

A Distributed Power Management Policy for Wireless Ad Hoc Networks

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Abstract—This paper presents a power management scheme that maximizes energy saving in wireless ad hoc networks while still meeting the required quality of service (QoS). We assume that battery-powered devices can be remotely activated by a waking-up signal using a simple circuit based on RF tag technology. In this way, devices that are not currently active may enter a *sleep state* and power up only when they have pending traffic. Radio devices select different time-out values, so called *sleep pattern*, to enter various sleep states depending on their battery status and quality of service. Performances of the proposed policy are derived by simulation for a simple ad hoc network scenario. Results show the achieved tradeoff between power saving and traffic delay.

I. INTRODUCTION

In wireless communication networks, energy consumption is a major performance metric: lower the energy consumption, longer the run-time of communication devices. Thus, there is an increasing interest in both low power RF devices and energy efficient communication protocols.

One of the most common techniques to reduce power consumption in wireless communication is discontinuous reception, i.e., users may power down and turn on their receiver again at a particular time instant in the future [1], [2], [3].

In IEEE 802.11 [4] users in power saving mode wake up in correspondence with a broadcast transmission from the base station that notifies which terminals have pending data. The same concept is used in the MAC protocol presented in [5]. In HIPERLAN [6], the wireless LAN standard specified by ETSI (European Telecommunications Standards Institute), radio nodes that need to save power, so-called *p-savers*, communicate their own sleep-awake schedule to the so-called *p-supporter* node. The p-supporter queues all the packets destined to the p-savers and transmits these packets during the p-savers active time.

In this paper we introduce a completely distributed power management technique for ad hoc networks, which aim to maximize energy saving in battery-powered devices while satisfying the required traffic quality of service.

We consider that a node can be in L different states depending on how many parts of the device circuitry are powered off. We assume that $1, \dots, L - 1$ are sleep states, while L corre-

sponds to the state in which the node is *active*, i.e., it is able to transmit/receive. Each sleep state is characterized by a certain power consumption and a delay overhead; deeper the sleep state, less the power consumption and longer the time to wake up.

It is clear that longer the time spent by the nodes in sleep state, greater the energy saving is. Thus, in our scheme user devices do not wake up unless they are remotely activated by other nodes. To make this feasible we need a method to remotely activate a node through a RF (Radio Frequency) signal and such an operation must have a negligible energy cost. A possible scheme of the switch that can be used to wake up a device while being in sleep state, is presented in Sect. II.

We also consider a *power management policy* implemented at the network nodes, which determines the state of operation of the various components in the node device during idle time. Several policies have been proposed in the literature [7], [8], [9] with the aim to minimize both performance degradation of electronic devices and power consumption; however, no policy has been proposed such that takes into account network protocol performances and traffic QoS.

The power management technique presented in this paper is described in detail in Sect. III, while performances are presented in Sect. IV. Conclusions and directions for further research are drawn in Sect. V.

II. REMOTE ACTIVATION OF THE NETWORK NODES

RF tags technology offers good examples of low power or totally passive devices that use the received RF power to supply the logic and the transmission part of the circuit [10], [11], [12]. RF tags have been used as transmitter/receiver devices (transponders) for remote localization and identification of animals, cars and other kinds of items typically over short-ranges [12], [13].

Based on RF tags technology, we can develop a switch that can be used to remotely activate a radio device while being in sleep state. In this way, nodes are woken up when necessary rather than getting active periodically to verify whether there is pending traffic.

The schematic representation of the switch, so-called RAS

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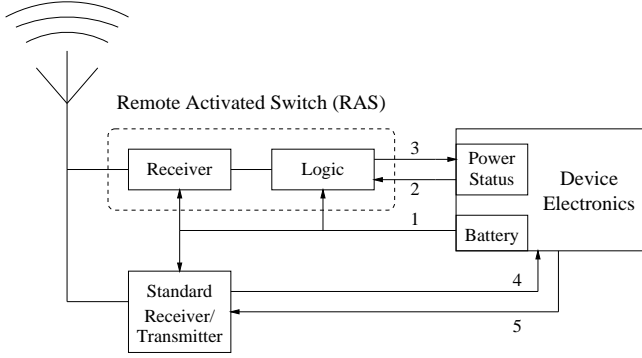


Fig. 1. Scheme of the communication device circuit.

(Remote Activated Switch), is shown in Figure 1.

Whenever a node becomes idle, it enters a sleep state, i.e., the standard receiver/transmitter is turned off as well as part of the device electronics. Waking-up signals are received and demodulated by the RAS, then the signal information is passed to the logic circuit that detects the sequence. If the received sequence matches the device's sequence, it turns on the standard receiver. Notice that the RAS receiver may be either totally passive (e.g., an amplitude demodulator) or supplied by the battery source through connection 1.

III. THE POWER MANAGEMENT SCHEME

Power management policies are used to make decisions on the state of operation of electronic systems such as portable computers and radio communication devices. In the field of computer systems, several power management techniques have been proposed [7], [8], [9].

The objective of our scheme is to implement a simple power management policy at the network nodes, which guarantees a power saving always greater than zero. The adopted policy can queue service requests and adapt to different needs and characteristics of the nodes.

Recall that a device can be in L different states where $1, \dots, L-1$ are sleep states and L corresponds to the state in which the node is active, i.e., it is transmitting/receiving. Each sleep state is characterized by a certain power consumption, denoted by P_l ($l=1, \dots, L$), and a delay overhead, denoted by W_l ($l=1, \dots, L-1$). We have that $P_1 < P_2 < \dots < P_L$ and $W_1 > W_2 > \dots > W_{L-1}$.

Let us define P_l^t as the power cost of the transition from state l ($l=1, \dots, L-1$) to state L ¹, and Z_l as the minimum time that a node has to spend in sleep state l to obtain a positive energy gain. We derive Z_l from the following formula,

$$Z_l \cdot (P_{l+1} - P_l) = \frac{W_l \cdot (P_l^t - P_{l+1}) + W_{l+1} \cdot (P_{l+1} - P_{l+1}^t)}{P_{l+1} - P_l} \quad (1)$$

¹For the sake of simplicity the cost associated with transitions from state l to state $l-1$ ($l=2, \dots, L$) is included in the cost of the back transitions to state L .

where the left term is the energy gain obtained from being in state l rather than in state $l+1$ and the right term is the additional cost due to transition from l to L with respect to transition from $l+1$ to L . Thus we have,

$$Z_l = \max \left\{ 0, \frac{W_l \cdot (P_l^t - P_{l+1}) + W_{l+1} \cdot (P_{l+1} - P_{l+1}^t)}{P_{l+1} - P_l} \right\}. \quad (2)$$

We assume that nodes select different *sleep patterns* $\mathbf{T}^{(q)} = [T_1^{(q)} T_2^{(q)} \dots T_{L-1}^{(q)}]$ ($q=1, \dots, Q$) depending on their battery status and required quality of service. The values $T_l^{(q)}$ ($l=1, \dots, L-1$) are the time-out values that determine when nodes enter sleep state l ($l=1, \dots, L-1$). For $q=1, \dots, Q$ and $l=2, \dots, L-1$, we impose the following constraint

$$T_{l-1}^{(q)} \geq T_l^{(q)} + Y_l, \quad (3)$$

where Y_l is a system parameter such that $Y_l \geq Z_l$. Thus, whenever a node enters a sleep state l with $l=2, \dots, L-1$, it can move to state $l-1$ only after a time period equal to Y_l .

If a node has little battery capacity left, it will use a vector $\mathbf{T}^{(q)}$ with small values for $T_l^{(q)}$ to quickly enter deep sleep states. In this case, the node will save energy, however, the delay penalty to pay may be significant. Instead, if a node is concerned mainly about traffic quality of service, it will use a vector $\mathbf{T}^{(q)}$ with higher and higher values for $T_l^{(q)}$ as l decreases such that it will enter deep sleep states less rapidly.

Now, let us consider the generic node j . We define τ_j as the time spent by j in sleep state, i.e., the time elapsed from the time instant when node j passed from state L to state $L-1$. We assume that j is assigned a waking-up signal (also called waking-up sequence), denoted by x_j .

Whenever a node in the ad hoc network, let's say node i , has packets to forward to node j , it regularly transmits the waking-up sequence x_j until node j powers on. (In the following the inter-paging time is denoted by IP .)

Upon detecting the signal x_j , node j , currently in state l , wakes up if and only if

$$\tau_j \geq T_l^{(q)} + Y_l, \quad (4)$$

i.e., node j always stays in a sleep state long enough to compensate for the transition power cost.

If the condition expressed in (4) is satisfied, node j becomes active after a time period equal to W_l . As soon as j is active, it sends back to node i an acknowledgment and remains awake until it receives all the pending packets.

A diagram of the proposed scheme is shown in Figure 2.

IV. RESULTS

Results are obtained for the network scenario shown in Figure 3 with four *source* nodes that generate traffic, and two *destination* nodes that receive only. The traffic load, denoted by

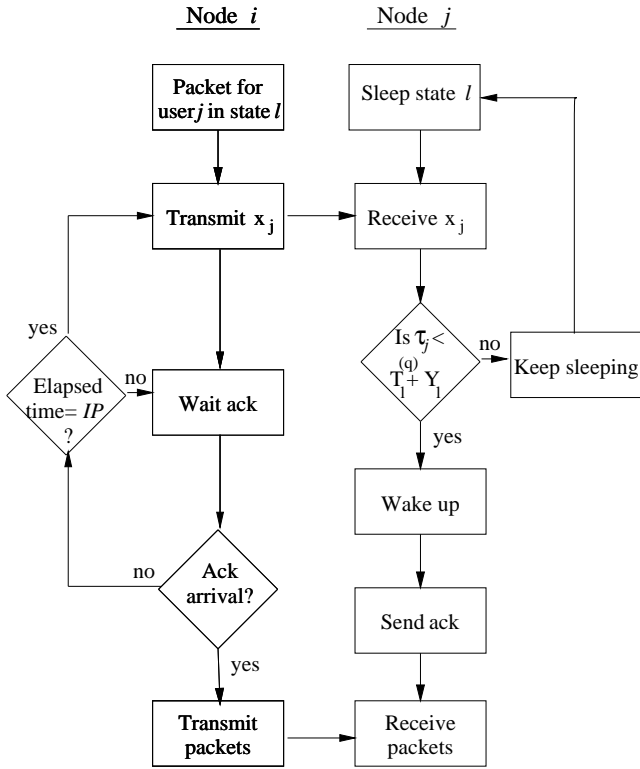


Fig. 2. Diagram of the power management scheme.

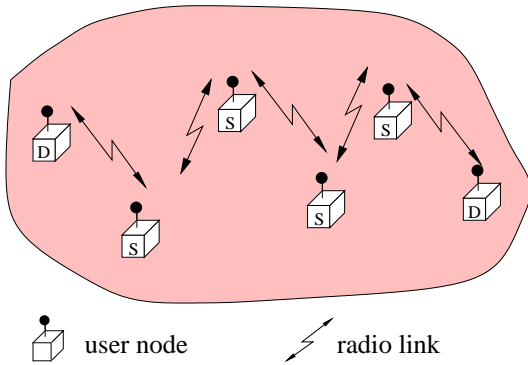


Fig. 3. Simulation network scenario.

λ , is uniformly distributed among the source nodes. Source nodes generate packets according to a Poisson distribution with mean value equal to $\lambda/4$, and each packet has a geometrically distributed length. The time scale is discretized into time intervals with duration equal to the mean packet transmission time.

We assume $L = 4$ and that the values of power consumed in the various sleep states are normalized with respect to the power consumed by a node in receiving mode. Thus, we have: $P_4 = 1$, $P_3 = 0.7$, $P_2 = 0.4$, $P_1 = 0.1$, and $P_l^t = 1.2 \cdot P_l$ for $l = 1, \dots, 3$. The values of the delay overhead are set equal to $W_l = 5 \cdot l$ for $l = 1, \dots, 3$. Also, we set the duration of the inter-

TABLE I

TIME-OUT VALUES FOR THE CONSIDERED SLEEP PATTERNS (EXPRESSED IN TIME UNITS).

	$q = 1$	$q = 2$	$q = 3$	$q = 4$
$T_3^{(q)}$	1	1	1	1
$T_2^{(q)}$	100	12	12	20
$T_1^{(q)}$	1000	30	30	50
$Y_l^{(q)}$	Z_l	Z_l	$Z_l + 5(L - l)$	$Z_l + 10(L - l)$

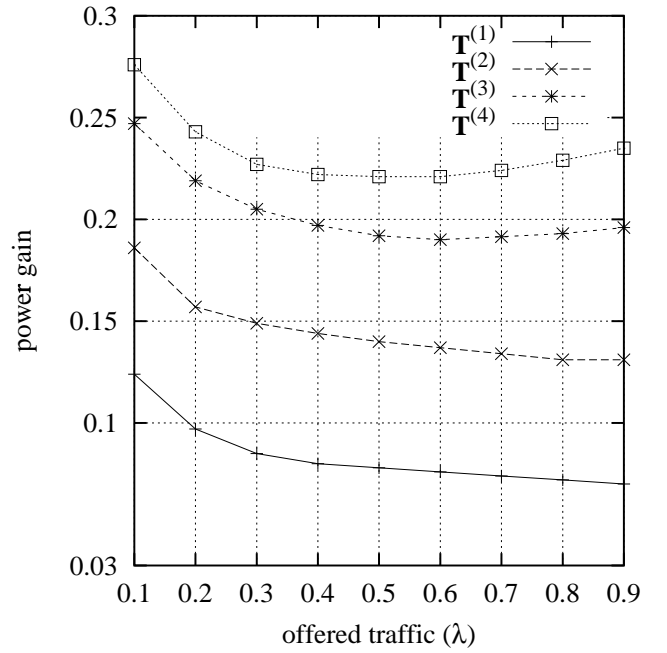


Fig. 4. Mean power gain per node as a function of the traffic load for different sleep patterns.

paging time, IP , equal to 5 time units, the acknowledgment duration equal to 0.02 time units, and the transmission power equal to 10 times the power spent in receiving mode.

Protocol performances are derived by simulation in terms of average power gain and of average delay from the time instant when a packet is generated to the time instant when the packet is delivered to the destination node. Figures 4 and 5 present the performance metrics as functions of the average traffic load.

Plots are derived for different sleep patterns, $\mathbf{T}^{(q)}$ with $q = 1, \dots, 4$, such that passing from $\mathbf{T}^{(1)}$ to $\mathbf{T}^{(4)}$, the time periods Y_l ($l = 1, \dots, 3$) increase and the time spent by the nodes in each sleep state becomes longer.

Figures 4 and 5 show that for sleep patterns $\mathbf{T}^{(1)}$ and $\mathbf{T}^{(2)}$ the packet delay is roughly constant while the average power gain decreases as the traffic load increases since nodes characterized by a lower traffic rate enter deep sleep states with higher probability. For sleep patterns $\mathbf{T}^{(3)}$ and $\mathbf{T}^{(4)}$, which are

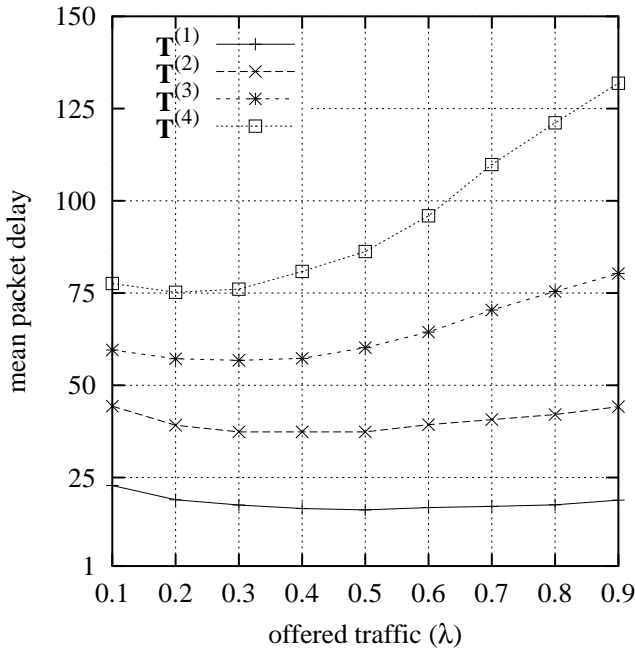


Fig. 5. Mean packet delay as a function of the traffic load for different sleep patterns.

characterized by higher values of Y_l ($l = 1, \dots, 3$), the packet delay grows significantly for high values of the traffic load allowing for a good power gain.

The presented plots can be used for system design: given a certain traffic delay, we can easily determine the power gain that can be achieved or given the power gain that nodes need, we have the mean delay that the traffic will experience.

Figure 6 presents the average total power consumed by the nodes to transmit paging signals and acknowledgments, and while being in receiving mode. The average power consumption is derived as a function of the offered traffic load and for different sleep patterns. We notice that when we consider patterns with increasing values of Y_l ($l = 1, \dots, 3$), the traffic becomes more bursty and the number of paging signals and acknowledgments decrease; thus, the average power consumption decreases too. A similar effect takes place as the average traffic load grows. However, power consumption due to paging, acknowledgment transmission and time spent in receiving mode, is always much less than the power gain obtained through the presented scheme as we can see by comparing Figure 4 to Figure 6.

Finally, we consider ON-OFF traffic sources with ON and OFF times that are random variables taking values according to a Pareto distribution:

$$p(x) = bk^b x^{-b-1} \quad b, k > 0; x \geq k. \quad (5)$$

An aggregation of such traffic sources results in a *self-similar* traffic if the distribution of the ON and OFF time periods is heavy-tailed, i.e., $b < 2$; we take $k=0.715$ and $b=1.06$ [14].

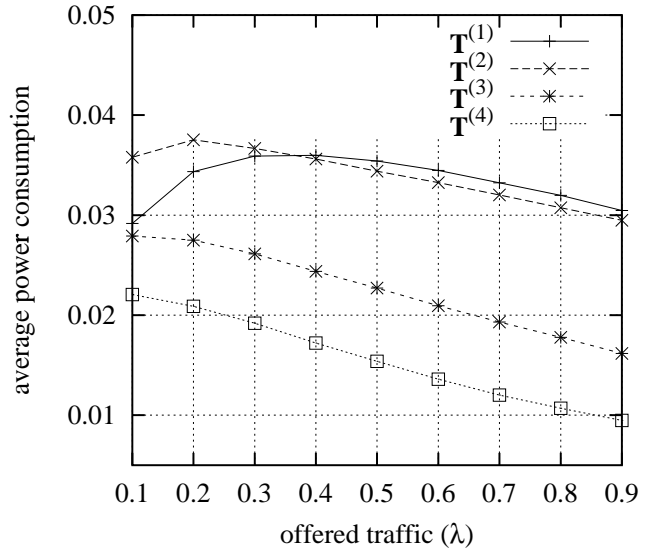


Fig. 6. Average power consumption due to packet reception, paging, and acknowledgment transmissions.

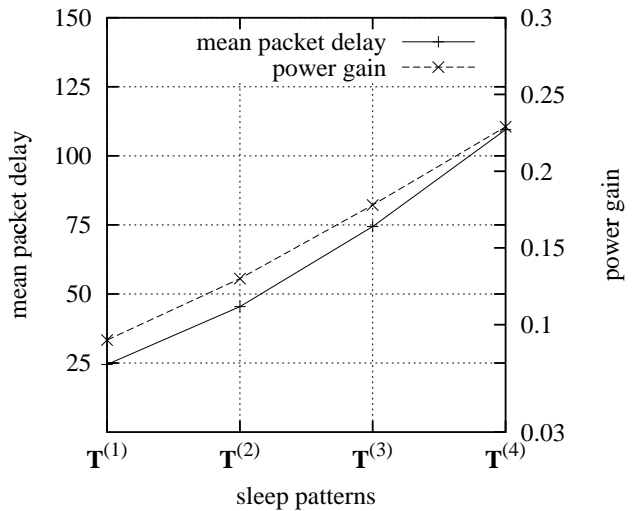


Fig. 7. Mean packet delay and power gain obtained when the packet generation process is assumed to be Pareto distributed.

Figure 7 shows the obtained mean packet delay and power gain as the sleep pattern varies. We have a behavior similar to the previous results presented in Figures 5 and 6: as we pass from $T^{(1)}$ to $T^{(4)}$, and hence the time intervals Y_l ($l = 1, \dots, 3$) become longer, both traffic delay and power gain increase. We notice that even in the presence of traffic sources with Pareto distributed ON and OFF time periods, the proposed scheme allows for a significant power gain at the expense of a limited additional delay.

V. CONCLUSIONS AND FUTURE WORK

This paper proposed a new power saving scheme that allows nodes to wake up only when necessary. Also, a simple power management policy is implemented: nodes select a sleep pattern according to the desired QoS and their battery status, and enter a sleep state only after they have been idle for a time period equal to or greater than the corresponding time-out value.

Results showed the power gain that can be achieved in the case of a simple network scenario as the average packet delay varies. It was shown that even at high traffic load (namely, $\lambda=0.9$) a power gain as high as 24% can be obtained.

Future work will deal with an ad hoc network scenario where the proposed power management scheme is applied. Nodes could be awake or asleep, and for each transmitting user the problem to select the “best relay” among the neighboring nodes arises. The choice of the best relay node should take into account both the required transmission power and the delay introduced while waiting for the relay node getting active.

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