A Wakeup Scheme for Sensor Networks: Achieving Balance between Energy Saving and End-to-end Delay

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Abstract

Energy saving is a critical task for sensor networks with limited energy supply. Wakeup schemes that turn off sensors' radio when communication is not necessary have great potential in energy saving. However, existing wakeup schemes encounter critical tradeoffs between energy saving and wakeup latency, and little attention has been paid to reducing the packet end-to-end delay while preserving the energy saving capability. We argue that a long delay can be detrimental for large sensor networks. This paper proposes a wakeup scheme that helps to achieve the balance between energy saving and end-to-end delay. The conditions under which the proposed scheme can show improvement are identified.

1. Introduction

The rapid development in microelectronics and wireless communication technologies makes the deployment of large scale sensor networks possible. The communication among sensors is typically driven by events. In many applications (e.g., intrusion detection, disaster alarming, etc.), events occur rather infrequently. For such scenarios, sensors spend a considerable fraction of lifetime to monitor the environment, during which little communication is needed and sensors are said to be in the "monitoring state". Once events are detected, sensors may need to leave the "monitoring state" and actively communicate with each other.

Sensor networks are characterized by the limited energy supply because wireless sensors are typically powered by batteries. As the radio transceiver consumes significant amount of energy even in the idle state, it is generally desired to turn off a sensor's radio when there is no need for communication. While allowing sensors' radio to be turned off, two directions of research have been taken to preserve the communication capability of a sensor network. One direction exploits the spatial redundancy by turning off radios that may not be needed for maintaining network connectivity, as the topology management schemes proposed in [4] and [11]. The other direction exploits the temporal potential in energy saving by turning off radios when not needed and providing some mechanisms to wake the radio up when communication is necessary, as the wakeup schemes proposed in [13], [3], [7], [14]. As shown in [7], these two directions are orthogonal to each other in the design space and can be combined together to obtain the aggregate energy saving. This paper mainly deals with wakeup schemes following in the second direction.

Wakeup schemes have great potential in energy saving for sensor networks where events occur infrequently. However, existing wakeup schemes have some limitations. Particularly, many proposed wakeup schemes, e.g., [2] [13] [7] [14] [10], encounter critical tradeoffs between energy saving and wakeup delay. We argue that a long delay can be detrimental for large sensor networks, in which it is not uncommon that a message needs to be forwarded dozens of hops to reach the destination. For instance, assuming a message needs to be forwarded 10 hops on average, the end-to-end delay only due to wakeup is 13 s with the wakeup latency of 1.3 s per hop as shown in [7]. In the target tracking application, a highly mobile target moving at the speed of 120 km/h travels around 433 meters within 13 s. Such a large latency could cause many difficulties for the timely tracking task.

The focus of this paper is to propose a wakeup scheme that helps to achieve the balance between energy saving and end-to-end packet delay. The rest of the paper is organized as follows. Section 2 summarizes the related work. The detail of the proposed wakeup scheme is presented in Section 3. In Section 4, analysis is given to identify conditions under which the proposed scheme can show improvements. Performance Evaluation is presented in Section 5. Finally, the conclusion is drawn in Section 6.

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2. Related Work

Wakeup schemes can be categorized as synchronous or asynchronous schemes. The power saving mechanism defined in IEEE 802.11 is one example of synchronous wakeup. Nodes all wakeup during the wakeup rendezvous and communicate with each other. The clock synchronization requirement makes it hard to be implemented in large sensor networks. [13] is another wakeup scheme that requires some level of synchronization among neighboring sensors.

There exist several proposals for asynchronous wakeup. [10] proposes three asynchronous power management protocols, in which each node follows a certain schedule to periodically wake up and go to sleep. The ultimate objective is to arrange the wakeup schedule so that any two neighboring nodes are guaranteed to detect each other in finite time. [14] shows the protocols in [10] are sub-optimal and further derives a theoretical limit for a "symmetric communication model".

The power saving capability and wakeup delay can be improved by using an additional wakeup channel. [5], [3] and [8] all assume there is a low power wakeup radio in addition to the usual high power data radio. Since the power consumption of the wakeup radio is assumed to be extremely low, it can stay awake for the entire time, consuming little energy. The major drawback encountered by such schemes is that the low power wakeup radio usually has a smaller transmission range than the high power data radio, which brings limitations to the communication between two nodes that are within each other's data radio transmission range but are out of the wakeup radio transmission range.

STEM (Sparse Topology and Energy Management) [7] also uses two radios, one functions as wakeup radio and the other is used for data transmissions. In STEM, each node periodically turns on their wakeup radio for T_{dstem} every T duration, where $\frac{T}{T_{dstem}}$ is defined as the *duty cycle ratio*. STEM achieves low power consumption of wakeup radio by using a large duty cycle ratio, instead of assuming a low power wakeup radio as in [5], [3] and [8], thus, avoids the issue mentioned above.

Whenever necessary, a source node sends a beacon on the wakeup radio to explicitly wake up the target node. The wakeup beacon will be repeated up to a maximum time period, unless a wakeup acknowledgment is received. If collisions happen on the wakeup channel, any node that senses such collisions turns on its data radio up to a certain timeout duration. Since nodes are not synchronized to each other, the receiver may start its duty time in the middle of a wakeup packet transmission. Let T_w, T_{wack} represent the transmission duration of the wakeup packet and the wakeup acknowledgment packet, respectively. The duty time of STEM, T_{dstem}, should at least be $2T_w + T_{wack}$ to ensure the correct reception of the wakeup packet, as shown in Figure 1. Lower bounded by $2T_w + T_{wack}$, the duty time T_{dstem} could be quite large when the wakeup radio bit rate is low. In such cases, T has to be large enough to achieve the desired energy saving, resulting in a large wakeup delay. The simulation results in [7] show that to achieve a ten-fold decrease of energy consumption, the wakeup latency is about 1.3 s per hop, using a wakeup radio with bit rate of 2.4 Kbps. STEM-T, presented as a variation of STEM in [6], discusses the possibility of using a wakeup tone to reduce the duty time. However, noticing the disadvantage that a tone will wakeup all nodes within its transmission range, [6] concludes that using a wakeup tone could be less energy efficient in general.

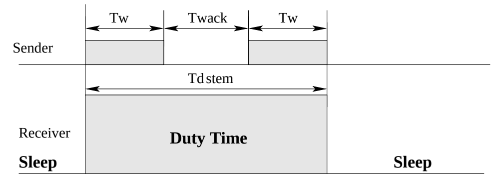


Figure 1. Minimum duty time of STEM

In this paper, we propose a wakeup scheme that explores the benefits of using a wakeup tone to achieve the balance between energy saving and end-to-end delay. In the proposed scheme, an asynchronous wakeup pipeline is constructed to overlap the wakeup procedures with the packet transmissions so that the degradation of end-to-end delay due to wakeup is thus largely reduced. Even though all neighboring nodes are awakened by the wakeup tone, in the proposed scheme, the time period in which a node stays active due to an unnecessary wakeup is minimized, thus preserving the energy efficiency.

3. Pipelined Tone Wakeup Scheme (PTW)

3.1. Using the Wakeup Tone

The proposed Pipelined Tone Wakeup (PTW) scheme uses a wakeup tone channel in addition to the regular data channel. In PTW, the wakeup radio of each sensor node will be awake for T_{dtone} duration and be asleep for T_{sleep} duration periodically, where $T_{dtone} + T_{sleep} = T$. When a node has packets to be sent, it sends a tone to the wakeup channel, which lasts for T_p duration. Once a node detects the wakeup tone during its duty time (i.e., T_{dtone}), this node will stay active on the data channel. As the wakeup tone does not contain receiver's identity, any node within the transmission range of sender will be awakened.

Wakeup tone detection involves detecting signals of the known form in the presence of noise, and a certain time duration is needed to ensure the correct tone detection. Following the derivation in [9], it can be shown that, with a tone detection time of 200 μs, the probability of correct detection corresponding to a false alarm probability of 10^{-3} can reach 99.1% [12]. A radio also needs some time to transit from sleep to receive state, which, for example, is up to $518\mu s$ for TR1000 from RF Monolithics using ASK (amplitude-shift keyed) modulation [1]. Let t_d be the required tone detection time and $T_{transit}$ be the transition time from sleep to receive state. T_{dtone} must satisfy the following constraint:

$$T_{dtone} \geq t_d + T_{transit} \quad (1)$$

As nodes are not synchronized to each other, the wakeup tone from the sender should at least last for T_p duration so that each neighboring node has at least one entire duration of T_{dtone} to detect the wakeup tone, where T_p needs to satisfy the following constraint:

$$T_p = 2 \times T_{dtone} + T_{sleep} = T + T_{dtone} \quad (2)$$

In this way, even in the worst case that a node starts its duty time (T_{dtone}) just before the sender starts to send the wakeup tone, the former node still has the next entire duration of T_{dtone} to detect the tone, as shown in Figure 2. After sending wakeup tone for T_p duration, the sender knows that all its neighbors have been awake and it proceeds to send packets on the data channel.

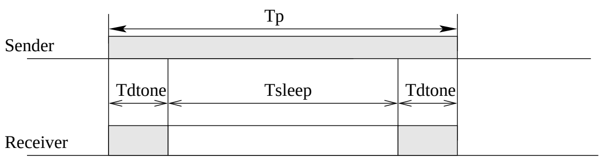


Figure 2. Minimum tone transmission time

Notice the difference between Figures 2 and 1. In Figure 1, the receiver duty time has to be at least $2T_w + T_{wack}$ to ensure the correct reception of the wakeup packet. On the other hand, the responsibility is shifted from the receiver to the sender in Figure 2, which can favor the energy saving. The reason is because the sender only needs to send the wakeup tone when events occur, while receivers need to stay on duty periodically.

3.2. PTW (Pipelined Tone Wakeup)

The "wakeup module", which is responsible for establishing a schedule to enable the communication between a pair of sender and receiver, is usually located above the MAC layer (even though some wakeup mechanisms are closely incorporated into the design of MAC protocols, they can be functionally separated out), and has direct control over the radio. The wakeup delay incurred at the "wakeup module" adds additional delay to the packet end-to-end delay.

Wakeup delay can be formally defined as the elapsed duration from the time a packet arrives at a node's wakeup module, to the time the node passes the packet to MAC layer, knowing that the target node is awake. Since the "wakeup module" can be functionally separated from the underlying MAC and physical layers, it seems intuitive to pipeline the wakeup procedure with the packet transmission so that the wakeup delay can be hidden. However, some difficulties arise in terms of realization. First, before a node receives a forwarding packet, it has no idea which node is the next hop. Second, even with the next-hop knowledge, the asynchronous wakeup schemes that rely on overlapped wakeup schedules among neighboring nodes (e.g., [14]) have difficulties in pipelining. For example, A has a packet for C via B. A and B discover each other through overlapped wakeup schedules. For the purpose of pipelining, immediately after the communication slots between A and B, B and C need to discover each other, which is hard to realize without synchronization among nodes.

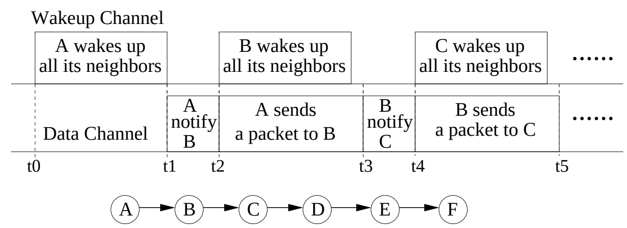


Figure 3. Pipelined Tone Wakeup (PTW)

The pipelined wakeup procedure in the proposed PTW scheme is illustrated in Figure 3 using an example. One message needs to be transmitted from A to F via B, C, D, and E. A starts by sending a tone on the wakeup channel from time t_0 to time t_1 to wake up all its neighbors, where $t_1 - t_0 = T_p$. By time $t1$, all A's neighbors should have been awakened and ready to receive packets from the data channel. A thus sends a short notification packet on the data channel to indicate that the subsequent data packet is for B. The notification packet serves two purposes:

1. Once B gets the notification packet, B will respond to A with a wakeup acknowledgment via the data channel. At the same time, B will start the pipelined wakeup stage to wakeup all its neighbors. From Figure 3, we can see that the time period B uses to wakeup its neighbors via the wakeup channel is in parallel to the time duration that A sends B the data packet via the data channel.

2. Once receiving the notification packet, all A's neighbors except for B know that the following packet is not intended for them. They can turn off their data radios immediately to reduce the energy consumption caused by the unnecessary wakeup.

By waking up all neighbors, the proposed PTW gets around the issue of finding the next hop node. With the help of a wakeup tone, PTW also avoids the synchronization requirements for implementing the wakeup pipeline.

The access of data channel is governed by MAC layer, and collisions can happen to notification packets. If a node does not receive any notification packet after being awakened, it will stay active up to a timeout duration.

Clearly, the proposed PTW scheme has a fixed wakeup delay T_p. Let T_{data} represent the duration from the time a packet arrives at the sender's MAC layer to the time it reaches the receiver. T_{data} usually consists queuing delay, channel access delay, transmission delay and propagation delay. Under the condition that $T_p \le T_{data}$, only the first hop wakeup delay appears in the end-to-end packet delay of PTW. The wakeup delay incurred at the following hops overlaps with the packet transmission duration. In the above example, all B's neighbors should have been awake and ready to receive on the data channel when B finishes receiving the data packet from A. B can thus forward the packet from A immediately to C. Above procedure repeats until the message reaches its destination F.

Considering that the radio used in sensor networks usually has a low bit rate and T_{data} could last from tens of milliseconds to hundreds of milliseconds, it is likely T_p can satisfy the condition (i.e., $T_p \le T_{data}$) in most cases while achieving the desired energy saving. On the other hand, even in the high data rate case that wakeup delay cannot be completely hidden, pipelined wakeup scheme can still reduce the end-to-end delay comparing with sequential wakeup.

4. Analysis for Energy Consumption

The radios of a sensor node are involved in three types of activities: periodic wakeup during the "monitoring state", the wakeup procedure upon messages being generated, and the transmission/reception of messages. In sensor networks, traffic tends to be bursty, i.e., multiple packets could be generated when an event occurs. Once a pair of sender and receiver are awakened, they can transmit multiple packets before going back to the "monitoring state" again. As radio stays active during the transmission period, there is no difference in terms of energy consumption for different wakeup schemes. In other words, wakeup schemes differ from each other mostly in the energy consumed in the "monitoring state" and the wakeup procedures, which is the focus of our analysis in this section. The objective of the analysis is to identify the conditions under which the proposed PTW is preferable to STEM in terms of energy saving.

We assume the same power consumption characteristics for both radios in STEM and PTW. The data channel bit rate is also assumed to be same for STEM and PTW.

4.1. Analysis Model

Among N nodes in the network, sender S has N_s neighbors including target D, where S needs to wakeup D upon an event. The elapsed duration in the "monitoring state" is represented as T_{event} and T is the period of the periodic wakeup during the "monitoring state" for both STEM and PTW. Let T_{dstem} and T_{dtone} represent the duty time of STEM and PTW, respectively. The duty cycle ratio of STEM is defined as $Duty_{stem} = \frac{T}{T_{dstem}}$ and the duty cycle ratio of PTW $Duty_{tone} = \frac{T}{T_{dtone}}$.

As shown in Section 2, T_{dstem} in STEM should at least be $2T_w + T_{wack}$ to ensure the correct reception of the wakeup packet, where T_w and T_{wack} represent the transmission time of wakeup packet and wakeup acknowledgment, respectively. For simplicity, we assume $T_w = T_{wack}$, thus,

$$T_{dstem} = 3T_w = 3T_{wack} \tag{3}$$

In PTW, after waking up all its neighbors using a wakeup tone, the sender sends a notification packet on the data channel to specify the target node. We assume the transmission time of the notification packet is also T_w and on receiving this packet, the target node D will reply with an acknowledgment with length of T_{wack}.

As the power consumption of a radio in the sleep state is relatively small, and it has little impact on the results we derive below, we simply ignore them to make the analysis more concise. We further simplify the analysis by assuming that the power consumption in the transmission, reception and idle states is the same, represented as P. Indeed, the power consumption of TR1000 [1] only differs slightly in these three states, as shown in Table 1.

4.2. Energy Consumption of One Wakeup Procedure

This part of analysis concerns with one wakeup procedure only. Later, we will extend the analysis to multiple wakeup procedures. The major difference between PTW and STEM is that PTW reduces the duty time significantly at the price of waking up all neighbors. In the analysis below, we consider the energy consumption of a specific node up to the time that the neighboring target node D has sent the wakeup acknowledgment back.

Each node spends some energy in the "monitoring state" via periodic wakeup. Let E_{MStem}, E_{MTone} represent the energy consumption of one node in the "monitoring state" using STEM and PTW respectively, then[1]

$$E_{MStem} = \frac{T_{dstem}}{T} \times T_{event} \times P \tag{4}$$

and

$$E_{MTone} = \frac{T_{dtone}}{T} \times T_{event} \times P \tag{5}$$

1 Here, we ignore the possible duty time during the wakeup procedure.

4.2.1. Energy Consumption of the Sender S: In STEM, as nodes are not synchronized to each other, the time node S starts to send the wakeup packet could fall on any point over the periodic wakeup interval [0, T] of node D. Therefore, S may have to repeat the wakeup packet multiple times so that D can receive it. Following the results from [7], the average time D for a receiver to receive the wakeup packet is:

$$T_{avgstem} = \frac{T + T_w + T_{wack}}{2} \quad (6)$$

The average energy consumed by the sender S to wake up target D, E_{SStem}, can thus be represented as $P \times T_{avgstem}$. Taking into account of the energy consumed in the "monitoring state", the total energy consumption of S is:

$$E_{SStem} = \frac{T_{dstem}}{T} T_{event} P + P T_{avgstem} \quad (7)$$

In PTW, the sender S sends wakeup tone for T_p ($T_p = T + T_{dtone}$) duration to wakeup all its neighbors, and then S sends a short notification packet on the data channel to indicate the target node. The corresponding energy consumption can be represented as $P \times (T_p + T_w + T_{wack})$. Considering the energy consumed in the "monitoring state", the total energy consumption of S can be represented as:

$$E_{STone} = \frac{T_{dtone}}{T} T_{event} P + P(T_p + T_w + T_{wack}) \quad (8)$$

Combining equations 3, 6, 7, and 8, E_{SStem} will be larger than E_{STone} under the constraint in Equation 9 below.

$$\frac{T_{event}}{T} \geq \frac{\frac{1}{2} + \frac{1}{3Duty_{stem}} + \frac{1}{Duty_{tone}}}{\frac{1}{Duty_{stem}} - \frac{1}{Duty_{tone}}} \quad (9)$$

For example, if $Duty_{stem} = 10$, $Duty_{tone} = 100$, then we need $T_{event} > 6.03T$, i.e., the "monitoring state" lasts for at least 6.03 duty cycles, so that node S consumes less energy in the proposed PTW scheme than in STEM.

4.2.2. Energy Consumption of the Target Node D: The energy consumed by the target node D during the wakeup procedure of STEM, E_{RStem}, can be represented as $P \times T_w + P \times T_{wack}$, where the first term is due to the receiving of a wakeup packet and the second term is due to the transmission of a wakeup acknowledgment. Combined with the energy consumption in the "monitoring state", the total energy consumption of the target node D is

$$E_{RStem} = \frac{T_{dstem}}{T} T_{event} P + P \times (T_w + T_{wack}) \quad (10)$$

In PTW scheme, the time a sender starts to send the wakeup tone can also uniformly fall on any point over the periodical wakeup interval [0, T] of receivers. Once a node detects the signal during its duty time, it will turn on the data radio. Therefore, the average time for node D having its radio on before S stops sending the wakeup tone is:

$$T_{avgtone} = \int_0^T \frac{t}{T} dt = \frac{T}{2} \quad (11)$$

The energy consumed by the target node D during the wakeup procedure of PTW can be represented as $P \times T_{avgtone} + P \times (T_w + T_{wack})$, where the latter part is due to exchange of the notification and acknowledgment packets. Combined with E_{MTone} in equation 5, the total energy consumption of target node D is

$$E_{RTone} = \frac{T_{dtone}}{T} T_{event} P + P \times (T_{avgtone} + T_w + T_{wack}) \quad (12)$$

From equations 10 and 12, in order for E_{RStem} to be larger than E_{RTone}, the following condition needs to be satisfied:

$$\frac{T_{event}}{T} \geq \frac{1}{2(\frac{1}{Duty_{stem}} - \frac{1}{Duty_{tone}})} \quad (13)$$

With $Duty_{stem} = 10$ and $Duty_{tone} = 100$, we need $T_{event} > 5.56T$ so that the target node D consumes less energy in the proposed PTW.

4.2.3. Energy Consumption of Other Neighboring Nodes of S: Now we observe S's neighboring nodes other than D, say node A. Because node A in STEM only consumes energy during its periodic duty time, its energy consumption can be represented as:

$$E_{A_{STEM}} = \frac{T_{dstem}}{T} T_{event} P \quad (14)$$

In PTW scheme, A will be awakened by the wakeup tone from S, and stay active until receiving the notification packet of length T_w, knowing it is not the target node. The total radio active time of node A since the event occurs is $T_{active} = T_{avgtone} + T_w$. The energy consumption of A in PTW consists of the energy consumed in the "monitoring state" and the energy consumed in the wakeup procedure:

$$E_{A_{TONE}} = \frac{T_{dtone}}{T} T_{event} P + P \times T_{active} \quad (15)$$

Combining equations 3, 6, 14, 11 and 15, in order for $E_{A_{STEM}}$ to be larger than $E_{A_{TONE}}$, the following condition needs to be satisfied:

$$\frac{T_{event}}{T} \geq \frac{\frac{1}{2} + \frac{1}{3Duty_{stem}}}{\frac{1}{Duty_{stem}} - \frac{1}{Duty_{tone}}} \quad (16)$$

With $Duty_{stem} = 10$ and $Duty_{tone} = 100$, we need $T_{event} \geq 5.93T$ so that node A consumes less energy in PTW.

4.2.4. A Loose Bound for T_{event}: For the nodes that never wake up, they always consume less energy in PTW than in STEM as long as $T_{dtone} < T_{dstem}$. Given equations 9, 13 and 16, for any individual node to have less energy consumption in PTW, the following condition is sufficient:

$$\frac{T_{event}}{T} \geq \frac{\frac{1}{2} + \frac{1}{3Duty_{stem}} + \frac{1}{Duty_{tone}}}{\frac{1}{Duty_{stem}} - \frac{1}{Duty_{tone}}} \quad (17)$$

Taking into account that $Duty_{stem} \geq 1$ and $Duty_{tone} \geq 1$, a simplified loose bound for T_{event} can be given as follows.

$$\frac{T_{event}}{T} \geq \frac{\frac{11}{6}}{\frac{1}{Duty_{stem}} - \frac{1}{Duty_{tone}}} \quad (18)$$

Notice that if the bandwidth of the wakeup radio used in STEM is extremely high such that T_{dstem} can reach the value of T_{dtone}, then the proposed PTW scheme can no longer perform better than STEM. Assuming the length of wakeup packet and wakeup acknowledgment as 144 bits, the lower bound of tone detection time as 100 μs[2], if the bit rate of wakeup radio is higher than 4.3 Mbps ($\frac{3\times144}{100} = 4.3$), then PTW cannot be any better than STEM. However, in most applications, it is not likely a low cost sensor will be equipped a wakeup radio with such a high bit rate. Therefore, we argue that PTW is a more efficient wakeup scheme in practice.

When concerning the total energy consumption of the entire network instead of the individual node energy consumption, equation 18 can be easily extended to the one as below:

$$\frac{T_{event}}{T}\frac{N}{N_s} \geq \frac{\frac{11}{6}}{\frac{1}{Duty_{stem}} - \frac{1}{Duty_{tone}}} \quad (19)$$

Equation 19 can be satisfied with either large T_{event} or large $\frac{N}{N_s}$. In other words, two dimensions' dynamics, temporal and spatial, help the proposed PTW to perform better than STEM.

4.3. Energy Consumption of Multiple Wakeup Procedures

A node may be involved in multiple consecutive wakeup procedures when an event occurs. For example, node D, after being awakened, may need to wakeup its next hop node. Also, node A can be awakened multiple times by its surrounding senders. Let H represent the maximum number of wakeup procedures a node is involved upon an event. It is straightforward to extend the bound in equation 18 to the one below so that any individual node will consume less energy in the proposed PTW than in STEM.

$$\frac{T_{event}}{T} \geq \frac{\frac{11}{6}H}{\frac{1}{Duty_{stem}} - \frac{1}{Duty_{tone}}} \quad (20)$$

If $Duty_{stem} = 10$, $Duty_{tone} = 100$, $H = 5$, then above loose bound requires $T_{event} \geq 102T$,i.e., the "monitoring state" lasts for at least 102 duty cycles, so that all node consume less energy in PTW than in STEM.

Packet collisions can degrade the energy efficiency of both STEM and PTW, which we do not capture in the analysis. Instead, we use simulation results to illustrate the energy saving and end-to-end delay with the presence of collisions.

5. Performance Evaluation

We use simulation results to evaluate the proposed basic PTW scheme in terms of energy consumption and end-to-end delay, and compare it with STEM [7] as well as the results without power management. All simulation results are based on the modified version of ns-2 from USC/ISI/LBNL, with wireless extensions from the CMU Monarch project. We assume each node has maintained its routing table and IEEE 802.11 DCF is used as the underlying MAC protocol. The simulated radio power consumption characteristics correspond to those of TR1000, as shown in Table 1. The radio transmission range is set to 20 meters, the length of the wakeup (notification) packet and the wakeup acknowledgment is set to 144 bits, the data packet is 1040 bits and the data acknowledgment is 128 bits[3].

Following the parameters in STEM [7], the bit rate of the wakeup radio and the data radio for STEM is set to 2.4 Kbps, T_{dstem} is 225 ms and $Duty_{stem}$ is 13.33[4] unless mentioned otherwise.

For PTW, T_{dtone} is set to 1 ms, which should be enough to satisfy equation 1 according to the tone detection time t_d and the radio transit time $T_{transit}$ we discussed earlier. $Duty_{tone}$ is set to 229 and the data channel bit rate of PTW is 2.4 Kbps.

transmit	receive	idle	sleep
14.88 mW	12.50 mW	12.36 mW	0.016 mW

Table 1. Radio power consumption

5.1. Cluster Scenario

As shown in Figure 4, 55 sensors are evenly distributed into 11 clusters. Cluster 1 includes sensors 0 - 4, cluster 2 includes sensors 5 - 9 and so on. All five sensors in one cluster are placed at the same location, and neighboring clusters are 20 meters away from each other. Packets are generated at node 0 and go to node 50, passing along the route 5 - 10 - 15 -

2 Notice that both T_{dstem} and T_{dtone} must respect the radio transit time from sleep to receive state.

3 The mentioned packet length includes the physical header.

4 When data rate is 2.4 Kbps, the transmission time of the wakeup packet and wakeup acknowledgment is 0.06 s. The minimum duration of T_{dstem} is 0.18 s. The value of T_{dstem} used in [7] is 0.225 s

20 - 25 - 30 - 35 - 40 - 45 - 50. This scenario simulates one of the extreme case where all nodes in the network will be awakened with multiple wakeup procedures and many nodes will be awakened multiple times.

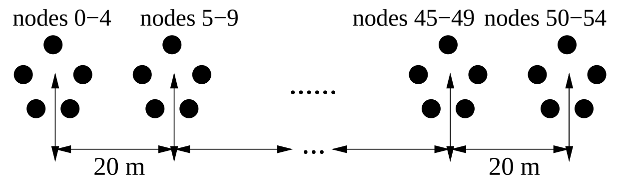


Figure 4. One simulation scenario

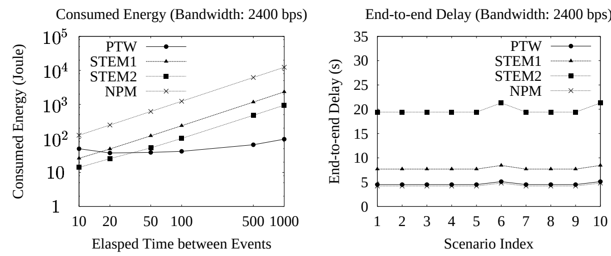
Once nodes are turned on, the energy consumed in packet transmissions are same for all wakeup schemes. To emphasize the energy saving capability between different schemes, we let the events periodically occur and only one packet is generated at node 0 upon detecting an event. Ten events occur for each simulation run and the presented results are averaged over 50 runs.

With the event period of 100 seconds, the energy consumption of several representative sensors is presented in Table 2(a). Notice “NPM” is the acronym for “No Power Management”.

Among the reported nodes, node 0 is the source, node 50 is the sink, node 20 is one of the forwarding nodes. Node 31 is one of the nodes that are not associated with packet transmissions but are within the neighborhood of packet senders. The simulation results of STEM show that the energy consumption of node 31 is more than just the energy consumed in the “monitoring state”. This is due to the collisions on the wakeup channel (e.g., collisions between wakeup packets from nodes 25 and 30). In STEM, when a node hears a collision on the wakeup channel, it will turn on its data radio up to a certain timeout duration. Similar situation happens to PTW as well. Without receiving a notification packet successfully, node 31 will stay active up to a timeout duration.

Among 4 reported nodes, node 31 represents the worst scenario of PTW comparing with STEM. Using PTW, node 31 will be unnecessarily awakened if one of its neighboring nodes sends wakeup tone. On the other hand, such things will not happen using STEM. However, the results in Table 2(a) show that, with the event interval of 100 s, all the reported nodes, including node 31, consume less energy in PTW, hence, less total energy consumption in PTW. The reason is because the energy saving during the “monitoring state” is the dominant factor with the considerably large event period 100 s.

The end-to-end delay is also shown in Table 2(b). The large wakeup period of STEM ($T = 13.33 \times 0.225 = 3s$) leads to its large wakeup delay. With total 10 hops and the sequential wakeup procedure, the end-to-end delay of STEM is as large as 28.6 s on average. On the other hand, even though the duty cycle ratio of PTW in this example is quite large (i.e., 299), it is achieved by reducing T_{dtone} instead of increasing T. With the help of a small wakeup period (299 ms) and the pipelined wakeup procedure, the end-to-end delay of PTW is quite close to the delay without power management.



(a) Energy consumption (Joule). Both horizontal and vertical axes are plotted in log scale.

(b) End-to-end Delay (s)

Figure 5. Total energy consumption and end-to-end delay (data rate: 2.4 Kbps).

	node0	node20	node31	node50
NPM	12.37	12.38	12.36	12.36
PTW	0.42	0.55	0.49	0.37
STEM	1.38	1.70	0.95	1.13

(a) Individual Energy Consumption (Joule)

	Energy (J)	Avg. E2E Delay (s)
NPM	680.14	6.02
PTW	25.50	6.32
STEM	59.62	28.6

(b) Total energy consumption & end-to-end delay

Table 2. Energy consumption and end-to-end delay (event period: 100 s)

5.2. Random Generated Networks

To simulate more general networks, 10 random topologies are generated, in which 100 nodes are uniformly distributed in the square area of 79.25 meters × 79.25 meters. Since the radio transmission range is 20 meters, the average number of neighbors each node has is $100 \times \frac{\pi 20^2}{79.25^2} = 20$. The node at the top left corner detects an event and sends a packet to the data sink located at the bottom right corner of the field. As different values of $Duty_{stem}$ in STEM trade off energy with delay, we report two simulation results for STEM, where STEM1 represents that $Duty_{stem} = 5.33$, STEM2 represents that $Duty_{stem} = 13.33$. The event period is increased from 10 s to 1000 s and there are 10 events for each simulation run. We compare the total energy consumption and packet end-to-end delay of PTW with STEM1, STEM2 and No Power Management (NPM).

From Figure 5(a), we can see that the energy consumption using the proposed PTW increases very slowly with the increase of the event period. On the other hand, the energy consumption with STEM1 and STEM2 increases rather rapidly. The reason is because PTW has a much larger duty cycle ratio than both STEM1 and STEM2.

When the event period is very small, say 10 s, the energy consumed during the wakeup procedure contributes most to the total energy consumption. As PTW will wakeup more nodes than STEM does, PTW consumes more energy. With the increase of the event period, energy spent in the "monitoring state" becomes dominant. For the simulated scenarios, when the event period is larger than 20 s, the energy consumption of PTW becomes less than STEM1. When the event period is larger than 50 s, the energy consumption of PTW is less than both STEM1 and STEM2. With the event period of 1000 s, the total energy consumption without power management is 12360 Joules, and the energy consumption with PTW, STEM1 and STEM2 is 95 Joules, 2335 Joules and 948 Joules, respectively.

Figures 5(a) and 5(b) illustrates how STEM trades off the energy saving with wakeup delay. STEM1 consumes more energy than STEM2 with a smaller $Duty_{stem}$, however, the end-to-end delay of STEM2 is much larger than STEM1. For the proposed PTW scheme, with the help of the pipelined wakeup procedure, the end-to-end delay of PTW is quite close to the result without power management, as shown in Figure 5(b). The delay of STEM2 is 4.3 times delay of PTW and the delay of STEM1 is 1.7 times delay of PTW. The reason that scenarios 6 and 10 have a larger delay than others is because the number of hops from source to destination is 8 in scenarios 6 and 10, and it is 7 in other scenarios.

More simulation results can be found in [12]. In all simulated scenarios, we observe that the event period being several minutes is sufficient for PTW to be more energy efficient than STEM.

6. Conclusion

In this paper, we have presented a Pipelined Tone Wakeup (PTW) scheme for sensor networks, which helps to achieve the balance between energy saving and end-to-end delay. PTW constructs an asynchronous wakeup pipeline to overlap the wakeup procedures with the packet transmissions. The use of wakeup tone enables a large duty cycle ratio without causing a large wakeup delay at each hop. It helps the pipeline to hide most of the wakeup delay while achieving a major energy saving.

Both the analysis and simulation results show that, if the elapsed time in the "monitoring state" for a sensor network lasts for more than several minutes, the improvement of PTW over existing schemes can be quite significant in terms of both energy saving and end-to-end delay, especially for sensor networks with low channel bit rate.

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