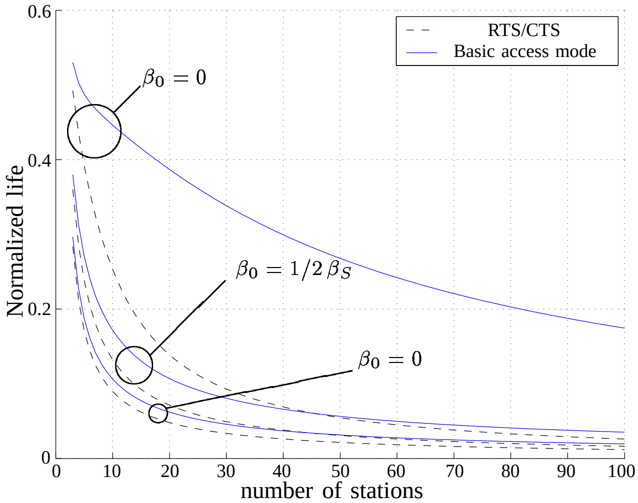

Fig. 2. Normalized Life of stations: basic access mode (solid line) and RTS/CTS access mode (dashed line), $\beta_0 = 0$, $\beta_0 = 1/2\beta_S$ and $\beta_0 = \beta_S$.

V. Case Study

In this section we describe a case study, and parameters for our energy model are taken from measures performed in [1] on a 11Mbps Lucent WaveLAN. In particular, after normalization, we obtain $\alpha = 1$ and $\beta_R = 0.67$ for the transmitting and receiving powers, and $\beta_S = 0.82\beta_R$ coincides with the sensing power consumption.

A IEEE 802.11 card may take advantage of the low–consumption mode whenever a non–destination transmission is detected. As we introduced before, the information about the duration on the on–going transmission can be used to switch to the low power consumption mode and improve CSMA/CA power consumption. In Fig. 2, we reported the average life of a terminal, normalized on the maximum possible number of transmitted packets. In particular, when the energy spent in low–power mode is negligible, there is a huge increase in the life of a terminal, with a clear gain of RTS/CTS compared to the basic access mode. But, the advantage of adopting a low power mode under discarding traffic vanishes as soon as the energy consumed in low power mode is as large as $1/2$ of the energy required to sense the channel. The scenario can be even worse once we take into account the energy to switch from the normal mode to the low power mode and viceversa. Insight is obtained from the complementary distribution function of the energy spent per packet, normalized to the plain energy required to transmit a packet E_T. In order to quantify the energetic cost of the CSMA/CA, let us refer to a specific value of Fig 3: in particular we ask about the probability that transmitting a packet

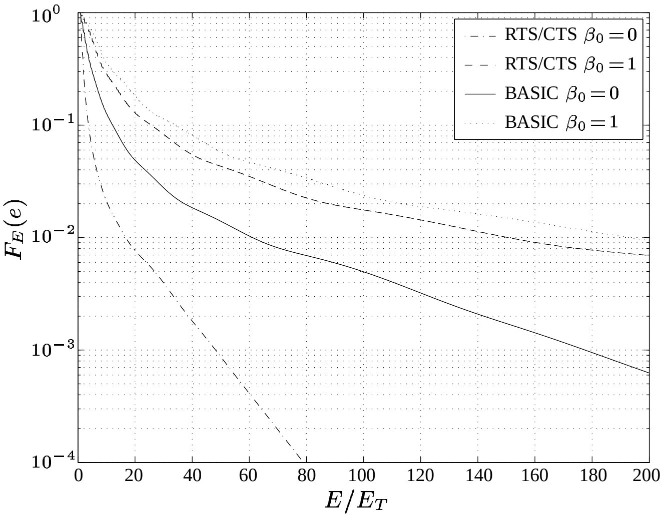

Fig. 3. Complementary distribution function for the energy spent to transmit a packet, $n = 20$.

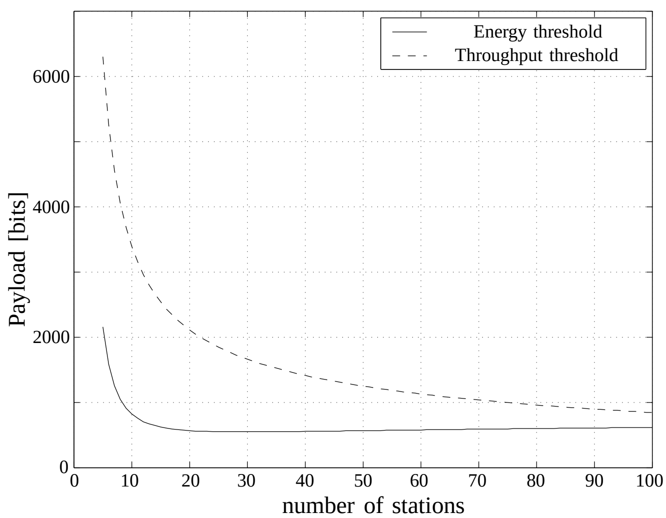

Fig. 4. Thresholds for energy per bit versus packet length (solid) and threshold for throughput versus packet length (dashed). Packets larger than the threshold cause better performance of the RTS/CTS mode compared to the basic access mode.

may cost 50 times E_T. Such probability (which indeed we wish to be as small as possible), turns out to be above $4.2 \cdot 10^{-2}$ for both access modes in the case $\beta_0 = 1$; under our ideal energy saving policy ($\beta_0 = 0$) the basic access shows a probability of $1.4 \cdot 10^{-2}$, whereas RTS/CTS reaches $9 \cdot 10^{-4}$.

The behavior shown in Fig 2 and Fig. 3 shows clearly that the energy spent in backoff, due to sensing and discarding traffic, plays the major role in the overall energy consumption of a terminal.

The above results are referred to 1500 bytes packets, but we observed that the behavior which we described above is typical of a very large interval of packet lengths. To explain this fact, we remind that, as proved in [4], there exists a packet length threshold above which the RTS/CTS access mode has better throughput than the basic access mode, i.e. the RTS/CTS access mode performs the basic access mode when the packet length exceeds a certain minimum length. Considering the energy per bit consumption, with similar techniques, we determined numerically a threshold in terms of average energy per bit versus packet length, as depicted in Fig 4.

As expected, the advantage shown by RTS/CTS versus the basic access mode is larger for increasing packet lengths and reminds us of what observed in the case of throughput [4]. But, interestingly, when the metric is the energy consumption, the RTS/CTS access mode turns out to be convenient over a broader region: in particular, for some packet lengths, transmitting with the RTS/CTS mode at a lower throughput than the basic access mode permits net energy savings.

VI. Conclusions

In this paper we proposed a detailed linear energy model and derived the complete statistical description of the energy spent per packet. Referring to the power consumption parameters typical of commercial WiFi cards, we developed a case study. Through this example of application, we could verify analytically that the energy consumption of IEEE802.11 cards is strongly affected by sensing and by alien traffic discarding, showing a huge impact on the power consumption of the CSMA/CA strategy. Also, due to short collision times, the region where the power consumption of the RTS/CTS access mode performs the basic access mode turns out to be larger than what expected considering only throughput.

As a final remark, using the NAV information and switching off receivers under discarding traffic turns out to extend significantly the lifetime of stations. But, we found that the advantage of such a technique disappears as soon as the power consumption in the *low–power mode* exceeds $1/2$ of the receiving power.

Finally, using our analytical model we can derive critical reference values for the power consumption of a IEEE 802.11 card: in the design of a wireless interface, such values can be used while choosing the appropriate technology, clock, frequency or voltage in order to meet certain cost and power constraints.

Further research will involve the implementation of an energetic module for the NS2 simulator able to capture the details of our model.

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