Energy Aware Sampling Schemes

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Abstract— **In an effort to conserve energy, mobile hosts wake up periodically to serve incoming traffic. This gives rise to a trade-off between energy consumption and delay. However, the deterministic strategy of current systems might not yield the desired performance. We show that knowledge of the statistical characteristics of incoming traffic can be used to better meet the energy and delay requirements of the mobile node. We consider zero-buffer and buffered models. We propose some strategies to improve energy efficiency and study the related trade-offs. We also introduce a new metric for energy efficiency and derive explicit expressions for the same. Our results prove that significant gains accrue by employing intelligent wake-up schemes.**

I. Introduction

There are a number of extant and emerging wireless applications which involve a large number of mostly dormant mobile nodes communicating with each other. Examples include Radio Frequency Identification Devices (RFID's), ad hoc networks and wireless Internet devices. These low power mobile nodes will be powered by batteries with finite capacity. Energy efficiency is consequently an important consideration in these scenarios. It would not be energy efficient for the mobiles to be awake when they are not receiving any data. Energy can be conserved by operating the mobiles in an intermittent fashion. Current systems [1], [2], employ a centralized controller which determines the wake-up schedule for the mobile nodes. Clearly, such a centralized scheme would be too complex to implement for a large number of nodes.

These wake up schemes are independent of the nature of the arrival traffic. We contend that knowledge of the statistical characteristics of arrival traffic can be used to devise smart wake up strategies. These schemes can result in reducing delays without compromising on energy efficiency and vice versa.

For motivational reasons, we first consider a simple arrival model with zero buffer at the base station. The results obtained from this simple model validate our hypothesis and illustrate the need for intelligent wake up schemes. We then consider an infinite buffer model at the base station fed by more realistic models of traffic. In the first case, we study the trade-off between Energy Efficiency and Capture Rate. In the second case, we consider the trade-off between Delay and Energy Efficiency. We provide simulation results for the performance under correlated traffic and derive analytical expressions for Energy Efficiency.

The rest of the paper is organized as follows. In section II, we consider the zero buffer model. We describe our analytical model and provide some results. Section III is concerned with the buffered model. We discuss the trade offs involved and provide some details on calculating Energy Efficiency. Finally we conclude in section IV.

II. The Zero Buffer Model

For the zero buffer case, we consider a discrete-time system where the packet inter-arrival times are independent and identically distributed. We assume that the inter-arrival periods are bounded by N. We say that a *capture* occurs when the receiver is awake and an arrival takes place. Arrivals which find the mobile asleep are assumed to be lost or blocked. We assume that one unit of energy is consumed per unit time when the mobile is awake. We define two performance metrics, Capture rate (τ) and Energy Efficiency (η). Capture rate is the fraction of arrivals which find the mobile awake. Energy Efficiency is the fraction of energy spent in serving the packets.

In the deterministic wake up scheme, the mobile wakes up at periodic instants and remains awake for a fixed period of time. It is easily shown that the Capture Rate is given by the duty cycle of the wake up scheme and the Energy Efficiency equals the arrival rate. Assume that the mobile wakes up for a units of time and sleeps for b units of time. Let λ be the arrival rate. Then, using basic renewal theory, the Capture rate and Energy Efficiency are given by

$$\begin{aligned} \tau &= \frac{a}{a+b} \\ \eta &= \lambda \end{aligned} \quad (1)$$

This scheme is inefficient since the wake up strategy is independent of the arrival mechanism. We propose the following scheme. Assume, initially, that a capture has occurred. Then the following algorithm is implemented.
1. Set $i = 1$.
2. While ($i <= K$) wake up after a_i units of time if capture repeat Step 1. else i = i+1
3. Remain awake till capture occurs

K represents the maximum number of times the receiver tries to capture the arrival process before remaining permanently awake. We have devised a numerical procedure to estimate the performance metrics for the above class of schemes.

A. Analysis

From the above description of our sampling scheme and the renewal assumption of traffic, we see that every capture

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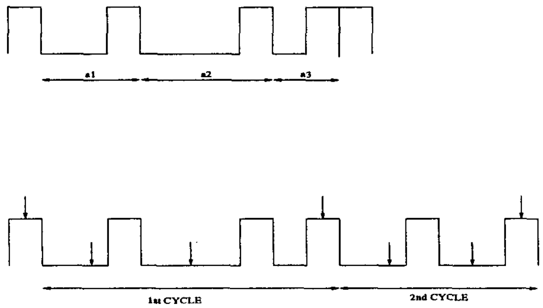

Fig. 1. A waking up strategy with $K = 3$

spawns a new renewal cycle. See Fig. 1 for $K = 3$. Let $p_i, (1 \le i \le N)$, be the probability that the inter-arrival period is i units. Let $a_i, (1 \le i \le K+N-1)$ be the interval of time between the i^{th} and $(i-1)^{th}$ awakening. When the receiver is in the active state, we like to think that the awakening-s are contiguous ($a_i = 1$). Let A_i denote the epoch of the i^{th} awakening. We have

$$\begin{aligned} a_i &= 1 \quad K+1 \le i \le K+N-1 \\ A_i &= \sum_{j=1}^{i} a_j \quad 1 \le i \le K+N-1 \end{aligned} \tag{2}$$

Let $q_i, (1 \le i \le N)$, be the probability that an arrival occurs in the $(k+i)^{th}$, given that an arrival has occurred in the k^{th} slot. Let B_k be the event that an arrival occurs at k^{th} slot. We denote the complement of a set B as B^c. We first derive the q_i's. Then we have

$$\begin{aligned} q_i &= P(B_{k+i}|B_k) \\ &= p_i + \sum_{j=1}^{\min(i-1,N)} p_j q_{i-j} \quad i > 1 \\ q_1 &= p_1 \end{aligned} \tag{3}$$

In the above equations, we condition on the first arrival after the k^{th} slot. It is thus possible to determine q_i's recursively.

In our model, a renewal cycle begins immediately after a capture has occurred and ends when the next capture event takes place. We now derive the probability mass function for the length of a cycle. Let X be the random variable describing the length of the first cycle. (We have chosen the first cycle for simplicity). We have

$$\begin{aligned} X &\in D = \{A_1, A_2, \ldots, A_{K+N-1}\} \\ u_{A_i} = P(X = A_i) &= P(\bigcap_{j=1}^{i-1} B^c_{A_j} \bigcap B_{A_i}|B_0) \\ & \quad 1 \le i \le K+N-1 \\ u_i &= 0, \quad i \notin D \end{aligned} \tag{4}$$

In words, a cycle has length A_i if an arrival takes place during the i^{th} awakening of the receiver and no arrival takes place during the earlier awakening-s. It is easy to show that

$$\begin{aligned} P(X = A_i) &= P(B_{A_i}|B_0) - \sum_{k<i} P(B_{A_k} \bigcap B_{A_i}|B_0) + \\ & \sum_{k<l<i} P(B_{A_k} \bigcap B_{A_l} \bigcap B_{A_i}|B_0) \ldots \\ & +(-1)^{(i-1)} P(B_{A_1} \bigcap \ldots \bigcap B_{A_i}|B_0) \end{aligned} \tag{5}$$

It now remains to calculate each term in the above expansion. We have

$$\begin{aligned} P(B_{k_1} \bigcap \ldots \bigcap B_{k_m}|B_0) &= q_{k_1} P(B_{k_2} \bigcap \ldots \bigcap B_{k_m}|B_{k_1} \bigcap B_0) \\ &= q_{k_1} q_{k_2-k_1} \cdots q_{k_m-k_{m-1}} \end{aligned} \tag{6}$$

TABLE I

ARRIVAL RATE = 0.1

Capture Rate	Energy Efficiency	
	Deterministic	New scheme
.76	.1	.28
.82	.1	.24
.89	.1	.22

B. Performance Metrics

Let T be the mean length of a renewal cycle. Then we have

$$\begin{aligned} T &= \sum_{i=1}^{A_{K+N-1}} i u_i \\ &= \sum_{i=1}^{K+N-1} A_i u_{A_i} \end{aligned} \tag{7}$$

(8)

Let E be the mean energy consumed in a renewal cycle. Then

$$E = \sum_{i=1}^{K+N-1} i u_{A_i} \tag{9}$$

The performance metrics , Energy Efficiency (η)and Capture Rate (τ) are given by

$$\begin{aligned} \eta &= \frac{1}{E} \\ \tau &= \frac{1}{\lambda T} \end{aligned} \tag{10}$$

(11)

where ($\lambda = \frac{1}{\sum_{k=1}^{N} k p_k}$) is the arrival rate.

C. Results

We found significant gains in Energy Efficiency using this scheme. Some results are shown in tables [I] and [II]. For our purposes, low values of arrival rate are of interest. As can be readily seen from the tables, *Energy Efficiency can be improved by a factor of 2 or more.*

TABLE II

ARRIVAL RATE = 0.2

Capture Rate	Energy Efficiency	
	Deterministic	New scheme
.61	.2	.39
.82	.2	.48
.93	.2	.42

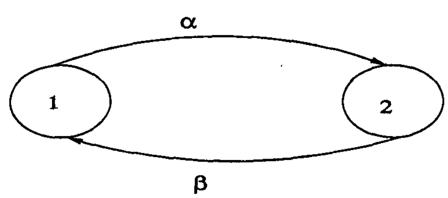

Fig. 2. Controlling Markov Chain

III. The Buffered Model

We next assume that the packets which find the mobile asleep are queued up at the base station. We assume that the buffer is infinite. When the mobile wakes up and finds packets in the queue, it serves all the packets until the queue is empty and then goes to sleep once again. The service time for each packet is one unit of time. In queuing parlance this is called the Exhaustive Service with Multiple Vacations model [3], [4], [5] and is denoted in Kendall's notation by $G/D/1/V_m$. We assume that the mobile can receive different classes of traffic e.g., voice and data. To characterize such traffic, we model the arrival process as a discrete-time version of the Markov Modulated Poisson process (MMPP). In particular, we consider an underlying Markov chain having two states. See Fig. 2. In each state, the inter-arrival times are given by a state dependent geometric distribution parameterized by $p_i, i = 1,2$. We retain the original definition of Energy Efficiency and study the trade-off between Delay and Energy Efficiency.

A. Energy Efficiency

A.1 The *$Geom/D/1/V_m$* queue:

For the sake of conceptual development, we shall first consider the geometric arrival case and derive an expression for Energy Efficiency. When the mobile host serves all the traffic queued up at the base station and finds no more traffic to serve, it sleeps for T units and then wakes up to check for traffic queued up at the base station. If there is traffic pending at the base station, it serves it. Otherwise, it goes back to sleep for another T units of time. Let ρ be the utilization of the queue, and v_0 be the fraction of times the mobile awakes to find no packets in the queue. Then the Energy Efficiency(η) is:

$$\eta = \lim_{t\to\infty} \frac{\text{Energy spent serving packets in time t}}{\text{Total energy spent by mobile in time t}} \quad (12)$$

i.e.,

$$\eta = \lim_{t\to\infty} \frac{\text{Prob. that mobile is busy}.t}{\text{Prob. that mobile is busy}.t + W} \quad (13)$$

where

$$W = \frac{\text{Prob. that mobile is asleep}.t}{T}.v_0$$

As is well known the steady state probability of the mobile being busy is given by ρ and the probability of it being asleep is $(1-\rho)$. Hence, the only unknown in equation (13) is the quantity v_0. For Geometric arrivals, this quantity can be computed from renewal theory.

We note that the instants at which the server finds the queue empty and goes on vacation are renewal instants. Hence the renewal cycle consists of a vacation period followed by a busy period. In one vacation period, V, the server comes up $\frac{V}{T}$ times. It does useful work only on the last time it wakes up to find packets pending in the queue. Therefore, the energy wasted is $\frac{V}{T}-1$. From the renewal reward theorem [6], the steady state probability of the server waking up to find no traffic queued up is:

$$v_0 = \frac{\frac{EV}{T} - 1}{\frac{EV}{T}} = 1 - \frac{T}{EV} \quad (14)$$

If p is the probability of a packet arrival, from elementary probability arguments, we can compute the expected vacation period to be:

$$EV = \frac{T}{1-(1-p)^T} \quad (15)$$

From equations (15), (14) and (13), we get the Energy Efficiency (η) as:

$$\eta = \frac{\rho}{\rho + \frac{(1-\rho)}{T}.(1-p)^T} \quad (16)$$

A.2 The $MMPP/D/1/V_M$ queue:

We now consider a traffic model that is driven by an underlying Markov process. For the sake of simplicity, we assume a two state discrete time Markov chain. The arrival in each state is Geometric and is parameterized by $p_i, i = 1,2$. We assume that the base station is aware of which state the Markov chain is in. This is not a farfetched assumption. Let each state represent a different kind of traffic, such as voice or data. Then depending on the kind of traffic being transmitted, the base station knows which state the Markov chain is in. When the queue goes empty, the base station transmits the state of the next arrival to the mobile host. The state information determines the sleep times of the mobile.

Let $T_i, i = 1,2$ be the sleep duration of the mobile when the arrival process is in state one or two respectively. Let $\pi_i, i = 1,2$ be the stationary probability of being in state

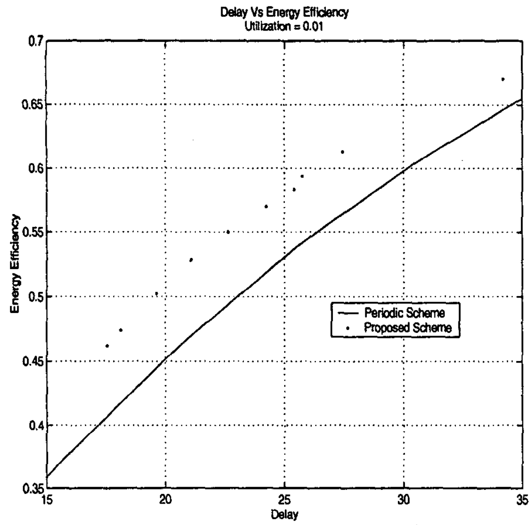

Fig. 3. Buffered Model, Arrival rate = 0.01

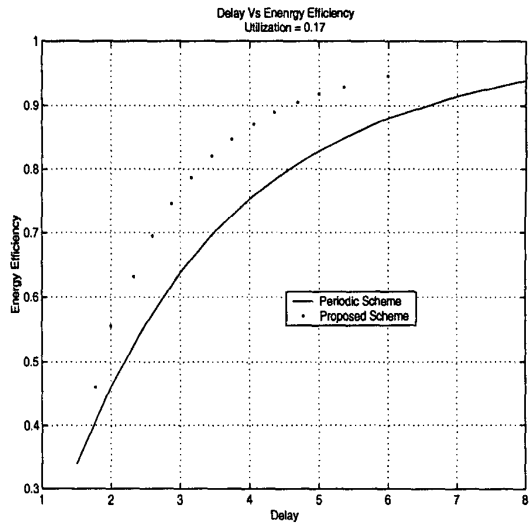

Fig. 4. Buffered Model, Arrival rate = 0.17

one or two respectively. Then using arguments similar to those in section III-A.1, the Energy Efficiency can be computed to be:

$$\eta \;=\; \frac{\rho}{\rho + (1-\rho)\sum_{i=1}^{2} \frac{\pi_i}{T_i}.(1-p_i)^{T_i}} \tag{17}$$

One immediately observes that equation(17) is not restricted to just a two state MMPP. It can be extended to any finite state MMPP. Let the number of states in the MMPP is N. Let $T_i, i = 1, \ldots, N$ be the sleep times for each state. Let the Geometric arrival process in each state be parameterized by $p_i, i = 1, \ldots, N$. Let $\pi_i, i = 1, \ldots, N$ be the stationary probability of being in each state. Then, we can extend the formula for Energy Efficiency from equation(17) as:

$$\eta \;=\; \frac{\rho}{\rho + (1-\rho)\sum_{i=1}^{N} \frac{\pi_i}{T_i}.(1-p_i)^{T_i}} \tag{18}$$

B. Results

In Fig. 3 and Fig. 4, we provide some results for different arrival rates. We note that this represents a lower bound on performance improvements possible. Gains of at least 10% appear to be feasible.

IV. Conclusions

We had set out to show the performance gains possible by using intelligent sampling schemes. We considered the different performance trade-offs which arise in zero-buffer and buffered systems. In both cases, we found significant improvements. This is especially so, when the arrival rate is low. This is the situation of interest in the near future.

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