

WiseMAC: An Ultra Low Power MAC Protocol for Multi-hop Wireless Sensor Networks

Amre El-Hoiydi and Jean-Dominique Decotignie

CSEM, Swiss Center for Electronics and Microtechnology, Inc,
Rue Jaquet-Droz 1,
2007 Neuchâtel, Switzerland
{[ae](mailto:ae@cssem.ch), [jdd](mailto:jdd@cssem.ch)}@cssem.ch

Abstract. WiseMAC is a medium access control protocol designed for wireless sensor networks. This protocol is based on non-persistent CSMA and uses the preamble sampling technique to minimize the power consumed when listening to an idle medium. The novelty in this protocol consists in exploiting the knowledge of the sampling schedule of one's direct neighbors to use a wake-up preamble of minimized size. This scheme allows not only to reduce the transmit and the receive power consumption, but also brings a drastic reduction of the energy wasted due to overhearing. WiseMAC requires no set-up signalling, no network-wide synchronization and is adaptive to the traffic load. It presents an ultra-low power consumption in low traffic conditions and a high energy efficiency in high traffic conditions. The performance of the WiseMAC protocol is evaluated using simulations and mathematical analysis, and compared with S-MAC, T-MAC, CSMA/CA and an ideal protocol.¹

1 Introduction

A wireless sensor network [1] is composed of numerous nodes distributed over an area to collect information. The sensor nodes communicate among them through the wireless channel to self-organize into a multi-hop network and forward the collected data towards one or more sinks. Because of the difficulty to recharge or replace the battery of each node in a sensor network, the energy efficiency of the system is a major issue. A meticulous design of the medium access control (MAC) protocol is key to reach a low power consumption.

Sensor networks are usually meant for the acquisition of data, either periodically and/or based on events. Applications include for example agriculture monitoring, environmental control in building or alarm systems. In most scenarios, it is anticipated that a sensor node will be idle most of the time. For example, in some agriculture monitoring application, measurements reported at

¹ The work presented in this paper was supported in part by the National Competence Center in Research on Mobile Information and Communication Systems (NCCR-MICS), a center supported by the Swiss National Science Foundation under grant number 5005-67322.

an interval of 1 hour may be satisfactory. In an alarm system, one would expect a periodic traffic from the alarms, with a period of e.g. 1 minute, to inform the sink (a central controller) that they are still in operation. From time to time, detected events can cause a large traffic to flow from the alarms to the sink. In alarm applications, a low transmission delay can be a very important additional requirement, beside the low power consumption requirement.

An energy efficient wireless MAC protocol must minimize the four sources of energy waste [14]: 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 packet headers and the signalling required by the protocol in addition to the transmission of data payloads.

With a conventional CSMA protocol, nodes listen to the radio channel whenever they do not transmit. As the power consumption of a transceiver in receive mode is far from being negligible, idle listening becomes clearly the main source of energy waste in scenarios where the channel is idle most of the time. Low power MAC protocols must use techniques to mitigate idle listening. Overhearing must however not be underestimated. If the idle listening problem is efficiently addressed by a MAC protocol, the following important source of energy waste becomes overhearing, especially in dense ad-hoc networks.

This paper presents WiseMAC (*Wireless Sensor MAC*), a novel medium access control protocol for multi-hop wireless sensor networks. This protocol has been briefly outlined in a poster abstract [2]. In [4], its performances were analyzed for the downlink of an infrastructure wireless network (i.e. a collisionless channel) in very low traffic conditions. The original contribution of this paper is the detailed presentation of the WiseMAC protocol and the study of its performance in a multi-hop wireless sensor network, in comparison with other protocols previously proposed by other authors.

The remaining of the paper is organized as follows: Section 2 presents related work. WiseMAC is described in Section 3. Its performance is analyzed in Section 4, considering both a lattice topology with parallel traffic and a random network topology with traffic collected at a sink. Finally, Section 5 gives concluding remarks.

2 Related Work

Among the contention-less medium access control protocols (time, frequency and code division multiple access), TDMA appears as an appealing candidate for a low power MAC protocol, as it causes neither overhearing nor collisions. Sensor nodes may sleep in-between assigned communication slots. In the context of sensor networks, it was proposed in [11], together with a TDMA schedule setup algorithm and signalling protocol. TDMA has several weaknesses when used for wireless sensor networks. First, it is only energy efficient when transporting

periodic traffic. When the traffic is sporadic, many communication slots are empty and energy is thereby wasted. Secondly, the signalling protocol required to setup and maintain the Spatial-TDMA schedule, and to maintain the network synchronization may be very complex and costly both in computational and energetic resources.

Schurgers *et al.* have proposed STEM [10]. This protocol uses two channels: one paging channel and one traffic channel. Most of the time, the network is expected to be in the monitoring state, and only the paging channel is used. In case of an alarm, for example, a path on the data channel is opened throughout the network, where communication occurs using regular wireless protocols (not low power). In STEM, the paging channel is implemented at the receiver side by regularly listening to the channel during the time needed to receive a paging packet. A transmitter that wants to page one of its neighbor will repeat a paging packet containing the destination address, until a reply is received. This protocol provides a low power consumption in the absence of traffic, the paging channel consuming little energy. A traffic burst resulting from an event detection can be transported in an energy efficient way using a classical protocol. The weakness of this protocol is mainly its inefficiency to transport small amount of periodic or sporadic traffic.

Ye *et al.* have proposed S-MAC (Sensor-MAC), which provides a low duty cycle without the need to precisely synchronize the sensor network [14]. This protocol defines sleep intervals, in which all the nodes of the network sleep, and active intervals, in which communication can occur. Because listen intervals are relatively large, only a loose synchronization is required among neighboring nodes. During the listen interval, sensor nodes having traffic to send attempt to reserve the medium and signal to the destination to remain awake for the data transmission using the request-to-send/clear-to-send packet exchange mechanism. With S-MAC, one must select the frame duration (i.e. the total of the listen and sleep intervals), as a trade-off between the average power consumption and the transmission delay. S-MAC exploits the concept of fragmentation to transmit large messages in an energy efficient way.

Van Dam *et al.* have proposed T-MAC (Timeout-MAC) [12]. T-MAC is an improvement of S-MAC. In the T-MAC protocol, the length of the active period is dynamically adapted to the traffic, using a timeout. The active period is ended whenever physical and virtual carrier sensing find the channel idle for the duration of the time-out. A similar idea was also and independently proposed by Ye *et al.* in [15].

S-MAC and T-MAC can currently be seen as benchmarks in the field of contention MAC protocols for sensor networks. WiseMAC will be compared to them.

Rabaey *et al.* have proposed a hardware based solution to wake-up a destination node [9]. They suggest the use of a separate super-low-power wake-up radio that will switch the main radio on at the start of the data packet. This solution is of great interest as it would provide small hop latencies. The wake-up preamble being short, this method would also preserve the channel capacity. The develop-

ment of such a super-low-power wake-up radio consuming only a few tens of μW being still a challenge, solutions using conventional radio transceivers remain of interest. If such a wake-up radio becomes available, it may also be envisaged to use it in combination with low power MAC protocols, to reduce even further the power consumption.

3 WiseMAC

WiseMAC is based on the preamble sampling technique [3]. This technique consists in regularly 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 frame is received or until the medium becomes idle again. At the transmitter, a wake-up preamble of size equal to the sampling period is added in front of every data frame to ensure that the receiver will be awake when the data portion of the packet arrives. This technique provides a very low power consumption when the channel is idle. The disadvantages of this protocol are that the (long) wake-up preambles cause a throughput limitation and a large power consumption overhead in transmission and reception. The overhead in reception is not only bared by the intended destination, but also by all other nodes overhearing the transmission. The WiseMAC protocol aims at reducing the length of this costly wake-up preamble.

The novel idea introduced by WiseMAC consists in learning the sampling schedule of one's direct neighbors to use a wake-up preamble of minimized size. It will be shown that this simple idea provides a significant improvement compared to the basic preamble sampling protocol, as well as to S-MAC and T-MAC. The basic algorithm of WiseMAC works as follows:

Because the wireless medium is error prone, a link level acknowledgement scheme is required to recover from packet losses. The WiseMAC ACK packets are not only used to carry the acknowledgement for a received data packet, but also to inform the other party of the remaining time until the next sampling time. In this way, a node can keep a table of sampling time offsets of all its usual destinations up-to-date. Using this information, a node transmits a packet just at the right time, with a wake-up preamble of minimized size, as illustrated in Fig. 1.

The duration of the wake-up preamble must cover the potential clock drift between the clock at the source and at the destination. This drift is proportional to the time since the last re-synchronization (i.e. the last time an acknowledgement was received). Let θ be the frequency tolerance of the time-base quartz and L the interval between communications. As shown below, the required duration of the wake-up preamble is given by

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

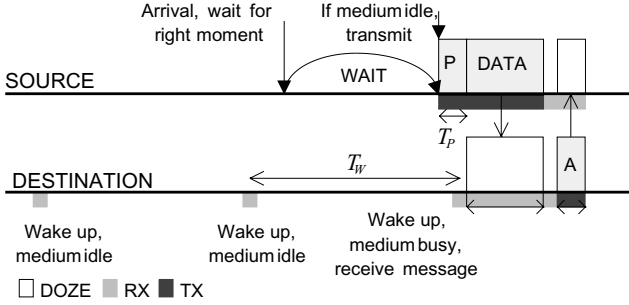


Fig. 1. WiseMAC

Expression (1) can be derived as follows: Assume that both the source and the destination are equipped with a clock based on a quartz with a tolerance of $\pm\theta$. Assume that the source has received fresh timing information from some sensor node at time 0, and that it wants to send a packet to this sensor node at the sampling time L . If the destination 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 transmission θL in advance. Because the clock of the source might be late, the source must target a time $2\theta L$ in advance to L . Because the clock of the source might be early, and the clock of the destination 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 period T_W . In those cases, a preamble of length T_W is used. We thus obtain $T_P = \min(4\theta L, T_W)$.

The transmission will be started at time $L - T_P/2$, to center the wake-up preamble on the expected scheduled sampling. If the medium is sensed busy at the scheduled transmission time, the attempt is deferred using non-persistent CSMA.

The first communication between two nodes will always be done using a long wake-up preamble (of length T_W). Once some timing information is acquired, a wake-up preamble of reduced size can be used. The length of the wake-up preamble being proportional to the interval L between communications, it will be small when the traffic is high. This important property makes the WiseMAC protocol adaptive to the traffic. The per-packet overhead decreases with increasing traffic. In low traffic conditions, the per-packet overhead is high, but the average power consumption caused by this overhead is low.

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.

The synchronization mechanism of WiseMAC can introduce a risk of systematic collision. Indeed, in a sensor network, a tree network topology with a number of sensors sending data through a multi-hop network to a sink often occurs. In this situation, many nodes are operating as relays along the path towards the sink. If a number of sensor nodes try to send a data packet to the same relay, at the same scheduled sampling time and with wake-up preambles of approximately identical size, there are high probabilities to obtain a collision. To mitigate such collisions, it is necessary to add a medium reservation preamble of randomized length in front of the wake-up preamble. The sensor node that has picked the longest medium reservation preamble will start its transmission sooner, and thereby reserve the medium.

A very important detail of the WiseMAC protocol, which is also found in the IEEE 802.11 power save protocol, is the presence of a *more* bit in the header of data packets. When this bit is set to 1, it indicates that more data packets destined to the same sensor node are waiting in the buffer of the transmitting node. When a data packet is received with the *more* bit set, the receiving sensor node continues to listen after having sent the acknowledgement. The sender will transmit the following packet right after having received the acknowledgement. This scheme permits to use a sampling period that is larger than the average interval between the arrivals for a given node. It also permits to reduce the end-to-end delay, especially in the event of traffic bursts.

The *more* bit scheme provides the same functionality as the fragmentation scheme used in S-MAC [14]. An application just needs to segment a large message into smaller packets to obtain the fragmentation behavior. However, the *more* bit scheme is more flexible. Packets that do not belong to the same message but that need to be sent to the same destination will be grouped when using the *more* bit, while they would be sent individually with the fragmentation scheme.

4 Performance Analysis

In this section, the performance of the WiseMAC protocol will be analyzed through simulation and mathematics. Comparisons will be made with the basic preamble sampling protocol [3] (called hereafter BPS), S-MAC, T-MAC, CSMA/CA and an ideal protocol. The purpose of the ideal protocol is to provide a target benchmark for implementable protocols. With the ideal protocol, a node 'magically' knows some time in advance that it has to power-on the receiver to receive a packet. The transceiver is only consuming energy to transmit and receive packets. There is absolutely no idle listening, overhearing nor collision overhead. Real protocols will always consume some energy to implement the wake-up scheme. Their comparison with the ideal protocol will indicate their overhead.

The performance of the WiseMAC protocol has been studied using both a regular lattice topology with traffic flowing in parallel and a typical sensor network topology with randomly positioned sensors forwarding data towards a sink.

The interest of a lattice topology [7] with traffic flowing in parallel is that it allows exploring the behavior of a MAC protocol without inserting aspects linked to routing, load balancing and traffic aggregation. The regularity of the topology allows deriving mathematical expressions to approximate the power consumption. After having introduced the system parameters, we will start the analysis considering the lattice topology in Section 4.2. The random network topology will be addressed in Section 4.3.

4.1 System Parameters

WiseMAC, BPS, S-MAC, T-MAC and CSMA/CA have been modeled on the GloMoSim platform [16]. The radio layer of GloMoSim has been extended to include a DOZE state and to mimic precisely the transition delays of the modeled radio transceiver. The protocols performance is computed using the parameters of the low power FSK radio transceiver developed at CSEM within the WiseNET project [8]. The power consumed in DOZE, RX and TX states is respectively $P_Z = 5 \mu\text{W}$, $P_R = 1.8 \text{ mW}$ and $P_T = 27 \text{ mW}$. The time needed to turn-on the transceiver into the RX or TX state is equal to 0.8 ms and the time to turn it around between these states is equal to 0.4 ms. A bit rate of 25 kbps is assumed. Relatively similar performance curves are obtained with other low power transceivers, such as the RFM TR1000 and Chipcon CC1000 used on Berkeley's mica and mica2 motes [6].

With the WiseMAC protocol, one must select the sampling period, as a trade-off between the hop delay and the average power consumed by the sampling activity. T_W should be chosen large enough such that only a fraction of the power budget is consumed by the sampling activity. The larger the value of T_W , the smaller the power consumption of the sampling activity and the larger the hop delay. However, in terms of lifetime and when using a leaking battery, it doesn't pay to have a power consumption for the sampling activity that is negligible compared to the leaked power. With the WiseNET transceiver and when using an AA alkaline battery with about $30 \mu\text{W}$ leakage power, a good value for the sampling period was found to be $T_W = 200 \text{ ms}$. Using a larger value for T_W increases linearly the delay without increasing much the lifetime.

With S-MAC and T-MAC, 3 different frame durations will be used such as to provide a duty cycle of 1, 5, and 10% in the absence of traffic (10% is the default duty cycle in the implementation of S-MAC on Berkeley's motes [13]). This corresponds to a frame duration of respectively 2000, 400 and 200 ms in the case of S-MAC and 2400, 480 and 240 ms in the case of T-MAC.

4.2 Lattice Network

Topology. In this section, we consider a lattice network topology as illustrated in Fig. 2. A separation of 40 meters between nodes is assumed. As in [12], the number of neighbors in range (the node degree) is chosen to be $N = 8$. This number has been chosen small to limit the local traffic but large enough to provide a well connected topology in a random plane network with the same

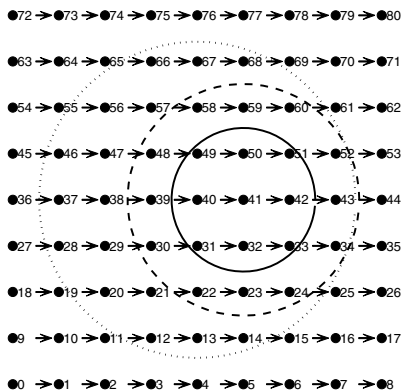


Fig. 2. Lattice network topology

node density (see the percolation theory [5]). Hence, obtained results are also applicable to random plane ad-hoc networks of equal degree.

Traffic. Poisson traffic is generated by nodes on the left (0,9, ..., 72) and transmitted in multi-hop fashion towards nodes on the right (8, 17, ..., 80). The rate λ of the packet generation is constant throughout a simulation. As long as no packets are dropped due to congestion, every node in the network forwards packets at rate λ . Simulations results are shown for packet generation rates varying between 0.001 and 1 packet per second (inter-arrivals L between 1000 s and 1 s). Such traffic can be expected in a sensor network for example as a result of a regular data acquisition (e.g. temperature monitoring) or the periodic transmission of alive messages by alarm sensors. The power consumption calculations are done for node number 40. As was shown in [7], the behavior of this central node is approaching the behavior of a forwarding node in a very large network. Having fewer neighbors, nodes on the sides of the network will suffer less from overhearing, collisions and backoff.

The size of the data portion of the packets is chosen to be of 48 bytes. The MAC layer overhead is of 8 bytes. The resulting frame size is of 56 bytes, and its transmission duration at 25 kbps is of 18 ms. An acknowledgement packet has a length of 12 bytes and a duration of 4 ms. Note that, in an optimized implementation, smaller overheads could be used.

Receive, Interference and Carrier Sense Ranges. The sensitivity of a transceiver is the minimum energy level at which a signal can be demodulated at some given bit error rate (typically 10^{-3}). In WiseMAC, we have chosen to use a receive threshold that is well above the sensitivity, in order to avoid useless wake-ups caused by noise or by weak signals, and wake up only when this is really worth it. Here, the lower power consumption is traded against a potential

transmission range extension. With the two-ray propagation model, the expected reception range for the WiseNET transceiver is 62 meters, as illustrated in Fig. 2 by the solid circle around node 41. All nodes located within this circle may transmit a packet successfully to node 41.

The radio layer model used in the simulation is based on a required SNR. If the sum of all interfering signals is, at any moment during the packet reception, above the packet signal power minus the required SNR, then the packet is declared lost. A SNR of 14 dB is chosen in order to declare a packet received without errors. If the source of the transmission is 40 meters away (node 40), this results in an interference range of 100 meters, as illustrated by the dashed circle around the node number 41.

The dotted circle around node 40 represents the sensitivity range, i.e. the range up to which a transmission is detected, and the medium is declared non-idle. A transmission is initiated by node 40 only if the medium is found idle, corresponding to the situation where none of the 37 nodes located within the dotted circle is transmitting. A reception is attempted only if the data is received at a power above the receive threshold. Having a carrier sensing range larger than the interference range yields a protection against the hidden node effect: all nodes located in the interference range of node 41 are within the sensitivity range of node 40. However, this very interesting property is gained at the cost of a reduced overall maximum throughput, as only one of 37 nodes may transmit at the same time. In a sensor network, this maximum throughput reduction can however be acceptable.

Power Consumption and Hop Delay. Fig. 3 presents the average power consumption (upper plot) and the average hop delay (lower plot) as a function of the traffic. Power consumption results are collected from simulations by recording the time spent by the radio transceiver of node 40 in the states DOZE, RX and TX. The average power is computed as $\sum_{i \in States} r_i P_i$, where r_i is the proportion of time spent in state i and P_i is the power consumed in that state. This average power corresponds to the task of forwarding one packet every L seconds. Power consumption values resulting from simulation have been verified through a theoretical analysis. The dashed lines in Fig. 3 show the theoretical power consumption of WiseMAC, BPS, S-MAC and the ideal protocol (The mathematical expressions and their derivation could unfortunately not be included in this paper for space limitation reasons). The hop delay has been obtained from the simulation by dividing the average end-to-end transmission delay between nodes 36 and 44 by the number of hops (8). The curves are plotted up to an injection rate that causes more than 5% packet loss.

It can be seen in Fig. 3 that WiseMAC provides both a low power consumption and a relatively low hop delay, while the other protocols provide only one or the other.

The comparison between WiseMAC and BPS shows the gain brought by the minimization of the length of the wake-up preamble. For $L = 100$, WiseMAC consumes 3.8 times less power than BPS. For higher traffic, the advantage is even

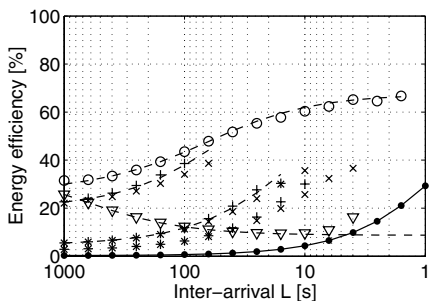
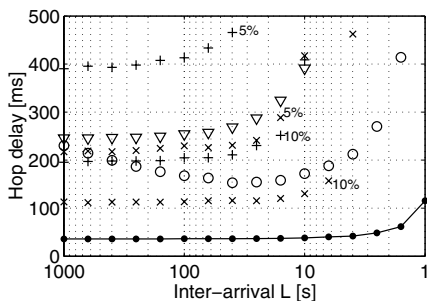
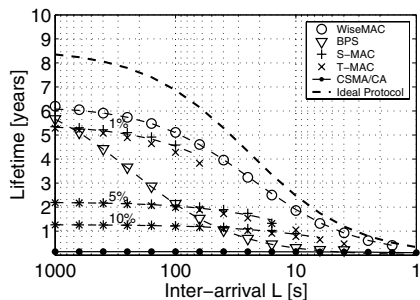
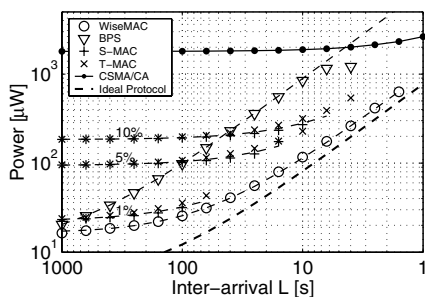


Fig. 3. Average power consumption and hop delay

Fig. 4. Lifetime using a single AA alkaline battery and energy efficiency

greater. As it does not mitigate idle listening, CSMA/CA consumes a minimum of $P_R = 1.8$ mW, which is 70 times more than WiseMAC for $L = 100$. S-MAC and T-MAC consume at least a fraction of P_R , corresponding to the selected duty cycle ($0.1 \cdot P_R = 180$ μ W with 10% duty cycle). The power consumption of S-MAC and T-MAC increases with increasing traffic. For $L = 100$, WiseMAC consumes 7 times less than S-MAC or T-MAC at 10% duty cycle. When used at 1 % duty cycle, S-MAC and T-MAC are closer to WiseMAC in terms of power consumption, but are penalized by a hop delay respectively 10 and 6 times higher than what is provided by WiseMAC.

The hop delay with S-MAC is approximately equal to the frame duration. With T-MAC, it is equal to half the frame duration. These simulation results are in line with the theoretical latency analysis presented in [15]. With BPS, the hop delay is at least equal to the sampling period (as this is also the size of the wake-up preamble). With WiseMAC, the hop delay can become smaller than the sampling period due to the use of short wake-up preambles.

As previously mentioned, simulation results are plotted up to an injection rate that causes more than 5% packet loss. Knowing this, one can notice in Fig 3 (upper plot) that WiseMAC can provide a higher throughput than S-MAC or T-MAC.

Lifetime and Energy Efficiency. The gain brought by a lower power consumption in low traffic conditions is best visible when looking at the lifetime that can be reached with an AA alkaline battery. We use here the battery model introduced in [3]. Fig. 4 (upper part) shows that a lifetime of 5 years can be achieved with WiseMAC when forwarding packets at a rate of 1 every 100 seconds. With BPS, only 2 years are reached. With S-MAC-10% and T-MAC-10%, a little more than 1 year is reached. If the sensor network is operated constantly under a high traffic load (1 packet per second), the lifetime will be very limited with any protocol, even the ideal one. This shows that, if several years of lifetime is a requirement, then high traffic periods should be kept rare.

A meaningful metric for the comparison of low power MAC protocols, especially in high traffic conditions, is their energy efficiency. We define the energy efficiency of a MAC protocol as the ratio between the average power consumed by the ideal protocol and the average power consumed by the protocol of interest. The resulting energy efficiency curves for the different protocols are shown in the lower part of Fig. 4. It can be seen that all protocols have a relatively low energy efficiency in low traffic conditions. Each protocol is associated with a constant minimum power consumption, even in the absence of traffic. With WiseMAC and BPS, this minimum overhead is the sampling activity. With S-MAC and T-MAC, it is the cost of periodically listening to the channel. When the traffic increases, the energy efficiency increases, as this overhead is shared among more packets. With WiseMAC and BPS, there is additionally the overhead of the wake-up preamble. With WiseMAC, the length of the wake-up preamble becomes small when the traffic increases, while it remains constant with BPS. WiseMAC reaches an energy efficiency over 60%. The energy efficiency of the other protocols remains below 40%.

4.3 Random Network

Topology and Traffic. Wireless sensor network are often foreseen to operate in a random multi-hop network topology, where sensors forward data to one or more sinks. Such a topology, as illustrated in Fig. 5, will be considered in this section. The network is composed of 90 sensor nodes, spread over an area of 300×300 meters. Traffic is generated by the 10 black nodes and relayed by the white nodes towards the sink, located on the lower right corner. Routing is pre-computed using Dijkstra's algorithm. The resulting minimum hop routing tree is represented by black lines. The remaining and unused links are represented by gray lines.

The following three experiments have been made:

Idle. No traffic is generated. The simulation is run for 4000 (simulated) seconds (about 1 hour).

Distributed traffic. The 10 black nodes generate periodically, with a period of 400 s, a packet of 48 bytes (56 bytes with MAC header). The first node starts at time 0, the second at time 40, ..., the last one at time 360. Traffic is thus distributed over time. As long as the end-to-end delay remains below

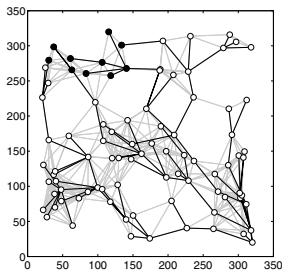


Fig. 5. Random network topology

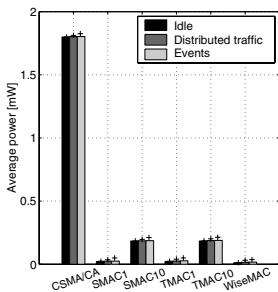


Fig. 6. Average power consumption

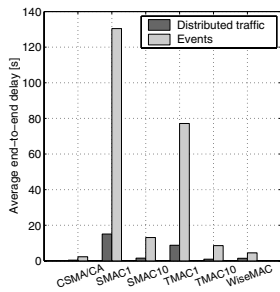


Fig. 7. Average end-to-end delay

40 seconds (which will be the case in this experiment), only one packet is in the network at any time. The simulation is run for 4000 seconds. A total of 100 packets is hence generated.

Events. The black nodes generate periodically, with a period of 400 s, a packet of 48 bytes (56 bytes with MAC header). They all start at the same times 0, 400, 800, ..., 3600 s. This generate periodically a burst of traffic. Again, the simulation is run for 4000 seconds and a total of 100 packets is generated.

The purpose of the *distributed traffic* experiment is to explore the behavior of MAC protocols in low traffic conditions. Such a traffic pattern can be expected in many environmental monitoring applications, such as for the periodic measurement of soil moisture in smart agriculture.

The purpose of the *events* experiment is to explore the behavior of MAC protocols in momentary high traffic conditions. Such a traffic pattern can be expected in alarm systems, such as fire or motion detection sensor networks.

In both experiments, a total 100 packets are forwarded towards the sink. In the *events* experiment, events have been spaced sufficiently such that only 10 packets are in the network at any time. The buffer capacity on each sensor node being of 10 packets, no packets will be lost. Some protocols will require more time to transport the 10 packets than others.

A comparison of the power consumption and delay performances of WiseMAC, S-MAC, T-MAC and CSMA/CA is made in the next sub-section.

Power Consumption and Delay. The bars in Fig. 6 show, for the different experiments and MAC protocols, the average power consumption spent by the nodes. To compute the average power, the total consumed energy is divided by the number of nodes and the simulation time. This average power gives information about the total energy spent in the network. As the lifetime of a network is often bounded by the lifetime of its weakest nodes, it is important to consider also the maximum average power consumed by any node. It is shown as the “+” markers in Fig. 6.

Fig. 7 shows the corresponding average end-to-end transmission delay. This is the average time required by the 100 packets to reach the sink.

The CSMA/CA protocol provides, of course, the lowest average delay for both distributed and events traffic. This is however paid by a power consumption that is much higher than all other protocols. The power consumption of CSMA/CA is lower bounded by the power consumption in receive mode $P_R = 1.8$ mW.

S-MAC-1% and T-MAC-1% provide a low average power consumption, in the order of what is provided by WiseMAC. However, the corresponding delay is very high, while it remains low for WiseMAC. S-MAC-10% and T-MAC-10% are able to provide a relatively low delay, but at the price of a power consumption that is much higher than the one of WiseMAC.

WiseMAC is able to provide a low average transmission delay even in the events experiment. This is made possible by the 'more' bit, which aggregates packets along the path towards the sink and transmit them in bursts.

5 Conclusion

WiseMAC is a contention protocol using the preamble sampling technique to mitigate idle listening. The novel idea introduced by WiseMAC is to minimize the length of the wake-up preamble, exploiting the knowledge of the sampling schedule of one's direct neighbors. Since a node will have only a few direct destinations, a table listing their sampling time offset is manageable even with very limited memory resources.

WiseMAC presents many appealing characteristics. It is scalable as only local synchronization information is used. It is adaptive to the traffic load, providing an ultra low power consumption in low traffic conditions and a high energy efficiency in high traffic conditions. Thank to the 'more' bit, WiseMAC can transport bursty traffic, in addition to sporadic and periodic traffic. This protocol is simple, in the sense that no complex signalling protocol is required. This simplicity can become crucial when implementing WiseMAC on devices with very limited computational resources.

WiseMAC was compared to S-MAC and T-MAC both in a regular lattice topology with traffic flowing in parallel, and in a random network topology with periodic or event traffic flowing towards a sink. When forwarding packets at an interval of 1 packets every 100 seconds, the power consumption of WiseMAC was found to be $25 \mu\text{W}$, providing 5 years of lifetime using a single AA alkaline battery. This was seen to be 70 times better than CSMA/CA and 7 times better than S-MAC and T-MAC at a duty cycle of 10%. It was shown that WiseMAC can provide simultaneously a low hop delay and a low power consumption, while S-MAC and T-MAC can only provide one or the other. Finally, it was shown that WiseMAC is able to provide a higher throughput than both S-MAC-10% and T-MAC-10%.

Acknowledgements. The authors would like to thank Erwan Le Roux for having guided us towards the preamble sampling technique.

References

1. I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: A survey. *IEEE Communications Magazine*, 40(8):102–114, August 2002.
2. A. El-Hoiydi, J.-D. Decotignie, C. Enz, and E. Le Roux. Poster Abstract: WiseMAC, An Ultra Low Power MAC Protocol for the WiseNET Wireless Sensor Network. In *Proc. 1st ACM SenSys Conf.*, pages 302–303, November 2003.
3. Amre El-Hoiydi. Spatial TDMA and CSMA with Preamble Sampling for Low Power Ad Hoc Wireless Sensor Networks. In *Proc. IEEE Int. Conf. on Computers and Communications (ISCC)*, pages 685–692, Taormina, Italy, July 2002.
4. Amre El-Hoiydi, Jean-Dominique Decotignie, and Jean Hernandez. Low Power MAC Protocols for Infrastructure Wireless Sensor Networks. In *Proc. European Wireless (EW'04)*, pages 563–569, Barcelona, Spain, February 2004.
5. E. N. Gilbert. Random Plane Networks. *Journal of the Society of Industrial and Applied Mathematics*, 9(4):533–543, Dec 1961.
6. Jason L. Hill and David E. Culler. Mica: a wireless platform for deeply embedded networks. *IEEE Micro*, 22(6):12–24, Nov.-Dec. 2002.
7. J. Li et al. Capacity of Ad Hoc wireless networks. In *Proc. ACM/IEEE MOBICOM Conf*, pages 61–69, 2001.
8. T. Melly, E. Le Roux, F. Pengg, D. Ruffieux, N. Raemy, F. Giroud, A. Ribordy, and V. Peiris. WiseNET: Design of a Low-Power RF CMOS Receiver Chip for Wireless Applications. *CSEM Scientific and Technical Report*, page 25, 2002.
9. J. Rabaey et al. Picoradio supports ad hoc ultra-low power wireless networking. *IEEE Computer Magazine*, pages 42–48, July 2000.
10. Curt Schurgers, Vlasios Tsiatsis, and Mani B. Srivastava. STEM: Topology Management for Energy Efficient Sensor Networks. In *Proc. IEEE Aerospace Conf.*, volume 3, pages 1099–1108, Mar 2002.
11. K. Sohrabi, J. Gao, V. Ailawadhi, and G.J. Pottie. Protocols for self-organization of a wireless sensor network. *IEEE Personal Communications*, 7(5):16–27, Oct. 2000.
12. Tijs van Dam and Koen Langendoen. An adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks. In *Proc. ACM SenSys*, pages 171–180, Nov. 2003.
13. Wei Ye, John Heidemann, and Deborah Estrin. A Flexible and Reliable Radio Communication Stack on Motes. Technical report ISI-TR-565, USC/ISI, Sept 2002.
14. Wei Ye, John Heidemann, and Deborah Estrin. An Energy-Efficient MAC Protocol for Wireless Sensor Networks . In *Proc. IEEE INFOCOM Conf.*, 2002.
15. Wei Ye, John Heidemann, and Deborah Estrin. Medium Access Control with Coordinated, Adaptive Sleeping for Wireless Sensor Networks. Technical Report ISI-TR-567, USC/Information Sciences Institute, Jan 2003.
16. X. Zeng, R. Bagrodia, and M. Gerla. GloMoSim: a Library for Parallel Simulation of Large-scale Wireless Networks. In *Proc. Int. Workshop on Parallel and Distributed Simulations*, pages 154–161, May 1998.