Energy Efficient Sleep/Wake Scheduling of Stations in Wireless Networks

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***Abstract*—A wireless ad hoc network is typically Constrained by battery power, and hence, it is important to conserve battery power in order to keep the network alive for a long time. We consider a wireless network consisting of an access point (AP) and a wireless node, which is limited by energy, and we seek scheduling algorithms that conserve battery power at the wireless node. Since the packet arrivals are stochastic, communication happens only during the time slots when packets are available. Hence, keeping the receiver ON at all times is wasteful of resources. However, when the receiver is turned OFF, a packet, on arrival, is stored in a buffer (at the AP) which incurs a holding cost. We propose sleep/wake scheduling at the wireless node with an objective of minimizing the power spent (at the receive node) and the queuing delay at the AP, while maintaining the stability of the queue. We note here that this energy optimum scheduling is a distributed problem in which the queue–length information at the transmitter is not known at the receiver. We show that the optimum wake process at the receiver follows closely as that of the arrival process of the packets at the AP. We numerically evaluate the optimum scheduler, and discuss the energy and queuing delay performance of our proposed optimum scheduler**.

***Index Terms*—Energy efficiency, network lifetime, sleep/wake scheduling**

I. INTRODUCTION

IN our day to day life, we use mobile devices such laptops, mobile phones, tablets, etc. All these devices run on batteries having finite energy which could drain rapidly due to the many hardware subsystems that are continuously powered ON. To utilise the battery power for a long time, it is important to power OFF the subsystems when not in use. Of the many subsystems available in a handheld device, our focus is on the radio transceiver. We are interested in turning the transceiver ON only when required, thereby reducing the power burnt in the hardware when there is no need for it to be turned ON. By efficiently turning the transceiver ON/OFF, we increase the utility (or the length of use) of the device for a given energy.

We demonstrate the need for turning ON/OFF the transceiver by a simple experiment. We use a Windows 7 laptop with a WiFi card and connect it to an access point (AP) through IEEE 802.11 (wireless LAN). At the beginning of the experiment, battery of the laptop is 100% charged. We consider two cases. In case 1) the WiFi card is switched OFF, and in case 2) the WiFi card is switched ON. In each of the cases, we note, in regular intervals, the usage of battery, which is 100% minus percentage of remaining battery power, and the remaining lifetime of the battery (measured in minutes), and plot the results in Fig. 1. From Figure 1,we observe that by turning the WiFi OFF, one can extend the lifetime by a maximum of 36.4% compared to that of keeping the WiFi ON at all times. We observe a similar phenomenon in Linux, where the lifetime can be extended by a maximum of 40.3% by keeping the WiFi OFF. Thus, this simple study motivates us to go for an optimal ON/OFF scheduler to increase the lifetime of a network.

In this paper, we study a scheduling problem which tries to keep the transceiver of a receive node ON at times when a transmit node has packets to transmit. We note that the transmit and receive nodes are geographically separated, and hence, the receive node has no knowledge when the transmit node transmits a packet. Ideally, we would like to keep the transceiver of the receive node ON only when the transmit node has a packet to transmit. But, this requires a centralized scheduler, which is not practical in a wireless network. Thus, we are interested in a distributed scheduling algorithm that minimizes the energy spent by the receive node, when the transmit node has no packets to transmit.

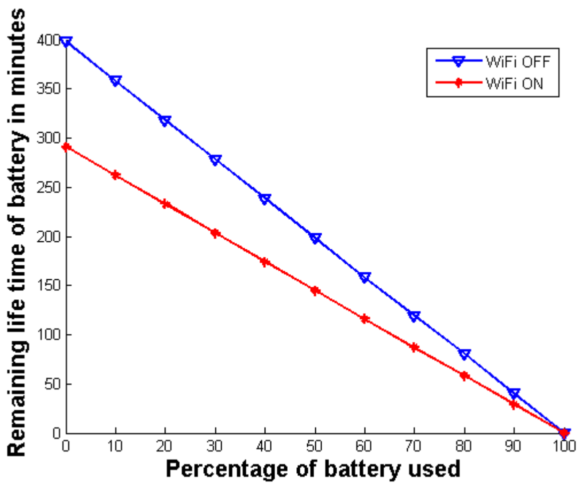

Fig. 1. **Experiment to demonstrate energy saving:** *Percentage of battery used versus remaining lifetime of battery* is measured in a laptop operating in a Windows 7 environment. We observe that by turning the WiFi OFF, one can extend the lifetime by a maximum of 36.4% compared to keeping the WiFi ON at all times.

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A. Main contributions of the paper

- We formulate the problem of optimum sleep/wake scheduling in a wireless network comprising an AP and a node (i.e., point–to–point link)
- We propose a class of distributed procedures that achieve energy efficiency
- We obtain an optimum sleep/wake scheduler that minimizes the average cost of energy expended at the receiver and the cost of queuing at the transmitter
- We numerically evaluate the optimum scheduler, and study its performance.

To the best of our knowledge, the sleep/wake scheduling problem has not been addressed in the context of wireless networks, and has been studied only in a wireless sensor network setting (where all the sensor nodes transmit the same information).

B. Literature

The problem of sleep/wake scheduling is considered by many authors in the context of sensor networks, where all sensors essentially carry the same information. However, in a wireless data network where nodes carry independent information, sleep/wake scheduling is essentially an unexplored area, and only very few works are reported so far. We outline only the most important work in this area. In [1], a control strategy on the duration of sleep is proposed based on Markov decision processes. In [2], various conventional scheduling strategies for delay constrained data is proposed. More details on scheduling can be found in [5], [6].

Our work is different from [1] and [2] in the following sense. We do not consider a delay constrained data, and the sleep duration is implicitly controlled using probabilistic ON/OFF strategy at the receiver for every time slot.

Outline of the paper: The rest of the paper is organized as follows. In Section II, we describe the system and the mathematical model that captures the packet communication. In Section III, we describe the costs involved in packet communication, and formulate the sleep/wake scheduling problem as an optimisation problem that minimizes the total cost. In Section IV, we solve the optimisation problem, and obtain the optimum sleep/wake scheduling algorithm. We numerically evaluate the optimum scheduler in Section V. In Section VI, we outline the conclusions and future work.

II. SYSTEM MODEL

We consider a wireless network consisting of an access point (AP) and a wireless node. We consider a data traffic flow from the AP to the wireless node. The AP is connected to the electric mains supply, and hence, energy is not an issue at the AP. However, the receive node (e.g., a handheld device) is typically an energy–limited device. We are interested in employing a scheduling algorithm at the receive node to conserve energy.

We consider a discrete–time system, in which time is measured in slots $k \in \{0, 1, 2,....\}$. *The length of a slot is normalized to that of a packet, and hence, one packet exactly fits in a slot.*

A. Idle/Busy Slots:

The transmit node (i.e., the AP), because of stochastic arrivals of packets, need not have packets to transmit in all time slots. Thus, there are some slots with data to transmit, and these slots are called busy slots; also, there are some slots without any data, and these slots are called idle slots. Whenever the transceiver of the receive node is kept ON during any of the idle slots, the power burnt in the transceiver of the receive node goes waste.

B. Sleep/Wake Scheduling

It is clear from Section II-A that it is not advisable to keep the transceiver ON in all the slots. This motivates us to focus on the following problem: *at what time slots should the transceiver at the receive node be turned OFF*. Ideally, we like to turn ON the transceiver during those slots when packets arrive at the transmit node (i.e., during busy slots). However, this is practically not possible, since the transmit and receive nodes are separated geographically and the receive node does not know a–priori whether a particular slot is an idle slot. Hence, we model the problem in the framework of probability and queuing theory.

We say that the receive node is in the wake state when it's transceiver is kept ON, and is in the sleep state when it's transceiver is kept OFF. When a packet arrives at the transmit node during the sleep state, it is stored in a first–in first–out (FIFO) buffer. When the receive node is kept in the sleep state for a long time, we expect a large queue–length at the transmit node (i.e., large number of packets are waiting to be transmitted; in other words, the queuing delay of packets is large). When the receive node is kept in the wake state for a long time, the receiver may see large number of idle slots, which is wasteful of energy. Thus, there is a trade–off between queuing delay at the transmit node and the energy cost at the receive node. We define the system cost as the sum of these two costs, and we seek an optimum sleep/wake scheduling algorithm that minimizes this total cost.

C. Arrival Process

During each time slot $k \in \{0, 1, 2,....\}$, an arrival of a packet occurs at the AP with probability p (where $0 < p < 1$), and no arrival occurs with probability $1 - p$. We also assume that a packet arrival during slot k is independent of all other processes in the system. Let $A_k \in \{0, 1\}$ represent the number of packet arrivals at the AP during slot k. Thus, $\{A_k : k \{0, 1, 2,....\}\}$ is an i.i.d. Bernoulli process with

$$P\{A_k = 1\} = p \qquad (1)$$

and, $P\{A_k = 0\} = 1 - p$,

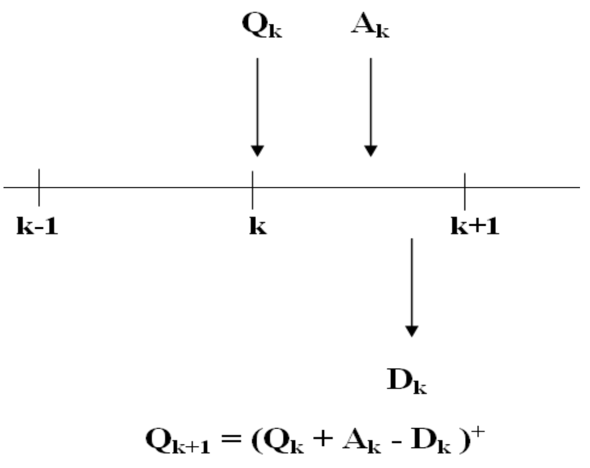

Fig. 2. **Queue–length dynamics:** Qk+1, the queue–length at the beginning of slot k + 1, is Qk + number of arrivals - number of departures during slot k.

D. Departure Process

Let $D_k \in \{0,1\}$ be the number of packets that are delivered to the receive node during slot k. Since one slot fits exactly one packet, there can be at most one packet that can be successfully transmitted during slot k. We will describe the departure process in detail in Section II-F.

E. Queue–length Process

Because the receive node employs a sleep/wake scheduling algorithm, the transmit node refrains from transmitting even if it has a packet to transmit. Thus, the backlogged packets need to be stored in a buffer (also called queue) at the transmit node for transmission during later time slots.

Let the random variable $Q_k \in \{0, 1, 2,...\}$ represent the number of packets waiting to be transmitted at the buffer of the AP at the beginning of slot k. We note that $Q_k \geq 0$, and can take infinite for some k. We describe the recursion between the queue–lengths at the beginning of slots k and k + 1 as follows. There are A_k arrivals during slot k which increases the queue–length by A_k, and there are D_k departures during slot k which decreases the queue–length by D_k. Thus, the queue–length at the beginning of slot $k + 1$ is given by

$$Q_{k+1} = (Q_k + A_k - D_k)^+ \qquad (2)$$

where $(x)+ := \max\{0, x\}$ is included to take care of the condition that there cannot be any departure from an empty queue.

F. Distributed Sleep/Wake Scheduling Procedure

In Eqn. (2), to describe the queue–length process $\{Q_k : k \in \{0, 1, 2,....,\}\}$ we need to describe the departure process $\{D_k : k \in \{0, 1, 2,....,\}\}$. If the receive node is awake at all time slots (i.e., there is no sleep/wake scheduling algorithm employed), $D_k = 1$ for all k. *We consider a probabilistic sleep/wake scheduling in which we choose each slot k to be awake with a certain probability $0 < q < 1$, which we discuss in detail in Section IV.*

III. PROBLEM FORMULATION

In this Section, we define the costs involved in sleep/wake scheduling, and formulate the sleep/wake scheduling problem in the framework of convex optimisation.

A. Queuing Delay Cost at the AP

If a packet on arrival is transmitted by the AP and received by the node without any delay, then there will not be any holding/ queuing cost at the AP. However, because of sleep/wake scheduling, the packets are stored in a buffer at the AP, and are released on a FIFO basis. Thus, naturally, there is a holding cost involved which is the delay due to queuing. The queuing delay cost is given by

$$C_Q = \lim_{k \to \infty} \lambda_Q \; E[Q_k] \qquad (3)$$

where $\lambda_Q > 0$ is the cost of holding one packet for one time slot. Note that the limit as time slot k goes to infinity means that we obtain the steady state cost, which is a common principle in designing optimal algorithms.

B. Probabilistic Sleep/Wake Scheduling Strategies

In Section II-F, we outline a probabilistic sleep/wake scheduling strategy, which we discuss in detail in this Section. We propose a class of scheduling strategies in which the sleep/wake process of the receiver follows closely as the arrival process. In particular, a Bernoulli(q) process is proposed for sleep/wake, which is described as follows.

$$D_k = \begin{cases} 1, & \text{with probability } q \\ 0, & \text{with probability } 1 - q \end{cases}$$

where we recall that $D_k = 1$ means a potential departure from the buffer at the AP, which is possible only when the receive node is awake. Thus, $D_k = 1$ represents awake state, and $D_k = 0$ represents sleep state. Note that q is the parameter of a scheduling strategy, which requires tuning.

C. Energy Expenditure Cost at the Receive Node

In the probabilistic sleep/wake scheduling strategy discussed in Section III–B, the cost due to energy expenditure is given by

$$C_E = \lambda_E \, . \, q, \qquad (4)$$

where $\lambda_E > 0$ is the cost of energy per time slot, and q has the following interpretation: the fraction of a time slot which is awake. Thus, we are interested in obtaining an optimum scheduling strategy (i.e., an optimum q) for which the total cost $C_Q + C_E$ is minimum.

D. Evolution Of The Queue

By employing probabilistic sleep/wake scheduling (with parameter q), we show that the queue–length process at the AP $\{Q_k : k \in \{0, 1, 2,....\}$ is a discrete–time Markov chain (DTMC) with the state space $\{0, 1, 2, ...\}$.

Fig. 2 shows the evolution of queue from time slot k to slot $k+1$. Recall that Q_k is the queue–length at the beginning of slot k. The following cases arise during slot k.

1) **A packet arrival and no packet departure:** Here, the queue–length at time slot $k + 1$ will be $Q_k + 1$
2) **A packet arrival and a packet departure:** Here, the queue–length at time slot $k + 1$ will be Q_k
3) **No packet arrival and no packet departure**: Here, the queue–length at time slot $k + 1$ will be Q_k
4) **No packet arrival and a packet departure:** Here, the queue–length at time slot $k + 1$ will be $(Q_k - 1)^+$

Analytical expression for the cases listed above are provided below. For $Q_k > 0$,

$$Q_{k+1} = \begin{cases} Q_k + 1, & \text{with probability } p(1 - q) \\ Q_k, & \text{with probability } pq + (1 - p)(1 - q) \\ Q_k - 1, & \text{with probability } (1 - p)q\,, \end{cases}$$

and for $Q_k = 0$,

$$Q_{k+1} = \begin{cases} Qk + 1, & \text{with probability } p \\ Qk\,, & \text{with probability } 1 - p\,, \end{cases}$$

where we recall that $0 < p < 1$ is the probability of arrival of a packet during k^{th} slot, and $0 < q < 1$ is the probability of departure of a packet during k^{th} slot. Thus, from the above expressions, it is clear that $\{Q_k\}$ is a DTMC (see Fig. 3 for a state transition diagram).

Note that to obtain the queuing delay cost at the AP, we require the average steady state queue–length, which is defined as

$$\lim_{k \to \infty} \mathrm{E}\,[Q_k] := \mathrm{E}Q_*$$

where Q_* is the stationary random variable. Because the DTMC $\{Q_k : k \;\; \{0, 1, 2, \ldots\}\}$ is irreducible, positive recurrent, and aperiodic, stationary distribution exits. Let p_{mn} denote the probability that the queue–length changes from m to n in one slot. Note that n can be either m - 1, or m, or m + 1. Thus, the transition probability matrix (TPM) of the DTMC is

$$\mathrm{P} = \begin{bmatrix} p_{00} & p_{01} & p_{02} & \cdot \\ p_{10} & p_{11} & p_{12} & \cdot \\ p_{20} & p_{21} & p_{22} & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

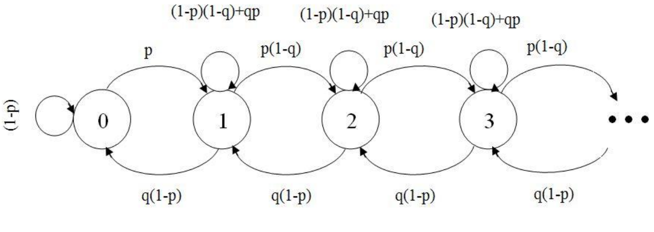

Fig. 3. State transition diagram of queue length process

The steady state distribution is given by the equation,

$$\pi = \pi \,.\, \mathrm{P} \qquad (5)$$

where $\pi = [\pi_0, \pi_1, \pi_2, \ldots, \pi_\infty]$ is the stationary distribution. Solving Eqn. (5), we obtain the values of $\pi_0, \pi_1, \pi_2, \ldots$

$$\pi_1 = \frac{p(1-q)}{q(1-p)}\,\pi_0$$

$$\pi_2 = \frac{p^2(1-q)^2}{q^2(1-p)^2}\,\pi_0$$

$$\pi_3 = \frac{p^3(1-q)^3}{q^3(1-p)^3}\,\pi_0$$

$$\pi_k = \frac{p^k(1-q)^k}{q^k(1-p)^k}\,\pi_0 \ldots\ldots$$

Since $\pi_0 + \pi_1 + \pi_2 + \ldots + \pi_\infty = 1$, substituting the values of $\pi_1, \pi_2, \ldots, \pi_\infty$ we obtain value of π_0, which is given by

$$\pi_0 + \alpha\,\pi_0 + \alpha^2\,\pi_0 + \ldots = 1$$

where $\alpha = \dfrac{p(1-q)}{q(1-p)}$

and hence $\pi_0 = 1 - \alpha$ We note that π_0 is the probability of queue being empty in the steady state. Substituting the value of α in π_0, we get

$$\pi_0 = \frac{q-p}{q(1-p)}$$

Thus, using π_0, π_k s can be computed.
The expected queue length in the steady state can be obtained using the stationary probability distribution as follows.

$$\mathrm{E}\,Q_* = \sum_{n=1}^{\infty} n\,\pi_n \qquad (6)$$

$$= \pi_0 \frac{\alpha}{(1-\alpha)^2} \qquad (7)$$

$$= p\,\frac{1-q}{q-p} \qquad (8)$$

Thus, we formulate the optimum sleep/wake scheduling problem using the costs C_Q (defined in Section III–A) and C_E (defined in Section III–C) as follows.

$$\text{minimize} \quad \lambda_Q\, p\, \frac{1-q}{q-p} + \lambda_E\, q \qquad (9)$$
$$\text{subject to } q \geq p\,,$$
$$\text{and } 1 - q \leq 1.$$

where we recall that q is the probability of receive node in the awake state, p is the probability of an arrival in queue, and λ_Q and λ_E are holding cost and energy cost respectively.

IV. OPTIMUM SLEEP/WAKE SCHEDULING

Define the cost function $\mathrm{c}(q) := \lambda_Q\, p\, \dfrac{1-q}{q-p} + \lambda_E\, q$ We first show that $\mathrm{c}(q)$ is convex, and then, using convex optimisation techniques, we solve for the optimal value of q.

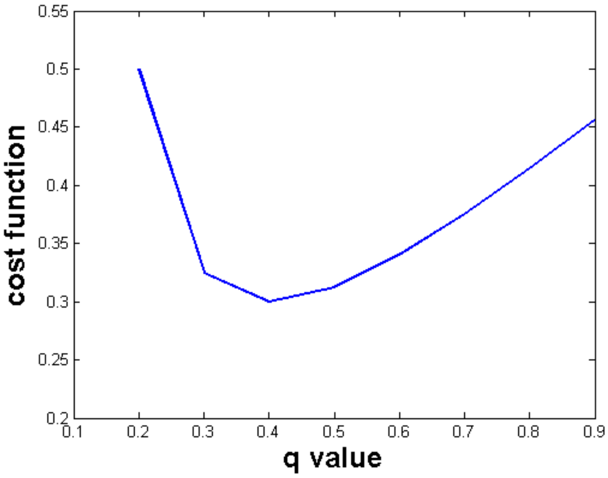

Fig. 4.Cost versus probability of awake: p = 0.1, $\lambda_Q = 0.5$, $\lambda_E = 0.5$

$$c(q) = \lambda_Q\, p\, \frac{1-q}{q-p} + \lambda_E\, q\,,$$

$$c'(q) = \lambda_Q p \left[-\frac{1}{q-p} - \frac{1-q}{(q-p)^2} \right] + \lambda_E,$$

$$= \lambda_Q p \left[\frac{p-1}{(q-p)^2} \right] + \lambda_E,$$

$$c''(q) = \lambda_Q \left[\frac{2p(1-p)}{(q-p)^3} \right]$$

Note that $c''(q) > 0$, and hence, c(.) is a convex function

A. Optimum Probability of Awake q^*

The minimizer of the cost function q^* is obtained by equating first derivative to zero. Thus, we have

$$c'(q^*) = 0$$

$$\Rightarrow -\lambda_Q \frac{p(1-p)}{(q^* - p)^2} + \lambda_E = 0$$

$$\Rightarrow \lambda_Q \frac{p(1-p)}{(q^* - p)^2} = \lambda_E$$

$$\Rightarrow \frac{\lambda_Q}{\lambda_E} p(1-p) = (q^* - p)^2$$

$$q^* = p + \sqrt{\frac{\lambda_Q}{\lambda_E}(p(1-p))} \qquad (10)$$

Remarks: From Eqn. (10), we infer the following:

- q^* is little larger than the probability of arrival p, and q^* is the same as p only for the extreme values of p, i.e., 0 or 1.
- When the cost of queuing λ_Q increases, q^* increases. This matches perfectly well with our intuition of making the queue–length smaller when its cost is higher.
- When the receive energy cost λ_E increases, q^* decreases. Again, this is due to the fact that a larger energy cost drives for a tight sleep/wake scheduling.

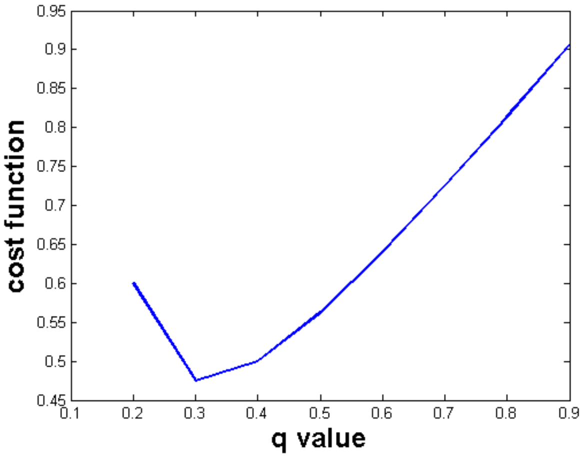

Fig. 5. Cost versus probability of awake: $p = 0.1$, $\lambda_Q = 0.5$, $\lambda_E = 1$

V. NUMERICAL RESULTS

We consider the following parameters: the arrival probability $p = 0.1$, queuing cost $\lambda_Q = 0.5$. For the energy cost, we consider two cases: case i) $\lambda_E = 0.5$, and case ii) $\lambda_E = 1$. We plot the cost function c(q) against the awake probability q for the two cases in Figures (4) and (5). For each of the two cases, we obtain the optimal q^* by our analysis, and found that they match perfectly well with that obtained through simulation.

We find that the optimum awake probability $q^* = 0.4$ for $\lambda_E = 0.5$, and $q^* = 0.3$ for $\lambda_E = 1$. This is because, as the energy cost increases, the tendency to be awake decreases. This is also clear from Eqn. (10). As λ_E increases, the cost function c(q) increases, but q^* decreases.

VI. CONCLUSION AND FUTURE WORK

We have formulated the problem of optimum (energy efficient) sleep/wake scheduling for a wireless network, and obtained a closed form expression for q^*, the optimum probabilistic sleep/awake strategy. We show by numerical examples that a wireless device on operating at q^* can save maximum amount of energy, and hence, can remain active for a long period of time.

Currently the focus of our work is on point–to–point network. A future work in this direction is to extend the work to point–to–multipoint (P2M) networks.

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