Energy Efficient Sampling Schemes for Wireless Networks

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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 buffered models under different channel assumptions. 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

As wireless technologies mature, we envision a scenario in which a large number of mostly dormant mobile nodes communicate 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. Consequently 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. An obvious alternative would be to allow the mobiles to wake up independently and check for pending packets. The mobile goes to sleep whenever it has no pending traffic at the base station and wakes up periodically to check for incoming traffic. Packets which arrive at the base station and find the mobile device asleep are queued up for later retransmission.

We define,
Energy Efficiency, as the fraction of the total energy spent in serving incoming packets. There exists a natural trade-off between energy efficiency and delay. Assume that arrivals occur every 100 seconds. If the mobile wakes up every 10 seconds, we note that 9 out of 10 times, the mobile is wastefully expending energy. On the other hand, each packet is not delayed more than 10 seconds. If instead, the mobile were to wake up every 50 seconds, its energy efficiency and would be much higher; however packets would experience greater delays. Hence wake-up schemes should not be designed independently of arrival traffic. Since the mobile devices of interest to us are assumed to have low computing support, the decentralized strategy must be as simple as possible.

The rest of this paper is organized as follows. In section II, we describe the arrival process we have used. In section III, we discuss the channel models we have considered. We also outline our wake-up scheme. Sections IV and V, contain respectively, the analyses for delay and energy efficiency, when the channel is perfect. We provide some results in section VI and conclude in section VII.

II. MARKOVIAN ARRIVAL PROCESS

We model the arrival process as a Markovian Arrival Process (MAP). The MAP process is versatile enough to model a wide variety of processes such as arbitrary renewal processes and the Markov Modulated Poisson Process. Adding two MAP processes results in another MAP process. Furthermore, the MAP process lends itself to a degree of analytical tractability. Algorithmic techniques have been devised to estimate performance metrics for queues fed by MAP [5] [6] [7].

The MAP process can be thought of as an $(M+1)$ state Markov chain. States $1,\ldots,M$ are transient. State $M+1$ is an absorbing state. Arrivals occur whenever the chain enters the absorbing state. Once an arrival occurs, the process restarts from one of the transient states. The probability law governing the state after absorption is dependent on the state immediately before absorption. By controlling the restart mechanism, several arrival processes can be modeled.

Let q_{ij} be the transition probability from state i to j without going to the absorbing state. Let p_{ij} be the transition probability from state i to j through the absorbing state (resulting in an arrival). Then, the transition structure of the MAP process can be decomposed into two matrices, C and D. C represents the transitions without any arrival and is given by $C_{ij} = q_{ij}$. D represents the transitions with a single arrival and is given by $D_{ij} = p_{ij}$. The time spent in the absorbing state is infinitesimal. The stationary probability vector of the MAP process, π, is given by

$$\begin{aligned} \pi(C+D) &= \pi \qquad (1) \\ \pi e &= 1 \end{aligned}$$

e is the column vector consisting of all ones. The arrival rate, λ, is given by

$$\lambda = \pi D e \qquad (2)$$

In this paper, we model the arrival process as a discrete-time version of the Markov Modulated Poisson process (MMPP). In particular, we assume that the arrival process can be in either of two states. In each state, the inter-arrival times are given by a state dependent geometric distribution parameterized by

$p_i, i = 1, 2$. We assume that arrivals occur more frequently in state 1 ($p_1 > p_2$). The C and D matrices are given by

$$C = \begin{bmatrix} (1-p_1)(1-\alpha) & (1-p_1)\alpha \\ (1-p_2)\beta & (1-p_2)(1-\beta) \end{bmatrix}$$
$$D = \begin{bmatrix} p_1 & 0 \\ 0 & p_2 \end{bmatrix} \quad (3)$$

III. CHANNEL MODELS AND SAMPLING SCHEMES

We first assume ideal channel conditions. 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 the mobile goes back to sleep once again. In queuing parlance this is called the Exhaustive Service with Multiple Vacations model. We assume that one unit of energy is consumed per unit time when the mobile is awake. In the deterministic setting, the sleep periods of the mobile are constant. In our scheme, we make the sleep times dependent on the state of the arrival process. When the queue becomes empty, and the arrival process is in state 1, the mobile host takes a vacation of duration T_1. At the end of the vacation, if the queue is still empty, the mobile host takes another vacation of duration T_1. This procedure is repeated till the mobile host finds packets in the queue. A similar procedure is adopted with vacations of duration T_2 if the arrival process was in state 2 at the end of a busy cycle. Since arrivals in state 2 are scarce compared to state 1, we make T_2 greater than T_1. The service time of each packet is one unit.

We next study the trade-off under imperfect channel conditions for the arrival process described earlier. We consider two channel models. For the first model, we assume that the channel state is described by a Bernoulli process. A packet transmitted by the base station is corrupted with probability q, independent of previous transmissions. We then consider a two state Gilbert-Elliott channel model. In this model, the channel state is assumed to be described by a two state Markov chain. We assume that a packet is successfully received when the channel is in the *good* state and completely corrupted when the channel is in the *bad* state. The packet remains at the head of the queue until it is successfully received by the mobile host. When the mobile wakes up and finds the channel is *good*, it operates as in the perfect channel case. If it finds that the channel is *bad*, it takes a vacation of duration T_B independent of the arrival state.

IV. DELAY ANALYSIS

A. Prior Work

Queues with vacations have been analyzed in the past using the decomposition property [4]. For the GI/GI/1 queue with independent and identically distributed vacations, the decomposition property states that

$$W_V \overset{d}{=} W + R_V \quad (4)$$

W_V is the random variable with the steady-state waiting time distribution of the GI/GI/1 queue with vacations, W is the random variable with the steady-state waiting time distribution of the same GI/GI/1 queue without vacations and R_V is the residual waiting time of the vacation process. This property has been shown to hold even when the arrival process is MAP. In

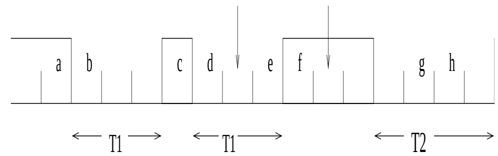

Fig. 1. A Sample Path : Vertical half-lines denote slot boundaries, rectangular pulses represent slots when the server is awake, downward arrows represent arrivals, $a, \ldots, f$ represent state of the system

[7], a discrete-time MAP model with independent vacations has been analyzed.

However, the decomposition property fails when the vacations are dependent on the arrival process. In our specific model, it turns out that the waiting time distribution can be obtained by a direct analysis of the underlying Markov chain.

B. Detailed Analysis

The state space of our model is given by $S = \{i, j, k, l : i \in \{0, \ldots, \max(T_1, T_2) + 1\}, j \in \{1, 2\}, k \in \{0, 1, 2\}, l \in \{0, \ldots, \max(T_1, T_2)\}\}$, where,

- i : number of packets in the system
- j : state of the arrival process
- k : state of the vacation process
- l : time elapsed since the mobile host was last awake

$k = 0$ means that the system is in a busy period. $k = 1(2)$ means the mobile host is taking vacations of durations $T_1(T_2)$. In figure (1), we provide a possible evolution of a sample path. The states $a, \ldots, f$ are described as follows.

- $a = (0, 1, 0, 0)$:

The queue is empty, arrival process is in state 1, the system is in a busy period and the mobile host is awake in the current slot.

- $b = (0, j, 1, 1)$:

The queue is empty, arrival process is in state j, the mobile host is on a vacation of duration T_1 and it was awake in the previous slot.

- $c = (0, j, 1, 0)$:

The queue is empty, arrival process is in state j, the mobile host is taking vacations of duration T_1 and it is awake in the current slot.

- $d = (0, j, 1, 1)$:

This is the same state as b.

- $e = (1, j, 1, T_1)$:

The queue has one packet, the arrival process is in state j, the mobile host is taking vacations of duration T_1 and it was awake T_1 slots before.

- $f = (1, j, 0, 0)$:

The queue has one packet, the arrival process is in state j, the mobile host is busy and it is awake.

- $g = (0, j, 2, 2)$:

The queue is empty, the arrival process is in state j, the mobile host is taking vacations of duration T_2 and it was awake 2 slots before.

It is clear from the above discussion that some combinations of (i, j, k, l) are not valid states. The only possible states are $(i, j, 0, 0)$, $(i, j, 1, 0)$, ..., $(i, j, 1, T_1)$, $(i, j, 2, 0)$, ..., $(i, j, 2, T_2)$, $i \in \{0, T_2 + 1\}$, $j \in \{1, 2\}$.

Let $P(i,j,k,l)(i',j',k',l')$ be the transition probability from state (i,j,k,l) to state (i',j',k',l'). The *non-zero* transition probabilities are given by

$$\begin{aligned} P(0,j,0,0)(0,j',j,1) &= q_{jj'} \\ P(0,j,0,0)(1,j',j,1) &= p_{jj'} \\ P(0,j,k,l)(0,j',k,(l+1)mod(T_k+1)) &= q_{jj'}, \\ (k \in \{1,2\}) \\ P(0,j,k,l)(1,j',k,(l+1)mod(T_k+1)) &= p_{jj'}, \\ (k \in \{1,2\}) \\ P(i,j,0,0)(i-1,j',0,0) &= q_{jj'}, \\ (i \geq 1) \\ P(i,j,0,0)(i,j',0,0) &= p_{jj'}, \\ (i \geq 1) \\ P(i,j,k,l)(i,j',k,(l+1)mod(T_k+1)) &= q_{jj'}, \\ (i \geq 1),(k \in \{1,2\}) \end{aligned} \quad (5)$$

The transition probability matrix (P) given above is of the M/G/1 type described in [nuets2]. The M/G/1 type matrix is of the form

$$P = \begin{bmatrix} B_0 & B_1 & B_2 & B_3 & B_4 & \dots \\ C & A_1 & A_2 & A_3 & A_4 & \dots \\ 0 & A_0 & A_1 & A_2 & A_3 & \dots \\ 0 & 0 & A_0 & A_1 & A_2 & \dots \\ . & . & . & . & . \\ . & . & . & . & . \end{bmatrix} \quad (6)$$

For our model, we note that B_0 represents the transitions from level [1] 0 to level 0. A_0 represents the transitions from level i to $i-1$. A_1 represents the transitions from level i to i. A_2 represents the transitions from level i to $i+1$. The dimension of these matrices is $2(1+T_1+T_2) \times 2(1+T_1+T_2)$.

$$\begin{aligned} C &= A_0 \\ B_i &= 0 \qquad i \geq 2 \\ A_i &= 0 \qquad i \geq 3 \end{aligned} \quad (7)$$

It remains to determine the stationary probability distribution, x of the system given by

$$\begin{aligned} x &= xP \\ xe &= 1 \end{aligned} \quad (8)$$

We think of x as $(x_0, x_1, \dots, x_{1+T_2})$, where each x_i is a row vector denoting the system probabilities at level i. Let y_i be the steady-state probability of being in level i. Let W be the mean waiting time and L be the mean number of packets in the system. Then, using Little's law, we have

$$\begin{aligned} y_i &= x_i e \\ L &= \sum_{i=1}^{1+T_2} i y_i \\ W &= \frac{L}{\lambda} \end{aligned} \quad (9)$$

where λ is obtained from equation(2). We used the software package TELPACK [8] to obtain the stationary distribution.

[1] level refers to the number of packets in the system

V. Energy Analysis

In this section we provide an analysis of the energy efficiency of our sampling scheme. We have assumed that the mobile is aware of the state of the arrival process at the instant the queue at the base station becomes empty. We define energy efficiency (η) as:

$$\eta = \lim_{n \to \infty} \frac{\text{Energy spent serving packets in time t}}{\text{Total energy spent by mobile in time t}} \quad (10)$$

Let ρ be the utilization of the queue. It is clear that the mobile does useful work for ρ% of the time. Let $p_i, i = 1,2$ be the stationary probability of the arrival process being in state i at the beginning of a vacation period. Let V_i be the random duration of the vacation period starting with the arrival process in state i. Then,the energy efficiency is given by:

$$\eta = \frac{\rho}{\rho + (1-\rho)\sum_{i=1}^{2} \frac{p_i}{T_i}.(1 - \frac{T_i}{EV_i})} \quad (11)$$

Proof: Consider the starting instants of the idle periods with the arrival process in state $i = \{1,2\}$. These instants constitute renewal epochs and the corresponding idle period constitute a renewal process $\{I_n^i\}, i = \{1,2\}$. Thus the idle periods can be thought of as the superposition of two renewal processes. Let v_0^i be the fraction of times the mobile wakes up to do unnecessary work in the vacation periods belonging to I_n^i. We note that the mobile does useful work when it wakes up for the last time in an idle period. Then, using the Renewal-Reward theorem [9], we have

$$\begin{aligned} v_0^i &= \frac{\frac{EV_i}{T_i} - 1}{\frac{EV_i}{T_i}} \\ &= (1 - \frac{T_i}{EV_i}) \quad i = 1,2 \end{aligned} \quad (12)$$

Hence, the long term time average of wasteful energy spent starting in state i, W_i is

$$\begin{aligned} W_i &= \lim_{t \to \infty} \frac{\text{(Prob. that mobile is in vacation state i)}\frac{t}{T_i} v_0^i}{t} \\ \Rightarrow W_i &= \frac{(1-\rho)p_i}{T_i} v_0^i \quad i = 1,2 \end{aligned} \quad (13)$$

Consequently, the total average amount of wasteful energy spent in both the states is

$$\begin{aligned} W &= W_1 + W_2 \\ \Rightarrow W &= (1-\rho)\sum_{i=1}^{2} \frac{p_i}{T_i}(1 - \frac{T_i}{EV_i}) \\ \Rightarrow \eta &= \frac{\rho}{\rho + (1-\rho)\sum_{i=1}^{2} \frac{p_i}{T_i}.(1 - \frac{T_i}{EV_i})} \end{aligned} \quad (14)$$

It remains to compute EV_i. For simplicity, we will derive the expression for EV_1 only. EV_2 can be derived in an exactly similar fashion. We first define a few quantities of interest[2].

$$\begin{aligned} l(n) &= \text{Prob.}\{V_1 = nT_1\} \\ \alpha_1 &= \text{Prob.}\{\text{At least one arrival in } T_1 \text{ slots} \\ &\quad \text{given the arrival process started in state 1}\} \\ \alpha_2 &= \text{Prob.}\{\text{At least one arrival in } T_1 \text{ slots} \\ &\quad \text{given the arrival process started in state 2}\} \\ \alpha &= [\alpha_1 \quad \alpha_2]^t \end{aligned}$$

[2] A^t is the transpose of the matrix A

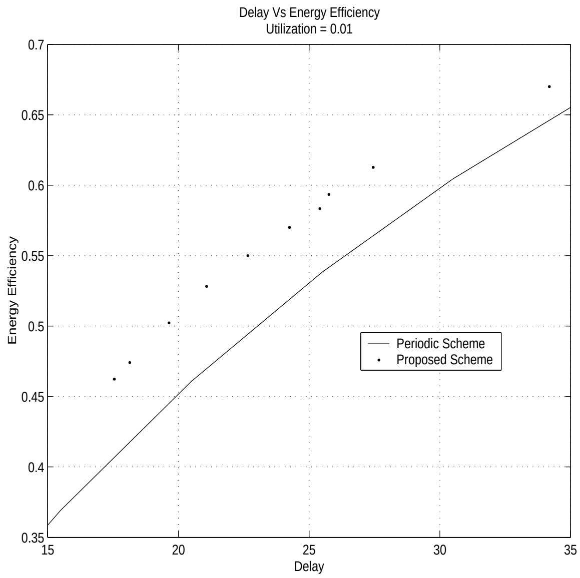

Fig. 2. Perfect Channel Model

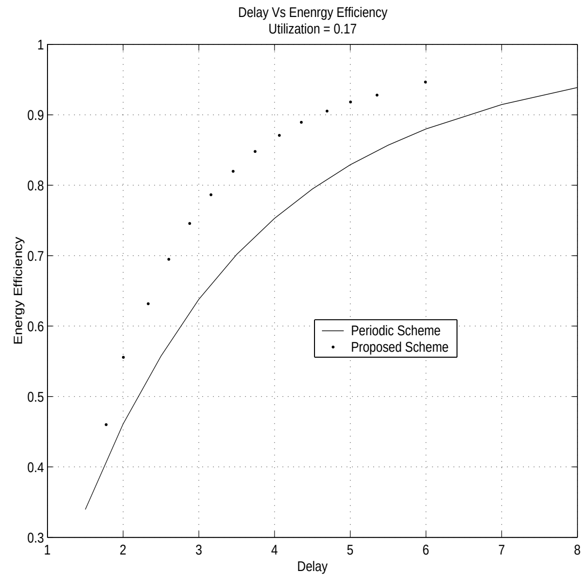

Fig. 3. Perfect Channel Model

Let $(x)_1$ denote the first element of the column vector x. Then, using the above notation, it is easily seen that

$$\begin{aligned} \alpha &= e - C^{T_1} e \\ l(1) &= (\alpha)_1 \\ l(2) &= (C^{T_1}\alpha)_1 \\ &\vdots \\ l(n) &= (C^{nT_1}\alpha)_1 \qquad (15) \\ & \qquad (16) \end{aligned}$$

Hence, we have

$$\begin{aligned} EV_1 &= \sum_{n=1}^{\infty} nT_1 l(n) \\ &= T_1([I - C^{T_1}]^{-2}\alpha)_1 \qquad (17) \end{aligned}$$

VI. RESULTS

In this section, we provide some simulation results. In Fig. (2) and (3), we assume that the channel is perfect. Fig. (4) and (5) were obtained under the Bernoulli and Gilbert-Eliot channel assumptions, respectively.

For the perfect channel case, we have considered two arrival scenarios. In Fig. (2), the parameters were: p_1 = 0.4, p_2 = 0.008, α = 0.1 and β = 0.001. For Fig. (3), they were: p_1 = 0.9, p_2 = 0.1, α = 0.1 and β = 0.001. The latter arrival process was also used to obtain Fig. (4) and (5). In Fig. (4), we assumed that the channel was good with probability 0.99 in any time slot. In Fig. (5), the channel transits from the good to the bad state with probability 0.001 and from the bad to the good state with probability 0.9.

VII. CONCLUSION

In this paper, we have proposed a simple wake-up scheme for improving the performance of mobile networks comprising of low power nodes. We have analyzed a queuing system with correlated arrivals and dependent vacations. We have derived an explicit expression for the energy efficiency of our scheme. We obtained an improvement of around 10% for the arrival processes we considered.

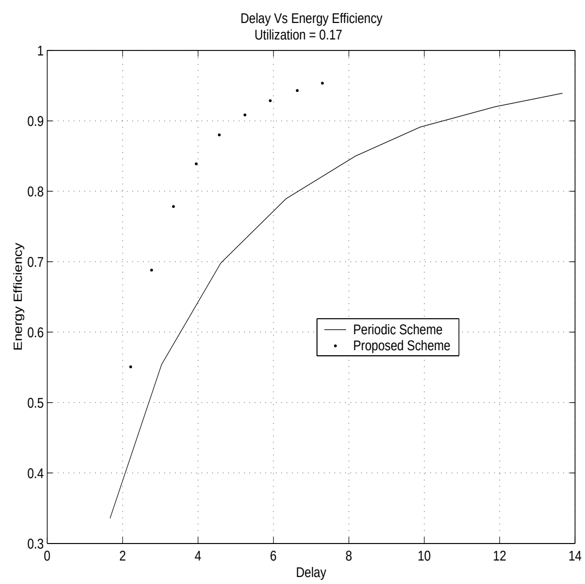

Fig. 4. Bernoulli Channel Model

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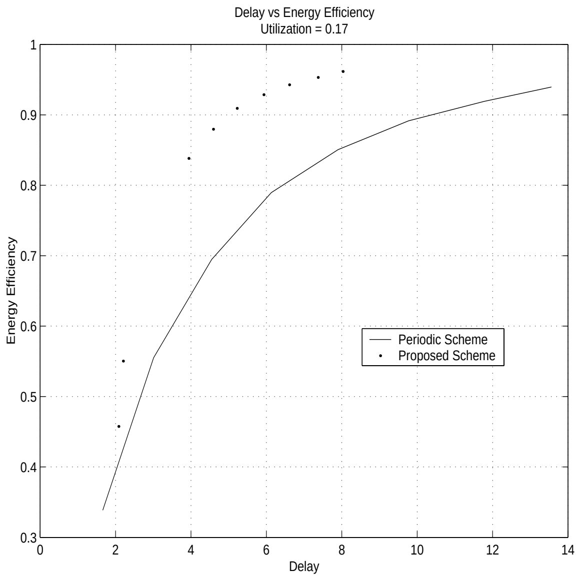

Fig. 5. Gilbert-Eliott Model

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