Non-Deterministic Preamble Sampling Periods for Low-Power Listening

T. Owens Walker III
Department of Electrical and Computer Engineering
United States Naval Academy, Annapolis, Maryland, USA
owalker@usna.edu

Murali Tummala and John McEachen
Department of Electrical and Computer Engineering
Naval Postgraduate School, Monterey, California, USA
{mtummala, mceachen}@nps.edu

Abstract—In this paper, we propose a novel low-power listening scheme that is comprised of non-deterministic preamble sampling periods and demonstrate how the mean of these sampling periods can be varied through the use of a preamble sampling probability parameter. This is in contrast to the existing literature which treats the preamble sampling periods as deterministic and seeks to vary them directly using heuristic algorithms. Per packet energy consumption analysis and accompanying simulation results for our non-deterministic approach are provided and we show that energy consumption can be minimized by varying this preamble sampling probability parameter.

Keywords-Wireless sensor networks, preamble sampling, low power listening.

I. INTRODUCTION

Energy management in wireless sensor networks continues to be the focus of significant research both in the commercial sector and within the Department of Defense. It has been well established that military applications such as unattended battlefield monitoring [1] and enemy signals collection [2] tend to be extremely power-constrained and battlefield sensor networks must feature low duty cycles that are often implemented using low-power sleep modes of operation.

Preamble sampling (also referred to in the literature as low-power listening) [3],[4] is one technique used to realize these low duty cycles. Here, a node will periodically wake up from a low-power sleep mode and listen to the channel for a time \( \tau \) to see if it has traffic pending. Thus, as in Figure 1, a node with a packet to transmit and no knowledge of the receiver’s listening schedule will need to transmit a beacon for the duration of the sampling period \( T_{\text{amp}} \) to notify the destination node of a pending packet transmission. Upon waking up and hearing the beacon, a node will then remain awake to receive the subsequent transmission.

Early work in preamble sampling techniques focused on a fixed length sampling period whose duration was optimized prior to runtime. In B-MAC [5], a commonly used reconfigurable MAC protocol that has been implemented on the Berkeley family of motes, a node with a packet to send will transmit a beacon for a period of time slightly longer than the duration of the receiver’s sampling cycle. Upon waking up and hearing the beacon, the intended destination node will then remain awake to receive the subsequent transmission. WiseMAC [6] reduced the requirement for the relatively long preamble by allowing neighboring nodes to exchange preamble sampling times. The preamble duration is then a function of the accuracy of the synchronization between the two nodes (bounded by the receiver’s preamble sampling period). X-MAC [7] further improves on this technique by breaking the preamble into smaller packets (referred to as “preamble strobing”) and including destination address information in the short preamble packets. This allows early termination of the preamble as the destination is provided time to acknowledge the preamble in-between the strobes and limits overhearing (receiving of packets for which a node is not the intended destination) by allowing nodes that are not the intended destination to return to the sleep state upon successfully receiving one of the preamble packets.

Recent low-power listening solutions have begun to address the idea of varying the length of the sampling cycle to adjust to changes in network load. Jurdak et al. [8] proposed the idea of adaptive sampling periods by arguing that local, nonuniform preamble sampling period settings provide improved performance over global settings due to the nonuniform nature of the traffic load in a wireless sensor network. Using a cost function to set the local sampling period in a tree-based topology, they demonstrated improved energy consumption performance over the network-wide sampling period of B-MAC. In [9], the authors propose switching MAC algorithms from among a set of low-power listening protocols based on current traffic characteristics and synchronizing listening schedules on slow-varying routes to improve delay performance as well as minimize energy consumption. The authors of [10] propose a pair of heuristic algorithms designed to adaptively arrive at a locally energy efficient sampling period. The first is based on a straight-forward linear...
increase/linear decrease approach while the second make use of control theory to ensure a target number of packets are delivered while reducing energy consumption.

Continuing our work in [11], the primary contribution of this paper is to introduce a preamble sampling technique that can generate non-deterministic sampling periods. In contrast to the existing proposals in the literature discussed above which assume a deterministic preamble sampling period [7] and vary it directly using heuristic algorithms [8],[9],[10], we propose a novel non-deterministic approach to varying the sampling period. We are motivated by the non-deterministic nature of the traffic within the network. To our knowledge, this is the first work that treats the preamble sampling period as a random variable.

The organization of this paper is as follows. Non-deterministic sampling periods are introduced in Section II and it is shown that we can vary the mean of the sampling period by varying the preamble sampling probability. We provide energy consumption analysis and accompanying simulation results for non-deterministic preamble sampling in Section III.

II. NON-DETERMINISTIC SAMPLING PERIODS UTILIZING PROBABILISTIC PREAMBLE SAMPLING

As in [11], we define probabilistic preamble sampling (or, more generally, non-deterministic preamble sampling) as a low-power listening technique in which the receiver wakes up from a sleep mode and samples the medium for a preamble every \( t_s \) seconds with some probability \( p_s \) (which we call the preamble sampling probability) where \( 0 \leq p_s \leq 1 \). Note that while \( t_s \) is deterministic, the actual sampling period \( T_{samp} \) is a random variable due to the effect of \( p_s \). Since the duration of the sampling period is unknown, some type of preamble sampling strobing technique such as that proposed in [7] is required to allow the receiver the opportunity to acknowledge and terminate the preamble transmission. In such a scheme, the sender periodically suspends transmission of the preamble to allow the receiver to reply with an acknowledgement packet. This acknowledgement packet provides the sender feedback to terminate the preamble and begin transmission of the packet.

In the following theorem, we demonstrate that we can vary the mean of the sampling period by altering the preamble sampling probability.

Theorem: For a non-deterministic preamble sampling scheme where a node samples the medium every \( t_s \) seconds with some probability \( p_s \), the expectation of the sampling period \( T_{samp} \) is given by

\[
E[T_{samp}] = \frac{t_s}{p_s}.
\]

Proof: The probability that the duration of a sampling period will be \( nT_{samp} \) can be shown to be

\[
\Pr[T_{samp} = nT_{samp}] = p_s (1-p_s)^{n-1}
\]

where \( n = 1,2,\ldots,\infty \). The expectation (or mean) of the sampling period is then

\[
E[T_{samp}] = \sum_{n=1}^{\infty} (nT_{samp}) p_s (1-p_s)^{n-1}.
\]

Rearranging and pulling the non-dependent terms out of the summation, we have

\[
E[T_{samp}] = \left(\frac{p_s}{1-p_s}\right)T_{samp}\sum_{n=1}^{\infty} n(1-p_s)^{n-1}
\]

Making use of the identity \( \sum_{n=1}^{\infty} nc^n = \frac{c}{(1-c)^2} \) for \( |c|<1 \),

\[
E[T_{samp}] = \left(\frac{p_s}{1-p_s}\right)T_{samp}\left[\frac{1-p_s}{(1-(1-p_s))^2}\right]
\]

since \( p_s < 1 \) (and thus \( |1-p_s|<1 \)) if we exclude the limiting case where the preamble sampling probability is one. Simplifying, we arrive at

\[
E[T_{samp}] = \frac{t_s}{p_s}
\]

for \( p_s < 1 \). To address the case of \( p_s = 1 \), we need only recognize that if \( p_s = 1 \) then the sampling period is deterministic and equal to \( t_s \) by definition. Q.E.D.

Thus, we see that while the sampling period is a random variable, we can vary the mean sampling period by varying the probability of preamble sampling. Specifically, we can increase the mean sampling period by decreasing the preamble sampling probability and vice versa. This is in contrast to the adaptive preamble sampling approaches in existing literature which treat the sampling period as deterministic and seek to vary it directly by using heuristic algorithms such as those in [8],[9],[10].

III. ENERGY CONSUMPTION

We can derive the per packet energy consumption of both the sender and the receiver for the proposed non-deterministic preamble sampling approach. For this initial analysis, we focus on the energy consumption effect of the preamble scheme and ignore the complexities introduced by the preamble strobing by assuming that the receiver utilizes an out-of-band acknowledgement to terminate the preamble. We also assume no more than one packet arrival per sampling period and make use of a simple three-state energy model (Transmit, Receive, and Sleep) to highlight our results.

The per packet energy consumption of the sender \( E_{sender} \) is the energy consumed in transmitting the preamble and the subsequent the packet as well as the energy consumed in the sleep state while awaiting packet arrival as in

\[
E_{sender} = \delta_{trans}T_{preamble} + \delta_{trans}T_{pkt} + \delta_{sleep}(T_{awt} - (T_{preamble} + T_{pkt}))
\]

where
where $\delta_{xmt}$ is the transmit power, $\delta_{sleep}$ is the sleep mode power, $T_{preamble}$ is the preamble transmission time, $T_{arvl}$ is the mean interarrival time, and $T_{pkt}$ is the packet transmission time. For a preamble sampling scheme such as the one proposed and ignoring the overhead of the acknowledgement mechanism, $T_{preamble} = \frac{T_{samp}}{2}$ since the packet will arrive during the sampling period with a uniform probability distribution. The average per packet energy consumption of the sender is then

$$E_{sender} = \delta_{xmt} \left( \frac{T_{samp}}{2} + T_{pkt} \right) + \delta_{sleep} \left( T_{arvl} - \frac{T_{samp}}{2} + T_{pkt} \right)$$  \hspace{1cm} (8)

which, from (1), is equivalent to

$$\bar{E}_{sender} = \delta_{xmt} \left( \frac{t_s}{2P_s} + T_{pkt} \right) + \delta_{sleep} \left( T_{arvl} - \frac{t_s}{2P_s} + T_{pkt} \right).$$  \hspace{1cm} (9)

Rearranging, we have

$$E_{sender} = \frac{t_s}{2P_s} \left( \delta_{xmt} - \delta_{sleep} \right) + T_{pkt} \delta_{xmt} + \left( T_{arvl} - T_{pkt} \right) \delta_{sleep}$$  \hspace{1cm} (10)

and, given a fixed mean packet size, the average energy consumption of the sender is inversely proportional to the preamble sampling probability.

The per packet energy consumption of the receiver $E_{receiver}$ is the energy spent waiting for the packet to arrive (i.e., the energy spent occasionally checking for it on the medium) and the energy spent in receiving both the preamble and the packet. For a given preamble sampling cycle of duration $T_{samp}$, the receiver will actively sample (receive) for duration $t$ and sleep for duration $(T_{samp} - t)$. The number of preamble sampling cycles during an interarrival period $T_{arvl}$ is simply $\frac{T_{arvl}}{T_{samp}}$ and thus the energy spent waiting for a packet to arrive is

$$E_{waiting} = \frac{T_{arvl}}{T_{samp}} \left[ \tau \delta_{rx} + (T_{samp} - \tau) \delta_{sleep} \right]$$  \hspace{1cm} (11)

where $\delta_{rx}$ is the receive power. Since (11) includes the energy spent receiving the preamble, we need only to add the energy spent receiving the packet $\delta_{rx} T_{pkt}$ to arrive at the per packet energy consumption of the receiver as in

$$E_{receiver} = \frac{T_{arvl}}{T_{samp}} \left[ \tau \delta_{rx} + (T_{samp} - \tau) \delta_{sleep} \right] + \delta_{rx} T_{pkt}.$$  \hspace{1cm} (12)

Assuming $T_{samp}$, $T_{arvl}$, and $T_{pkt}$ are independent, the average per packet energy consumption at the receiver is

$$E_{receiver} = \frac{T_{arvl}}{T_{samp}} \left[ \tau \delta_{rx} + (T_{samp} - \tau) \delta_{sleep} \right] + \delta_{rx} T_{pkt}.$$  \hspace{1cm} (13)

Substituting in (1) and rearranging, we have

$$\bar{E}_{receiver} = P_s \left( \frac{T_{arvl} \tau}{t_s} \right) \left( \delta_{rx} - \delta_{sleep} \right) + \delta_{rx} T_{pkt} + \delta_{sleep} T_{arvl}$$  \hspace{1cm} (14)

and it can be seen that the average energy consumption of the receiver is proportional to the preamble sampling probability.

Our results, then, are consistent with the findings in [12] which demonstrate that longer sampling periods (indicated in (9) and (14) by smaller values of $p_s$) favor the energy consumption of the receiver vice the sender. In other words, as the probability that the sender will sample for a preamble decreases, the mean time of preamble transmission for the sender increases while the time spent sampling for the preamble decreases at the receiver. Hence, as the preamble sampling probability is decreased, the energy consumption at the sender increases while the energy consumption at the receiver decreases.

Combining (9) and (14), the average total per packet energy consumption is

$$\bar{E}_{total} = \frac{t_s}{2P_s} \left( \delta_{xmt} - \delta_{sleep} \right) + \frac{T_{arvl} - T_{pkt}}{T_{samp}} \delta_{sleep}$$

$$+ P_s \left( \frac{T_{arvl} \tau}{t_s} \right) \left( \delta_{rx} - \delta_{sleep} \right) + \delta_{rx} T_{pkt} + \delta_{sleep} T_{arvl}$$  \hspace{1cm} (15)

which, after rearranging, is

$$\bar{E}_{total} = \frac{1}{P_s} \left( \frac{t_s}{2} \right) \left( \delta_{xmt} - \delta_{sleep} \right) + P_s \left( \frac{T_{arvl} \tau}{t_s} \right) \left( \delta_{rx} - \delta_{sleep} \right)$$

$$+ \delta_{rx} T_{pkt} + \delta_{sleep} T_{arvl}.$$  \hspace{1cm} (16)

Per packet energy consumption is plotted in Figure 2 as a function of sampling probability for various packet interarrival times.
times using the power values for the specifications from the Texas Instruments CC2420 radio transceiver shown in Table 1. This is the transceiver utilized in the current generation Crossbow TelosB sensor mote [14].

The plots in Figure 2 clearly show the existence of a minimum energy consumption value. By manipulating $p_s$, we can trade off energy consumption at the receiver with energy consumption at the sender to achieve this minimum value. We can calculate this “optimal” value of $p_s$ by differentiating (16) with respect to $p_s$ and setting the result to zero as in

$$
\frac{\delta}{\delta p_s} \left[ \frac{t_s}{2} \right] (\delta_{\text{mst}} - \delta_{\text{sleep}}) + p_s \left( \frac{T_{\text{arvl}}}{t_s} \right) (\delta_{\text{rrx}} - \delta_{\text{sleep}}) + T_{\text{pkt}} (\delta_{\text{mst}} + \delta_{\text{rrx}} - \delta_{\text{sleep}}) + 2\delta_{\text{sleep}} T_{\text{arvl}} = 0.
$$

After differentiating, we have

$$
-(p_s)^{-2} \left[ \frac{t_s}{2} \right] (\delta_{\text{mst}} - \delta_{\text{sleep}}) + \left( \frac{T_{\text{arvl}}}{t_s} \right) (\delta_{\text{rrx}} - \delta_{\text{sleep}}) = 0
$$

since the final two terms do not depend on $p_s$. Solving for the optimal value for $p_s$ in terms of energy efficiency, we arrive at

$$
p_s = \frac{t_s}{2} \sqrt{\frac{1}{T_{\text{arvl}}} \left( \frac{\delta_{\text{mst}} - \delta_{\text{sleep}}}{\delta_{\text{rrx}} - \delta_{\text{sleep}}} \right)}.
$$

Thus, we find that we can assign a value to the preamble sampling to minimize per packet energy consumption and, furthermore, this value is inversely related to the packet interarrival time (and, hence, proportional to the packet arrival rate). In other words, as the packet arrival rate increases, so should the preamble sampling probability which is intuitively satisfying. We can substitute (19) into (16) to arrive at the minimum total energy consumption of

$$
\min \left( E_{\text{total}} \right) = (\delta_{\text{mst}} - \delta_{\text{sleep}}) \sqrt{\frac{1}{T_{\text{arvl}}} \left( \frac{\delta_{\text{mst}} - \delta_{\text{sleep}}}{\delta_{\text{rrx}} - \delta_{\text{sleep}}} \right)}^{-1} + \frac{T_{\text{arvl}}}{2} (\delta_{\text{rrx}} - \delta_{\text{sleep}}) \sqrt{\frac{1}{T_{\text{arvl}}} \left( \frac{\delta_{\text{mst}} - \delta_{\text{sleep}}}{\delta_{\text{rrx}} - \delta_{\text{sleep}}} \right)}
$$

$$
+ T_{\text{pkt}} (\delta_{\text{mst}} + \delta_{\text{rrx}} - \delta_{\text{sleep}}) + 2\delta_{\text{sleep}} T_{\text{arvl}}.
$$

We note that this minimum energy consumption value is independent of our choice of the base sampling period $t_s$ since $t_s$ is directly proportional to $p_s$ in (19). Finally, we also observe that given our constraint of no more than one arrival per sampling period, we minimize the per packet energy consumption by setting the mean packet interarrival time equal to the mean sampling period. This can be seen in (16) where the value of $T_{\text{arvl}}$ that minimizes (16) is $T_{\text{arvl}} = T_{\text{samp}}$ (given the constraint that $T_{\text{arvl}} \geq T_{\text{samp}}$).

Simulation results are provided in Figure 3 for the parameters and analysis of the preceding section. These simulation results exhibit the anticipated curve and correspond very well with the analysis for larger values of $p_s$. For lower values of $p_s$, we see that the analysis begins to deviate from the observed results. This is primarily due to the constraint of one packet arrival per sampling period that we have made in the analysis. In practice, as the preamble sampling probability decreases, the mean sampling period increases as seen in (1) and the probability of multiple arrivals in a sampling period increases.

**IV. CONCLUSION**

In this paper, we have proposed a novel approach to low-power listening in which a receiver samples the medium for the presence of a preamble with some probability and the resulting preamble sampling periods are non-deterministic. We have demonstrated that the mean of the preamble sampling cycle is inversely proportional to this preamble sampling probability and can thus be manipulated through the use of this parameter. This is in contrast to the low-power listening approaches in existing literature which treat the sampling period as deterministic and seek to vary it directly by using heuristic algorithms. Per packet energy consumption analysis and accompanying simulation results were also provided and it was demonstrated that by varying the value of the preamble sampling probability, we can minimize total energy consumption by trading off energy consumption of the receiver.

<table>
<thead>
<tr>
<th>Radio Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit power, $\delta_{\text{mst}}$</td>
<td>25.5 mW</td>
</tr>
<tr>
<td>Receive power, $\delta_{\text{rrx}}$</td>
<td>56.4 mW</td>
</tr>
<tr>
<td>Sleep power, $\delta_{\text{sleep}}$</td>
<td>0.06 mW</td>
</tr>
<tr>
<td>Carrier sensing time, $\tau$</td>
<td>128 $\mu$s</td>
</tr>
</tbody>
</table>

Table 1. CC2420 Transceiver specifications [13].

![Figure 3. Per packet energy consumption as a function of sampling probability for various packet interarrival times. The simulation results are provided as asterisks (with connecting dotted lines) solid lines while the solid slines represent the corresponding analysis (from Figure 2).](image-url)
with that of the sender. This “optimal” sampling probability was shown to be inversely related to the packet interarrival time.

REFERENCES


