ANALYZING THE ENERGY CONSUMPTION OF IEEE 802.11 AD HOC NETWORKS

Daniel de O. Cunha, Luís Henrique M. K. Costa, and Otto Carlos M. B. Duarte
Grupo de Teleinformática e Automação - PEE/COPPE - DEL/POLI
Universidade Federal do Rio de Janeiro - Rio de Janeiro, Brazil[*]
doc,luish,otto@gta.ufrj.br

Abstract This paper analyzes the energy consumption of ad hoc nodes using IEEE 802.11 interfaces. Our objective is to provide theoretical limits on the lifetime gains that can be achieved by different power saving techniques proposed in the literature. The evaluation takes into account the properties of the medium access protocol and the process of forwarding packets in ad hoc mode. The key point is to determine the node lifetime based on its average power consumption. The average power consumption is estimated considering how long the node remains sleeping, idle, receiving, or transmitting.

Keywords: Energy Conservation, Wireless Communication, Ad Hoc Networks

1. Introduction

A critical factor of the wireless ad hoc network operation is the energy consumption of the portable devices. Typically, wireless nodes are battery-powered and the capacity of these batteries is limited by the weight and volume restrictions of the equipments. Consequently, it is important to reduce the energy consumption of the nodes in the ad hoc network. Moreover, in multihop ad hoc networks each node may act as a router. Thus, the failure of a node due to energy exhaustion may impact the performance of the whole network.

Most works on ad hoc networks assume the use of IEEE 802.11 wireless LAN interfaces. Nevertheless, IEEE 802.11 interfaces operating in ad hoc mode have some peculiarities that are frequently disregarded. Chen *et al.* [1] analyzed the energy consumption of the IEEE 802.11 MAC protocol in infrastructured mode. Feeney and Nilsson [2] measured the energy consumption of IEEE 802.11 interfaces in ad hoc mode and showed that the idle cost is relatively high, since the nodes must constantly sense the medium in order to

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identify the transmissions addressed to them. Monks *et al.* [3] analyzed the effect of transmission power control on the energy consumption of the nodes. Singh and Raghavendra [4] analyzed the potential gain of their PAMAS protocol, but ignored the power consumption of idle interfaces. Bhardwaj *et al.* [5] derived upper bounds on the lifetime of sensor networks considering the collaborative profile of such networks. The derived bounds relate to the network as a whole and not to specific nodes.

In this paper, we analyze the energy consumption of ad hoc nodes taking into account the interactions of the IEEE 802.11 MAC protocol and the packet forwarding performed on the ad hoc multi-hop networks. This is done based on the fraction of time that the interfaces spend in each operational state and on the capacity of the ad hoc networks. Finally, we analyze the potential gain of different power saving techniques. The theoretical limits of each technique can be used as guidelines in the development of novel power-saving schemes.

This paper is organized as follows. Section 2 analyzes the effects of ad hoc packet forwarding on the node energy consumption. The potential gains of different power saving techniques are obtained in Section 3. Finally, Section 4 concludes this work.

2. Energy Consumption of the Nodes

The analyses presented in this section assumes the use of IEEE 802.11b interfaces operating in ad hoc mode at 11Mbps using the Distributed Coordination Function (DCF), with RTS/CTS handshake [6]. We can model the average power (P_m) consumed by the interface as

$$P_m = t_{Sl} \times P_{Sl} + t_{Id} \times P_{Id} + t_{Rx} \times P_{Rx} + t_{Tx} \times P_{Tx} \ , \qquad (1)$$

where t_{Sl}, t_{Id}, t_{Rx}, and t_{Tx} are the fractions of time spent by the interface in each of the possible states: Sleep, Idle, Receive, and Transmit, respectively. These fractions of time satisfy the condition $t_{Sl} + t_{Id} + t_{Rx} + t_{Tx} = 1$. Analogously, P_{Sl}, P_{Id}, P_{Rx}, and P_{Tx} are the powers consumed in the four states. Considering P_m and the initial energy of the node (E), we can calculate the node lifetime (T_v), which represents the time before the energy of the node reaches zero, as

$$T_v = \frac{E}{P_m} \ . \qquad (2)$$

The lifetime analysis presented here takes into account only the energy consumption of the wireless interfaces, ignoring the energy consumed by the other circuits of the equipment. Initially, we assume the absence of any power-saving strategy, which implies $t_{Sl} = 0$. With this restriction, the maximum lifetime of a node is achieved with the node permanently in Idle state, as Eq. 3 shows.

$$T_{idle} = \frac{E}{P_{Id}} \ . \qquad (3)$$

In order to evaluate the effect of DCF over the energy consumption, we first analyze two nodes in direct communication. This scenario enables maximum transmission capacity because there is no contention. Then, we analyze the effect of ad hoc forwarding in the energy consumption.

Direct Communication

This scenario consists of two nodes separated by a distance that allows direct communication. The maximum utilization is achieved if the source always has a packet to transmit when the medium is free. In this case, t_{Id}, t_{Rx}, and t_{Tx} are the fractions of time the node spends in each state to transmit one data frame, according to DCF operation. Ignoring the propagation delay, the transmission time of a data frame is divided as shown in Figure 1.

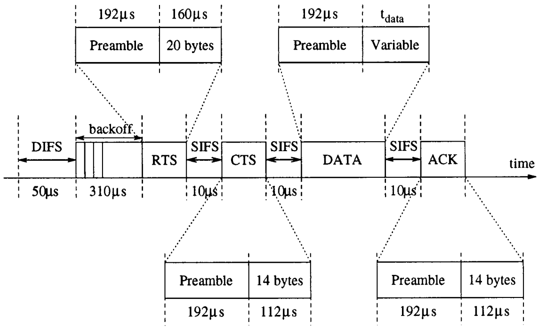


Figure 1. Total transmission time of a data frame.

The backoff time is uniformly distributed between 0 and 31 (CW_{min}) slots of $20\mu s$ each. The average backoff is 15.5 slots, or $310\mu s$ per frame. The interframe spaces are SIFS = $10\mu s$ and DIFS = $50\mu s$. Moreover, a preamble is sent before each frame. This preamble can be long, lasting for $192\mu s$, or short, lasting for $96\mu s$ [7]. Our analysis considers the long IEEE 802.11 preamble, since the short preamble is not compatible with old interfaces. The RTS, CTS, and ACK control frames are transmitted in one of the IEEE 802.11 basic rates. We assume a basic rate of 1Mbps. Thus, the 20 bytes of the RTS are transmitted in $160\mu s$, while the 14 bytes of CTS and ACK take $112\mu s$. The data frame includes a 34-byte MAC header in addition to the data payload, which includes any overhead added by upper layers. Therefore, the transmission time is

$$\begin{aligned} T_{frame} &= backoff + 4 \times t_{pr} + 3 \times SIFS + DIFS + \\ &\quad t_{RTS} + t_{CTS} + t_{data} + t_{ACK} \ . \end{aligned} \tag{4}$$

We can obtain t_{Id}, t_{Rx}, and t_{Tx} for the emitter and destination nodes as a function of the packet length used. The Backoff, DIFS, and SIFS are periods where both nodes stay idle. During the periods corresponding to the RTS and data packets the emitter is in Tx and the destination in Rx state. The opposite situation occurs during the CTS and ACK periods.

Based on the results for the emitter and destination nodes, we can also calculate t_{Id} and t_{Rx} for "overhearing" nodes, which is necessary to the forwarding chain analysis. Overhearing nodes do not take part in the point-to-point communication but they are in the range of the emitter and/or the receiver. Thus, these nodes spend energy receiving frames addressed to other nodes. There are three kinds of overhearing node: a node that only overhears traffic originated from the emitter, $overhearing_e$, a node that only overhears traffic originated from the destination, $overhearing_d$, and a node that overhears traffic originated from both the emitter and the destination, $overhearing_{ed}$.

Forwarding Chain

In ad hoc networks, when a node needs to communicate with someone out of its direct transmission range, the node must rely on its neighbors to deliver the packets. The intermediate nodes form a forwarding chain with its extremities connected to the source and to the sink of the communication. The packets are forwarded hop by hop through the chain. In this configuration, consecutive packets compete with each other, increasing contention. Li *et al.* [8] showed that the ideal utilization of a generic forwarding chain is $\frac{1}{4}$ of the one-hop communication capacity. Li *et al.* used a propagation model where a packet can be correctly received at a distance r from the emitter and where the packet transmission can interfere with other transmissions in a radius of approximately $2r$. We assume in this paper that when a node is overhearing a communication from a distance d such that $r < d < 2r$, the signal strength is still able to change the state of the interface to Rx. Even if the correct reception is impossible, the interface tries to receive the frames.

Therefore, a node in an ideal forwarding chain spends $\frac{1}{4}$ of the time as an emitter, $\frac{1}{4}$ of time as a destination and $\frac{1}{2}$ as an $overhearing_{ed}$ node. Then, the average power consumption of a node in the forwarding chain is

$$P_m = \frac{1}{4} \times P_e + \frac{1}{4} \times P_d + \frac{1}{2} \times P_{o_{ed}} \ , \qquad (5)$$

where P_e, P_d, and $P_{o_{ed}}$ are, respectively, the average power consumed by a node spending all the time as an emitter, a destination, and an $overhearing_{ed}$ node.

Quantitative Analysis

In order to provide a quantitative analysis, we adopt the measurements by Feeney and Nilsson [2] for IEEE 802.11b interfaces operating at 11Mbps. Table 1 presents an approximation of their results. To ease the comparison with

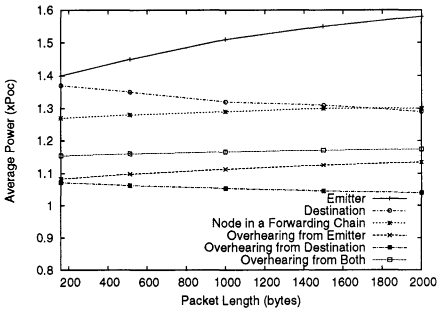


Figure 2. Average power for nodes in different situations.

the maximum lifetime with no energy saving of Eq. 3, Table 1 also shows the consumption of the four states relatively to the Idle consumption (P_{Id}). Based on Table 1, and on Eqs. 1, 2, and 5, we obtain the average power and lifetime of nodes in different situations as a function of P_{Id} (Figure 2). As Figure 2 shows, for emitters and nodes taking part of forwarding chains the average power consumed, P_m, increases as the data length increases. This is due to the increasing of t_{Tx} with the augmentation of the data frame, and implies in a reduction of the node lifetime. Nevertheless, the node lifetime (Eq. 2) decreases slowly with the packet size comparing to the maximum throughput achievable. Thus, it is possible to transmit more data using large packets. Moreover, nodes in the $overhearing_{ed}$ condition have a lifetime from 13% (for 160-byte packets) to 15% (for 2000-byte packets), shorter than idle nodes.

Table 1. IEEE 802.11b interface energy consumption.

State	**Consumption (W)**	**Ratio**
Sleep	0.050	$0.07P_{Id}$
Idle	0.740	P_{Id}
Rx	0.900	$1.2P_{Id}$
Tx	1.350	$1.8P_{Id}$

3. Power Saving Techniques

This section analyzes three major power saving techniques for ad hoc networks. The first one uses the remaining energy as routing metric [9]. The idea is to avoid the continuous use of the same nodes to forward packets. The second approach is transmission power control [3]. Due to the attenuation of RF signals, it may be interesting to reduce the distance of a communication, even if it increases the total number of hops. The third technique is the transition to low power mode [4]. The objective is to maximize the time a node spends at the low power state. The following sections detail each technique.

Energy-Aware Routing

Energy-aware routing balances the energy consumption of the nodes by selecting routes through nodes with more remaining energy. Since the source and the sink of a communication are fixed, these nodes do not benefit from this technique. The nodes in the forwarding chain may save energy. The following analysis considers that traffic is evenly distributed among n disjoint paths. Thus, each intermediate node takes part in the active forwarding chain $\frac{1}{n}$ of the time. Nevertheless, the analysis can be easily extended to the case where the traffic is unevenly divided among the paths. In this case, the fraction $\frac{1}{n}$ should be replaced by the fraction of time each node takes part in the forwarding chain.

In order to evaluate the gain achievable by this technique, we use the consumption of the node when continuously forwarding packets, and the consumption of the node when not taking part of the forwarding chain. The average power consumption can be expressed as

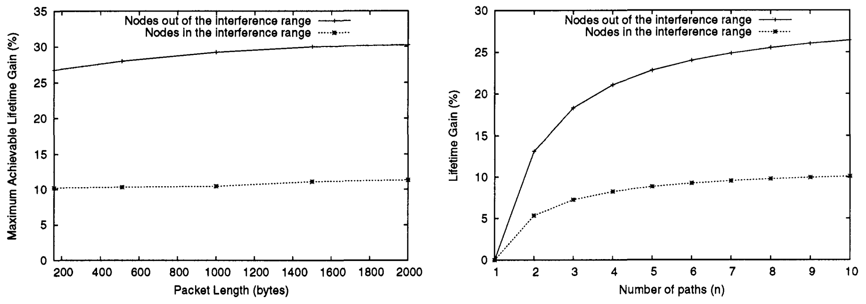
$$P_{m_{bal}} = \frac{P_{fc}}{n} + \frac{(n-1)P_{\overline{fc}}}{n}, \tag{6}$$

where P_{fc} is the average power consumption in the active forwarding chain, whereas $P_{\overline{fc}}$ is the average power consumed when not forwarding. While P_{fc} is plotted in Figure 2, we have two limit cases for $P_{\overline{fc}}$. In the best case, the node that leaves the active forwarding chain does not overhear the traffic of the new active chain, and thus consumes P_{Id}. In the worst case, however, the node continuously overhears the traffic of the active forwarding chain, thus consuming $P_{o_{ed}}$ (Figure 2). In this case, the node is close enough to the active forwarding chain, being in the interference range of the forwarding nodes.

Using the average power consumptions, we obtain the limit lifetime gain of this technique. Figure 3(a) shows the limit gain as the number of used paths increases ($\frac{1}{n} \to 0$) and as a function of the packet length for the two cases discussed above. Note that the packet length has a small effect on these limits, since they depend on the relation between P_{Id}, $P_{o_{ed}}$, and P_{fc}. While the values showed in Figure 3(a) are limits when $\frac{1}{n} \to 0$, Figure 3(b) plots the variation of this gain with n for the case of 2000-byte packets. With $n = 4$, at least 66% of the maximum lifetime gain is achieved, for both situations. The important result is that energy-aware routing achieves significant gains using few paths.

Transmission Power Control

Min and Chandrakasan [10] analyzed the conditions under which it is advantageous to use two hops instead of one, by reducing the transmission power. They model the energy consumption as $\alpha + \beta d^n$, where α is the distance-independent, and βd^n is the distance-dependent term. The coefficient n represents the path loss and is typically between 2 and 6 [3]. Min and Chandrakasan claim that the use of two hops is profitable when the reduced distance-



(a) (b)

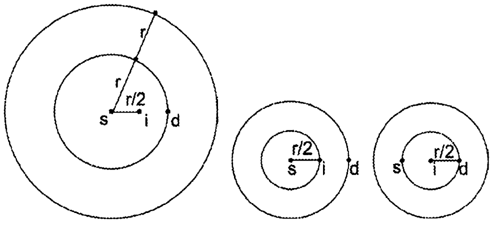
Figure 3. Limits of the lifetime gains with the energy-aware routing.

dependent consumption is higher than the fixed cost associated to the inclusion of an additional hop. The variable portion of the energy consumption of the wireless interface is due to the RF amplifier. Assuming that all the difference between P_{Tx} and P_{Rx} is due to the power amplifier, the lower limit of P_{Tx} is P_{Rx} and all the additional consumption scales with the distance, as modeled by βd^n. Hence, given the values adopted in our analysis (Table 1), the distance-dependent consumption ($P_{Tx} - P_{Rx}$) is equal to $0.6P_{Id}$ for $d = r$. Moreover, assuming no power saving, the interface consumes at least P_{Id}. Thus, the fixed cost of the communication can be estimated by the difference between P_{Id} and P_{Rx}, which is $0.2P_{Id}$. Let T_{Tx} and T_{Rx} be, respectively, the amount of time that the emitter stays in the Tx and Rx states during the transmission of one packet. The terms α and βd^n for $d = r$ for the emitter, destination, and *overhearing$_{ed}$* nodes are shown in Table 2.

Table 2. Packet transmission costs for different node types.

Node	α	βd^n
Emitter	$(T_{Tx} + T_{Rx})\,0.2P_{Id}$	$T_{Tx} \times 0.6P_{Id}$
Destination	$(T_{Tx} + T_{Rx})\,0.2P_{Id}$	$T_{Rx} \times 0.6P_{Id}$
Overhearing$_{ed}$	$(T_{Tx} + T_{Rx})\,0.2P_{Id}$	0

Under these conditions and ignoring overhearing nodes, the per-packet cost of direct communication is $2(T_{Tx} + T_{Rx})0.2P_{Id} + (T_{Tx} + T_{Rx})0.6P_{Id}$, while the two-hop communication cost with $d = \frac{r}{2}$ is $4(T_{Tx} + T_{Rx})0.2P_{Id} + 2\beta\frac{r}{2}^{n}$, where $\beta\frac{r}{2}^{n}$ is the distance-dependent cost of one hop communication at a distance $d = \frac{r}{2}$. Thus, the use of two hops is advantageous if the resulting $\beta\frac{r}{2}^{n}$ is lower than $(T_{Tx} + T_{Rx})0.1P_{Id}$, i.e., if the resulting power consumption of the Tx state, P_{Tx}, for the communication is lower than $1.3P_{Id}$. This indicates that for channels with a path loss coefficient (n) higher than 2.58 the use of two hops instead of one is advantageous.

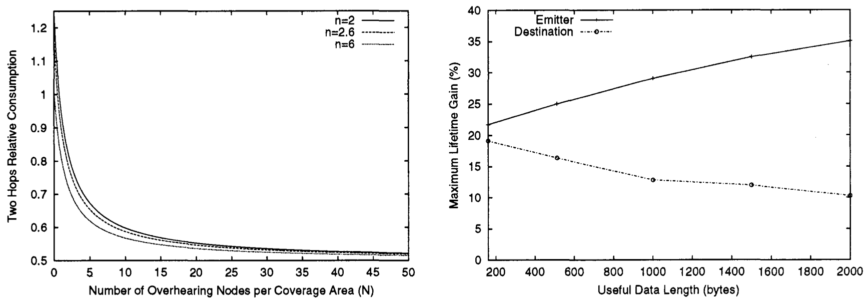


(a) (b) (c)

Figure 4. Transmission and interference ranges of the communications.

Nevertheless, the overhearing nodes can significantly increase the overall energy consumed. Supose the situation of Figure 4, where the source, s, wants to communicate with the destination, *d*, at a distance r from s and there is a third node, i, between s and *d*, at a distance $\frac{r}{2}$ from the source, which can be used as an intermediate hop. Considering only these three nodes and the propagation model where the interference range is twice the transmission range, the use of two hops instead of one is not profitable because nodes in the interference range overhear the transmissions. The use of a second hop causes two transmissions of the same packet, with half the original range. In direct communication, s would use a range of r, resulting in a interference range of $2r$ (Figure 4(a)). Node d can correctly receive the packet and i is an overhearing node. Using two-hop communication, node s uses a transmission range of $\frac{r}{2}$ in order to node i be able to receive the packet. The $\frac{r}{2}$ range implies a interference range of r, making d an overhearing node for this transmission (Figure 4(b)). After the first transmission, i sends the packet to *d*. In this second transmission s is an overhearing node (Figure 4(c)). Considering the overhearing nodes, the per-packet cost of direct communication is $3(T_{Tx} + T_{Rx})0.2P_{Id} + (T_{Tx} + T_{Rx})0.6P_{Id}$, while the two-hop communication cost with $d = \frac{r}{2}$ is $6(T_{Tx} + T_{Rx})0.2P_{Id} + 2\beta\frac{r}{2}^{n}$. Note that $\beta\frac{r}{2}^{n}$ is always positive, which means that the two-hop communication of Figure 4 always consumes more than direct communication, independently of the path loss coefficient.

Nevertheless, the two-hop communication with a range of $\frac{r}{2}$ covers an area four times smaller than the area covered by the direct communication with range r. In general, there are other nodes near the three nodes of Figure 4 that will be overhearing. If we assume an uniform distribution of overhearing nodes, each transmission of the two-hop scenario implies $\frac{1}{4}$ of the overhearing nodes of direct communication. Accounting for the two transmissions of the two-hop scenario, the total number of overhearing nodes is half the number of overhearing nodes in the single transmission of direct communication. Therefore, as the number of overhearing nodes (N) per communication range (given by a πr^2 area) increases, the ratio between the total energy consumed in



(a) (b)

Figure 5. Energy conservation with transmission power control.

the two-hop scenario and the total energy consumed in direct communication approaches 0.5.

Figure 5(a) plots the ratio between the total energy consumed in the two-hop scenario and in direct communication, i.e., the two hops relative consumption, with varying density of overhearing nodes, for different path loss coefficients (n). When there is no overhearing node near the communication, the two-hop consumption tends to the consumption of one-hop communication as n increases, and even a low density of overhearing nodes can result in significant energy savings using two hops (Figure 5(a)). Even for $n = 2$, the two hops relative consumption is around 0.7, assuming four overhearing nodes per communication range.

Considering only direct communication, the reduction of P_{Tx} to the lowest possible value is attractive, because all the reduction is converted into lifetime gain. Figure 5(b) shows the limit of the lifetime gain for the emitter and the destination nodes for different packet lengths, as $P_{Tx} \rightarrow P_{Rx}$ (and the distance between emitter and destination tends to zero). In this case, there is a significant difference in the gain for different packet lengths. As the length increases, the emitter gain increases while the destination gain decreases. As the packet length increases, the fraction of time spent by the emitter in Tx increases, and the time spent by the destination in Tx decreases.

Transition to Sleep State

The significant difference of consumption between the Idle and Sleep states makes the transition to sleep state profitable. Nevertheless, due to the distributed nature of ad hoc networks, the use of this technique is limited. A sleeping node must rely on its neighbors to store eventual packets addressed to it. Moreover, as the node may be asleep at packet arrival, the network latency increases. Thus, most works on this technique admit larger delays.

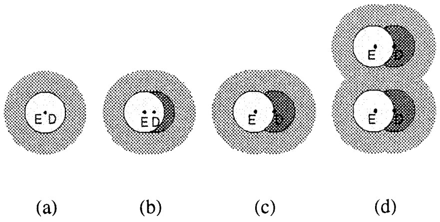
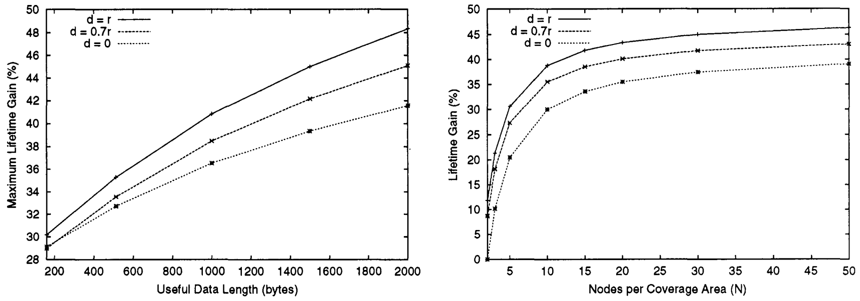


Figure 6. Situation of the nodes at different distances.

The PAMAS protocol [4] aims to reduce the energy consumption without latency increase. Nodes fall asleep only at times when they would not be able to transmit or receive packets. This is the case when a node is overhearing the communication of two other nodes. This approach reduces the time nodes spend in the Idle state, as well as reduces the periods in which the nodes are consuming energy by overhearing the communication of other nodes.

PAMAS uses a separate signaling channel to decide when nodes must fall asleep. Nevertheless, we can adopt a PAMAS-like technique over IEEE 802.11. In the IEEE 802.11 standard, when a node receives a RTS or CTS frame, the node sets its NAV (Network Allocation Vector) according to the virtual carrier sense mechanism. In practice, a node that overhears the RTS/CTS exchange will not be able to transmit or receive packets for the period specified in the NAV, therefore this node can fall asleep during that period, without affecting the network performance.

As Figure 6 shows, the nodes in the range of the emitter (white area) can sleep just after the end of the RTS transmission, while the nodes in the range of the destination (dark-gray area) can sleep only after the transmission of the CTS frame. We refer to the union of these two areas as the *Power Saving area* (PS-area). The nodes in the interference range (light-gray area) of both the emitter and the destination are unable to fall asleep since they can not correctly receive the RTS or CTS frames. They are overhearing nodes. Depending on the distance, *d*, between the emitter and the destination, the fraction of nodes that are in each situation changes. Figs. 6(a) and 6(c) show the limit situations where the emitter and the destination are at distances $d = 0$ and $d = r$, respectively. Figure 6(b) shows an intermediate situation: the distance $d = 0.7r$ is the radius of a circle with half the area of the original circle of radius r. The power saved increases as the fraction of overhearing nodes decreases. Therefore, we consider two neighbor PS-areas that are as close as possible, i.e., two PS-areas with overlapping interference areas (the light-gray portion in Figure 6(d)). Then, we assume that each PS-area is responsible for only half the adjacent interference area. The average power consumption of the nodes that fall asleep after the transmission of the RTS and of the CTS frames are P_{rts} and P_{cts}, respectively, and N is the average number of nodes in the commu-



(a) (b)

Figure 7. Limits of the lifetime gains of the PAMAS-like power saving scheme.

nication range, given by a πr^2 area. Assuming the fair sharing of the channel among all nodes and that the cost of the transition to sleep state is negligible, the average power consumptions can be computed by weighting the average power of nodes in the different possible situations based on the involved areas, and consequently the number of nodes in each situation. The average powers consumed for the different distances discussed above are

$$P_{m_{d=0}} = \frac{P_e + P_d + (N-2)P_{rts} + 1.5P_{o_{ed}}}{2.5N}\ , \tag{7}$$

$$P_{m_{d=0.7r}} = \frac{P_e + P_d + (N-2)P_{rts} + 0.44NP_{cts} + 1.82NP_{o_{ed}}}{3.26N},\ and \tag{8}$$

$$P_{m_{d=r}} = \frac{P_e + P_d + (N-2)P_{rts} + 0.61NP_{cts} + 1.83NP_{o_{ed}}}{3.44N}\ . \tag{9}$$

The limit gain achievable by this technique (when $N \rightarrow \infty$), as a function of the packet length, is shown in Figure 7(a). The maximum gain is achieved with the limit distance $d = r$. Moreover, the gain using large frames is 50% higher than using small frames. As Figure 7(b) shows for the gain using 2000-byte frames, with a node density of 10 nodes per communication range, more than 70% of the maximum gain is achieved.

4. Conclusions

This paper analyzed the energy consumption of ad hoc nodes considering the interactions of the IEEE 802.11 MAC protocol and the ad hoc packet forwarding. Our goal was to provide theoretical gain limits which help the development of power-saving schemes. The use of larger packets increases the fraction of time spent by the interface in the Tx state, reducing the node lifetime. Nevertheless, our results show that the lifetime reduction is compensated by the higher throughput achieved using larger packets. Therefore, large packets are more energy efficient. Our analysis shows that an overhearing node has a lifetime up to 15% smaller than idle nodes.

Then, we analyzed the potential gains of three widely studied power saving techniques: energy-aware routing, transmission power control, and transition to sleep state. The limit gain of energy-aware routing varies from 11%, for nodes in disjoint paths with overlapping radio ranges, to 30%, for nodes in isolated forwarding chains. Moreover, up to 66% of the maximum gain is achieved using only four disjoint paths. Using transmission power control, the results show that the use of two hops instead of one can save up to 50% of the total energy consumed per packet, by reducing the number of overhearing nodes. Additionally, transmission power control increases the lifetime of nodes in direct communication from 21%, for small packets, to 35%, for large packets. Destination nodes can also benefit from this technique. Finally, a PAMAS-like power saving scheme, which uses the transition to sleep state, achieves up to 48% lifetime gain. More importantly, more than 70% of the possible gain is achieved with a density of 10 nodes per communication range.

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