Decomposition of Energy Consumption in IEEE 802.11

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***Abstract*— We derive formulas for the energy $J(n)$ that a station's radio consumes when it transmits 1 MB of data in an IEEE 802.11 network with n stations. Calculations show that $J(n)$ grows approximately linearly with n, for $n \geq 4$. The useful energy consumed in successful transmission and reception of data is constant; the remaining energy is wasted. When $n = 15$, the waste amounts to 80 percent of total energy, and this proportion grows with n. More than 60 percent of the waste is due to overhearing—reception of packets intended for another station. Overhearing can be eliminated by using information in RTS/CTS packets.**

***Index Terms*— IEEE 802.11, J/bit, Energy Rate, Markov Model, Distributed Coordination Function, Power Control.**

I. Introduction

We derive formulas for the total energy $J(n)$ that a station's radio consumes when it transmits 1 MB of data in an IEEE 802.11 network with n stations. (All nodes are one hop away from each other and use the CSMA/CA DCF protocol.) The formulas also divide the total energy among six different MAC operations: (a) successful transmission; (b) successful reception; (c) overhearing (reception of packets intended for other stations); (d) idle listening (when the channel is idle); (e) unsuccessful (colliding) transmissions; and (f) reception of collisions.

Only operations (a) and (b)—the successful transmission and reception of 1 MB of data—usefully consume energy. This energy is a constant, which depends on the bit rate and packet size. The others, (c)-(f), waste energy. This waste depends on several factors: the number of stations, n; the pattern of traffic, assumed here to be symmetric and saturated, i.e., destinations are uniformly selected and every station has data to send; whether the basic access or the RTS/CTS mechanism is used; the packet size and bit rate; and the power consumed in different radio states, *transmit, receive,* etc.

Most energy is wasted in overhearing packets intended for other destinations. For $n = 15$ (using radio data from [1]), overhearing wastes 60 percent of the total energy for the basic mechanism, and 75 percent for the RTS/CTS mechanism. Because the RTS/CTS packets contain the destination address and information about the duration of the transmission (NAV), stations could avoid overhearing, saving significant energy. The three other wasteful operations (d)-(f) cannot be avoided without major changes in the protocol.

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The energy calculations presented here are unimportant for a laptop PC platform in which the radio consumes only 9 percent of the total energy [1]. However, an 802.11 radio in a PDA, cell phone, or wireless sensor, will consume a larger portion of the total energy, so these calculations would be more significant for these devices.

II. Formulation

Two assumptions underlie the formulation. The first concerns the Markov chain model of the 802.11 protocol. The second concerns the radio's physical states that determine how much power is consumed.

The Markov chain model is taken from [2], which in turn is an improvement of the model in [3]. The chain, depicted in Figure 1, has states (i, j), in which j is the back-off timer value $(0 \leq j \leq W_i - 1)$ and i is the back-off stage $(0 \leq i \leq m)$. For an exponential back-off, $W_i = 2^i W$, $0 \leq i \leq m$. For the numerical calculations, we take $W = 16$ and $m = 7$.

The key simplifying assumption is that each station faces a constant *conditional collision probability* p that is independent of the number of collisions the station has experienced and independent of all other stations. With this assumption the stations are modeled by independent copies of the Markov chain depicted in Figure 1. The equilibrium probabilities, denoted $b_{i,j}$, can be obtained in closed form by solving the balance equations [4], [2].

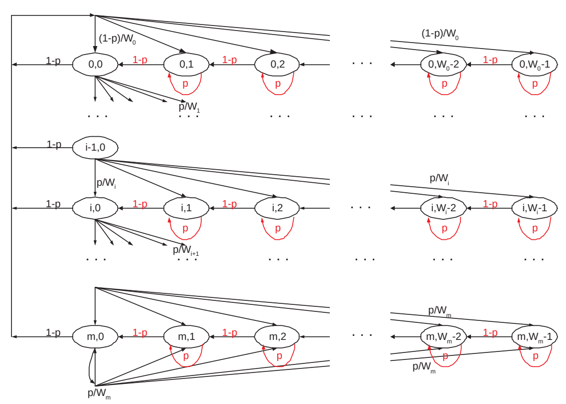

Fig. 1. Independent Markov model of 802.11$^+$ for multi-level backoff

A station transmits when its state is of the form $(i, 0)$, and the probability of transmission works out as (see [2])

$$\tau = \sum_i b_{i,0} = \frac{1}{\frac{(1-2p)(W+1)+pW(1-(2p)^m)}{2(1-2p)(1-p)}}. \quad (1)$$

This gives τ in terms of (the unknown) p. On the other hand, the collision probability p in terms of τ is

$$p = 1 - (1-\tau)^{n-1}. \quad (2)$$

The simultaneous equations (1) and (2) can be solved to obtain $\tau = \tau(n), p = p(n)$. The probability P_{tr} that there is at least one transmission and the probability P_s that there is a successful transmission in one step are then given by

$$\begin{aligned} P_{tr} &= 1-(1-\tau)^n, \\ P_s &= n\tau(1-\tau)^{n-1}. \end{aligned} \quad (3)$$

A discrete *step* of the Markov chain corresponds to a variable-duration time *slot* of the station's continuous-time operation. There are two types of virtual slot: an idle slot and a transmission slot. From the standard, an idle slot has duration $SLOT$ and the duration of a transmission slot depends on whether it is a data, RTS or CTS packet.

Let $J(n)$ be the total energy (Joules) consumed by station l, say, in order to transmit 1 MB of data. Because of symmetry, $J(n)$ does not depend on l. Moreover,

$$J(n) = \frac{E[\text{energy consumed by } l \text{ in one slot}]}{E[\text{MB transmitted by } l \text{ in one slot}]}. \quad (4)$$

The denominator in (4) is easily calculated: since P_s is the probability of a successful transmission,

$$E[\text{MB transmitted by } l \text{ in one slot}] = \frac{P_s}{n} E[P], \quad (5)$$

in which $E[P]$ is the expected packet size in MB.

To calculate the numerator in (4), we note that there are six kinds of slots. The energy consumed by each kind and its probability of occurrence are listed below:

J_σ: Idle slot, probability $(1-P_{tr})$;

$J_s^{rx}(l)$: Successful reception of packet destined for l, probability $\tau(1-\tau)^{(n-1)}$;

$J_s^{rx}(\sim l)$: Successful reception of packet *not* destined for l, probability $(n-2)\tau(1-\tau)^{(n-1)}$;

J_c^{rx}: Reception of a collided packet, probability $(1-\tau)[1-(1-\tau)^{(n-1)}-(n-1)\tau(1-\tau)^{n-2}]$;

J_s^{tx}: Successful transmission of a packet by l, probability $\tau(1-p)$;

J_c^{tx}: Colliding transmission of a packet by l, probability τp.

Hence the numerator in (4) can be expressed as

$$\begin{aligned} &E[\text{energy consumed by } l \text{ in one slot}] = \\ &(1-P_{tr})J_\sigma + \tau(1-\tau)^{(n-1)}J_s^{rx}(l) + (n-2)\times \\ &\tau(1-\tau)^{(n-1)}J_s^{rx}(\sim l) + (1-\tau)[1-(1-\tau)^{n-1}- \\ &(n-1)\tau(1-\tau)^{n-2}]J_c^{rx} + \tau(1-p)J_s^{tx} + \tau p J_c^{tx}. \end{aligned} \quad (6)$$

It only remains to calculate the energy consumed in each kind of slot, which is the duration of the slot multiplied by the power consumption in that slot. We assume that the power consumption depends on which of five physical states the radio is in: *transmit*, *receive*, *listen*, *sleep*, and *off*. As we are assuming that each station is saturated, its radio never enters the *off* or *sleep* states. Let $\rho_{tx}, \rho_{rx}, \rho_\sigma$ denote the power (Watts) consumed in *transmit, receive* and *listen*, respectively.

The result is given in (7), in which T_{DATA} is the time taken to send a packet of size P MB; T_{RTS}, T_{CTS}, T_{ACK} are the times taken to send the corresponding packets; T^*_{DATA} is the average time taken to send $E[P^*]$, the average length of the longest packet involved in a collision. When all packets have the same size P, $E[P] = E[P^*] = P$. These durations depend on the data rate. $SLOT, SIFS, DIFS$, and $EIFS$ are durations of intervals fixed by the standard.

III. Prior Work

This paper builds on prior work on power measurement, proposals to reduce energy waste, and Markov models of 802.11 networks. From (7), the power consumed in one packet is $(b_m + a_m P)$, in which m is the slot type: *transmit, receive,* etc., and P is the packet size. The fixed power b_m and the variable power a_m can be taken from manufacturer's data sheet [1] as in this and most other papers, or estimated by direct measurement of the current consumed by the NIC as in [5], [6].

Several schemes reduce power in wasteful operations (c)-(f). Thus [7], [8], [9] investigate reducing overhearing by forcing the NIC to enter reduced-power states, based on the destination address and NAV. The effect of network size is explored through simulation.

In an ad hoc 802.11 network, increasing transmission power reduces the number of hops from source to destination but it also increases interference. That tradeoff is explored via simulation in [8], [10]; however, [10] does not consider waste from overhearing.

In the (rarely used) 802.11 power saving mode, stations save power by moving into a *doze* state. However, they are required to be awake for a fixed duration called ATIM, to learn about pending transmissions. The adaptive mechanism in [11] increases the ATIM window as the network size increases. Simulation results show improvement over the fixed size ATIM.

By contrast with these simulation studies, [12] formulates an analytical power consumption model that is close to this paper. The six slot types considered here are grouped into two: a successful transmission, which occurs with probability P_s (see (3)); and a 'backoff' slot which groups the other slot types. Only two power levels are considered: ρ_{tx} for successful transmission, and ρ_b for backoff (i.e., radio power in the other states is assumed to be the same). As in this paper, [12] finds that energy consumpion per node per packet grows linearly with the network size, n, although explicit formulas like (8), (9), (10) are not available. Moreover, [12] does not decompose the total energy in detail as done here, nor does it consider the basic access mechanism.

Lastly, there is significant research in energy-aware MAC protocols for sensor networks. Since these protocols are very different from the 802.11 standard, they are not considered here.

$$
\begin{aligned}
J_\sigma &= \rho_\sigma SLOT \\
&\text{Basic Access Mechanism} \\
J_s^{rx}(l) &= \rho_{rx}T_{DATA} + \rho_\sigma(SIFS+\delta) + \rho_{tx}T_{ACK} + \rho_\sigma(\delta + DIFS) \\
J_s^{rx}(\sim l) &= \rho_{rx}T_{DATA} + \rho_\sigma(SIFS+\delta) + \rho_{rx}T_{ACK} + \rho_\sigma(\delta + DIFS) \\
J_c^{rx} &= \rho_{rx}T^*_{DATA} + \rho_\sigma(\delta + EIFS) \\
J_s^{tx} &= \rho_{tx}T_{DATA} + \rho_\sigma(SIFS+\delta) + \rho_{rx}T_{ACK} + \rho_\sigma(\delta + DIFS) \\
J_c^{tx} &= \rho_{tx}T^*_{DATA} + \rho_\sigma(\delta + EIFS) \\
&\text{RTS/CTS Access Mechanism} \\
J_s^{rx}(l) &= \rho_{rx}T_{RTS} + \rho_\sigma SIFS + \delta + \rho_{tx}(T_{CTS} + T_{ACK}) + \rho_\sigma(SIFS+\delta) \\
&+\rho_{rx}T_{DATA} + \rho_\sigma(SIFS+\delta) + \rho_\sigma(\delta + DIFS) \\
J_s^{rx}(\sim l) &= \rho_{rx}T_{RTS} + \rho_\sigma SIFS + \delta + \rho_{rx}(T_{CTS} + T_{ACK}) + \rho_\sigma(SIFS+\delta) \\
&+\rho_{rx}T_{DATA} + \rho_\sigma(SIFS+\delta) + \rho_\sigma(\delta + DIFS) \\
J_c^{rx} &= \rho_{rx}T^*_{RTS} + \rho_\sigma(\delta + EIFS) \\
J_s^{tx} &= \rho_{tx}T_{RTS} + \rho_\sigma(SIFS+\delta) + \rho_{rx}T_{CTS} + \rho_\sigma(SIFS+\delta) \\
&+\rho_{tx}T_{DATA} + \rho_\sigma(SIFS+\delta) + \rho_{rx}T_{ACK} + \rho_\sigma(\delta + DIFS) \\
J_c^{tx} &= \rho_{tx}T^*_{RTS} + \rho_\sigma(\delta + EIFS) \\
&\text{Modified RTS/CTS Access Mechanism (see text)} \\
J_s^{rx}(\sim l) &= \rho_{rx}T_{RTS} + \rho_\sigma SIFS + \delta + \rho_{rx}T_{CTS} + \rho_\sigma(DIFS+\delta)
\end{aligned}
\tag{7}
$$

IV. PERFORMANCE

Figure 2 plots τ, p, P_{tr}, and P_s as functions of n, using equations (1), (2), (3).

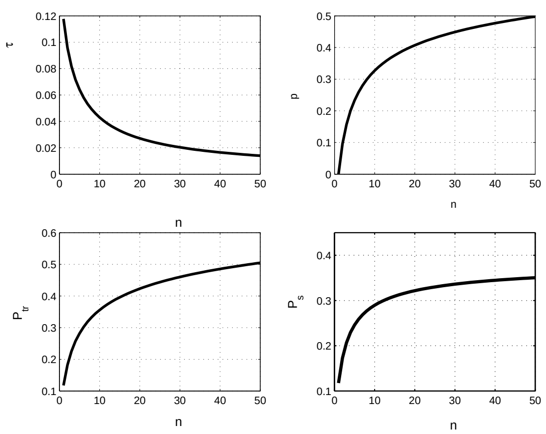

Fig. 2. Probabilities τ, p, P_{tr}, and P_s as functions of n

For the numerical calculations and simulation described below, the values of the radio power in the different states are taken from [1]:

$$\rho_{tx} = 0.3W, \rho_{rx} = 0.185W, \rho_\sigma = 0.066W.$$

Of course, other values can be substituted in the formulas. The data rate is assumed to be 6 Mbps of IEEE 802.11a.

Figure 3 plots the numerator of (4), the average energy (J) consumed in one slot by each station, for different packet sizes and for basic access and RTS/CTS. The additional overhead of RTS/CTS packets is overcome with increasing n and packet size.

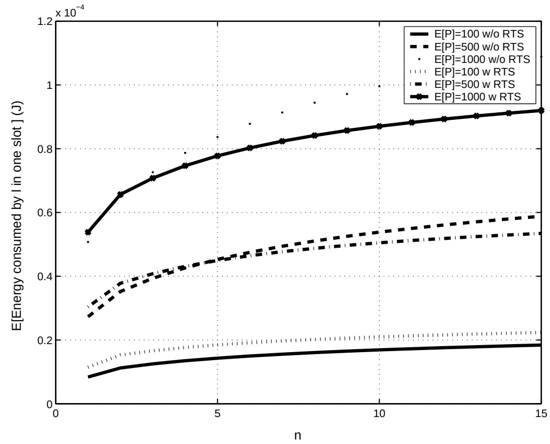

Fig. 3. Average energy (J) consumed in one slot

Figure 4 plots the denominator of (4), the average payload (MB) per node transmitted in one slot. As is to be expected, the payload increases with packet size. There is virtually no difference between basic access and RTS/CTS mechanisms.

Figure 5 plots the ratio in (4)—the average energy $J(n)$ consumed in transmitting 1 MB of data. The energy grows linearly with n with a slope that depends on packet size and the access mechanism. The linearity is investigated later. Figure 6 plots the average energy consumed per node in transmitting 1 MB of data with 1 KB packets for different data rates.

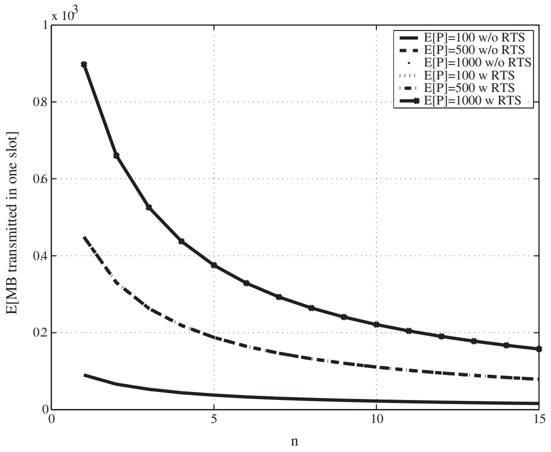

Fig. 4. Average payload (MB) transmitted in one slot

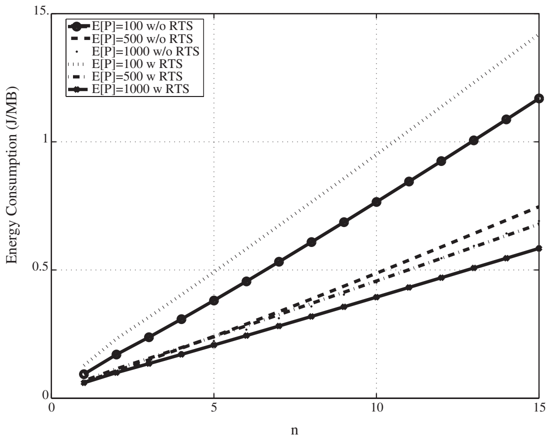

Fig. 5. Energy consumed $J(n)$ for different packet sizes and data rate of 6Mbps

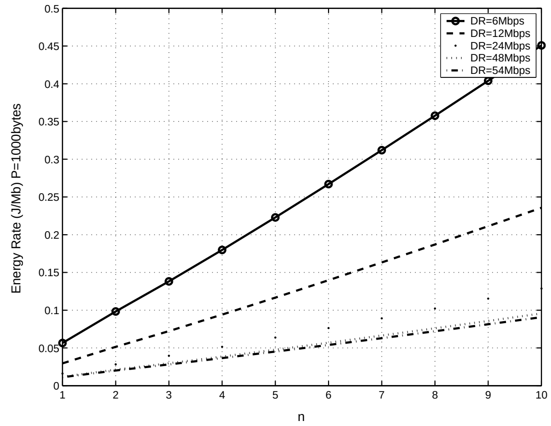

Fig. 6. Energy consumed $J(n)$ for different data rates for 1KB packet

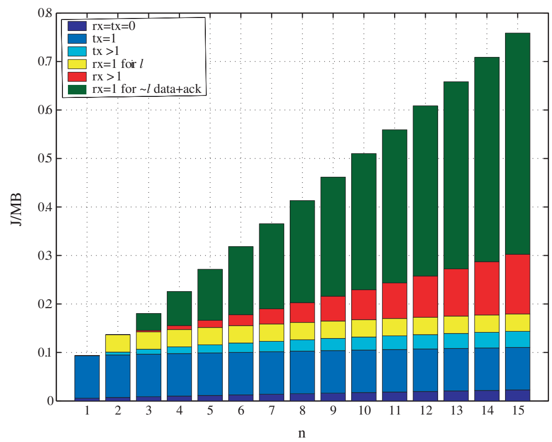

Fig. 7. Decomposition of $J(n)$ for basic access, E[P] = 1KB

Figures 7 and 8 display, for the basic and RTS/CTS mechanisms respectively, the energy per MB of payload consumed in the different operations of the 802.11 protocol, assuming 1KB packets.

The figures reveal interesting properties. As expected, the useful energy consumed in the successful transmission and reception of data is constant; hence, the remaining energy, which grows to 100 percent of all energy, is wasted. The most wasteful operation is overhearing ('rx=1 for $\sim l$'). For $n = 15$, it wastes 60 percent of total energy for the basic mechanism and 75 percent for the RTS/CTS mechansim. For the basic mechanism, the next most wasteful operation is reception of collided packets ('rx $>$ 1'), amounting to 16 percent of the total. For the RTS/CTS mechanism, the next most wasteful operation is reception of RTS/CTS packets ('rx = 1 for $\sim l$').

RTS/CTS packets contain the destination address and the duration of the data packet (the NAV field). Station l, upon decoding an RTS or CTS packet and learning that the packet is destined for another station, could put its radio into a reduced-power state for the duration, as investigated in [7], [8], [9]. With this modified RTS/CTS mechanism, the energy consumed in overhearing is drastically reduced, as shown in the last equation in (7) (power consumption in the reduced-power state is considered to be zero, but one can substitute other values). The resulting energy consumption is shown in Figure 9.

V. Linear Approximation

We provide a linear approximation to $J(n)$. From (3)-(6)

$$J(n) = \frac{1}{E[P]}[\frac{1-\tau}{\tau}J_\sigma + J_s^{rx}(l) + (n-2)J_s^{rx}(\sim l) + (\frac{n(1-\tau)}{P_s} - \frac{(1-\tau)}{\tau} - (n-1))J_c^{rx} + J_s^{tx} + (n\frac{\tau}{P_s} - 1)J_c^{tx}]. \quad (8)$$

Approximating each term linearly gives

$$J(n) \approx \frac{1}{E[P]}[(0.8J_\sigma + J_s^{rx}(l) + J_s^{rx}(\sim l) + 1.2J_c^{rx} + 0.0019J_c^{tx})n + 38J_\sigma + J_s^{rx}(l) - 2J_s^{rx}(\sim l) + -93J_c^{rx} + J_c^{rx} + 1.1J_c^{tx}], \quad (9)$$

which simplifies further for $n \to \infty$,

$$\lim_{n\to\infty} J(n) \approx \frac{1}{E[P]}[(J_s^{rx}(\sim l) + 1.2J_c^{rx})n - 2J_s^{rx}(\sim l) - 93J_c^{rx})]. \quad (10)$$

The linear approximation depends on $E[P]$ and the data rate. For instance for $E[P] = 1KB$ and $DR = 6Mbps$, energy values are given in Table I. Figure 10 validates the linear approximation for large n.

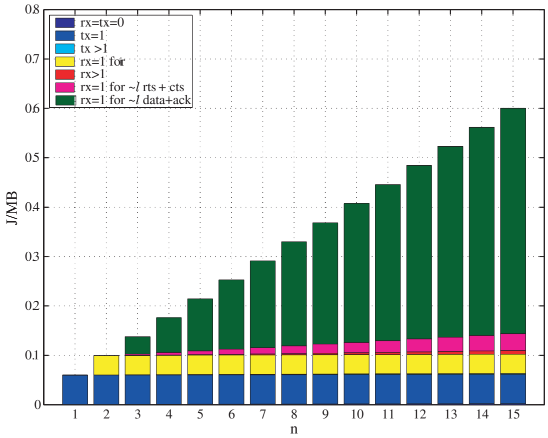

Fig. 8. Decomposition of $J(n)$ for RTS/CTS, E[P] = 1KB

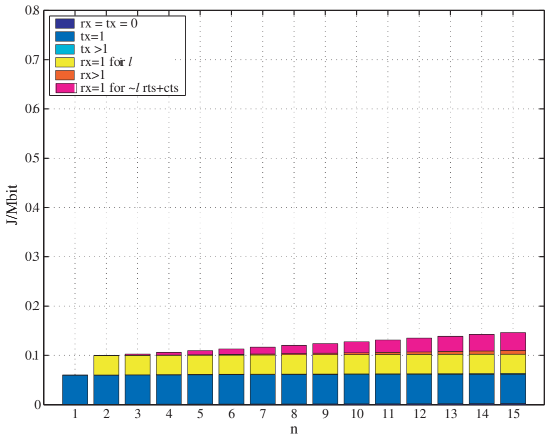

Fig. 9. Decomposition of $J(n)$ for the modified RTS/CTS mechanism, E[P] = 1KB

VI. Conclusion

We derived explicit formulas for the components of the total energy $J(n)$ consumed by a station's radio in order to transmit 1 MB of data in a 802.11 network with n stations. We found that $J(n)$ is linear in n for large n. Only a constant amount of the total energy is usefully consumed in successful transmission and reception; the rest is wasted. The largest waste is due to overhearing, i.e., reception of packets intended for another destination. For an RTS/CTS mechanism, a station can avoid overhearing by making use of information in the RTS/CTS packets, and save 75 percent of the total energy consumed. This would require a small change in the state machine of the physical layer, without sacrificing conformity to the standard (if the radio state can be switched quickly).

The other energy-wasting operations are: (d) listening to an idle channel, (e) unsuccessful (colliding) transmissions, and (f) reception of collisions. The RTS/CTS mechanism significantly reduces energy consumed by operations (e) and (f), as can be seen by comparing Figures 7 and 8. It is not possible to reduce idle listening: the CSMA/CA protocol permits a station to transmit at any random time, so a station must constantly listen to the channel.

(J/MB)	J_σ	$J_s^{rx}(l)$	$J_s^{rx}(\sim l)$	J_c^{rx}	J_s^{tx}	J_c^{tx}
$*10^{-3}$	0.0006	0.272	0.267	0.262	0.426	0.421

TABLE I

Coefficients of the linear decomposition of $J(n)$.

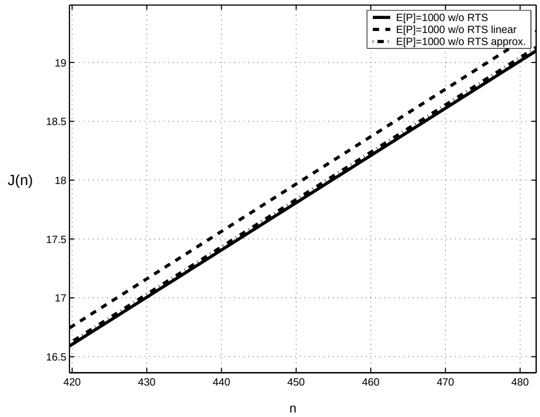

Fig. 10. Linear approximation to $J(n)$, DR=6Mbps

The study focuses on the saturated case, when stations always have data to transmit. In [4], [2] one can find a Markov chain model for the unsaturated case. That model can also be modified to account for energy consumption, as was done in this paper. Of course, under very light load, energy consumed in idle listening will be proportionately greater.

The 802.11 radio consumes a small fraction of the total energy in a laptop PC. However, the radio will be a large energy consumer in small devices, e.g. PDAs, cellphones or wireless sensors. The explicit formulas developed here may be useful in the design of radios and MAC protocols for these devices.

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