On the Limits of Power Saving Techniques for Ad Hoc Networks

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Abstract

This paper analyzes the energy consumption of ad hoc nodes using IEEE 802.11 interfaces. The objective is to provide theoretical limits for the lifetime gains achievable by different power-saving techniques proposed in the literature. We assume that the lifetime is the most important metric from the user point of view. Our evaluation takes into account the properties of the medium access protocol and the packet forwarding process in ad hoc mode. The key point is to determine the node lifetime based on its average power consumption, which is estimated considering the time a node remains in the states sleeping, idle, receiving, or transmitting. We show that energy-aware routing may achieve a lifetime gain as large as 30% for nodes individually, allowing low-battery nodes to operate more time. The use of two-hops instead of direct transmission, when possible, reduces the total packet-transmission cost up to 50%, due to the smaller number of overhearing nodes. Nevertheless, despite the significant gain for the network as a whole, the nodes themselves can not obtain lifetime gains larger than 35%. Furthermore, our results highlight the importance of the transition to sleep state and show that a scheme based on the transition of overhearing nodes to sleep state increases the node lifetime up to 48%, and that this improvement also applies to networks with a moderate node density.

Key words: Energy Conservation, Wireless Communications, Ad Hoc Networks

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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 of the equipments. Hence, it is important to reduce, as much as possible, the energy consumption of the nodes in ad hoc networks. 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 [1,2]. Nevertheless, concerning the energy consumption, IEEE 802.11 interfaces operating in ad hoc mode have some peculiarities that are frequently disregarded. Feeney and Nilsson [3] 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 identify the transmissions addressed to them. This analysis highlights the importance of taking the idle consumption of the interface into account in order to observe the true effect of the analyzed mechanisms over the lifetime of the node. Nevertheless, aiming to isolate a specific aspect of the energy consumption, it is commonplace to use simplified energy models while analyzing power saving mechanisms. Energy-aware routing mechanisms are frequently analyzed by per packet models [4], while transmission power control techniques usually assume, in their analyses, the scaling of all the consumption of the node with the transmission range [5,6]. Even some schemes based on the transition to sleeping state disregard the important role played by the idle time of the interfaces. Singh and Raghavendra [7] analyze the potential gain of their PAMAS protocol, but ignored the power consumption of idle interfaces because their main objective was the reduction of the consumption of overhearing nodes. Our point is that the lifetime of the node is the most representative metric [8] from the user point of view, and the adoption of a more complete energy model can avoid misleading results.

In this paper, rather than proposing novel energy-conservation schemes, we derive upper bounds for the achievable gains of different power saving techniques based on a more representative energy model. Our approach is based on classifying the existing solutions into three categories: energy-aware routing, transmission power control, and sleeping-based techniques. Our first step is to analyze the energy consumption of ad hoc nodes taking into account the interactions of the medium access protocol of the IEEE 802.11 standard with the packet forwarding tasks performed on the ad hoc multihop networks. This is done based on the fraction of time that the interfaces stay in each operational state and on the capacity of the ad hoc networks. Finally, we discuss each of the above categories of power saving techniques and its achievable gain.

The theoretical limits of the achievable gain of each technique can be used as guidelines in the development of novel power-saving schemes.

This paper is organized as follows. Section 3 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 4. Finally, Section 5 concludes this work and discusses future directions.

2 IEEE 802.11 Networks

IEEE 802.11 interfaces are the most used wireless LAN technology. The IEEE 802.11 standard [1] has two different medium access techniques. The distributed scheme (*Distributed Coordination Function* - DCF) is used in both ad hoc and infrastructured operation while the centralized scheme (*Point Coordination Function* - PCF) is used only for infrastructured networks.

The DCF scheme is based on the medium access method *Carrier-Sense Multiple Access with Collision Avoidance* (CSMA/CA). Before the transmission of a frame, the terminal must listen to the medium for a specific amount of time (*DCF interframe space* - DIFS) plus a random backoff time. If the medium stays idle for that period, the frame is sent. After the reception of an unicast frame the receiver waits a SIFS (*Short Interframe Space*) period and then sends a positive acknowledgement (ACK) frame.

DCF has a virtual carrier sense mechanism, called *Network Allocation Vector* (NAV), which represents how long the medium will stay busy. This mechanism aims to reduce collisions and to eliminate the hidden terminal problem [9]. Two special control frames are needed: *Request to Send* (RTS) and *Clear to Send* (CTS). Before the transmission of the data frame, the emitter transmits a RTS frame and waits for a CTS from the data receiver. All neighbors that hear this handshake update their NAVs with the communication duration informed in the RTS and CTS frames.

The IEEE 802.11 standard [1] defines a power-saving mode for ad hoc networks. Nodes in power-saving mode wake up periodically to announce their packet transmissions and listen to the announcements of transmissions addressed to them. These wakeup periods are called *Announcement Traffic Indication Map windows (ATIM windows)*. In order to this power-saving scheme to work properly, all the nodes must be synchronized to ensure that the ATIM window starts at the same time for all nodes. The nodes synchronize using *beacon frames* transmitted at fixed beacon *intervals*. This power-saving scheme works well for fully connected networks but presents some problems when applied to multihop networks [10], including: clock synchronization, neighbor discovery, and network partitioning. Due to the complexity of this power-saving mode, it is commonplace not to implement it in the network interface cards.

2.1 Energy Model

As we discussed in Section 1, the idle consumption should not be neglected by the energy-consumption model. The per-packet models do not take the idle consumption into account. Therefore, we adopt a per-state model. Hence, the consumed energy will be computed by multiplying the time spent in a given state by the average consumption of the state. We can distinguish four operating states in IEEE 802.11 interfaces: *Sleeping* (Sl), *Idle* (Id), *Receiving* (Rx), and *Transmitting* (Tx).

The Sleeping state has the lowest power consumption. Nevertheless, in practice, it is difficult to manage the transitions to and from the Sleeping state without a centralized infrastructure. Thus, it is commonplace to assume that an ad hoc node is in Idle state, if not transmitting or receiving. The Idle state consumption is considerably higher than the consumption of the Sleeping state because an ad hoc node must constantly listen to the medium in order to receive frames directed to the node. The Rx state consumes slightly more energy than the Idle state: the additional energy is consumed by processing the received frames. The Tx state is the most consuming of the four states, since the strong attenuation of RF signals imposes the use of power amplifiers. Some interfaces can control the output signal power, reducing the consumption of these amplifiers. The transmission power control technique exploits this feature, as addressed in Section 4.

3 Energy Consumption of the Nodes

The analyses presented in this section assume the use of IEEE 802.11b interfaces operating in ad hoc mode at 11Mbps using the Distributed Coordination Function (DCF), with RTS/CTS handshake [1]. Based on the energy-consumption model discussed in Section 2.1, we compute the average power (P_m) consumed by the interface as

$$P_m = t_{Sl} \times P_{Sl} + t_{Id} \times P_{Id} + t_{Rx} \times P_{Rx} + t_{Tx} \times P_{Tx} \quad , \tag{1}$$

where t_{Sl}, t_{Id}, t_{Rx}, and t_{Tx} are the period of time that the node interface stays in the states: Sleeping, Idle, Receiving, and Transmitting, respectively. These periods of time are normalized to meet the condition

$$t_{Sl} + t_{Id} + t_{Rx} + t_{Tx} = 1. \tag{2}$$

In a similar way, P_{Sl}, P_{Id}, P_{Rx}, and P_{Tx} are the power consumptions in the four states. Given P_m and the initial energy of the node (E), the node lifetime (T_l), which represents the time when the energy of the node reaches zero, is given by

$$T_l = \frac{E}{P_m} \quad . \tag{3}$$

The node lifetime only takes into account the energy consumption of the wireless interfaces, ignoring the energy consumed by the other circuits of the device.

Initially, we assume that the power-saving mode is not used, which implies $t_{Sl} = 0$. In this case, the maximum lifetime of a node is achieved if the node permanently stays in Idle state:

$$T_{idle} = \frac{E}{P_{Id}} \quad . \tag{4}$$

Nevertheless, the minimum lifetime of a node is not achieved if it stays in the transmitting state all the time. This is not possible because the IEEE 802.11 MAC protocol operation [1] requires that the node listen to the medium free (Idle state) before transmitting a frame and receive an acknowledgement (Receiving state) for each transmitted frame. In a multihop data transfer, the above procedure is repeated for every hop and each hop can not receive a new frame while it is forwarding the previous one. Thus, to evaluate the energy consumption of a node in IEEE 802.11 ad hoc mode, we first analyze the energy consumption of two nodes in direct communication and afterwards the effect of ad hoc forwarding.

For sake of clarity, we adopt in our analyses the following notations. As the transmission of a data frame requires the exchange of other frames, the Emitter is the node that transmits the data frame in a direct communication whereas the node receiving the data frame is called the Destination. In a similar way, as a communication through a forwarding chain is composed by a sequence of direct communications, we use the terms *source* and *sink* to designate the end points of the communication. The terms send and receive are used to denote the transmission of an individual frame.

A direct communication occurs when the sink is inside the transmitting coverage area of the source. The maximum communication throughput is achieved when there is no contention, that is, a source node always has a data frame to transmit and all the other nodes do not. The Emitter always finds the medium free. In this case, t_{Id}, t_{Rx}, and t_{Tx} can be directly obtained by evaluating the transmission procedure of a data frame, according to the MAC protocol in ad hoc mode. The total transmission time of a data frame is:

$$T_{frame} = backoff + 3 \times SIFS + DIFS + 4 \times t_{pr} + t_{RTS} + t_{CTS} + t_{data} + t_{ACK} \quad . \tag{5}$$

The backoff time in this scenario is uniformly distributed between 0 and 31 (CW_{min}) slots of 20μs. The average backoff is 15.5 slots, or 310μs, per frame. The interframe spaces are defined in the standard as SIFS = 10μs and DIFS = 50μs. Moreover, a physical layer preamble must be sent at the beginning of each frame. This preamble can be long (192μs) or short (96μs) [2].

The RTS, CTS, and ACK control frames are transmitted in one of the 802.11 basic rates. The basic rate is the lowest rate that must be supported by all the stations in the network. The low basic rates maintain compatibility with old equipments, but higher basic rates allow larger throughput. For basic rates of 2Mbps and above, it is possible to use the short preamble, reducing the physical-layer overhead. Moreover, higher basic rates speed-up the transmission of the control frames (t_{RTS}, t_{CTS}, and t_{ACK}), which represent a high overhead in DCF. The data frame transmission time (t_{data}) includes the transmission of a 34-byte MAC header in addition to the data payload. The data payload includes all the overhead added by upper layers. Table 1 shows the extra time required to transmit a data frame ($T_{frame'} = T_{frame} - t_{data}$) for different basic rates and preamble lengths.

Table 1
Transmission times with different basic rates.

Basic Rate	**Preamble**	t_{RTS}	t_{CTS}	t_{ACK}	$T_{frame'}$
1Mbps	192μs	160μs	112μs	112μs	1542μs
2Mbps	192μs	80μs	56μs	56μs	1344μs
2Mbps	96μs	80μs	56μs	56μs	966μs
11Mbps	192μs	15μs	10μs	10μs	1193μs
11Mbps	96μs	15μs	10μs	10μs	809μs

As Table 1 shows, the preamble length is an important component of the total transmission time. The use of higher basic rates and the short preamble allow a reduction of nearly 50% in $T_{frame'}$. Nevertheless, to ensure compatibility and to increase the robustness to the medium noise, the use of the lowest possible basic rate is commonplace. Therefore, this analysis assumes the long IEEE 802.11 preamble, since the short preamble is not compatible with old interfaces, and a 1Mbps basic rate. Ignoring the propagation delay, the transmission time of a data frame is divided as shown in Figure 1.

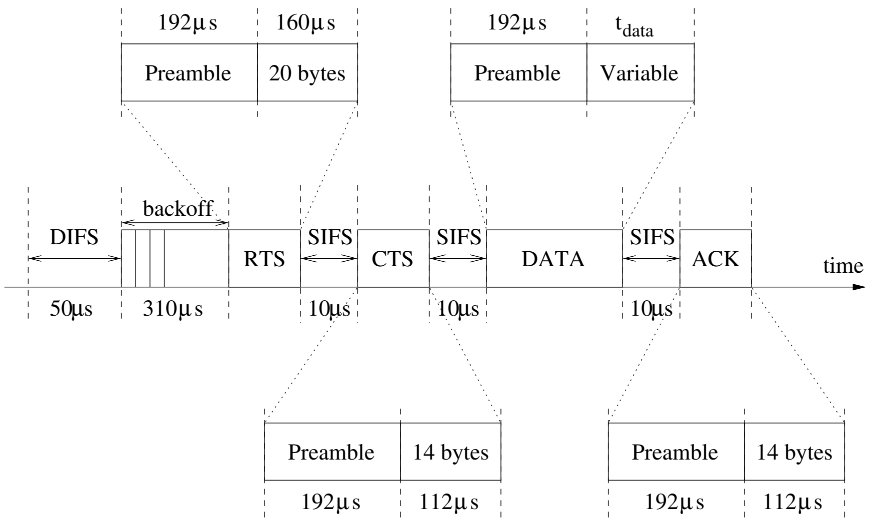


Figure 1. Total transmission time of a data frame.

As the only variable term in Equation 5 is t_{data}, we can obtain t_{Id}, t_{Rx}, and t_{Tx} for the Emitter and Destination nodes as a function of the packet length used. During $backoff$, $DIFS$, and $SIFS$ both nodes stay idle. During the periods corresponding to the RTS and data frames the Emitter is in Tx state whereas the Destination is in Rx state. The opposite occurs during the CTS and ACK periods. Figure 2 shows the time spent in Tx state by the Emitter and Destination nodes.

Based on the results for the Emitter and Destination nodes, we can also calculate t_{Id} and t_{Rx} for "overhearing" nodes. Overhearing nodes do not take part in the point-to-point communication, but they are in the transmission range of the Emitter and/or the Destination. Thus, these nodes consume energy receiving frames addressed to other nodes. There are three types 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, $overhearing_{ed}$. Since overhearing nodes never switch to the Tx state, the Rx state is the most energy consuming state for these nodes. Figure 3 shows the period of time that overhearing nodes stay in the Rx state.

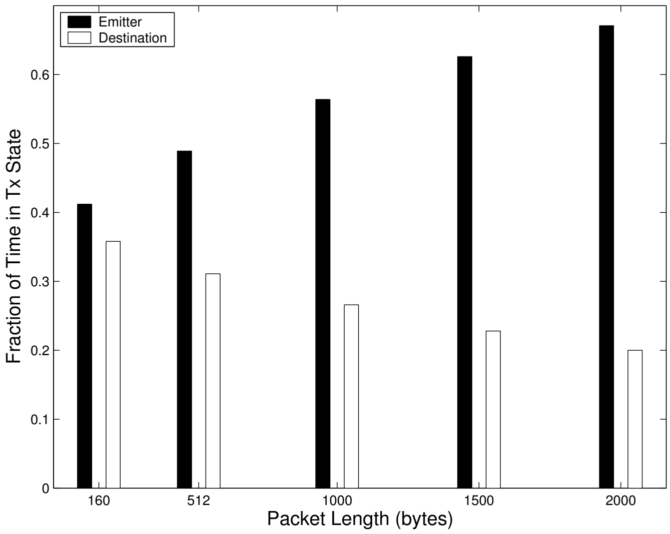


Figure 2. Period of time in Tx state.

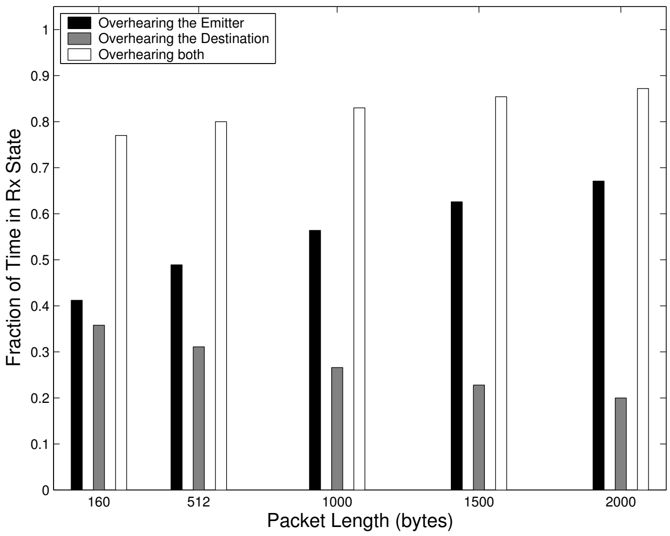


Figure 3. Period of time in Rx state.

3.2 Forwarding Chain

In ad hoc networks, when a node needs to communicate with another node that is 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. The packets are forwarded hop by hop through the chain.

In this configuration, consecutive packets compete for the medium, increasing contention. Li *et al.* [11] showed that the ideal utilization of a generic forwarding chain is $\frac{1}{4}$ of the one-hop communication capacity. Li *et al.* use 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. Thus, the power consumption in this case is P_{Rx}. 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 $\frac{1}{2}$ of the time as an $overhearing_{ed}$ node. Then, the average power consumption of a node in the forwarding chain is

$$P_m = \frac{1}{4} \times P_e + \frac{1}{4} \times P_d + \frac{1}{2} \times P_{o_{ed}}, \tag{6}$$

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

3.3 Quantitative Analysis

In order to provide a quantitative analysis, we adopt the power consumption measurements by Feeney and Nilsson [3] over IEEE 802.11b interfaces operating at 11Mbps. Table 2 presents an approximation of their results. To facilitate the comparison between the resulting lifetimes and the maximum lifetime without energy saving of Eq. 4, Table 2 also shows the consumption of the four states relatively to the Idle state consumption (P_{Id}). Based on

Table 2
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	$1.8P_{Id}$

Table 2 and on Eqs. 1, 3, and 6, we obtain the average power and lifetime of nodes in different situations as a function of P_{Id}. Figure 4 shows the average power consumed by active nodes in direct communication and by nodes taking part in a forwarding chain.

As shown in Figure 4, the consumption of the Destination node decreases with the increase of the packet size. The reason is the increase of the term t_{data} of Eq. 5 with the increase of the packet size. The augmentation of t_{data} increases the fraction of time the receiver spends in the Rx state and reduces the fraction

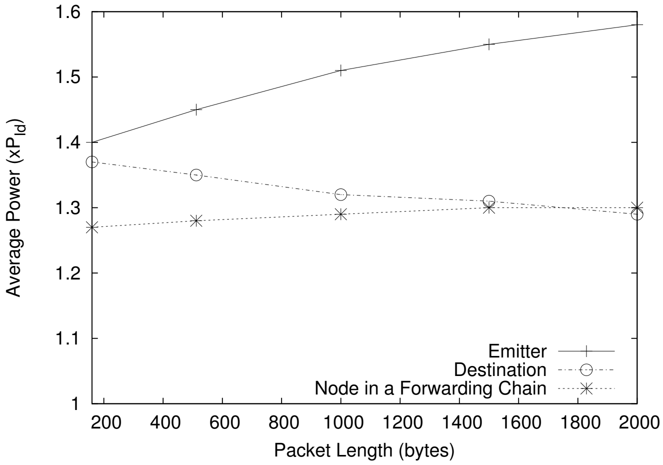


Figure 4. Average power for active nodes.

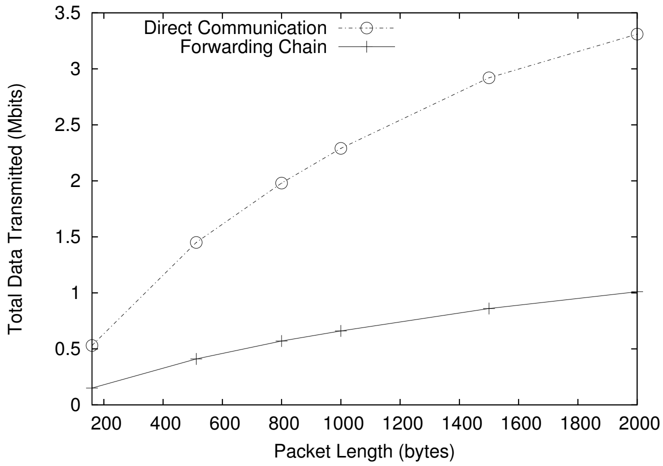


Figure 5. Normalized transmitted data.

of time spent in the most consuming state, Tx. For the Emitter, and nodes taking part of forwarding chains, the opposite occurs. The average power consumed, P_m, increases with the packet length. This is due to the increasing of t_{Tx} for these nodes with the augmentation of the data frame, and implies in a reduction of the node lifetime. Nevertheless, the node lifetime (Eq. 3) decreases slowly with the packet size compared to the maximum throughput achievable. Thus, for a given initial energy, it is possible to transmit more data using larger packets. Figure 5 shows the normalized data transmitted by nodes in direct communication or participating in forwarding chains.

As depicted in Figure 5, the use of large packets is much more efficient. When larger frames are used, the overhead represented by the RTS/CTS handshake and physical layer requirements is relatively smaller.

In order to analyze the effects of the overhearing condition over the energy consumption, Figure 6 shows the average power of overhearing nodes. We

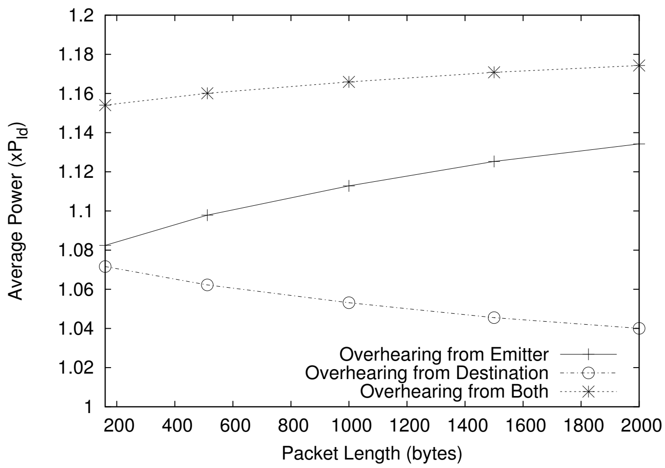


Figure 6. Average power for overhearing nodes.

can conclude that the overhearing of third-party traffic strongly impacts the consumption of the nodes. Nodes in the $overhearing_{ed}$ condition would have a lifetime from 13% (for 160-byte packets) to 15% (for 2000-byte packets), shorter than idle nodes.

Figures 4 and 6 illustrate the basic ideas of the power-saving techniques. Energy-aware routing aims to reduce the consumption of exhausted nodes by taking them out of the forwarding chain and turning them into overhearing or idle nodes. The transmission power control reduces the consumption of the active nodes, which stay some time in the Tx state. Moreover, the reduction of the transmission power reduces the communication range and, as a consequence, the number of overhearing nodes. The transition to sleep state tries to turn overhearing nodes into sleeping nodes. The next section discusses in more detail three power-saving techniques.

4 Power Saving Techniques

This section analyzes three major power saving techniques for ad hoc networks. Energy-aware routing uses the remaining quantity of energy of the nodes as a routing metric [12,13,14]. This technique aims to avoid the frequent use of the same nodes to forward packets, which leads to their fast energy exhaustion. The second technique is transmission power control [5,15,16]. The basic assumption is that, due to the attenuation of RF signals, it may be interesting to reduce the distance of the communication hop, even if it implies an increase of the total number of hops. The third technique is the transition of a node to a low power mode [7,17,18]. The objective is to maximize the time a node stays at the low power state (Sleeping state).

Energy-aware routing balances the energy consumption of the nodes by selecting routes through nodes with more remaining energy. The objective of this technique is not to reduce the total consumption in the network, but to protect nodes with less remaining energy. For every communication the source and the sink nodes are the end-points and, as a consequence, they 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 is expressed by

$$P_{m_{bal}} = \frac{P_{fc}}{n} + \frac{(n-1)P_{\overline{fc}}}{n}, \qquad (7)$$

where P_{fc} is the average power consumption of the node in the active forwarding chain, whereas $P_{\overline{fc}}$ is the average power consumed by the node when not forwarding. The consumption P_{fc} is plotted in Figure 4 and 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 forwarding chain, and then 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 4). 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 for this technique. Figure 7 shows the limit gain as the number of multiple disjoint 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}. The values showed in Figure 7 are limits when $\frac{1}{n} \to 0$, but Figure 8 plots the variation of this gain with n for the case of 2000-byte packets.

As Figure 8 shows, for $n = 4$, at least 66% of the maximum lifetime gain is achieved, for both situations. The important result is that energy-aware routing achieves significant gains even using few different paths, which means that splitting the traffic through some region by four different nodes would

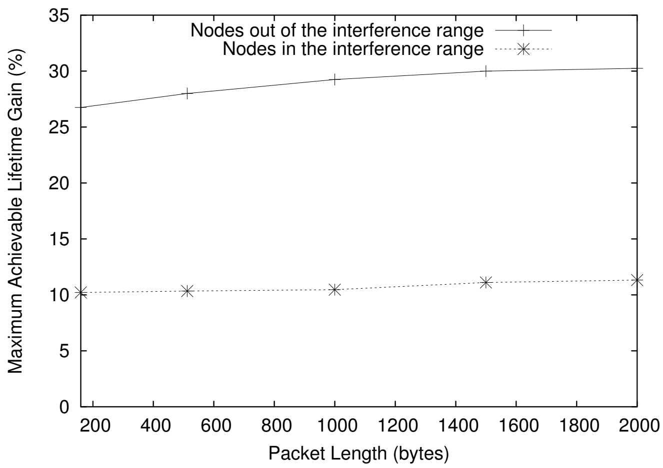


Figure 7. Limits of the lifetime gain with energy-aware routing.

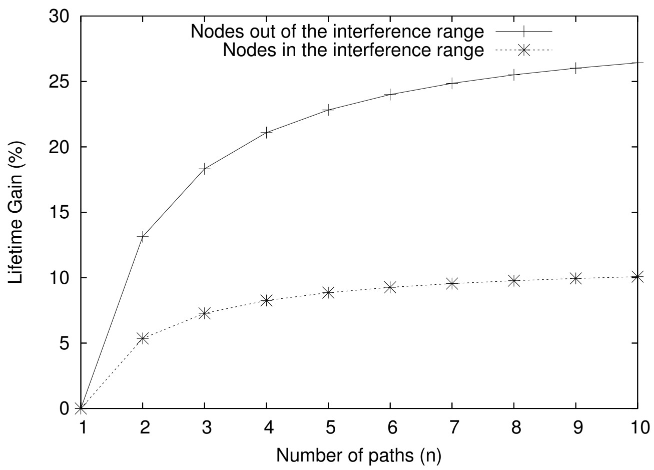


Figure 8. Achievable gain of energy-aware routing for 2000-byte packets.

allow these nodes to live up to 20% longer.

4.2 Transmission Power Control

The analyses of this technique consider two cases: the transmission power reduction resulting in the use of two hops instead of one direct transmission and the reduction of the transmission power to the minimum value allowing direct communication.

4.2.1 Use of Multiple Hops

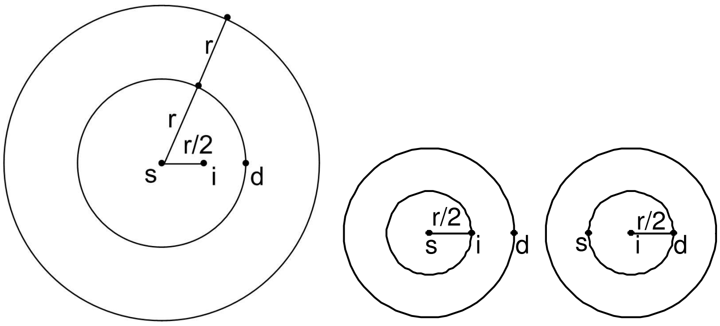
Min and Chandrakasan [19] investigate whenit is an advantage to use two hops instead of one, by reducing the transmission power. They modelled the energy consumption as $\alpha + \beta d^n$, where α is the distance-independent, and βd^n is the distance-dependent term. The coefficient n represents the transmission path loss and is typically between 2 and 6 [20]. Min and Chandrakasan claim that the use of two hops is profitable when the reduced distance-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. Indeed, even for RF output powers as low as 1mW the average consumption of the interface, P_{Tx}, is slightly larger than P_{Rx} [21]. Hence, given the values adopted in our analysis (Table 2), the distance-dependent consumption $(P_{Tx} - P_{Rx})$ is equal to $0.6P_{Id}$ for $d = r$. Moreover, assuming no power saving technique, the interface consumes at least P_{Id}. Thus, we estimate the fixed cost of the communication 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 3.

Table 3
Packet transmission costs for different node types.

Node	$\boldsymbol{\alpha}$	$\boldsymbol{\beta d^n}$
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

Assuming the discussed 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.

Nevertheless, the overhearing nodes can significantly increase the energy consumption caused by the transmission of one packet to the network as a whole. We can extend the analysis of the use of two hops by considering the situation of Figure 9, where a source node, s, wants to communicate with a destination node, d, at a distance r from s and there is a intermediate node, i, between the source and the destination, at a distance $\frac{r}{2}$ from the source, which can eventually be used as an intermediate hop. Considering only these three nodes and



(a) One hop. (b) Two hops.

Figure 9. Transmission and interference ranges of the communications.

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 inclusion of a second hop causes two transmissions of the same packet with half the original transmission range. In direct communication, s would use a transmission range of r, resulting in a interference range of $2r$ (Figure 9(a)). Node d can correctly receive the packet, and node 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 node d an overhearing node for this transmission (Figure 9(b)). After the first transmission, node i sends the packet to node d. In this second transmission node s becomes an overhearing node (Figure 9(b)). 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 $\beta\frac{r}{2}^n$ only takes positive values, which means that the two-hop communication of Figure 9 always consumes more than direct communication, independently of the path loss coefficient.

Nevertheless, the two-hop communication with a transmission range of $\frac{r}{2}$ covers an area four times smaller than the area covered by the direct communication with a transmission range r. In the general case, there may be other overhearing nodes near the three nodes of Figure 9. If we assume an uniform distribution of overhearing nodes, each individual 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 total number of overhearing nodes in the single transmission of the direct communication scenario. 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 the two-hop scenario and the total energy consumed in direct communication approaches 0.5.

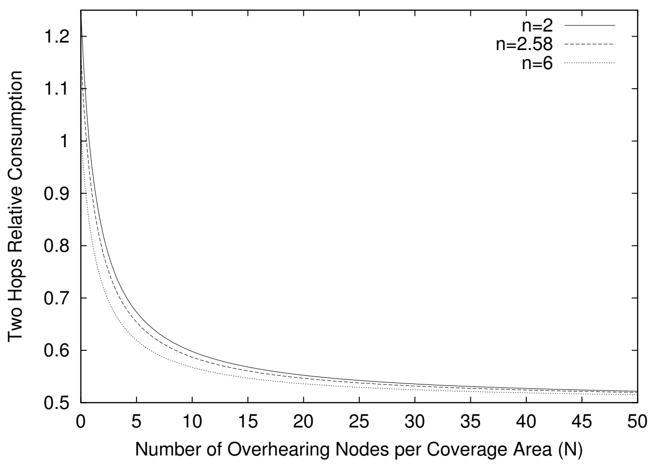


Figure 10. Total energy-consumption ratio using two hops instead of one.

Figure 10 shows the evolution of the ratio between the total energy consumed in the two-hop scenario and the total energy consumed in direct communication, i.e., the two hops relative consumption, with varying density of overhearing nodes, for different values of the path loss coefficient (n).

As Figure 10 shows, when there is no overhearing nodes (nodes inside the interference range of the communication), the consumption of the two-hop communication approaches the consumption of the one hop communication as n increases, and even a low density of overhearing nodes allows significant energy savings with the use of two hops instead of one (Figure 10). Even for $n = 2$, the ratio between the total consumed-energy in the two-hop scenario and the total consumed-energy in direct communication is around 0.7, assuming four overhearing nodes per communication range.

4.2.2 Direct Communication

For a scenario of direct communication, where every node is inside the transmission range of all the other nodes, the reduction of P_{Tx} to the lowest possible value is quite attractive, because all the reduction is converted into lifetime gain. Figure 11 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 between the achievable lifetime gain for different packet lengths. As the packet length increases, the gain obtained by the emitter increases while the gain achieved by the destination decreases. This is because as the packet length increases, the period of time that the emitter stays at the Tx state increases whereas the period of time the destination stays at Tx decreases. It is worth mentioning that the lifetime gain directly impacts the total useful data transmitted by the nodes.

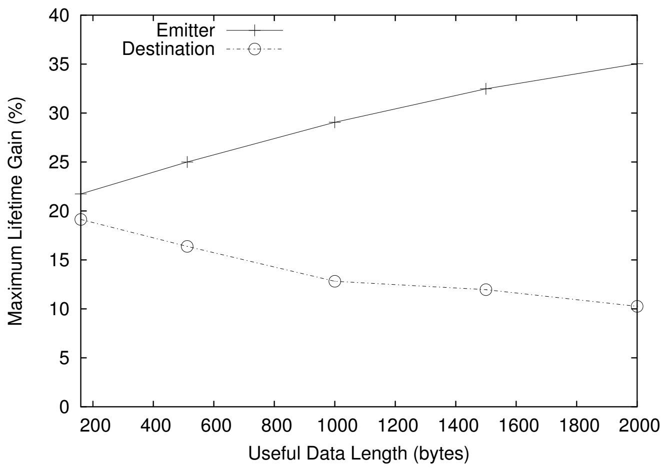


Figure 11. Limit of the lifetime gain for the transmission power-control technique.

The most common metric to evaluate the effectiveness of this technique is *Joules per successful bit transmitted*. Nevertheless, this metric suffers the effect of the spatial re-use and is a network-scale metric. This metric does not reflect the effects of the energy-savings for a specific node. As a consequence, it does not show the gain for individual users. In general, users are not interested in the operation of the network as a whole, but rather in having their devices working for as long as possible.

4.3 Transition to Sleep State

The analysis of the transition to sleep state can also be divided in two special scenarios. The first one is to keep just enough active nodes to guarantee full connectivity of the network, with other nodes awaking and sleeping, as they need to send or receive a packet. The second case is to put overhearing nodes to sleep, as proposed in the PAMAS protocol [7].

4.3.1 Topology Maintenance

The timing of the network while operating in power-saving mode is organized in ATIM windows, as discussed in Section 2. We estimate the cost of network maintenance based on the size of the ATIM window relatively to the beacon interval, since this ratio indicates the period of time nodes must stay awake. If the ATIM window is large enough in comparison to the time required to transmit a beacon frame, we can ignore the energy consumption of this transmission in the overall energy consumption. Woesner *et al.* [22] showed that an optimum throughput is achieved for a beacon interval of approximately 95 ms and a ratio between the ATIM window and beacon interval around $\frac{1}{4}$. This results for an ATIM window of approximately 24 ms.

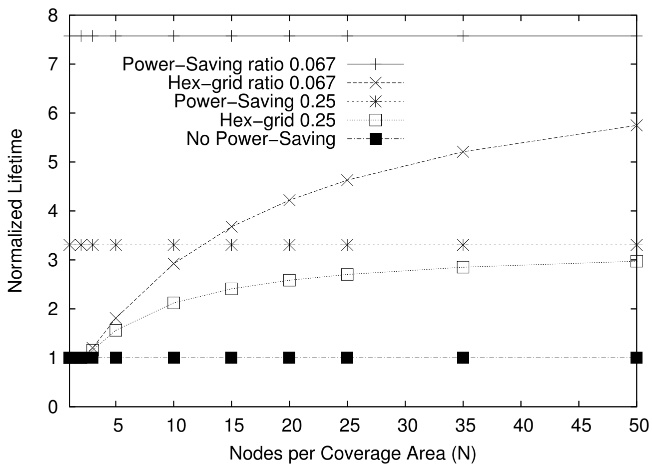


Figure 12. Limit of the lifetime of Idle networks.

Chen *et al.* [18] propose the maintenance of some nodes awake. These nodes are selected as the *coordinators*, and form a virtual backbone in order to reduce delays and maintain the network capacity. All the other nodes enter an enhanced power-saving mode based on the one defined in the IEEE 802.11 standard. Nevertheless, the modified power-saving mode has the same maintenance cost of the original IEEE 802.11 power-saving mode. The nodes rotate as coordinators in such a way that no node stays awake for too long. The ideal number of coordinators is defined as the required number to form an hexagonal grid layout in the network, with one coordinator in each hexagon vertex. The side of each hexagon is r, and each coordinator is responsible for half the area of a hexagon, or an area of $0.4135\pi r^2$ square units. Moreover, a beacon interval of 300 ms and an ATIM window of 20 ms are used for the power-saving nodes. The ATIM window to beacon interval ratio is around 0.067.

Figure 12 shows the lifetime (normalizing $T_{Idle} = 1$) of networks in different cases as the number of nodes (N) per communication range, given by a πr^2 square units area, increases and allows to analyze the energy consumption gains of the IEEE 802.11 power-saving mode and the effect of the use of coordinators. We derived these results disregarding the cost of the transition among states and only taking into account the maintenance cost. We assumed ATIM windows long enough to make negligible the beacon cost, and also considers five different cases: networks with no power-saving strategy (Equation 4), IEEE 802.11 power-saving mode with ATIM window to beacon ratios of 0.25 and 0.067, and networks with the hexagonal grid layout with ratios 0.25 and 0.067 for the power-saving nodes.

Figure 12 shows that as the ratio between the ATIM window and the beacon interval increases, the lifetime taking only the maintenance cost into account decreases. The choice of this ratio is important because the ATIM window must be long enough to announce the traffic of the nodes, but not so long that it can announce more traffic than the beacon interval supports. The beacon interval can not be too large, because increasing the beacon interval leads to higher latencies in multihop networks. Additionally, as the beacon interval increases, the chance that a node has something to transmit in the interval increases, causing the nodes to stay awake more time. Analyzing the results for the networks with the hexagonal grid layout, we observe that when the node density is low, their lifetime is equal to the no power-saving network, and as the node density increases, their lifetime approaches the lifetime of the network with all nodes in power-saving mode. For a node density of 20 nodes per coverage area, more than 50% of the maximum lifetime gain is achievable. Another important point is that the use of coordinators can reduce the impact of a large beacon interval because packets are routed through coordinators, which are always awake.

4.3.2 Putting Overhearing Nodes to Sleep

The significant difference of power consumption between the Idle and Sleep states makes the transition to sleep state an interesting technique for ad hoc networks. Nevertheless, the distributed nature of ad hoc networks severely restricts the use of this technique because a sleeping node must rely on its neighbors to store eventual packets addressed to it. Moreover, the possibility of the node being asleep at the arrival of a packet addressed to it potentially increases the latency of the network. Thus, most works using this technique admit larger network latencies.

The PAMAS protocol [7] 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 period of time the nodes stay at the Idle state, as well as the periods when the nodes are consuming energy by overhearing the communication of other nodes.

The PAMAS protocol 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. Figure 13 shows that 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 only sleep 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

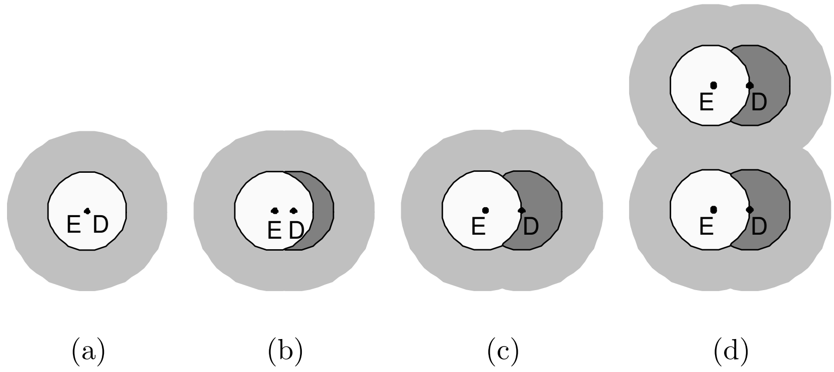


Figure 13. Scenarios for nodes at different distances.

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. Figures 13(a) and 13(c) show the limit situations where the emitter and the destination are at distances $d = 0$ and $d = r$, respectively. Figure 13(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 saved power 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 13(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 CTS frames are P_{RTS} and P_{CTS}, respectively, and N is the average number of nodes in the communication range, given by a πr^2 area. We assume a fair sharing of the channel among all nodes, a negligible transition cost to the sleep state, and an uniform node density. As a consequence, we compute the average power consumptions by weighting the average power of nodes in different possible situations based on the involved areas, which ultimately defines the number of nodes in each situation. The average power consumption for different distances from the Emitter to the Destination are

$$P_{m_{d=0}} = \frac{P_e + P_d + (N-2)P_{RTS} + 1.5NP_{o_{ed}}}{2.5N} \quad , \tag{8}$$

$$P_{m_{d=0.7r}} = \frac{P_e + P_d + (N-2)P_{RTS} + 0.44NP_{CTS} + 1.82NP_{o_{ed}}}{3.26N}, \; and \tag{9}$$

$$P_{m_{d=r}} = \frac{P_e + P_d + (N-2)P_{RTS} + 0.61NP_{CTS} + 1.83NP_{o_{ed}}}{3.44N} \quad . \tag{10}$$

The limit achievable gain for this technique (when $N \to \infty$), as a function of

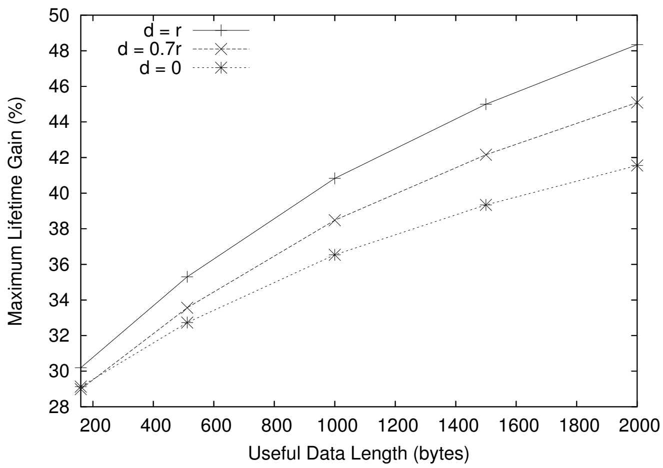


Figure 14. Limit of the gain when overhearing nodes go to sleep state.

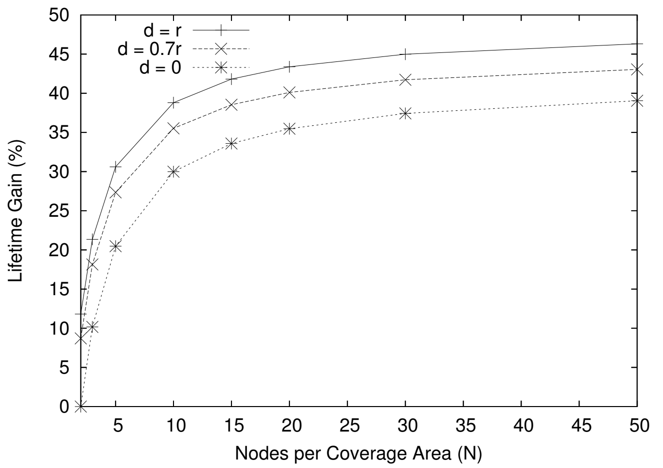


Figure 15. Achievable gain when overhearing nodes go to sleep state for 2000-byte packet length.

the packet length, is shown in Figure 14. The maximum gain is obtained for the limit distance $d = r$. Moreover, the gain using large frames is 50% higher than using small frames. As Figure 15 shows for the gain using 2000-byte frames, for a node density of 10 nodes per communication range, more than 70% of the maximum gain is achieved.

5 Conclusions

This paper analyzed the energy consumption of ad hoc nodes considering the interactions of the IEEE 802.11 MAC protocol and the packet forwarding peculiarities of ad hoc environments. Our goal is to provide theoretical gain limits, which may serve as guidelines to the development of novel power-saving schemes.

The use of larger packets increases the period of time that the interface stays at the transmitting state, reducing the node lifetime. Nevertheless, our results show that the higher throughput achieved by using larger packets compensates the lifetime reduction. Therefore, the use of large packets is more energy efficient. Moreover, we show that a node may have a reduction of lifetime up to 15% due to the fact of overhearing third-party communications instead of being in the idle state.

We also analyzed the potential gains of three power saving techniques: energy-aware routing, transmission power control, and transition to sleeping state. Considering the energy-aware routing techniques, an important result is that if a node is dismissed from routing tasks, it can live up to 30% longer, which is more useful for severely energy-constrained nodes. Moreover, up to 66% of the maximum gain is achievable splitting the traffic of one region by only four disjoint paths. For the transmission power control technique, the results show that the use of two hops instead of only one can save up to 50% of the total energy consumed in the packet transmission by reducing the number of overhearing nodes. Nevertheless, from a user point of view, this technique increases the lifetime of nodes from 21%, when the node transmits small packets, to 35%, for large packets. It is worth mentioning that the Destination nodes also benefit from this technique. Moreover, we highlight the importance of the transition to sleep state due to the very low consumption of this state. We show that the transition of overhearing nodes to the sleeping state achieves up to 48% lifetime gain. For a density of 10 nodes per communication range, more than 70% of the possible gain is already achievable when overhearing nodes go to sleep instead of staying at idle Idle state.

The results emphasize the importance of combining these three techniques. The transition to sleep state is the technique that enables the highest gain, but it has a limited use for loaded network when most of nodes always have packets to send or receive. In this case, the nodes must remain much of the time awake. The combination of this technique with energy-aware routing allows nodes with less remaining energy go to sleep for longer periods, since these nodes will not participate of the packet-forwarding procedure. Moreover, the transmission power control always provides energy savings for a direct communication range.

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