

Low Power MAC Protocols for Infrastructure Wireless Sensor Networks

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Abstract: This paper addresses low power MAC protocols for the downlink of infrastructure wireless sensor networks. We are interested in the trade-off between power consumption and transmission delay, focusing on low traffic. We describe *WiseMAC* (Wireless Sensor MAC), a new protocol for the downlink of infrastructure wireless sensor networks. Another original contribution is the analysis of the performance of *PTIP* (Periodic Terminal Initiated Polling). Here, polling is used in the reversed direction as compared to common polling protocols. *WiseMAC* and *PTIP* are compared with *PSM*, the power save protocol used in both the IEEE 802.11 and IEEE 802.15.4 Zig-Bee standards. Analytical expressions are given for the power consumption and the transmission delay for each protocol, as a function of the wake-up period. It is shown that *WiseMAC* provides, for the same delay, a significantly lower power consumption than *PSM*. Although less energy efficient than *WiseMAC* and *PSM*, it is shown that *PTIP* can, thanks to its implementation simplicity, become attractive for applications tolerating large transmission delays¹.

1 Introduction

Inexpensive integrated system-on-a-chip devices comprising a radio transceiver and a microcontroller have been since a few years a subject of research [1, 2]. Industry is now selling such devices [3]. They will permit to implement ubiquitous computing applications where small battery powered nodes are interconnected via a wireless network. As now widely recognized, one of the main issues is the power consumption of such devices.

1.1 Problem Statement

This paper discusses the power consumption of medium access control protocols in an infrastructure wireless sensor network, focusing on low downlink traffic. The term "sensor" is used to emphasize the low power requirement. The mobile nodes considered in this paper may be sensors (e.g. fire alarm), but also other kinds of devices such as actuators, personal digital assistants, etc.

Unlike most research dealing with wireless sensor networks, we do not consider an ad hoc multi-hop network topology, but an infrastructure network. An infrastructure network is composed of a number of access points interconnected through a backbone network. Each access point is serving a number of sensor nodes. Such a topology can be envisaged for example in smart building applications, where the Ethernet or powerline cabling can be used for the backbone network. The main

characteristic of access points is that they are assumed to be energy unconstrained. In this sense, this work can also apply to clustered ad hoc networks with solar powered cluster heads, as proposed in [4]. Finally, one can imagine a vehicle mounted mobile access point moving through an cloud of sensors to collect data.

An energy efficient wireless MAC protocol should minimize the four sources of energy waste [5]: idle listening, overhearing, collisions and protocol overhead. Idle listening refers to the active listening to an idle channel, waiting for a potential packet to arrive. Overhearing refers to the reception of a packet, or of part of a packet, that is destined to another node. Collisions should of course be avoided as retransmissions cost energy. Finally, protocol overhead refers to the frame headers and the signalling required by the MAC protocol.

As the power consumption of a transceiver in receive mode is far from being negligible, idle listening can become the main source of energy waste, especially in low traffic conditions. To reach a low average power consumption, the transceiver must be shut down part of the time (i.e. duty cycling).

In infrastructure networks, one must distinguish the downlink (access point to sensor nodes) from the uplink (sensor nodes to access point). In the downlink direction, the challenge is to transmit data from the access point to some sensor node, without requiring the sensor node to continuously listen to the channel. The MAC protocol must mainly mitigate idle listening and overhearing on the sensor nodes. The problem is different in the uplink direction. As the access point is not energy limited, it can listen all the time to the channel. The uplink MAC protocol requires no wake-up scheme. The issue to resolve in the uplink direction is the multiple access to a shared medium. If the system is operated near capacity, this problem is very complex. However, if only a moderate traffic is present on the channel, the simple non-persistent CSMA protocol [6] can clearly approach the ideal case, with no idle listening, no overhearing and little collisions. In this paper, we will therefore focus on the downlink problem.

Sensor networks are usually meant for the acquisition of data, either periodically or based on events (e.g. alarms). The uplink traffic can be expected to be high, at least during certain periods. On the other hand, the downlink is foreseen to carry configuration and querying traffic. With such a traffic, inter-arrivals measured in minutes or hours will be common. We will assume throughout this paper that the inter-arrival between packets is much larger than the time needed to transmit a packet.

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1.2 Original Contributions

This paper contains two original contributions. The first one is the proposal of WiseMAC (*Wireless Sensor MAC*) for the downlink of infrastructure wireless sensor networks. This protocol has been proposed in [7] for multi-hop wireless sensor networks. We show here that it is also of interest for infrastructure wireless sensor networks. The second contribution is the analysis of the *Periodic Terminal Initiated Polling* protocol (PTIP). Polling protocols are usually used to poll mobile stations from a central access point in order to avoid collisions in the uplink direction [8]. In this paper, we analyze the reversed usage of polling, for the downlink direction. Such a usage of polling has received little attention from the research community, because it is very inefficient in high traffic conditions. We show that this simple protocol can become attractive in certain conditions. WiseMAC and PTIP are compared with the power save protocol used in IEEE 802.11 [9] and IEEE 802.15.4 ZigBee [10] and to an hypothetical ideal protocol.

1.3 Related Work

A large effort has been devoted by the research community to the development of medium access control protocols for wireless computer networks [6, 11]. Such protocols have been primarily designed to minimize the delay and to maximize the throughput. The power consumption has only later become an issue of large interest. In [12], a comparison between the power consumption of several wireless MAC protocols is given. In their analysis, the authors focused on high traffic conditions. In this paper, we focus, in the contrary, on low traffic conditions. Low traffic is expected to be very common in many applications of ubiquitous computing, where a very long lifetime is required. It is therefore necessary to understand and minimize the energy consumption of MAC protocols in low traffic conditions.

Research on ultra low power MAC protocols for ad hoc wireless sensor network has started a few years ago. A number of proposals are available, from which one can cite S-MAC [5], Piconet [13] and wake-up radio [2]. Protocols for ad hoc sensor networks can potentially be interesting for the downlink of infrastructure sensor networks. For example, the Piconet protocol can be seen as a distributed version of PTIP. The wake-up radio scheme would certainly be of interest for the downlink of infrastructure networks, if a wake-up radio receiver hardware consuming almost nothing becomes a reality. The work presented in this paper differs from previous research on MAC protocols for sensor networks, mainly because we focus on an infrastructure topology, and investigate how the unconstrained energy supply of the access point can be exploited.

Another field related to infrastructure sensor networks is the field of paging systems. Several standards have been developed over the years, from which POCSAG and FLEX [14, 15]. The techniques used by paging systems are useful inspiration sources, but these protocols cannot be used as such for infrastructure wireless sensor networks. Paging protocols seek the capacity-energy optimum, while we seek the delay-energy optimum.

1.4 Paper Organization

The rest of the paper is organized as follows: Section 2 describes the mentioned low power MAC protocols. The power consumption and the delay of these protocols are given in Section 3. A performance comparison is made in Section 4. Section 5 contains the main findings from a sensitivity analysis. Section 6 gives concluding remarks.

2 Low Power Downlink MAC Protocols

Before proceeding to the description of the protocols, let us define models for the radio transceiver and the traffic.

2.1 Radio Model

When considering low power protocols, it is very important to model precisely the transition delays between the different states of a transceiver and the power consumption in those states. The following states can be identified:

DOZE The transceiver is not able to transmit nor receive, but is ready to quickly power on into the receive or the transmit state,

RX The transceiver is listening to the channel (receiving data or trying to demodulate data out of a noisy or idle channel),

TX The transceiver is transmitting data.

The power consumed in these states will be denoted as P_Z , P_R and P_T . To simplify analytical expressions, we define $\hat{P}_R = P_R - P_Z$ as the increment in power consumption caused by being in the RX state (as compared to the DOZE state), and $\hat{P}_T = P_T - P_Z$ as the increment in power consumption caused by being in the TX state.

We denote with T_S the setup time required to turn on the transceiver into the RX state, starting from the DOZE state. We finally denote with T_T the turn-around time which is required to switch the transceiver between the RX and TX states. During the state change phases, we assume that the transceiver consumes a power P_R , as all electronics is powered on at the exception of the last stage RF power amplifier.

2.2 Traffic Model

We consider a population of N sensor nodes under the responsibility of one access point. Downlink Poisson traffic arrives at the access point from the fixed network at a global rate λ . We assume that an equal part $\frac{\lambda}{N}$ of this traffic is destined to each sensor node. A given sensor node will receive packets with an average packet inter-arrival time of $L = \frac{N}{\lambda}$.

Data packets have a constant duration T_D . Control packets (pollings, acknowledgements, traffic indication map beacons) have a constant duration T_C .

As mentioned in the introduction, we assume a low traffic, where the inter-arrival $1/\lambda$ is much larger than the sum of the durations of a data packet, of the turn-around and of a control packet:

Low Traffic Assumption: $1/\lambda \gg T_D + T_T + T_C$

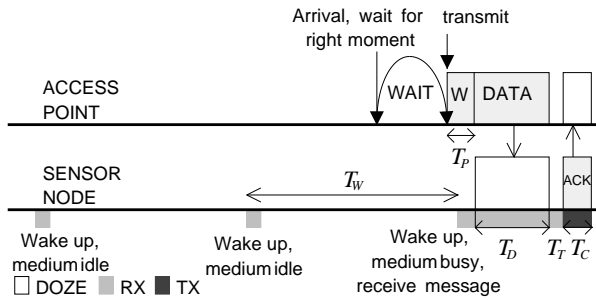


Figure 1: WiseMAC - Principle of Operation

2.3 WiseMAC

WiseMAC is based on the preamble sampling technique. This technique consists in periodically sampling the medium to check for activity. By *sampling the medium*, we mean listening to the radio channel for a short duration, e.g. the duration of a modulation symbol. All sensor nodes in a network sample the medium with the same constant period T_W . Their relative sampling schedule offsets are independent. If the medium is found busy, a sensor node continues to listen until a data packet is received or until the medium becomes idle again. At the access point, a wake-up preamble of duration equal to the medium sampling period is transmitted in front of every data frame to ensure that the receiver will be awake when the data portion of the packet will arrive. This technique provides a very low power consumption when the channel is idle. See [16] and [17] for details. The disadvantages of this protocol are that the (long) wake-up preambles cause a throughput limitation and a large power consumption overhead in reception. The overhead in reception is not only born by the intended destination, but also by all other nodes overhearing the transmission.

The novel idea introduced by WiseMAC consists in letting the access point learn the sampling schedule of all sensor nodes. Knowing the sampling schedule of the destination, the access point starts the transmission just at the right time with a wake-up preamble of minimized duration T_P as illustrated in Fig. 1. The access point keeps an up-to-date table with the sampling schedule of all sensor nodes. The sampling schedule information is gained through the inclusion in every acknowledgement packet of the remaining time until the next scheduled sampling.

The duration of the wake-up preamble must be computed such as to compensate for the drift between the clock at the access point and on the sensor nodes. This drift is proportional to the time since the last re-synchronization (i.e. the last time an acknowledgement was received from a given sensor node). Let θ be the frequency tolerance of the time-base quartz, T_W be the interval between preamble samplings and L the interval between two communications. The required duration of the wake-up preamble is

$$T_P = \min(4\theta L, T_W) \quad (1)$$

This expression is obtained as follow: Assume that the access point has received fresh timing information

from some sensor node at time 0, and that the access point wants to send a packet to this sensor node at the sampling time L . If the sensor node quartz has a real frequency of $f(1 + \theta)$ instead of f , its clock will have an advance of θL at time L . It is hence needed to start the preamble θL in advance. Because the clock of the access point might be late, it must target a time $2\theta L$ in advance. Because the clock of the access point might be early, and the clock of the sensor node late, the duration of the wake-up preamble must be of $4\theta L$. If L is very large, $4\theta L$ may be larger than the sampling interval T_W . In those cases, a preamble of duration T_W is used.

If the traffic is high, the interval L between transmissions will be small, and so the wake-up preamble ($4\theta L$). If the traffic is low, the interval between transmissions will be high, but at maximum equal to T_W . This important property makes the WiseMAC protocol adaptive to the traffic. The per-packet overhead decreases in high traffic conditions.

Overhearing is naturally mitigated when the traffic is high, thanks to the combined use of the preamble sampling technique and the minimization of the wake-up preamble duration. As already mentioned, sensor nodes are not synchronized among themselves. Their relative sampling schedule offsets are independent. In high traffic conditions, the duration of the wake-up preamble being smaller than the sampling period, short transmissions are likely to fall in between sampling instants of potential overhearers.

Finally, it is interesting to note that collisions are not possible using WiseMAC for a downlink channel, as the access point is the only initiator of transmissions.

2.4 Periodic Terminal Initiated Polling - PTIP

With the PTIP protocol, the access point buffers downlink traffic. Sensor nodes regularly send a POLL packet to the access point to get potentially buffered data. The access point replies with a DATA packet if one was buffered, or with a (shorter) control packet if the queue for the requesting node was empty. To mitigate collisions between sensor nodes, POLL packets are sent using the CSMA protocol. To avoid systematic contentions between synchronized nodes, the time interval between POLL transmissions is a random variable with mean value T_W . The basic principle of operation of PTIP is illustrated in Fig. 2.

If the response to the POLL is correctly received, the sensor node goes back to sleep until the next scheduled polling time. With PTIP, it is not required to send an acknowledgement when a downlink DATA packet has been received correctly. Instead, the POLL is repeated until a response is received correctly. To let the access point know whether a DATA packet has to be retransmitted or not, the sequence number of the last correctly received DATA packet is piggy-backed on every POLL packet.

2.5 IEEE 802.11/802.15.4 Power Save Mode - PSM

A power save mode (PSM) has been specified in the IEEE 802.11 standard to permit a lower power consumption at the cost of a larger delay [9]. The same scheme has been selected for the newer IEEE 802.15.4 ZigBee standard [10]. The access point buffers incoming traffic.

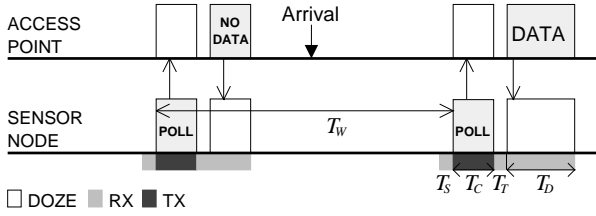


Figure 2: Periodic Terminal Initiated Polling (PTIP) - Principle of Operation

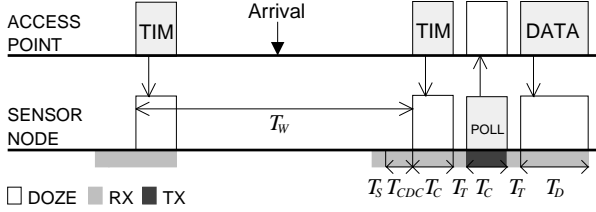


Figure 3: Optimized Power Save Mode (PSM) - Principle of Operation

A beacon is periodically transmitted with period T_W . This beacon contains the *traffic indication map* (TIM), which lists the sensor nodes for which data packets have been buffered. All sensor nodes wake-up regularly to receive the TIM. If they discover their address in the TIM, they poll the access point to receive the buffered data.

The standard requires the access point to reply to a POLL after a given delay ($10 \mu s$ in DS 802.11b). In practice, it is difficult for the access point software to find the right packet and prepare it for transmission within the specified delay. Instead, the access point replies to the POLL with an ACK. This instructs the sensor node to remain in listening mode. As soon as possible, the access point sends the DATA packet, which is then acknowledged back by the sensor node. In summary, the polling procedure is composed of four packet transmissions: POLL-ACK-DATA-ACK. In this paper, we are interested in the basic performance of protocols that would use a traffic indication map. For a fair comparison with the other protocols, we consider a version of the PSM protocol, that is fully optimized for low power operation. We assume first that access point replies to a POLL with a DATA packet (after the needed delay), and secondly that a DATA packet is not acknowledged (as in PTIP, the acknowledgement is piggy-backed on the following POLL). This procedure is illustrated in Fig. 3. Note that sensor nodes must listen to the channel $T_{Cdc} = 2\theta T_W$ before the expected start of the TIM packet to compensate for a potential drift between the access point clock and their clock.

2.6 More bit

A very important detail shared by WiseMAC, PTIP and PSM is the presence of a *more* bit in the header of data packets. When this bit is set to 1, this indicates that more data packets destined to the same sensor node are waiting in the access point buffer. With WiseMAC, this indicates to the sensor node that it must continue to listen after having sent the acknowledgement. The next packet will follow. With PTIP and PSM, this indicates to the

sensor node that it must poll the access point to download the following packet. This scheme permits to use a wake-up interval that is larger than the average interval between the arrivals for a given node ($T_W > L$). It permits to reduce the queuing delay at the access point, especially in the event of traffic bursts.

3 Power Consumption and Delay

This section introduces analytical expressions to compute the power consumption and the delay of WiseMAC, PTIP and PSM, under the low traffic assumption ($1/\lambda \gg T_D + T_T + T_C$). Due to space limitations, little explanation is given on the derivation of those expressions. Interested readers are referred to [18] for details.

It can be shown that the average power consumed by WiseMAC, PTIP and PSM is respectively given by

$$\begin{aligned}
 P_{WiseMAC} &= P_Z + \frac{\hat{P}_R(T_S + 1/B)}{T_W} \\
 &+ \frac{\hat{P}_R(T_P/2 + T_D + T_T) + \hat{P}_T T_C}{L} \\
 &+ \hat{P}_R(N-1) \frac{(T_P + T_D)^2}{2LT_W} \quad (2)
 \end{aligned}$$

$$\begin{aligned}
 P_{PTIP} &= P_Z + e^{-\frac{T_W}{L}} \frac{\hat{P}_T T_C + \hat{P}_R(T_S + T_T + T_C)}{T_W} \\
 &+ \frac{\hat{P}_T T_C + \hat{P}_R(T_S + T_T + T_D)}{L} \quad (3)
 \end{aligned}$$

$$\begin{aligned}
 P_{PSM} &= P_Z + 2\theta \hat{P}_R + \frac{\hat{P}_R(T_S + T_C)}{T_W} \\
 &+ \frac{\hat{P}_T T_C + \hat{P}_R(T_D + 2T_T)}{L} \quad (4)
 \end{aligned}$$

Expression (2) is composed of the power consumed in the DOZE state, of the power consumption increments caused by the preamble sampling activity (wake-up and sense the channel during one radio symbol every T_W), the reception of the packet (listen in average to half of the wake-up preamble, receive the data, turn-around the transceiver and send the acknowledgement) and the overhearing of this packet by the $N - 1$ other sensor nodes ($(T_P + T_D)^2/2T_W$ is the average duration during which a transmission of duration $T_P + T_D$ is overheard by some node sampling the medium with period T_W , see [18]).

In expression (3), the first term represents the power consumed in DOZE state, the second term the cost of useless pollings ($e^{-\frac{T_W}{L}}$ is the probability of having no arrivals in between two pollings) and the third the cost of downloading buffered packets.

In expression (4), the first term represents the power consumed in DOZE state. The second term, $2\theta \hat{P}_R$, accounts for the time spent listening to the channel to cover the drift between the access point clock and the sensor node clock (see [18]). The third term represents the power consumed to power-on and listen to the beacon of duration T_C every T_W seconds. Finally, the fourth term accounts for the transmission of poll packets and the reception of data packets, including turning the transceiver

around before the POLL transmission and the DATA reception.

The transmission delay is defined as the time elapsed between the arrival of a packet at the access point and the end of its transmission to the destination sensor node. Under the low traffic assumption, it can be shown that the transmission delay with WiseMAC, PTIP and PSM is respectively given by

$$D_{WiseMAC} = T_W/2 + T_P + T_D \quad (5)$$

$$D_{PTIP} = T_W/2 + T_T + T_D \quad (6)$$

$$D_{PSM} = T_W/2 + 2T_C + 2T_T + T_D \quad (7)$$

Expression (5) is composed of the average time between the arrival of a packet at the access point and the start of the preamble transmission, the time to transmit the preamble and the data.

Expression (6) is composed of the average time between the arrival of a packet and the end of the POLL reception, the time to turn-around into transmit state and to transmit the data packet.

Expression (7) is composed of the average time between the arrival of a packet and the start of the TIM transmission, the time to transmit the TIM and the time for the sensor node to send a POLL and receive the data packet.

In the case of PTIP, we assume no collisions between POLL packets. This implies that the sum of the data and polling traffic must be small. In addition to the low traffic assumption, we need to set $T_W \gg NT_C$ for expressions (3) and (6) to be valid.

In the case of PSM, when the TIM broadcast period T_W is chosen to be larger than the global inter-arrival $1/\lambda$, several sensor nodes will enter in contention to download the buffered packets. The computation of the duration of the collision resolution interval with non-persistent CSMA is unfortunately a problem for which no analytical solution is available. Solutions exist in the steady state [6] or when using more complex protocols such as the binary tree collision resolution protocol [19]. We do not consider such results in this paper for space limitation reasons and because we do not need to consider collisions to compare these protocols in a useful manner. To avoid the problem of potential collisions, we consider with PSM a traffic sufficiently low such that at most one packet is received in average in a period T_W . Expressions (4) and (7) will be evaluated for $T_W \leq 1/\lambda$.

4 Performance Comparison

In this section, we compare the power consumption and delay performance of WiseMAC, PTIP and PSM as a function of the protocol parameter T_W . The choice of T_W permits to trade a higher delay against a lower average power consumption.

The performance of the protocols is also influenced by a number of system parameters. For the radio transceiver parameters, we will consider those of the WiseNETTM wireless sensor System-on-a-Chip (SoC) developed at CSEM [20], as listed in Table 1. This SoC

Param.	Value	Param.	Value
P_Z	$5 \mu\text{W}$	T_D (50 bytes)	16 ms
P_R	1.8 mW	T_C (10 bytes)	3.2 ms
P_T	27 mW	N	10
T_S	0.8 ms	L	1000 s
T_T	0.4 ms	θ	$30 \cdot 10^{-6}$
B	25 kbps		

Table 1: System Parameters

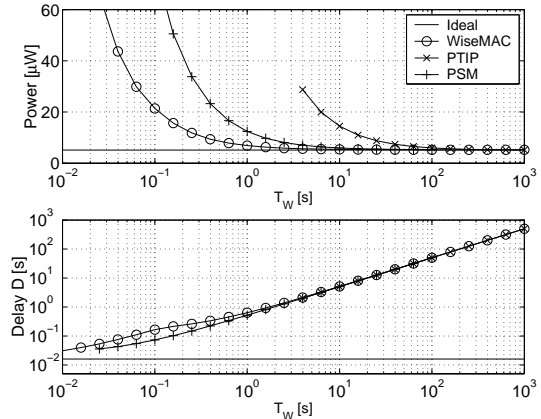


Figure 4: Power consumption and delay of WiseMAC, PTIP and PSM as a function of the wake-up period T_W .

includes a low power FSK radio transceiver (dual-band 434 and 868 MHz) [21], the CoolRISC 8 bits low power microcontroller core [22], a random access memory as well as digital and analog interfaces. It is designed on the $0.18 \mu\text{m}$ standard digital CMOS process, and operates from 1.5 V to 0.9 V such that a single inexpensive alkaline battery can be used as the energy source. The remaining parameters have been chosen as follows: The frequency tolerance of the quartz is chosen to be $\theta = \pm 30 \cdot 10^{-6}$, which corresponds to an inaccuracy of 2.6 seconds over one day. This value is conservative, as 32.768 kHz crystals targeted for the wristwatch market reach a frequency tolerance better than $20 \cdot 10^{-6}$ at 25°C (see for example [23]). The length of the data and of the control packets are chosen to be respectively 50 and 10 bytes. We consider $N = 10$ sensor nodes and an inter-arrival per sensor node of $L = 1000 \text{ s} = 16.6 \text{ min}$. Recall that this traffic is supposed to consist in configuration and query commands sent by the sensor network controller. Such large inter-arrivals make hence sense in this context. The sensitivity of the results to variations of the system parameters will be discussed in section 5.

Fig. 4 shows the power consumption P and the delay D as a function of the protocol parameter T_W . The horizontal line in the upper plot represents the power consumption of an ideal protocol, which is defined as the power needed to power on, receive the data, turn-around the transceiver and send the acknowledgement. In this case, we have $P_{IDEAL} = P_Z + \frac{\hat{P}_R(T_S+T_D+T_T)+\hat{P}_T T_C}{L} = 5.12 \mu\text{W}$. It can be noticed that the incremental cost due to the data reception is only of $0.12 \mu\text{W}$, a small value compared to $P_Z = 5 \mu\text{W}$.

In the lower plot, the horizontal line represents the

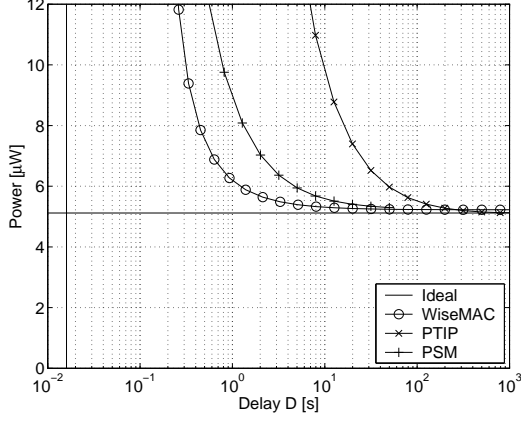


Figure 5: Power-delay characteristics of WiseMAC, PTIP and PSM.

minimum delay that would be obtained with an ideal protocol, i.e. $D_{IDEAL} = T_D = 16$ ms. WiseMAC and PSM can approach this limit for small values of T_W , but at a high power cost. PTIP cannot provide such short delays, as using a short T_W would result in an excessive polling traffic. For increasing values of T_W , the three curves converge to $D = T_W/2$, i.e. the transmission delay becomes negligible as compared to the waiting delay.

Using both plots, a designer can choose a protocol and a value for the parameter T_W , making a trade-off between the consumed power and the average transmission delay. To compare the protocols between them, one can combine both plots and draw the power as a function of the delay as shown in Fig. 5. The horizontal line represents the ideal power consumption and the vertical line the ideal delay. The power consumption of PSM is drawn only up to a delay of 50 s. For larger values of the delay, the assumption $1/\lambda \geq T_W$ would be violated.

With delays below 200 s, one can see that WiseMAC consumes less power than PTIP and PSM. The cost of receiving data being negligible when $L = 1000$ s, this can be understood by comparing the basic cost of their respective wake-up scheme. With an infinitely low traffic ($L \rightarrow \infty$), the power consumption of WiseMAC, PTIP and PSM becomes

$$\lim_{L \rightarrow \infty} P_{WiseMAC} = P_Z + \frac{\hat{P}_R(T_S + 1/B)}{T_W}$$

$$\lim_{L \rightarrow \infty} P_{PTIP} = P_Z + \frac{\hat{P}_T T_C + \hat{P}_R(T_S + T_T + T_C)}{T_W}$$

$$\lim_{L \rightarrow \infty} P_{PSM} = P_Z + 2\theta \hat{P}_R + \frac{\hat{P}_R(T_S + T_C)}{T_W}$$

With WiseMAC, the transceiver powers up every T_W to listen to the channel during the duration of a radio symbol. With PTIP, the transceiver periodically sends a POLL packet and receives a reply. With PSM, the transceiver periodically receives a TIM packet. As the duration of a TIM packet is always larger than the duration of a modulation symbol, the wake-up scheme of

WiseMAC consumes less than the one of PSM. As receiving a TIM packet consumes less than transmitting a POLL and receiving a reply, PSM consumes less than PTIP.

Assuming that, based on the requirements of some application, one would choose the value $T_W = 1$ s. With WiseMAC, this would result in an average delay of 0.6 second and a power consumption of $7 \mu\text{W}$, only $2 \mu\text{W}$ above the DOZE power consumption. When powered by a single alkaline battery of 2.6 Ah capacity with a constant power leakage of $27 \mu\text{W}$, this power consumption would translate into a lifetime of 8 years without uplink traffic. See [17] for a description of the battery model.

For the same delay of 0.6 second, the power consumption of PSM amounts to $11 \mu\text{W}$, i.e. 57% more than WiseMAC. To consume $7 \mu\text{W}$ with PSM, the average delay must be extended to 2 seconds using $T_W = 4$ s.

With the PTIP protocol, a delay of more than 20 seconds must be accepted to reach a low power consumption of $7 \mu\text{W}$. Although PTIP consumes more energy than WiseMAC and PSM, it can be of interest because it is extremely simple to implement. If some application can tolerate a large transmission delay (e.g. automated meter reading), the PTIP protocol can become an excellent choice. It must also be noticed that uplink traffic can be used to piggy-back POLL requests. If an application requires periodic uplink transmissions, then the PTIP protocol can be implemented for the downlink at no cost.

5 Sensitivity Analysis

In the previous section, typical values have been chosen for the system parameters. A sensitivity analysis has been performed to understand the impact of the variations of those parameters. Details can be found in [18]. The main findings are listed below.

Impact of large inter-arrival and scalability: For small values of L , the duration of the WiseMAC wake-up preamble is smaller than the wake-up interval, we have $T_P = \min(4\theta L, T_W) = 4\theta L$. Overhearing is mitigated in a probabilistic way. For large values of L , we have $T_P = \min(4\theta L, T_W) = T_W$. Overhearing is not mitigated anymore, but with very large values of L , the impact of overhearing becomes small. When $T_W = 4\theta L$ (or $L = \frac{T_W}{4\theta} = 8333$ s = 2.3 hours), overhearing is maximized. With only a few sensor nodes in a network, this has no serious impact. WiseMAC remains extremely energy efficient. However, as the overhearing component is proportional to $N - 1$ (the number of potential overhearers), WiseMAC presents a scalability limitation, especially when the inter-arrival L is near $\frac{T_W}{4\theta}$. A solution to reduce the overhearing when L is large consists in repeating the data frame within the wake-up preamble. Overhearers stop listening to the transmission as soon as they have received a copy of the data frame, and realized that it is destined to another node.

One can observe in expression (4) that the power consumption of PSM is independent of N . The PSM protocol is perfectly scalable. This is made possible through the combined use of the polling technique (which avoids

overhearing) and the regular broadcast of the traffic indication map (which avoids excessive useless polling traffic). The PTIP protocol, on the other hand, is clearly not scalable, the polling traffic being proportional to the number of nodes.

Packet Size: It was seen that the incremental power consumption caused by the transmission of data traffic is negligible when L is large. The variation of the data packet duration T_D has hence little impact. Because the power consumption of the PTIP and PSM wake-up schemes depends on T_C , an increase of the control packets duration would negatively impact PTIP and PSM.

Transceiver bit rate. With a high bit rate transceiver such as a Lucent IEEE 802.11 PC-Card [24], the transmission duration of a 10 bytes control packet is of 0.08 ms, while the setup time remains in the order of 1 ms. As a result, the power consumption of WiseMAC, PTIP and PSM becomes nearly identical.

TX/RX Power Ratio. If the ratio between the power consumption in TX and in RX states approaches 1, then the power consumption of the PTIP protocol approaches the power consumption of PSM.

6 Summary and Conclusion

This paper has proposed WiseMAC and PTIP for the downlink of infrastructure wireless sensor networks. A comparison was made with PSM, the power save protocol used in the IEEE 802.11 and IEEE 802.15.4 Zig-Bee standards. The trade-off between power consumption and delay was analyzed in low traffic conditions. Analytical expressions were given to compute the power and delay of each protocol, as a function of the wake-up period. It was shown that WiseMAC provides, for the same delay, a significantly lower power consumption than PSM. When the wake-up period can be chosen to be very large, it was seen that all protocols approach the power consumption in DOZE state. In such a case, the PTIP protocol becomes attractive as well, because of its implementation simplicity.

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