O-MAC: A Receiver Centric Power Management Protocol

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***Abstract*— Energy efficiency is widely understood to be one of the dominant considerations for Wireless Sensor Networks. Based on historical data and technology trends, the receiver energy consumption will dominate all energy, to the point that for the majority of applications, power management research must focus on receiver efficiency.**

By modeling several popular MAC layer protocols, we derive bounds on performance for receiver efficiency. In particular, we analyze four abstract models, Synchronous Blinking (e.g. T-MAC, S-MAC), Long Preamble (e.g. B-MAC), Structured Time-Spreading (called Asynchronous Wake-Up in some literature), and Random Time Spreading. These results strongly suggest that scheduling the receiver so as to minimize (or eliminate) the potential for interference (or collisions) could be from 10 fold to 100 fold more efficient than current practice.

We provide two new receiver scheduling methods, *Staggered On* **and** *Pseudorandom Staggered On*, **both of which are designed to exploit the untapped opportunity for greater receiver efficiency. Compared with the centralized deterministic scheduling in Staggering On, the decentralized scheduling in Pseudo random Staggered On achieves only slightly lower power efficiency.**

In addition, we design a new MAC protocol, called *O-MAC*, **based upon Pseudorandom Staggered On that achieves near optimal power efficiency. In order to realize the efficiency potential of Pseudorandom Staggering, the protocol must match the duty cycle of the communication system to the message generation rate of the application. Finally, we describe two variations of our O-MAC protocol — with local broadcast channel and preamble-sized slots.**

I. Introduction

Energy is a fundamental bottleneck of wireless sensor network. It is widely understood in the literature that radio communication is the dominant power consumption in all the components [1].

A. Receiver Centricity

The following table shows the power specifications for the historical sequence of radios used by the Berkeley motes [2].

Vendor	RFM	Chipcon	Chipcon
Part No.	TR1000	CC1000	CC2420
Rx power (mW)	11.4	28.8	59.1
Tx power (mW)	36	49.5	52.2

For comparison, the power specifications of CPUs is also listed in the following table [2].

Type	ATmega163	ATmega128	MSP430
Active (mW)	15	8	3
Sleep (mW)	0.045	0.075	0.015

Although the amount of data is small, it suggests three trends:

1) The communication power consumption is increasing.
2) The receiver radio power consumption is growing much faster than the transmitter.
3) The CPU active power decreases with time.

Those trends are, in fact, real and fundamental. The modest but steady increase in transmitter power is largely caused by an increase in the data rates. The more significant growth in receiver power is due to growth in receiver complexity. We expect the first trend to be restrained by system energy. However, it seems that that second trend may accelerate over the next 5 to 10 years because of sophisticated despreading and Forward-Error Correction (FEC), which will dramatically increase the relative power required by the receiver. In the future the receiver power may be 1 to 2 orders of magnitude higher than the transmitter power because of the cost of receiver computations and dramatic improvements in other sources of efficiency.

The dominance of receiver power consumption requires receiver centric power management design. This is different from the sender based design that current MAC layer protocols have assumed. In the sender centric design, the sender wakes up all the potential receivers during the transmission even if the message is unicast. In contrast, receiver centricity means the sender must follow the wake-up schedule of receiver. In this case, it is common that only one receiver will wake up to receive its message in a region at one time.

B. Almost Always Off Communication

In typical sensor network applications such as environment monitoring, the systems are required to survive for several years. This means most of nodes must be almost always off (**AAO**) to conserve energy.

For a MAC protocol in a low duty cycle sensor network, energy is wasted due to the following sources of overhead [3]:

- **Idle listening**: Since a node does not know when it will be the receiver of a message from one of its neighbors, it must keep its radio in receiving mode at all times.
- **Overhearing**: Since the radio channel is a shared medium, a node may receive packets that are not destined to it.

- **Collisions**: If two nodes transmit at the same time, packets may be corrupted. Hence, the energy used during transmission and reception is wasted.
- **Protocol overhead**: The MAC headers and control packets used for signaling (ACK/RTS/CTS). This source of overhead can be significant since many applications only send a few kilobytes of data per day.

In AAO networks, idle listening and overhearing are two major source of power consumption. The protocol overhead should also be minimized because the application traffic is low. However, the low duty cycle tends to alleviate collisions.

One of the more significant practical challenge for AAO communication is dealing with traffic fluctuations. The communication system needs to provide a small amount of overcapacity; under-meeting the needs of the application may cause application failure and providing excess capacity simply increases idle listening, which rapidly becomes the primary source of inefficiency.

C. Our Contributions

- In this paper we identify the fact of receiver dominance and the design paradigm of receiver centricity, which is opposite to current sender based MAC layer design. We believe this new paradigm will dominate energy sensitive designs.
- By defining an energy efficiency metric, power management schemes embedded in current MAC layer protocols are analyzed. Bounds on the performance suggest that sender based scheduling inherently suffers from overhearing and idle listening. These results show the limits of the sender based scheduling. We provide two receiver based scheduling techniques. One is centralized deterministic scheduling, the other is decentralized pseudo-random scheduling. Surprisingly, the decentralized pseudo-random scheduling achieves only slightly lower power efficiency compared with the global scheduling. Both of the receiver based scheduling techniques show orders of magnitude improvement over current transmitter based scheduling protocols.
- We design a new MAC protocol (O-MAC) that can achieve near optimal energy efficiency. The adaptivity in the protocol can match the duty cycle of the communication system to variations in the application's message generation rate. By changing the communication duty cycle in-situ, the proposed dynamic control scheme avoids excess inefficiency while still satisfying the requirements of application, several extensions to the basic scheme are also discussed.

D. Related work

About 20 power aware MAC layer protocols have been proposed in recent years. The power management methods embedded in those protocols fall into three categories: synchronous blinking (S-MAC[5], T-MAC[6]), asynchronous wake-up ([4], [7]), and long preamble (usually called low power listening in the WSN literature)(B-MAC[9]). In the synchronous blinking case, all the nodes wake up at the same time periodically; in the asynchronous wake-up case, every node wakes up using a complex pattern designed to ensure that any two neighbor nodes can communicate irrespective of the time shift between the patterns; in the long preamble case, the transmitter uses a long enough preamble so that all nodes are guaranteed to wake-up before he transmits, once receivers detect the preamble they wait for the packet.

Because current MAC layer protocols assume that the underlying communication between sender and receiver is local broadcast, the energy wasted on overhearing is substantial. All the neighbors around the sender must wake up to receive the packet which may be a unicast packet. In contrast, TDMA based approaches (SS-TDMA[11], L-MAC[12]) can avoid overhearing, but their idle-listening overhead is non-negligible, unless the TDMA duty cycle exactly matches the application's data rate. Essentially, these protocols focus on providing higher throughput by collision avoidance and transmission scheduling, power efficiency is only a second consideration. A new energy efficient MAC layer protocol is needed for AAO communications.

The rest of this paper is organized as follows. In Section II, we formally define the system model and an energy efficiency metric to evaluate the performance of the protocols. In Section III, by generalizing common MAC protocols into several abstract models, we compare their power efficiency and provide theoretically performance bounds for each abstract model. In Section IV, we explain the highlights of the design of a power-conserving based MAC protocol,(O-MAC), that achieves near optimal energy efficiency.

II. Definition and System Model

A. Definitions

In this paper, we generalize the frame format common in several protocols, such as IEEE 802.15.4, B-MAC, S-MAC, and T-MAC, into a common logical structure. The schematic view of this abstraction is described in the following:

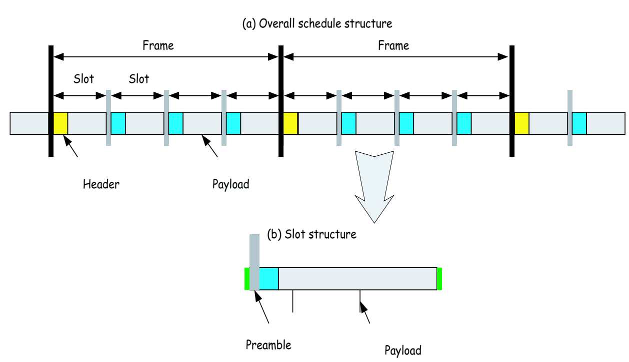

Fig. 1. Structure of the schedule

- Packet-length slot: Slots are fixed time intervals that are long enough to receive (send) a packet, include a "guard region" to allow for small scale time misalignments.

- Preamble: It is used by the receiver to identify the start of a transmission. It appears before the header and is used internal to the radio for fine-scale time synchronization, carrier acquisition, etc. Usually, the preamble length is about 10% of the packet size. Most protocols can achieve better energy efficiency with shorter preambles.On the receiver side, partial slot listening is used to detect the preamble.
- Frame: Frames are the minimum interval over which a receiver is guaranteed to turn on at least once. Frame size is closely related to latency requirements.

We make the following assumptions:

- The cost of transmission and reception are same. This is the case of Chipcon CC2420. In fact, all the analysis can be extend easily to other ratio models. We normalize the cost of sending in one slot to unity.
- The cost of partial slot listening is assumed to be δ_p.

B. Problem Statement

Traditional MAC layers are designed to achieve high throughput by collision avoidance. However, in the low duty cycle applications, the primary goal is to maximize goodput for a given energy budget, which can be measured by **energy efficiency**, defined as:

$$E = \frac{\sum\sum M_i^j}{\sum\sum(S_i^j + R_i^j)} \quad (1)$$

where

$$S_i^j = \begin{cases} 1 & \text{When node } i \text{ transmits at slot } j \\ 0 & \text{When node } i \text{ sleeps at slot } j \end{cases}$$

$$M_i^j = \begin{cases} 2 & \text{Node } i \text{ succeeds in unicast at } j \\ 1 + N_r & \text{Node } i \text{ succeeds in broadcast at } j \\ 0 & \text{Otherwise} \end{cases}$$

$$R_i^j = \begin{cases} 1 & \text{When node } i \text{ listens at slot } j \\ 0 & \text{When node } i \text{ sleeps at slot } j \\ c_p & \text{Otherwise: partial slot listening} \end{cases}$$

(Note: N_r is the number of receivers in the broadcast.) The goal is to achieve maximum power efficiency by scheduling transmission and reception. Notes:

- M_i^j is decided by the sender S_i^j, receiver R_i^j, and the possibility of collisions.
- If all the transmissions are well scheduled so that collisions are avoided, then for unicast communication:

$$\sum\sum M_i^j = 2\sum\sum S_i^j = 2\sum\sum R_i^j \Rightarrow E_{max} = 1$$

  Achieving such a schedule would require exact knowledge of the message generation pattern, which is almost never available.

C. Models

In our analysis, we consider the following models:

1) **Communication Model**: If a receiver receives more than two transmissions at the same time, none of them can succeed.
2) All communication is unicast.
3) **Traffic Model**: All the sensor nodes will send messages with the same probability p_t when they are active. If message is lost, it will be retransmitted with random delay.

D. Notations

Before analyzing the performance of different power management schemes, we define several variables:

- Let ϵ be the probability that on average a node needs to transmit in one slot. Typically, $\epsilon \in [10^{-6}, 1/500]$.
- Let N_e be the average number of neighbors, this is determined by the communication range and the node density. Typically, $N_e \in [2, 6]$.
- Let η be the average number of nodes that would interfere with a particular transmission. Typically, $\eta \in [5, 50]$, because the interference range is significantly larger than the communication range.
- Let ψ be the overall duty cycle. Typically, $\psi \in [\frac{1}{32}, \frac{1}{256}]$. Mission lifetime dictates this. Here, the ψ is defined as number of active slots (sending and receiving) divided by total number of slots.
- Let ψ_r be the receiver duty cycle. ψ_r is defined as number of listening slots divided by total number of slots.
- Let T be the cycle time, or the duration of one frame. Typically, $T \in [0.1, 100]s$. The average single hop latency is half of this number.
- Let δ be the slot time, the time it takes to wakeup and power up the communications to send one packet. Typically, $\delta \in [5, 50]ms$.

Note: In a stable network where all communications are unicast, $2N_t\epsilon = \sum\sum M_i^j$ and $N_t\psi = \sum\sum(S_i^j + R_i^j)$, where N_t is total number of slots. Then the power efficiency can be computed by:

$$E = \frac{\sum\sum M_i^j}{\sum\sum(S_i^j + R_i^j)} = \frac{2\epsilon}{\psi} \quad (2)$$

III. Power Efficiency Analysis

In this section, we investigate the theoretical performance bounds of several abstract models that represent key features of widely used protocols. The following assumptions are made in this section:

- The number of interfering nodes η is constant. In Section III-G.1, we prove that our analysis is still valid in the case of varying η.
- To simplify our analysis, we do not consider CSMA effects in the analysis. We relax this assumption in section III-G.2.
- We assume a node will wake up for a full slot other than partial slot. In section III-G.3, we will analyze these protocols with partial slot listening enabled.

Before the analyisis, we first introduce two lemmas.

Lemma 1: Assume the probability of transmission for any node at slot t is p_t, then the conditional probability of collision

p_c when a node wants to send at slot t is:

$$p_c = 1 - (1 - p_t)^{\eta - 1} \quad (3)$$

Note: this equation is derived from the fact that for any receiver only one neighbor node can send out message. In addition, all the transmissions are independent. Clearly, the probability of collisions depends on the number of interfering nodes.

Lemma 2: When one packet is sent, the expected number of transmissions is:

$$E(Trans) = (1 - p_c)(1 + \sum_{k=1}^{\infty}(k+1) * p_c^k) = \frac{1}{1 - p_c} \quad (4)$$

where p_c is the probability of collision.

A. The Synchronous Blinking Case

Based on the global time, all the nodes wake up at the same time. During these short on-intervals any traditional protocol may be used. S-MAC and T-MAC belong to this category.

Theorem 1: When $p_t^* = \frac{1}{\eta}$, the Synchronous Blinking Case attains its the maximal power efficiency:

$$E_{smax} = \max\left(\frac{2\epsilon}{\psi}\right) = \frac{2(1 - \frac{1}{\eta})^{\eta}}{\eta - 1} \approx \frac{2}{(\eta - 1)e} \quad (5)$$

Proof: Assuming the probability of transmission when a receiver wakes up is p_t, then the percentage of time for transmission is defined as:

$$Tr = p_t * \psi \quad (6)$$

Tr can also be calculated by:

$$Tr = E(Trans) * \epsilon = \frac{\epsilon}{1 - p_c} = \frac{\epsilon}{1 - (1 - (1 - p_t)^{\eta - 1})} = \frac{\epsilon}{(1 - p_t)^{\eta - 1}} \quad (7)$$

By solving equation 6 and 7, we can get:

$$\frac{\epsilon}{\psi} = p_t(1 - p_t)^{\eta - 1}$$

By differentiating with respect to p_t, we get the maximal efficiency at $p_t^* = 1/\eta$:

$$E_{smax} = \max\left(\frac{2\epsilon}{\psi}\right) = \frac{2(1 - \frac{1}{\eta})^{\eta}}{\eta - 1} \approx \frac{2}{(\eta - 1)e}$$

Note: The approximation in the last step is the asymptote as $\eta \to \infty$, but it is already a fairly good approximation by the time $\eta = 5$.

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Remark:

- If all the senders are well scheduled, they can send messages sequentially to avoid collisions. The power efficiency is $2/\eta$. Compared with this scheduled sender case:

$$\frac{E_{smax}}{E_{imax}} = \frac{\frac{2(1 - \frac{1}{\eta})^{\eta}}{\eta - 1}}{\frac{2}{\eta}} = \frac{(1 - \frac{1}{\eta})^{\eta}\eta}{\eta - 1} \approx \frac{1}{e}$$

Because of collisions, only $1/e$ of the messages are successfully transmitted.
- Since $\eta \gg e$, the maximal power efficiency in this case is dictated by the number of interfering nodes.

B. The Long Preamble Case

In this case, all the nodes wake up periodically. No time synchronization is required. If a node wants to send a message, it uses a long preamble. When a receiver wakes up and if it detects an ongoing permeable, it stays awake for the message; otherwise it goes back to sleep. B-MAC [9] falls into this category. There are two cases as shown in Figure 2:

- In case one, a long preamble is used to wake up the receiver, all the nodes that hear the preamble will wake up. After the long preamble, the payload is transmitted.
- In case two, the same packet is sent repeatedly during the frame time and the receiver wakes up.

Our analysis focuses on case two since it is more power-efficient than the case one [9].

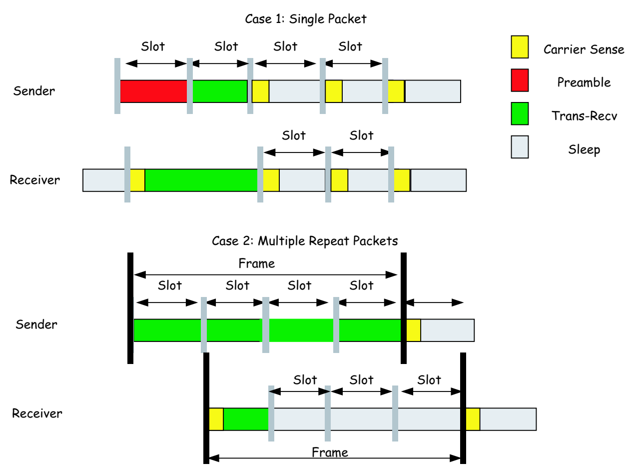

Fig. 2. Structure of the Long Preamble Case

Theorem 2: When $p_t^* \approx \psi/2$, we get the highest power efficiency in the Long Preamble case (two):

$$E_{lmax} = \max\left(\frac{2\epsilon}{\psi}\right) \approx \frac{\psi(1 - \psi)^{\eta - 1}}{2} \approx \frac{\psi}{2} \quad (8)$$

Proof: Assume the probability of transmission at every frame is p_t, so the probability of a receiver gets message successfully can be calculated by:

$$p_s = p_t(1 - 2p_t)^{\eta - 1}$$

Note: The factor of 2 is introduced by the fact that the transmission in one slot can interfere with transmissions in two slots due to slot misalignment.

Let the receiver duty cycle be ψ_r during the long preamble transmission, the power efficiency is:

$$\frac{\epsilon}{\psi} = \frac{p_s \psi_r}{p_t + \psi_r}$$
$$\psi = p_t + \psi_r$$

We can get:

$$\frac{\epsilon}{\psi} = (1 - \frac{p_t}{\psi})p_t(1-2p_t)^{\eta-1} \tag{9}$$

By differentiating it with p_t, we can get the maximum ϵ/ψ when

$$p_t^* = \frac{\psi}{\sqrt{\eta^2\psi^2 + 1 - 2\psi} + \eta\psi + 1} \approx \frac{\psi}{2}$$

when $1 \gg \eta\psi$ and we have the maximal efficiency:

$$E_{lmax} = \max(\frac{2\epsilon}{\psi}) \approx \frac{\psi(1-\psi)^{\eta-1}}{2} \approx \frac{\psi}{2}$$

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Remarks:

- To get the maximal power efficiency, the receiver duty cycle must be approximately equal to the sender's duty cycle $\psi_r = \psi - p_t^* \approx \frac{\psi}{2} \approx p_t^*$.

C. The Asynchronous Wake-up Case

In this case, all the nodes wake up according to a schedule described in [4] and [7]. By using these schedules, it is possible to wake up in only k slots out of total k^2 slots and to guarantee that for any two nodes at least one slot exists during which both nodes are awake, no matter what shift exists between the two schedules. We regard these k^2 slots as one frame. We

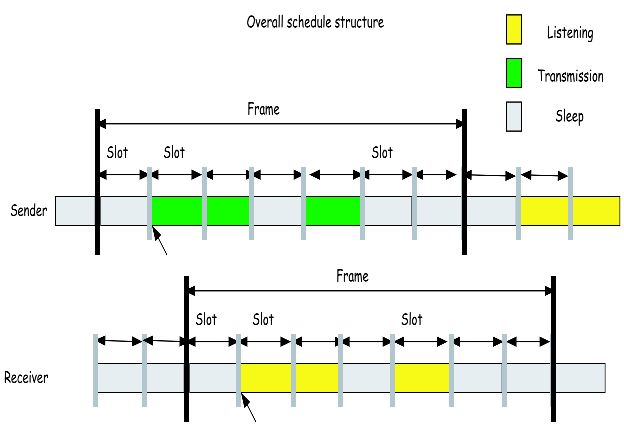

Fig. 3. The structure view of Asynchronous Wake-up Case

define the frame length as n, i.e.:

$$n = \frac{T}{\delta} = k^2 \text{ (Note: } \psi \approx \frac{k}{k^2} = \frac{1}{k} = \frac{1}{\sqrt{n}} \text{)}$$

Theorem 3: The maximal power efficiency where ψ is small and $1 > 2\eta\psi$ is:

$$E_{dmax} = \max(\frac{2\epsilon}{\psi}) \approx \frac{2}{\sqrt{n}} = 2\psi \tag{10}$$

when $p_t^* = 1$

Proof: Assume the probability of transmission in one frame is p_t, then the conditional probability of collision given transmission is:

$$p_c = 1 - (1 - p_t * \frac{2}{\sqrt{N}})^{\eta-1}$$

Note: Similarly to the Long Preamble case, factor 2 is used to compensate for desynchronized slot. The percentage of transmission time Tr is

$$Tr = p_t * \psi \tag{11}$$

Tr can also be computed by equation:

$$Tr = E(Trans) * \epsilon * \sqrt{N} = \frac{\epsilon\sqrt{N}}{1-p_c} = \frac{\epsilon\sqrt{N}}{1-(1-(1-p_t*\frac{2}{\sqrt{N}})^{\eta-1})} = \frac{\epsilon\sqrt{N}}{(1-p_t*\frac{2}{\sqrt{N}})^{\eta-1}} \tag{12}$$

by using similar steps as the Synchronous Blinking case, we can get:

$$\frac{\epsilon}{\psi} = \frac{1}{\sqrt{n}}p_t(1-p_t*\frac{2}{\sqrt{n}})^{\eta-1} \tag{13}$$

By varying p_t, we can get the maximum energy efficiency. when $1 \le 2\eta\psi$:

$$E_{dmax} = \max(\frac{2\epsilon}{\psi}) = \frac{(1-\frac{1}{\eta})^\eta}{\eta - 1} \approx \frac{1}{e(\eta-1)} \tag{14}$$

$$p_t^* = \frac{\sqrt{N}}{2\eta} = \frac{1}{2\eta\psi} \tag{15}$$

when $1 > 2\eta\psi$, we have the maximal efficiency:

$$E_{dmax} = \max(\frac{2\epsilon}{\psi}) = \frac{2}{\sqrt{n}}(1-\frac{2}{\sqrt{n}})^{\eta-1} = 2\psi(1-2\psi)^{\eta-1} \tag{16}$$

$$p_t^* = 1 \tag{17}$$

In a low duty cycle sensor network, n is large enough, so the maximal efficiency is:

$$\max(\frac{2\epsilon}{\psi}) \approx \frac{2}{\sqrt{n}} = 2\psi$$

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Remark:

- The power efficiency of Asynchronous Wake-up method is proportional to total duty cycle, which is very low in a typical AAO network.
- Since no time synchronization is required, the method is robust to network uncertainty and mobility.

D. Random Time Spreading Case

In this case, the wakeup schedule is totally random. Every time slot, the receiver will wake up with probability p_r. In addition, time synchronization is not required.

Theorem 4: The maximal power efficiency in low-duty-cycle random time spreading sensor network is:

$$E_{smax} = \max_{p_t \in [0,1]}(\frac{\epsilon}{\psi}) \approx \frac{2\psi}{\eta} \tag{18}$$

Proof: Assume the probability of sending a message in one time slot is p_t, then the probability of successfully receiving a message is:

$$p_{su} = N_e * \frac{p_t}{N_e} p_r (1-p_t)^{\eta-1} = p_t p_r (1-p_t)^{\eta-1}$$
$$\epsilon = p_{su}$$
$$\psi = p_r + p_t$$

The power efficiency can be calculated by:

$$E_{smax} = \max_{p_t \in [0,1]} (\frac{2\epsilon}{\psi}) = \max_{p_t \in [0,1]} (\frac{2p_t p_r (1-p_t)^{(\eta-1)}}{p_t + p_r}) \approx \frac{2\psi}{\eta}$$

where,

$$p_t^* = \frac{\sqrt{\eta^2 + 4\eta - 4} - \eta}{2(\eta - 1)} p_r \approx \frac{p_r}{\eta}$$

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Remark:

- This fully random wake-up case has the worst power efficiently because the energy is wasted not only in time (duty cycle ψ), but also in space (η).
- Here, we ignore the effect of possible unaligned slots. If we consider this effect, the energy efficiency is worse by a factor of 2.

E. The Staggered On Case

All the solutions we have described so far are sender based scheduling. They are intended as surrogates of the bulk of schemes in common use today. We provide one solution, which we call Staggered-On wake-up in order to highlight the key difference between it and the synchronous blinking case. In this case, all the receivers are scheduled to wake up in a way that no receivers can interfere with each other. Specifically, any transmitter that is within the communication range of one receiver is outside the interferences range of the other receiver as shown in figure 4. Every node knows the wake-up schedule of their neighbor. If they want to send unicast message to a neighbor, they wait until the destination node is awake.

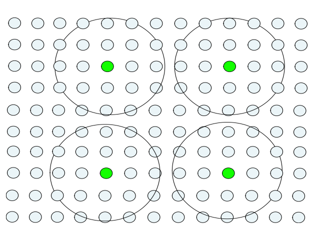

Fig. 4. The spatial view of Staggered On Case

Theorem 5: When $p_{tm}^* \approx 0.62/N_e$, we get the highest power efficiency in the Staggered On case:

$$E_{smax} = \max(\frac{2\epsilon}{\psi}) \approx 0.42 \quad (19)$$

where p_{tm}^* is the possibility of transmission when the neighbor's receiver is on.

Proof: Assume when any receiver is on, the probability of transmission is p_t, then the probability of transmitting to one particular receiver is $p_{tm} = p_t/N_e$.

Let the receiver duty cycle be ψ_r, then the sender duty cycle ψ_s is

$$\psi_s = N_e * p_{tm} * \psi_r$$
$$\frac{\epsilon}{\psi_r} = N_e p_{tm} (1 - p_{tm})^{N_e - 1}$$
$$\psi = \psi_s + \psi_r = N_e * p_{tm} * \psi_r + \psi_r$$

we can get:

$$\frac{\epsilon}{\psi} = \frac{N_e p_{tm} (1 - p_{tm})^{(N_e - 1)}}{N_e p_{tm} + 1} \quad (20)$$

By differentiating with respect to p_{tm}, we can get the maximal efficiency with collision is:

$$E_{smax} = \max(\frac{2\epsilon}{\psi}) \approx 0.42$$

when :

$$p_{tm}^* = \frac{\sqrt{5N_e^2 - 4N_e} - N_e}{2N_e(N_e N_e - 1)} \approx \frac{0.62}{N_e}$$

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Remark: Because of sender collision, we can only successfully transmit 42% of the ideal capacity. However, compared with the Synchronous Blinking case, scheduling the receiver, increases the power efficiency increases by degree of η, i.e. the number of interfering neighbors.

F. Pseudo-random Staggered On Case

To overcome the difficulty of implementing and maintain a global schedule in Staggered On case, we relax the constraints by letting every node wake up independently with probability $1/\eta$. There is no guarantee that receiver collision is avoided.

Theorem 6: The maximal power efficiency in the Pseudo-random Staggered On Case is

$$E_{dsmax} = \max(\frac{\epsilon}{\psi}) \approx 0.26 \quad (21)$$

when $\eta \gg N_e$

Proof: On average, a node will wake up with the probability of $1/\eta$. Assume a node named A wakes up as a receiver, since its neighbors know the schedule of A, they will only act as senders. The total possibility of to be active as a listener is $1 - N_e/\eta$.

Note: The only difference between Pseudo-random Staggered ON and Centralized Staggered On is that the expected number of interferers is

$$\frac{(\eta - N_e)N_e}{\eta} + N_e - 1$$

This may include the sender itself, but since we assume $\eta \gg N_e \gg 1$, this sender effect can be ignored.

$$\frac{\epsilon}{\psi_r} = N_e p_{tm} (1 - p_{tm})^{\frac{(\eta - N_e)N_e}{\eta} + N_e - 1}$$
$$\psi = \psi_s + \psi_r = N_e * p_{tm} * \psi_r + \psi_r$$

we can get:

$$\frac{\epsilon}{\psi} = \frac{N_e p_{tm}(1-p_{tm})^{\frac{(\eta-N_e)N_e}{\eta}+N_e-1}}{N_e p_{tm}+1} \approx \frac{N_e p_{tm}(1-p_{tm})^{2N_e}}{N_e p_{tm}+1} \tag{22}$$

By differentiating with respect to p_{tm}, we get the maximal efficiency with collision:

$$E_{smax} = \max\left(\frac{2\epsilon}{\psi}\right) \approx 0.26 \tag{23}$$

when $p_{tm}^* \approx 0.37/N_e$

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G. Extensions to the Analysis

1) Adaptation to interference range variation: The value of η is decided by interference range. In this section, we focus on its influence on the power efficiency. We evaluate the influence of variation using two standard distribution: uniform distribution and normal distribution to show that our analysis is still valid even under those variations. We use the Synchronous Blinking Case as an example.

a) Uniform distribution: Assume η is uniformly distributed in $[\eta_0-\sigma, \eta_0+\sigma]$. However, the wakeup schedule uses the average value η_0. Then the expected efficiency can be calculated by:

$$E(e_f) = \int_{\eta_0-\sigma}^{\eta_0+\sigma} \frac{1}{2\sigma} p(1-p)^{\eta-1} d\eta = \frac{p}{1-p}\frac{(1-p)^{\eta_0+\sigma}-(1-p)^{\eta_0-\sigma}}{2\sigma\log(1-p)}$$

Compared to the efficiency of the network with constant η_0,

$$E(e_{f_0}) = p(1-p)^{\eta_0-1}$$

$$\frac{E(e_f)}{E(e_{f_0})} = \frac{(1-p)^{\sigma}-(1-p)^{-\sigma}}{2\sigma\log(1-p)} \approx 1$$

$$(\text{ when } p = \frac{1}{\eta_0} \text{ is small })$$

b) Normal Distribution: Assume η is normally distributed in (η_0, σ^2). However, the wakeup schedule uses the average value η_0. Then the expected efficiency can be calculated by:

$$E(e_f) = \int_{-\infty}^{+\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\eta-\eta_0)^2}{2\sigma^2}} p(1-p)^{\eta-1} d\eta = p(1-p)^{\eta_0-1} e^{\frac{\sigma^2\log^2(1-p)}{2}} \tag{24}$$

Compared to the efficiency of the network with constant η_0,

$$E(e_{f_0}) = p(1-p)^{\eta_0-1} \tag{25}$$

$$\frac{E(e_f)}{E(e_{f_0})} = e^{\frac{\sigma^2\log^2(1-p)}{2}} \approx 1 \tag{26}$$

$$(\text{ when } p = \frac{1}{\eta_0} \text{ is small })$$

2) Carrier Sensing and Collision Avoidance: To avoid collisions, carrier sensing can be applied in all the previous methods. However, this may increase the idle listening time. In addition, carrier sensing can not avoid the hidden terminal problem completely. So, the benefit for power efficiency by carrier sensing is limited. From previous analysis, we have seen the channel utilization can be up to 63% by simply letting every node access the channel randomly with probability $\frac{1}{\eta}$. In other words, the maximum improvement of power efficiency by using carrier sensing is only 37%, which is less important than scheduling receivers properly.

3) Partial Slot Listening: Partial slot listening can reduce the idle listening. The power efficiency for different cases can be computed by following equations:

- Synchronous Blinking Case:

$$E = \frac{2\epsilon}{\psi} = \frac{2p_t(1-p_t)^{\eta-1}}{c_p(1-p_t)^{\eta}+1-(1-p_t)^{\eta}} \tag{27}$$

- Long preamble Case:

$$E = \frac{2\epsilon}{\psi} = \frac{2p_t(1-p_t)^{\eta-1}(\psi-p_t)}{p_t+(\psi-p_t)((1-c_p)(1-p_t)^{\eta}+1)} \tag{28}$$

- Asynchronous Wake-up Case: no change since the node needs to wake up for a full slot to listen to any possible traffic.
- Staggered On case:

$$E = \frac{2N_e p_t(1-p_t)^{N_e-1}}{(1-c_p)N_e p_t + c_p + N_e p_t} \tag{29}$$

4) Matching Duty Cycles: All of the efficiencies reported in this section have been computed for ideally chosen message rates. In each case, the derivation considers a range of communication load levels and selects the load level that maximizes the efficiency. Table I summarizes the relationship between message rate and duty cycle corresponding to optimal efficiency.

TABLE I
THE RELATIONSHIP BETWEEN RECEIVER DUTY CYCLE AND MESSAGE GENERATION RATE CORRESPONDING TO MAXIMUM EFFICIENCY.

Case Name	Message Rate	Receiver duty cycle
Sync Blinking	$\frac{\psi}{\eta}$	ψ
Long Preamble	$\frac{\psi^2}{2}$	$\frac{\psi}{2}$
ASync Wakeup	ψ^2	$\frac{\psi}{2}$
Fully random	$\frac{\psi}{\eta+1}$	$\frac{\psi\eta}{\eta+1}$
Staggered-On	$\frac{0.62\psi}{N_e}$	0.62ψ
Random-Staggered	$\frac{0.37\psi}{N_e}$	0.73ψ

Figure 5 shows how the efficiency varies with the ratio of message rate and receiver duty cycle.

The network should pick a duty cycle that meets the needs of the application in the most efficient manner, i.e., according to the formula in the table I, unless the application's message generation rate can be adjusted, the receiver should adjust in situ to the needs of the application.

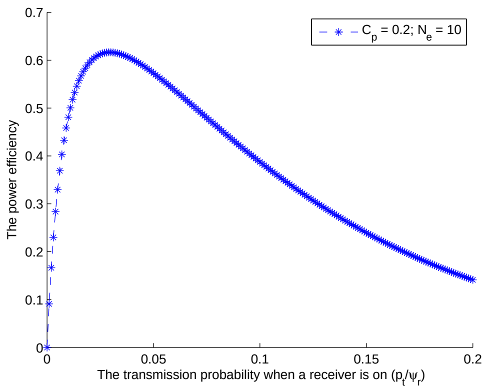

Fig. 5. The loss of efficiency due to the mismatch between message generation rate and receiver duty cycle.

H. Results

1) Full Slot Listening: The power efficiency comparison for all the methods is shown in Figure 6. For clarity, we translate these values into dB($20\log(E)$), show in the Figure 7. The figures are drawn under 1% total duty cycle.

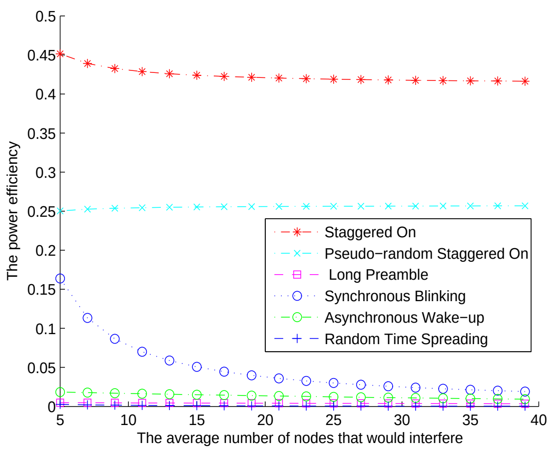

Fig. 6. The Power Efficiency Comparison with Full Slot Listening

- Staggered On achieves the highest power efficiency, succeeded by Pseudorandom Staggered On, Synchronous Blinking, Asynchronous Wake-up, Long Preamble, and Random Time Spreading.
- The power efficiency of the Synchronous Blinking case and Random Time-Spreading decrease with the number of interfering nodes.

2) Partial Slot Listening: The maximal power efficiency comparison for these methods is shown in figure 8 when $c_p = 0.1$. It is computed numerically by varying $p_t \in [0, 1]$.

Several observations:

- Staggered On and Synchronous Blinking case can benefit from partial slot listening. Their power efficiency increases with a factor approaching 2 as $\delta_p \to 0$.
- Staggered On can achieve a 70% energy efficiency.

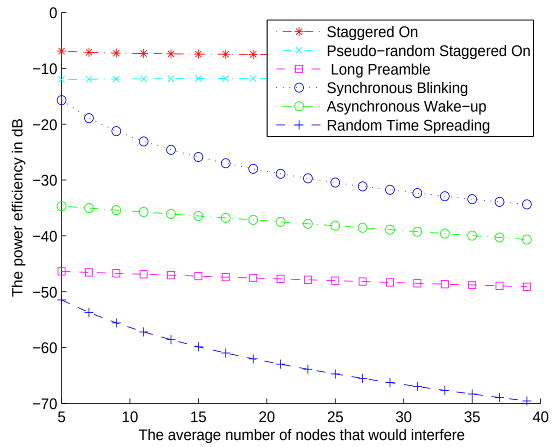

Fig. 7. The Power Efficiency Comparison with Full Slot Listening

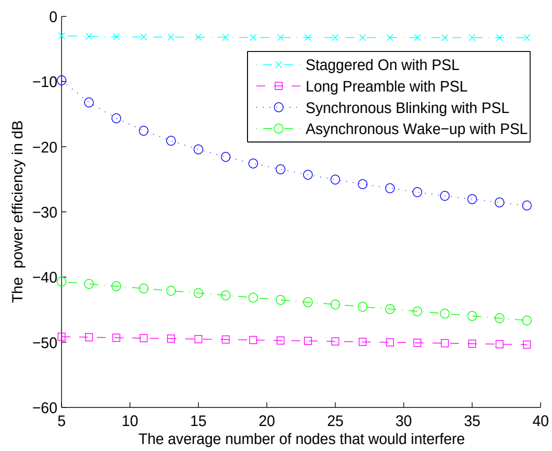

Fig. 8. The Power Efficiency Comparison with Partial Slot Listening (PSL)

IV. Power Efficient Protocol Design

The analysis of the previous section indicates that it is possible to achieve an order of magnitude better energy efficiency than current best practice.

A. The Core Protocol

We propose a basic link layer abstraction where each node may communicate directly with each of its neighbors. In this protocol the synchronous mode of operation employs a Pseudo-random Staggered On approach and the asynchronous discovery portion of the protocol is based on a long permeable.

1) Interfaces: A skeletal form of the interface is:

```
interface OMac {
  command int NumOfNeighbor();
  command int SlotsNextListen(neighborID);
  command QueueSend(neighborID, eventID);
  event  Receive(eventID, *neighborID);
  event  AckResult(eventID, *result);
 }
```

- **Receiving** : In O-MAC, each receiver wakes up and listen for the preamble. If the preamble is not detected, the node will go to sleep, otherwise it keeps listening until the end of the slot. Because the partial slot listening time is short, very little energy is consumed.
- **Synchronous ACK**: After a unicast, the sender will stay up for a while to receive the receiver's ACK. In contrast to other MAC protocols that are based on local broadcast, O-MAC is based on unicast. Therefore, the ACK can be sent reliably because of few collisions.
- **Broadcasts**: Broadcasts are performed through a sequence of unicast operations; the loss of efficiency is slightly less than 2-fold, but it is assumed that logical broadcasts do not dominate the communication pattern.
- **Synchronization** : When synchronization is lost and an asynchronous discovery is required, long preamble is superimposed on the Pseudo-random Staggered On protocol.

2) Pseudo-random Scheduler: Schedules need to be communicated in a highly compressed format to save communication cost. We propose an extreme form of this, generating the schedule from a small amount of state simultaneously on both the sender and the receiver. When a node discovers a new neighbor, it must receive that neighbor's state for schedule generation. In order to minimize storage space associated with maintaining schedules of neighbors, a node will incrementally generate the next few steps in each of its neighbors schedules with the passage of time. In order to vary the duty-cycle, the duty cycle must explicitly exposed as part of the schedule generator state.

We experimented with several pseudo-random schedule generators. But an especially simple example can be based on a linear-congruent random number generator where the state representation is

```
typedef StateT {
  int Seed;
  int FrameStart;
  int FrameLen;
  }
```

In this example, the seed defines which slot within the current frame is to be used. Computing the next slot in the schedule consists of advancing the frame-start to the first slot, past the end of the current frame, and incrementing in the seed. In this scheme the schedule allocates exactly one slot in every frame. The control algorithm may perform fine grain adjustment of duty cycle even for very low duty cycles.

Because the schedules are random, this protocol avoids most of the common issues associated with local changes to schedules. The protocol simply accommodates a small percentage of collisions.

3) Adaptive Duty Cycle: When a node modifies its schedule it must send the new schedule to each of its neighbors. In O-MAC this only happens when a node decides to change its duty cycle in order to better match the message generation rate.

The formula in table I show that the optimum operating point for the Pseudorandom mechanism is independent of the number of the interference nodes, but depends on the number of neighbors. A simple mechanism that works with some hardware is for each receiver to directly monitor its efficiency. Based on the rate of collisions, the receiver can change its duty cycle adaptively.

4) Asynchronous Neighbor Discovery.: Even a fully synchronized node may need to update its neighbor list from time to time. This could happen because of changes in connectivity, which in turn could be caused by daily fluctuations in the noise floor or a host of other environmental changes. O-MAC includes a synchronous neighbor discovery mechanism for this purpose. This synchronous neighbor discovery mechanism operates on a separate network wide schedule with a duty cycle that might be as low as one slot every ten minutes. This schedule can be used to opportunistically discover long-link.

B. Variations

This section discusses two variations on the core protocol.

1) Local Broadcast Channel: If a nontrivial portion of the network traffic is logical broadcast, implementing this traffic using a series of unicasts may be slightly inefficient. In such cases, it makes perfect sense for each node to have a broadcast schedule and a unicast schedule. The broadcast schedule defines slots in which all of the node's neighbors should wakeup. The unicast scheduled defines slots on which the node will wake up. For most applications the duty cycle of the broadcast schedule is dramatically lower than the duty cycle of the unicast schedule.

2) Preamble-Sized Slots: For expository reasons we have suggested that there are some applications for which latency is an unimportant metric.

One variation on O-MAC allows a reduction in latency at the expense of some reduction in energy efficiency. Specifically, if $C_p \ll 1$ then it is possible to shorten the length of each slot to correspond to the length of the preamble. When a preamble is detected, the rest of the packet will be transmitted over succeeding slots.

For example, a frame of preamble-sized slots might be 25x shorter than a frame of packet-sized slots. As a result the latency would be shortened 25-fold. However, when a packet is received it would "wipe-out" 26 slots, 1 for the preamble and 25 for the packet. As a result the duty cycle would have to be raised slightly to account for the higher collision rate.

C. Why Distributed Staggered On may not be Practical

Implementing a pure form of the staggered-on algorithm is fairly difficult. In general each node would need to have a schedule with a different average receiver duty cycle, and yet such that each schedule avoids overlapping with any of the schedules for any of the other nodes within its interference zone. A conceptual approach to this problem is to pre-designing a constellation of schedules, such that there are many different schedules at each of many different duty-cycle rates. A simple application of the pigeon-hole principle reveals that this is only possible for exceedingly low duty cycles, i.e., with a vary large number of slots. However, the idea of implementing a few schedules at each of a few different duty cycles may be of value to some specific applications.

Once such a constellation of schedules is constructed, every node would have to be assigned a schedule that is unique within its interference zone. Because the interference zone normally extends to more than just a nodes neighbors, doing this in a distributed fashion has high complexity. And in the end, situations will still arise where either no solution to the schedule assignment problem exists, or the only solutions are severely suboptimal, because of the static nature of the schedule constellation.

If the message-rate is nearly constant across the entire network as might be the case for an environmental monitoring application with local processing, it may be reasonable to assume a fixed frame size for the entire network. In this case the number of non-overlapping schedules becomes significantly larger than the number of nodes in an interference zone and the distributed schedule assignment problem becomes tractable, perhaps even with a simple algorithm.

However, because of the hidden node problem it is still necessary to collect a list of all the schedules within a nodes interference zone and check for conflicts. And schedule changes would need to be sent to all of the nodes within the interference zone.

D. Performance Evaluation

1) Cycle Time: The cycle time is:

$$T = \frac{\delta}{\psi_r} \tag{30}$$

The cycle time depends on idle receiver duty cycle ψ_r.

2) Delay: The expected delay D_o is:

$$D_o = \frac{T}{1-(1-(1-p_t)^{N_e-1})} = \frac{\delta}{\psi_r(1-p_t)^{N_e-1}} \tag{31}$$

The expected delay is decided by on idle receiver duty cycle ψ_r and the average number of neighbor nodes. The expected delay is smaller than for the Synchronous Blinking case with the same condition.

3) Throughput: At every frame T, every node can wake up once. If the senders are not scheduled, then the probability that node i can receive a message successfully is:

$$p_{su} = N_e * p_{tm}(1-p_{tm})^{N_e} \tag{32}$$

when $p_t^* = 1/N_e$. The maximal throughput for one node is:

$$\max_{p_t\in(0,1)} r_t = \max_{p_t\in(0,1)} p_{su}\frac{\psi_r}{\delta} = \frac{\psi_r}{e*\delta} \tag{33}$$

Remark:

- The optimal transmission p_t^* to get maximal throughput is different from the value to get maximal power efficiency. The reason is that increasing collision rates limit energy efficiency more quickly than they limit throughput.

V. Conclusion

In this paper, we have argued that the receiver radio dominates the power consumption. By deriving the bounds on power efficiency for various models, we have shown that receiver scheduling can increase the power efficiency by orders of magnitude. In addition, we have provided two new receiver based scheduling methods: Staggered On and Pseudo-randomized Staggered On and designed one new MAC protocol that achieves the near optimal power efficiency. The adaptivity in the protocol can match the duty cycle of the communication system to the needs of the application across variations in message generation rate. Finally, we have described several implementation details such as asynchronous discovery, Pseudo random scheduler design, and adaptive duty cycling. Two variations of our O-MAC—local broadcast channel and preamble-sized slots have also been discussed.

In the future, we will implement this protocol and apply it to two typical traffic patterns: local gossip and convergecast. We will also work on the stability issues in the receiver centric scheduling and the theoretical analysis of adaptive duty cycling protocol.

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