Available online at www.sciencedirect.com

ScienceDirect

Ad Hoc Networks 6 (2008) 953–969

Ad Hoc Networks

www.elsevier.com/locate/adhoc

FP-MAC: A distributed MAC algorithm for 802.15.4-like wireless sensor networks

Ioannis Gragopoulos [a], Ioannis Tsetsinas [a], Eirini Karapistoli [b,*], Fotini-Niovi Pavlidou [b]

[a] *CERTH – Informatics and Telematics Institute, 1st km Thermi-Panorama Road, GR-57001 Thessaloniki, Greece*
[b] *Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Panepistimioupolis, Thessaloniki GR-54124, Greece*

Received 5 October 2006; received in revised form 23 August 2007; accepted 1 September 2007
Available online 7 September 2007

Abstract

In this paper we focus on the problems of high latency and low throughput arising from the periodic operation of MAC protocols for wireless sensor networks. In order to meet both design criteria we propose an energy-efficient, low delay, *fast-periodic* MAC algorithm, namely FP-MAC, that is exclusively designed for 802.15.4-like networks utilizing in full the standard's physical layer. Our proposal relies on the short periodic communication operation of the nodes comprising the WSN. This is achieved by decreasing the actions that a node needs to perform at the start of every communication period and by incorporating a variable radio-on operation. Moreover, the algorithm introduces differences in nodes' scheduling to further reduce delay. Local synchronization and the crucial task of determining the proper timing for transmission and reception of data is achieved through the periodic broadcast of special synchronization frames at the beginning of each on-period. FP-MAC is evaluated and compared to S-MAC and T-MAC through extensive simulations, showing a significant improvement in terms of low energy consumption and average MAC delay.

Keywords: Wireless sensor networks; Medium access control; Energy and latency efficiency

1. Introduction

Wireless sensor networking is an emerging technology that has a wide range of potential applications including environmental control, home automation, military sensing and health monitoring [1]. The recent release of standards in the field, such as the IEEE 802.15.4 [2] for low-rate wireless personal area networks (LR-WPANs), brought the technology out of research labs and stimulated the development of numerous commercial products. Since its proposal in 2003, the IEEE 802.15.4 protocol has been attracting more and more research work enforcing its deployment in wireless sensor networks (WSNs). Also, many manufacturers of the WSN technology (namely all the ZigBee Alliance members [3]) are shifting towards this standard

* Corresponding author. Tel.: +30 2310 233722.
E-mail addresses: grag@iti.gr (I. Gragopoulos), tsetsinas@iti.gr (I. Tsetsinas), ikarapis@auth.gr (E. Karapistoli), niovi@auth.gr (F.-N. Pavlidou).

1570-8705/$ - see front matter
doi:10.1016/j.adhoc.2007.09.001

solution due to its increasing popularity and interesting technical features [4]. The provision of low cost and low power wireless connectivity within short ranges of up to 20 m, are some of the characteristics that make the 802.15.4/ZigBee protocol particularly suited for WSNs.

A typical WSN is a large set of wireless nodes, with sensing, monitoring and processing capabilities, deployed in an *ad hoc* fashion [5]. These wireless nodes are autonomous, battery-operated devices, with limited energy capacity and computational processing capability, mostly designed for unattended operation. These devices require mechanisms to minimize energy consumption, in order to ensure a long-lasting operation without the need for replacement/recharging the battery. Several special mechanisms need to be implemented in all the network layers, from physical to application. In this study, we concentrate on medium access control (MAC) protocols since this gives a fine-grained control to switch the wireless radio on and off and therefore to effectively prolong the network lifetime.

As already mentioned, energy conservation is the primary and most important challenge to meet since it determines the lifespan of a sensor network [6]. Since the power consumption of a transceiver is remarkably high during channel listening, the best way to achieve energy conservation is to turn off the radio electronics on every network node for as long as possible. The crucial challenge is to keep the nodes' radios on only for the time necessary to exchange data. Since there is no "Wake-Up Radio" in the market products developed (i.e. an ideal receiver that wakes-up only when it detects signal at its antenna), the only solution that approaches this, is to periodically switch on and off a node's radio, ultimately to keep the radio on only when communication is needed.

Another concern in the design of an efficient MAC is to fairly and efficiently share communication resources between sensor nodes. Generally, MAC protocols can be broadly classified based on their resource sharing mechanisms in two major categories: (a) schedule-based and (b) contention-based. Both techniques can be used in wireless sensor network applications, albeit with different advantages and disadvantages each. Schedule-based techniques can more easily satisfy WSN's requirements, since they have the inherent capability of power conservation and can lead to collision-free MAC protocols. Contention-based techniques require an additional control stage in order to implement the periodic on and off turning of the radio. Moreover, when several sensor nodes wish to transmit to a common destination they have to contend for the medium during the destination's on-period. This implies that their performance under high contention suffers because of high overhead in resolving contention and collision [7]. From this point of view, schedule-based protocols have natural advantage over contention-based protocols, but, on the other hand, local or global synchronization between network nodes as well as complicated slot assignment procedures are required.

Derived from the above description, novel algorithms are of need, to effectively tackle the unique resource constraints and application requirements of WSNs. The common reference point of the above techniques and the key factor for energy conservation appeared to be the *periodic operation*. As already seen, periodicity can be implemented either in a straightforward way (i.e. in schedule-based MAC protocols) or not (i.e. in contention-based MAC protocols). Yet, whatever of the access technique in use, the selection of a proper *duty cycle*, which is the percentage of on-time with respect to total period duration, is mandatory. Smaller duty cycle values improve power consumption but also lead to higher end-to-end delays which can be a serious drawback, especially in multi-hop systems [5]. This tradeoff between consumption and delay with respect to period selection was the major motivation for this paper.

In this paper, we propose a new MAC algorithm for wireless sensor networks, namely FP-MAC. Current MAC solution is successfully integrated with the IEEE 802.15.4/ZigBee standard and is capable of using small period values by decreasing the actions that a node needs to perform at the beginning of every communication period and by incorporating a variable radio-on operation. The algorithm also incorporates the idea of scheduling the listening times of the nodes, while using contention over the transmission of data during each node's on period with a simple back-off mechanism. The above features together with the algorithm's fast-periodic operation lead to an energy-efficient MAC algorithm that lowers the delay in wireless sensor networks.

The remainder of the paper is organized as follows: Section 2 describes several existing widely accepted access methods proposed for WSNs. In Section 3 we introduce several features of the underlying 802.15.4 standard in order to provide a better understanding of the FP-MAC algorithm. In Section 4, we present an analytical description of the proposed algorithm, while in Section 5 we illustrate the obtained simulation results, followed by detailed reports. Finally, conclusions are given in Section 6.

2. Related work

Piconet [8] was one of the first contention-based MAC protocols that introduced periodic sleep for energy conservation. However, there is no coordination and synchronization among nodes about their sleep and listen time. The scheme to enable the communications among neighboring nodes is to let a node broadcast its ID when it wakes-up from sleeping. If a sender wants to talk to a neighbor, it must keep listening until it receives the neighbor's broadcast. Although ID reception secures that the destination node is alive, there is no information about its schedule. This results in energy waste, since the source node may have to wait for unnecessary long time with its receiver on, until the reception of neighbor's ID.

One of the famous contention-based access protocols is the sensor-MAC protocol or S-MAC [9]. S-MAC inspired by PAMAS [10], uses a coordinated sleeping mechanism, similar to the IEEE 802.11 DCF power saving (PS) mode [11], and in-channel signaling to avoid overhearing. In S-MAC, neighbor nodes are organized in virtual clusters by adapting a common schedule for their fixed sleep and wake-up cycles. At the beginning of each active period, nodes exchange synchronization information. Following this, data may be exchanged for the remainder of the active period using the RTS–CTS mechanism. Although RTS–CTS can alleviate the hidden terminal problem, it incurs high overhead because data packets are typically very small in sensor networks. Exchanging control messages in the order of the actual data packets leads to bandwidth waste and increased protocol overhead (40% to 75% of the channel capacity in sensor networks [12,13]). Moreover, although S-MAC achieves low power operation, it accomplishes this by trading off energy for latency. In a follow up work [14], the increased latency caused by the periodic sleep of each node, is improved by utilizing an adaptive listening mechanism that allows a node which overhears its neighbor's RTS or CTS packet transmission to wake up for a short period of time at the end of the transmission and immediately receive data if it is the next-hop node.

Several S-MAC variations have been proposed since then, mainly concentrated on further energy conservation during the radio on time of a sensor node. Timeout-MAC (T-MAC) [15] is one of them and improves S-MAC's energy usage by using a very short extendable listening window at the beginning of each active period. After the SYNC section of the active period, there is a short window to send or receive RTS and CTS packets. If no activity occurs in that period, the node returns to sleep, otherwise it remains awake for the packet delivery to be performed. By changing the protocol to have an adaptive duty cycle, T-MAC saves more energy under variable traffic, but, unlike FP-MAC, and due to its identified early sleeping problem, T-MAC achieves lower throughput.

Data gathering-MAC (D-MAC) [16] achieves very low latency for convergecast communications (data gathering trees) compared to other sleep/listen period assignment methods in energy-efficient way. Low latency is achieved by assigning subsequent slots to the nodes that are successive in the data transmission path. Each node first listens to its children, then propagates any messages up to its parent. D-MAC uses simple CSMA with acknowledgements. When a number of nodes that have the same schedule (the same level in the tree) try to send to the same parent node, collisions will occur. Nodes losing contention do not need to wait for the next upwards flow, but may try again in an over flow slot scheduled after any occupied Recv/Send pair. The down side of D-MAC is that it lacks the flexibility to support communication patterns other than convergecast. In particular, local-gossip based on broadcast does not work because neighbors (children and parents) listen at different times.

TDMA-based protocols, such as [17–21], are naturally energy conserving, because they have a built-in duty cycle, and do not suffer from collisions, thus making them favorable when maximum bandwidth utilization is required. However, maintaining a TDMA schedule in an ad-hoc network is not an easy task and requires much complexity in the nodes. TDMA-based protocols usually require the nodes to form communication clusters. Thus, when the number of nodes within a cluster changes, due to addition or removal of sensor nodes, it is not easy for a TDMA protocol to dynamically change its frame length and its time slot assignment. So, its scalability is not as good as that of a contention-based protocol. Their scalability efficiency is reduced and is substantially bounded by parameters reported in [22] (i.e. the inaccurate synchronization among neighboring nodes). Finally, another drawback of these schemes is that, like most fixed scheduling mechanisms, time slots are wasted if a node does not have any data to send to the intended receiver and since WSNs are to support low data rates applications, TDMA-protocols are not suited for them.

From our knowledge, no adequate MAC-related work exist in the context of the IEEE 802.15.4 standard and more specifically in its unslotted CSMA-CA mode. Most efforts were made in the direction of evaluating the performance of the beacon-enabled 802.15.4 mode [23,24]. Moreover, in all the above proposals, the main effort has been focused on energy consumption minimization (which is fundamental for the operation of WSNs), disregarding in a degree other critical system parameters such as delay and throughput. This work, which distinguishes itself from previous work by relying on the IEEE 802.15.4 physical layer, addresses both energy, latency and throughput issues by introducing a novel distributed MAC algorithm, namely FP-MAC, where no synchronization and topology information is needed. Next, we provide an overview of the underlying standard.

3. Overview of the IEEE 802.15.4 standard

IEEE 802.15.4 (Zigbee) [2] is the new standard that has been developed to provide low power, low cost and highly reliable wireless connectivity among inexpensive, battery-powered devices that are deployed for lengthy periods of time without maintenance [5]. The standard defines the physical (PHY) and the medium access control (MAC) layers. The PHY and MAC layers provide building blocks for supporting multiple network topologies, including both star and peer-to-peer networks depending on the application requirements. The personal operating space (POS) of 10 m determines the range over which the wireless links are feasible. An 802.15.4 network can simply be a one-hop star/peer-to-peer, or, when lines of communication exceed 10 m, a self-configuring, multi-hop network.

Application scenarios for WSNs are defined by the ZigBee Alliance [3] that uses the IEEE 802.15.4 standard and adds layers for application, security and networking. These applications, which have relaxed throughput requirements and are often measured in a few bytes per day, include industrial control and monitoring, home automation and consumer electronics, security and military sensing, asset tracking and supply chain management, and health monitoring. Resource limitations typically found in sensor devices accentuate the need for algorithm optimizations in such applications. Cross-layer interactions are favored over strict layering of the network components and regarded as the basis to provide the optimization capabilities required by the aforementioned sensor network applications. In the following subsections, we give a brief overview of the 802.15.4 PHY and MAC layers, followed by an introduction into the configurability of these two layers. A detailed description on the IEEE 802.15.4 PHY and MAC can be found in [25].

3.1. The PHY layer

The PHY layer dictates how 802.15.4 devices may communicate with each other over the wireless channel. It offers two PHY functions which are both based on direct sequence spread spectrum (DSSS) methods that result in low cost digital IC implementation, and both share the same basic packet structure [25]. The difference between the two PHYs is the operating frequency band and the supported data rates. The 2.4 GHz PHY specifies operation in the worldwide 2.4 GHz ISM band, while the 868/915 MHz PHY specifies operation in the European 868 MHz band and 915 MHz ISM band (in the United States). The 2.4 GHz PHY provides a transmission rate of 250 kb/s and a maximum MAC protocol data unit (MPDU) of 127 Bytes which, after accounting for the PHY-layer preamble (6 bytes), translates to a total packet size of 133 bytes (Fig. 1). The 868/915 MHz PHY offers rates of 20 kb/s and 40 kb/s for its two bands, respectively.

This layer is responsible for activation and deactivation of the transceiver according to the request from the MAC sublayer, channel frequency selection (one out of 27 available), and data transmission/reception. Furthermore, the PHY performs channel energy detection (ED), link quality indication (LQI) for received packets, and clear channel assessment (CCA) for the MAC's carrier sense multiple access with collision avoidance (CSMA-CA) protocols. In addition to the packet length information and the PHY payload, a PHY packet includes a 5 byte synchronization header (SHR) which allows

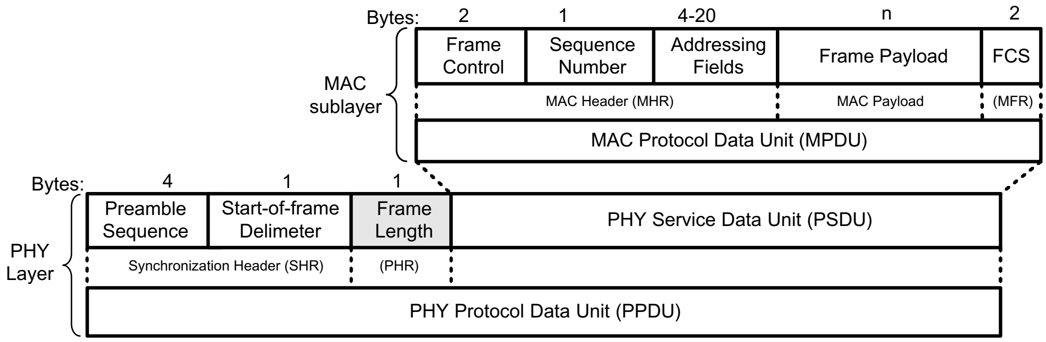


Fig. 1. The general IEEE 802.15.4 Frame Format.

devices to synchronize with the bit stream which forms the transmitted message.

3.2. The MAC sublayer

The MAC sublayer coordinates access to the shared channel among the competing devices and in IEEE 802.15.4 it can operate on both *beacon enabled* and *non-beacon enabled* modes. In the beaconless mode, decentralized channel access is managed through an unslotted CSMA-CA mechanism, where devices may directly communicate with each other in peer-to-peer connections. The new standard, unlike other protocols designed for wireless networks such as the IEEE 802.11 standard [11], does not include the request-to-send (RTS) and clear-to-send (CTS) mechanism, in consideration of the low data rate used in LR-WPANs. In the beacon-enabled mode or slotted CSMA-CA approach, a star topology is formed. In this, the PAN coordinator relies on a superframe structure in order to provide services such as beacon generation and synchronization, PAN association and disassociation, channel accessing via the CSMA-CA mechanism and maintenance of the guaranteed time slot (GTS). The PAN coordinator periodically transmits a beacon that specifies the superframe start and which other devices use both for synchronization and for determining when to enable transmission and reception of messages. Since the FP-MAC algorithm relies on the unslotted CSMA-CA version of the standard, the analysis that follows is concentrated on it.

3.3. Configuring 802.15.4

In the unslotted CSMA/CA version of the standard two attributes of particular importance are: *aTurnaroundTime* and *aMaxFrameRetries*. The first one describes the necessary time for the transceiver to swap between the following states: Rx-to-Tx and Tx-to-Rx and requires a total of 12 symbols or equally 192 μs (hardware limitation). This time is enough for a contending node to assess clear channel and begin transmission of a new packet, since only 160 μs are required for the CCA to be performed [2]. The transmission procedure begins with a randomly selected back-off time from an initial window of $[0, 2^{BE} - 1]$, where BE is the back-off exponent and has an initial value of 3.[1] After this time elapses, carrier sense (CS) is performed at the physical layer and if no radio activity is detected, transmission starts. If the *TxOptions* parameter specifies that an acknowledged transmission is required, the MAC sublayer will enable its receiver immediately following the transmission of the MPDU and wait for an acknowledgment from the recipient for at most *macAckWaitDuration* symbols (54–120 symbols). If the MAC sublayer does not receive an acknowledgment within this time, the device concludes that the single transmission attempt has failed. A device shall repeat the process of transmitting the data, up to a maximum of *aMaxFrameRetries* times, equal to 3. If an acknowledgment is still not received after *aMaxFrameRetries* retransmissions, the MAC sublayer shall assume the transmission has failed and notify the next higher layer of the communications failure. Within the FP-MAC algorithm these parameters remained unchanged.

[1] The maximum number of permitted random back-off stages is determined by the parameter *macMaxCSMABackoffs*, which has a default value of 5.

4. Proposed algorithm description

4.1. The concept

In a contention-based MAC algorithm, the key element in optimizing the energy consumption is to minimize the duration of receiver's on time before the actual data exchange can take place. This time interval, which we refer to as *minimum active time* (t_{m}), consists of possible signaling, handshaking, collision avoidance mechanisms, plus the necessary Tx/Rx turnaround and calibration time and poses the lower bound on the radio on time. This bound varies in different MAC implementations. An implementation that needs more time to accomplish the above procedures clearly requires to operate in longer periods so as to achieve the same duty cycle d. This is shown in Fig. 2, where the sum ($t_{\mathrm{m}} + t_{\mathrm{on}}$) corresponds to the radio-on time and the fraction $(t_{\mathrm{m}} + t_{\mathrm{on}})/d$ to the period length (p) given the duty cycle's definition. Furthermore, in those systems that operate in a periodic manner, data transfer latency naturally depends on the frequency of the operation cycle (namely period) with faster cycle iterations yielding better performance. Summing up, the ability of a MAC algorithm to shrink the period and therefore reduce latency, emanates from its potential to operate at a very short minimum active time, otherwise either there will be no useful time interval to exchange data, or the duty cycle will be increased in such values that practically no energy conservation will be achieved.

In S-MAC and its variations, the synchronization phase plus the RTS–CTS handshaking procedure implies a long *minimum active time*, restricting their ability to absorb the traffic fluctuations in a wireless sensor network while keeping the average radio-on time, the delay and throughput in efficient levels. In a typical WSN, a sensor node spends most of its operation time without communicating (in [26] it is shown that idle listening accounts for more than 90% of the power consumption), so it has to operate in a minimum duty cycle that will extend network lifetime. On the other hand, the same duty-cycle should guarantee an acceptable delay and throughput when traffic (sensing information, signaling, routing, etc.) exists. As it will be shown in Section 5, S-MAC and T-MAC do not fulfill the above requirements.

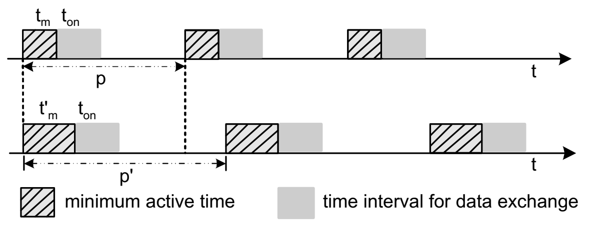


Fig. 2. Minimum active time with respect to the operation period.

In this study, we remedy these issues by spreading neighbor nodes' wake-up schedules within a period (in contrast to S-MAC where nodes synchronize their schedules), and by replacing the RTS–CTS handshaking with a simple back-off algorithm. These techniques allow us to highly reduce the *minimum active time*, improving the overall performance, while keeping the implementation complexity at low levels.

4.2. Detailed description

The core of the proposed algorithm relies on the periodic sleep/wake-up operation of the wireless nodes comprising the WSN. At the beginning of every period there is a radio-on time (T_{L}) which consists of the broadcasting of a synchronization frame and a minimum idle listen time that a node requires in order to identify possible transmissions (Fig. 3).

The synchronization frames contain essential parameters of the transmitting node, such as its id, its period and its oscillator's drift. A node that receives a synchronization frame, stores its information locally and consequently learns the consecutive moments that the corresponding neighbor node will be able to receive data. Considering that in 802. 15.4-compliant radio transmitters[2] the current consumption is similar during the receive, transmit states, there is no extra power consumption during the transmission of these frames. Moreover, in 802.15.4-like radios, "*listening*" describes the procedure where the receiver seeks the channel in order to acquire the preamble sequence and "*receiving*" the procedure where the receiver have acquired the preamble sequence and is receiving frame bytes [28]. Since coherent reception is performed within the DSSS technique, there is no difference between

[2] We use the transceiver characteristics of the commercially available CC2420 Chipcon radio [27] where each sensor consumes as high as 19.7 mA, 17.4 mA and 20 μA, in receive, transmit and power down modes, respectively.

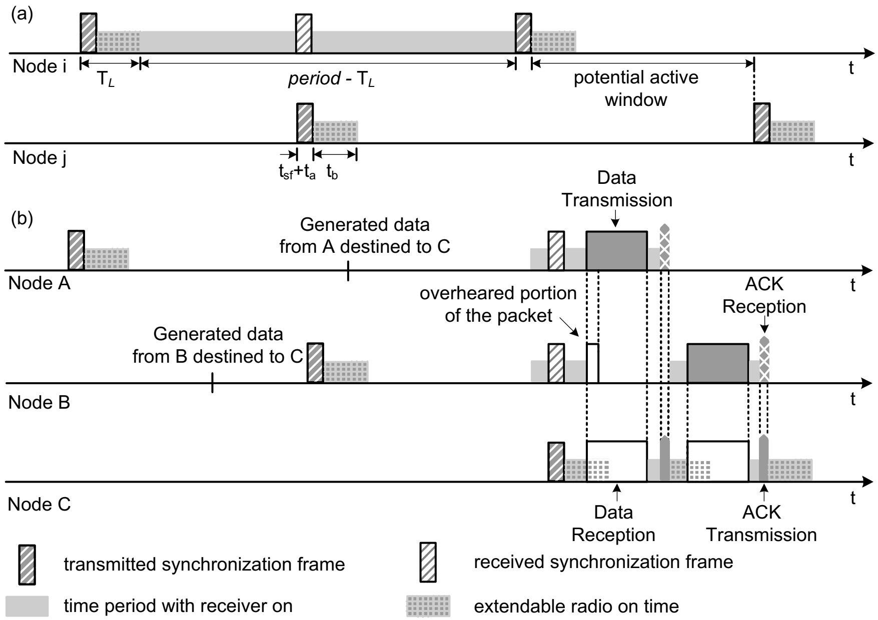


Fig. 3. (a) Channel activity while node *i* is searching for neighbors nodes and (b) channel activity for receive and transmit processes between node *a*, *b* and *c*.

listening and receiving in these radio transceiver models.

Immediately after broadcasting the synchronization frame, the node turns over from Tx to Rx and listens for potential data. If no channel activity occurs after time T_L, the node turns its radio off. If data is detected, the node extends its active time interval in order to complete the reception procedure, which includes the acknowledgment mechanism. After the reception of a complete packet, the node continues to listen for an additional time, equal to t_b (Fig. 3a), for further possible transmissions. This procedure can be repeated (attempted), if it can be completed, until the next successive synchronization frame of any other neighbor node. This time duration is called the *potential active window* and it depends both on the duration of the operation period and the number of nodes comprising the network. As the number of nodes within vicinity increases the length of the operation period should be long enough to provide the nodes with sufficient potential active window for data transmission. The remaining data, if any, will be deferred to the next active cycle of the receiving node. Both the *potential active window* and the period duration are constant and application-related parameters known by all nodes comprising the WSN. Simulation results would verify that a period of 200 ms may efficiently accommodate the applications requirements of a dense network consisting of 20 nodes located in the same cluster (one-hop topology). Finally, a 5-packet long *potential active window* (as the one used in simulations for the FP-MAC algorithm) may deliver data with very low delay.

When a node wishes to transmit to its neighbors it needs to wait their scheduled wake-up period. Thus, the node first checks the corresponding stored timing information and switches on its radio slightly before the expected broadcast of the neighbor's synchronization frame in order to receive it. The reception of this frame is mandatory in order to confirm that the destination node is still alive and operational. Upon reception of this frame the transmission procedure begins with a randomly selected back-off time. After this time elapses, carrier sense is performed at the physical layer and if no radio activity is detected, transmission starts. During the back-off time, all the contending nodes have their receivers on, so when one acquires the channel and starts data transmission, the rest of the contenders are able to listen the transmission and consequently to learn the packet length in order to calculate the end of the transmission. During this time interval, they switch off their receivers (since another node has gained the channel and transmits data) and schedule a new back-off contention period, if the destination's potential active window allows it, immediately after the completion of transmission which includes the acknowledge mechanism. Note that in 802.15.4-like networks [2] the addressing scheme used (Fig. 1) allows this trick to be implemented very easily, since the packet length resides at the beginning of each packet, immediately after the preamble sequence and before the address bytes. So each node that overhears a transmission has the ability to learn its length, even if it is destined to another node, before address recognition mechanism fails.[3] Thus, a contenting node overhears just six bytes of the total packet (4 bytes preamble, 1 byte start frame delimiter and 1 byte packet length), which are actually useful information in order to safely schedule the next contention interval in the same active window.

The benefits of the described procedure are a significant decrease of overhearing energy waste and elimination of retransmissions due to lost acknowledgement packets. An acknowledgement packet can be destroyed because the time interval between the end of the data reception and the start of the transmission of the acknowledgement packet (Rx/Tx turnaround time, see Section 3.3) is enough for a contending node to assess clear channel and begin transmission of a new data packet. This actually destroys two packets, the one already received and being acknowledged and the new one being transmitted, and in our case is effectively avoided.

During the network setup stage and before each node starts its periodic operation, it needs to run a neighbor discovery (ND) protocol and to schedule its on-period in a *free* time window. Hence, the node first listens for a certain amount of time, equal to *two* periods. This constraint gives the receiver enough time to collect synchronization frames in the neighborhood. If during the listening time it does not hear channel activity, it immediately broadcasts its synchronization frame. On the other hand, if a node receives synchronization frames during the listening time, it chooses a time window that will not overlap with the already scheduled ones and starts broadcasting its own synchronization frame. The neighborhood discovery process described above, during which data reception is disabled, is essential since it enables nodes to adapt to network changes and to compensate timing errors attributed to oscillators' drift. Moreover, it is fully distributed, meaning that each node runs it at its own, and can be performed either periodically or reactively according to the application requirements. In the former case, the frequency with which a node performs neighbor discovery depends on the node density in its vicinity. If a node does not have any neighbor, it performs neighbor discovery more aggressively than in the case that it has many neighbors. In FP-MAC algorithm a node performs neighbor discovery every 50 cycle periods if it has at least one neighbor. The latter case on the other hand, can either be performed after a node assesses that it does not contain a fully updated neighbor list or can be part of a reactive routing protocol that runs on top of the network layer.

Another issue occurs if two-hop distant nodes have the same period for transmitting the synchronization frame or for simplicity the same schedule. For example, consider a sensor network of 3 nodes as the one shown in Fig. 4a, where nodes *a* and *c* are assigned the same schedule (1) while node *b* (the intermediate common node) is assigned schedule (2). When a delivery is performed from node *b* to node *a* it shall also be heard from node *c*. The non-intended receiving node *c* that overhears the delivery, schedules to transmit a MAC command frame to node *b* (in node *b*'s active window) informing its neighbor for the colliding schedules (phase I). Then, node *b* shall reply to node *a* with another MAC command frame that contains the collided schedule and its neighbor list (phase II). Node *a* in turn, after evaluating that information together with its own neighbor list it chooses a new collide-free schedule (3) and announces it to their neighbors (phase III). Apparently, that change will not be known at node's *a* neighbors until the next neighbor discovery protocol is run by them.

The reliability of the algorithm is based on each node's uninterrupted process of transmitting syn-

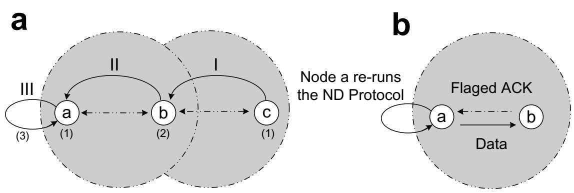


Fig. 4. Conflict situations: (a) two-hop distant nodes have the same period for transmitting the synchronization frame and (b) a collision in synchronization frame is identified.

[3] Since an overhearing node is not actually interested for the data payload integrity, no CRC reception is required. Even if data is damaged, the transmission will be terminated after *frame length* bytes.

chronization frames, since this is the only way for the nodes to announce their presence at their neighbors and also to obtain a unique time to schedule their radio on operation. Keeping the correct timing for broadcasting synchronization frames is the highest priority task for each node and guarantees algorithm's reliable operation. Whatever a node is doing, it will be interrupted for the accurate on-time transmission of the synchronization frame.

Although CSMA/CA algorithm is used for every transmission, there is still probability for collisions in data as well as in synchronization frames. In the case of data frames, collisions can easily be identified and coped with retransmissions. However in synchronization frames, which are broadcast packets, it is impossible to detect collisions due to lack of an acknowledgement mechanism. For example, consider the case shown in Fig. 4b, where node *a* does not succeed in getting a schedule due to a collision of its synchronization frame. Then, the neighboring within-range node *b* that receives a packet destined from *a* (note that node *a* does not appear in node's *b* neighboring list), informs the latter for a possible collision by enabling a flag at the acknowledgement packet of the first data delivery. In turn, node *a* re-runs the neighbor discovery protocol to obtain a non-colliding schedule. Node *b* on the other hand, removes node *a* from its list of neighbors until fresh synchronization information is received by this node.

4.3. Performance considerations

The crucial parameter in FP-MAC algorithm is the determination of an effective minimal amount of idle listening T_L (Fig. 3a). The T_L time duration is the sum of three elements:

$$T_L = t_{sf} + t_a + t_b, \tag{1}$$

where t_{sf} is the required time to broadcast the synchronization frame, t_a is the Tx/Rx turnaround time and t_b is the maximum time required to implement one back-off. The values of t_{sf} and t_a are deterministic. Time t_{sf} depends on the transmission rate (250 kbps for 802.15.4-like networks) and the number of bytes transmitted within the synchronization frame. Time t_a depends on the transceiver's PLL lock and calibration time. Thus, the only parameter that significantly affects T_L and can be adjusted, is the time required to implement one back-off, t_b. The back-off is performed as follows; time is divided in slots of 160 μs, i.e. the minimum time for a 802.15.4 receiver to assess clear channel [2]. A node randomly selects a number of slots with uniform distribution within the range of [1,B_{max}]. The value of B_{max} depends on the possible medium contenders, namely neighbor nodes. It should be small enough to maintain a short T_L (otherwise it will lead to energy waste), while keeping collisions in negligible levels. The probability P_s that a node will acquire the channel in a single contention period is therefore a function of B_{max}.

Let us assume that *n* is the number of contending nodes and that node *x* selects a slot out of B_{max} available (all B_{max} slots are independent, thus they have the same chance of being selected). Since every node selects a slot with uniform distribution, namely $1/B_{max}$, the probability that a node does not acquire the *1*st slot is equal to $(1 - 1/B_{max})$. Moreover, for a node to acquire a slot and for that slot not to be the *1*st nor the *2*nd, the probability becomes:

$$1 - \left(\frac{1}{B_{max}} + \frac{1}{B_{max}}\right) = 1 - 2 \cdot \frac{1}{B_{max}}. \tag{2}$$

Evidently, for a node to acquire a slot and for that slot not to be from the *1*st to the *i*th one, the probability is:

$$1 - \left(\frac{1}{B_{max}} + \frac{1}{B_{max}} + \cdots + \frac{1}{B_{max}}\right) = 1 - \frac{i}{B_{max}}. \tag{3}$$

It is known that, a node can gain access to the channel by reserving the *i*th slot, if the rest of the $n - 1$ contenders select a slot greater than *i*. This probability is given by

$$\begin{aligned} P_i &= \frac{1}{B_{max}}\left(1 - \frac{i}{B_{max}}\right) \cdots \left(1 - \frac{i}{B_{max}}\right) \\ &= \frac{1}{B_{max}}\left(1 - \frac{i}{B_{max}}\right)^{n-1}, \end{aligned} \tag{4}$$

where $1/B_{max}$ is node's *x* probability of selecting the *i*th slot and $(1 - i/B_{max})$ the probability of a node selecting a slot different from the *1*st to the *i*th one, obtained from Eq. (3). If Eq. (4) is applied for all independent slots, 1 through B_{max}, the probability P_s becomes as follows:

$$P_s = \sum_{i=1}^{B_{max}} P_i \overset{(2)}{\Rightarrow} P_s = \sum_{i=1}^{B_{max}} \frac{1}{B_{max}}\left(1 - \frac{i}{B_{max}}\right)^{n-1}. \tag{5}$$

Finally, since *n* is the total number of contenders, the probability P_s is given by

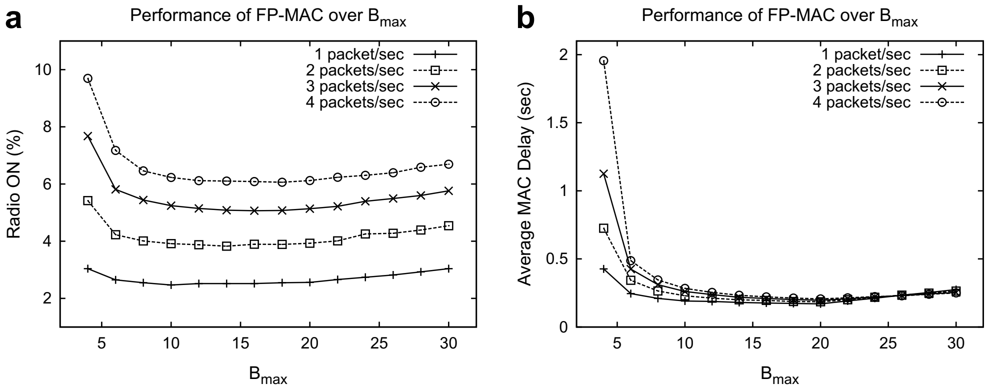


Fig. 5. (a) Radio on percentage and (b) average MAC delay with respect to B_{max} variations.

$$P_s = n\sum_{i=1}^{B_{max}} \frac{1}{B_{max}}\left(\frac{B_{max}-i}{B_{max}}\right)^{n-1}. \quad (6)$$

Fig. 5a and b depict the effect of B_{max} on the radio on operation and the average MAC delay, respectively, for different traffic load conditions. A minimum radio on operation appears in Fig. 5a showing that B_{max} can be tuned in order to provide improved radio on performance. On the other hand, the average MAC delay shows a stable behavior regardless of the B_{max} variations. Moreover, most values of B_{max} are close to optimal both for the radio on and the average MAC delay, rendering any B_{max} value between 10 and 20 a proper choice. The probability P_s exceeded the 80% for this choice.

5. Performance evaluation

5.1. The simulation model

In order to test the robustness of the FP-MAC algorithm, we conducted a series of simulation tests. The simulation environment which resembles a static wireless sensor network was created using the OMNeT++ discrete event simulator [29]. OMNeT++ has been enhanced with the functionality of the FP-MAC algorithm. Its wireless channel model has also been modified to support all the available 802.15.4 radio states and other 802.15.4-related PHY characteristics.

Sensor nodes are distributed in an $50 \times 50\ m^2$ area under the topologies shown in Fig. 6. Each node was characterized by a radio transmission range of 15 m and a radio interference range of 20 m. Two different types of traffic that are typical of sensor networks are considered in our study; a *peer-to-peer* and a *sink-type* application traffic [30]. The latter case represents traffic driven by data gathering applications where a sink located either at the corner or the center of the network, collects the relayed data for further processing (Fig. 6c).

In the application patterns described above, all wireless nodes generate sensing data based on an exponentially distributed inter-arrival time. The packet rate was varied from 0.25 packets/s to 4 packets/s. With such inter-arrival times, the need

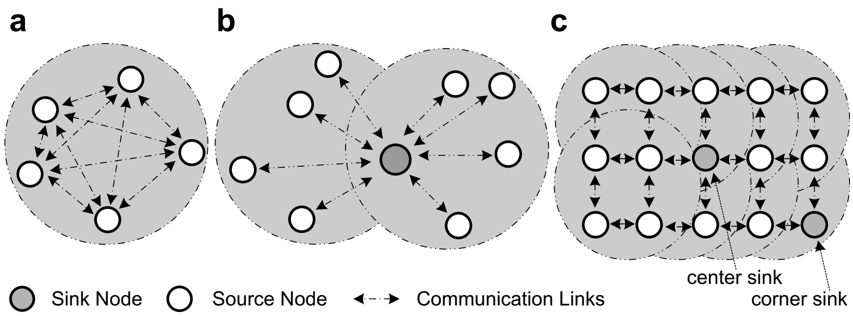


Fig. 6. A sample (a) one-hop topology, (b) two-hop topology (the two clusters' radio range overlap on the sink node) and (c) multi-hop (grid) topology.

for information transfer (sensing data and control data as well) is satisfied in a typical WSN [25]. Each data packet has a size of 37 bytes including a preamble of 6 bytes, a header of 11 bytes and data payload of 20 bytes which are transmitted at 250 kbps. Finally, each simulation is run for a fixed duration of 3600 s and each point on the curves to be presented is an average of multiple runs.

The protocols that have been chosen for comparison were S-MAC [9] and T-MAC [15]. Both protocols were implemented in OMNeT++ and simulated as they appear in the literature. In these protocols the sleep schedules are established using SYNC packets which are exchanged once every *sync_interval*. We set the *sync_interval* equal to 10 s and we varied the duty cycle to be 10% and 15% of a 200 ms period (the duty cycle determines the length of the sleep interval). For the T-MAC protocol with the adaptive duty cycle, we used the same period and an interval TA equal to 2.5% of the period duration as suggested in [15]. Overhearing avoidance, full-buffer priority and FRTS features that aim at addressing the early sleeping problem and therefore at increasing the algorithm's achieved maximum throughput, were not enabled when T-MAC was simulated, since T-MAC achieves the 100% throughput limit we set in all testing scenarios. All the nodes are time synchronized and hence we favored S-MAC and T-MAC by allowing the listen and sleep periods to be synchronized across the entire network. Finally, FP-MAC for the one-hop scenario has a 200 ms period, equal to S-MAC's and T-MAC's period. Moreover, the ND protocol runs every 10 s (i.e. every 50th cycle period) for an interval equal to two periods durations. In each simulation set, all three protocols share the same network parameters and conditions.

The metrics we consider to evaluate the performance of the protocols are

1. Radio-ON time: is the percentage of time that the node's receiver is ON. This metrics fairly suites the 802.15.4-like transceiver characteristics stated in Section 4.2. It is obvious that, the smaller the radio-ON time percentage, the higher the node's lifetime extension.
2. Average (maximum) MAC delay: is the average (maximum) end-to-end delay of a packet from its birth until correct reception at its destination.
3. Probability of collision: accounts for the number of collided packets to the total transmitted.

All graphical presentations that follow show simulation results with a constraint of zero lost probability (no packet drops), meaning that all packets are successfully delivered to their destinations. If a protocol starts dropping packets under certain conditions, the corresponding result entry is empty.

5.2. Simulation results

5.2.1. One-hop scenario

The network setup consists of 8 sensor nodes with overlapping radio ranges, randomly placed within a 15 m × 15 m area (Fig. 6a). Initially, extensive simulations were realized so as to see how FP-MAC behaves at very short periods. For that reason, we varied the period length from 60 ms to 250 ms. In Fig. 7a the vertical axis represents the percentage of time the radio receiver is on, whereas the horizontal axis resembles the traffic load variations. FP-MAC algorithm operates effectively in all cases and regardless of the traffic variations. Its radio-on operation never surpasses 7.8% showing

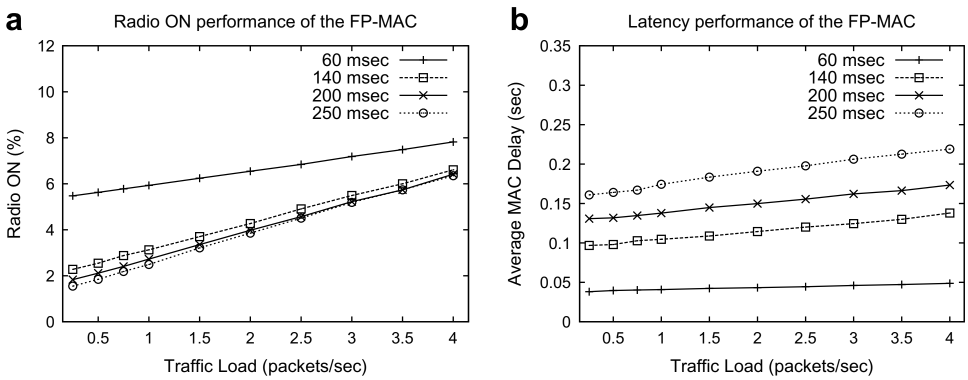


Fig. 7. (a) Radio on percentage and (b) average MAC delay with respect to traffic load variations.

that the idle listening is highly reduced and that FP-MAC remains on just for the time necessary the transmission needs to be completed. Fig. 7b depicts the average MAC delay with respect to traffic load variations. We can easily derive that the shorter the period, the lower the obtained MAC delay following the analysis illustrated in Section 4.1. FP-MAC algorithm successfully serves the heavy traffic conditions, keeping the average MAC delay at lower values than their respective period durations that were each time selected.

Following on, we conducted comparative simulations over the three protocols. Fig. 8a shows the energy consumption with respect to traffic load variations. We can clearly see that regardless the traffic conditions, FP-MAC algorithm results in very low radio-on operation, which is significantly lower than the one of the two other protocols. The descending percentage of radio on that S-MAC achieves with respect to the traffic load increase, is attributed to its overhearing avoidance and message passing mechanisms. As expected, S-MAC with a 10% duty-cycle fails to serve traffic conditions higher that 3 packets/s. The results expose one main drawback that algorithms based on a fixed schedule have; the inability to adapt to the traffic variations met in a sensor network. A fixed duty cycle adjusted for high traffic load results in significant energy waste when traffic is low, while a duty cycle for low traffic load results in low message delivery and long queuing delay. On the other hand, T-MAC for light traffic conditions remains active for a short percentage of time, and, as traffic increases, it has to stay on for a long time. Simulation results highlight that FP-MAC is the most energy-efficient algorithm, thanks to its fast-periodic operation and the variable radio-on operation it implements. Simulation results concerning the measured message latency are illustrated in Fig. 8b. From the figure we derive that S-MAC due to its fixed sleep/listen schedule, increases the queuing delay and therefore the average MAC delay highlighting the trade-off S-MAC falls in when it comes to heavy traffic load conditions [14]. T-MAC instead, presents lower levels of latency compared to S-MAC when the traffic load becomes high. However, FP-MAC shows the lowest latency levels, which remain stable regardless of traffic. The interesting performance characteristic of the FP-MAC algorithm, is that it succeeds in keeping both metrics low at the same time without the need of making a tradeoff between them.

We also ran the simulations with higher period lengths, such as 500 ms and 1000 ms, and we obtained very similar results. FP-MAC, at these high period lengths where its fast-periodic operation advantages are hidden, operates in an equally energy-efficient way compared to S-MAC's and T-MAC's performance. However, we observed a 7% and a 16% increase in measured latency respectively. The slight increase in latency, however, only occurs under increased period lengths that are best avoided in our algorithm.

To verify FP-MAC's robustness to scalability, we varied the number of nodes located within the same cluster. In this one-hop testing scenario, each node generates packets to random destinations at a 2 packets/s poisson rate. FP-MAC outperforms S-MAC and T-MAC in both metrics depicted in Fig. 9a and b. It presents an almost 90% improvement in terms of energy consumption and 16% in delay when compared to T-MAC, while the delay reduction is more obvious when FP-MAC is compared to S-MAC. The traffic-independent characteristics that FP-MAC algorithm presents together

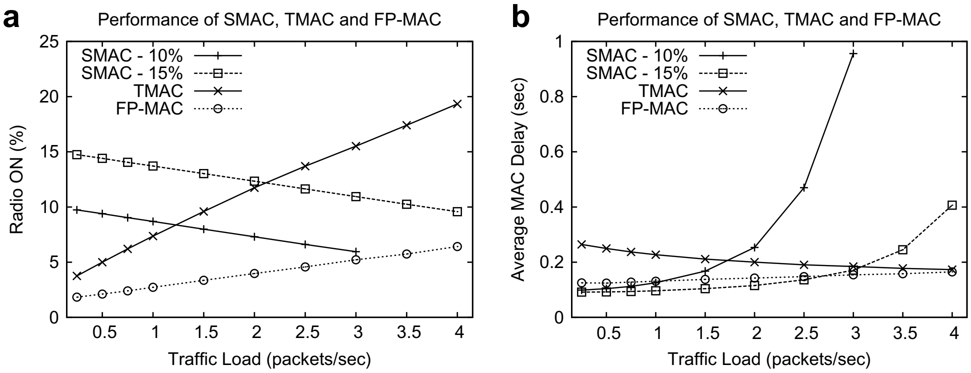


Fig. 8. (a) Radio on percentage and (b) average MAC delay with respect to traffic load variations.

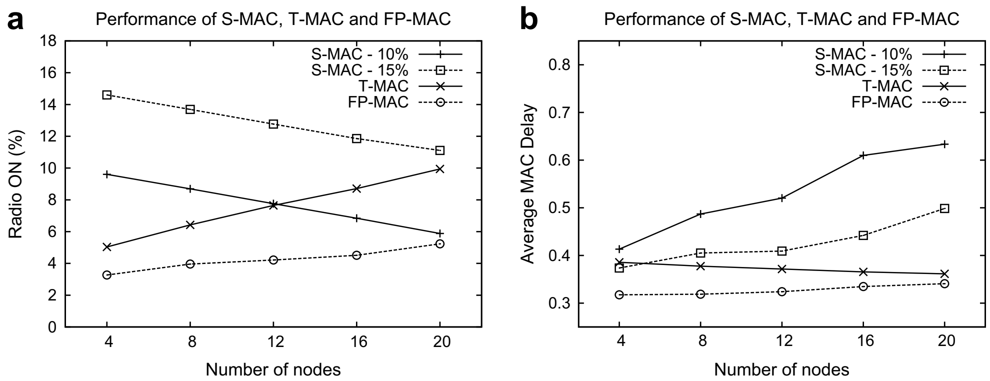


Fig. 9. (a) Radio-ON time and (b) average MAC delay over changeable number of nodes located in the same cluster.

with its stability, results from its fast-periodic operation and the fact that the wake-up schedules of the nodes are spread within the period and are not synchronized.

5.2.2. Two-hop scenario

The two-hop topology (Fig. 6b) consists of two clusters of 4 nodes each and a sink node. The two clusters can only communicate directly with the sink node, and thus act as *hidden terminals* for each other. For the *sink-type* communication pattern all wireless nodes generate sensing data at different rates varying from 0.25 packets/s to 4 packets/s. S-MAC's and T-MAC's period length was chosen equal to 200 ms, whereas a smaller 60 ms period that better reflects a fast-periodic operation was chosen for the FP-MAC algorithm.

Fig. 10a shows that FP-MAC algorithm consumes less energy than S-MAC and T-MAC in almost all traffic conditions. S-MAC with a 10% duty cycle achieves slightly better radio-on performance. A closer look at Fig. 10b though, shows that this reduction is traded off with a higher average MAC delay. T-MAC on the other hand, exhibits the optimal latency performance especially when the traffic load is high (above 3 packets/s) showing that its adaptive behavior positively results in that direction. However, once again, FP-MAC exhibits the best overall and un-traded performance since it succeeds in keeping both metrics low at the same time. Though it does not use the RTS–CTS handshake mechanism, the simple back-off algorithm that it implements together with the overhearing avoidance trick, proves to be sufficient to handle the hidden terminal problem observed in this testing scenario.

5.2.3. Multi-hop scenario

The multi-hop topology consists of 15 nodes placed in a 3 by 5 grid with 15 m distance between adjacent nodes (Fig. 6c). We have chosen a radio range so that all non-edge nodes have 4 neighbors. Though a small numbered multi-hop setting, the conclusions that we obtain are indicative of the

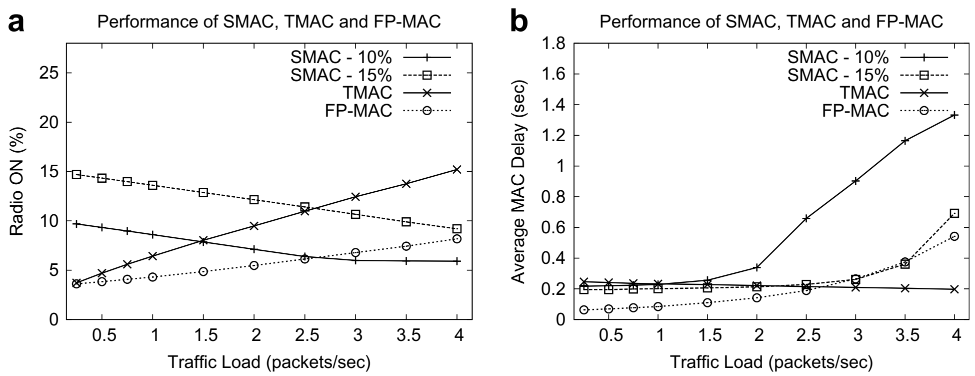


Fig. 10. (a) Radio on percentage and (b) Average MAC delay with respect to traffic load variations (two-hop scenario).

algorithms' performance. In this testing scenario we also applied a *sink-type* communication pattern, where nodes send packets to a single sink at the corner of the network (*corner sink* traffic). A randomized shortest path routing scheme was used where next hop nodes are eligible if they have fewer hops to the destination. From these next hops, a random one is chosen. Thus packets flow in the correct direction, but do not use the same path every time. S-MAC was tested with and without adaptive listening and a 10% duty cycle as suggested in [14]. Period lengths were kept the same as in the two-hop topology.

Fig. 11a shows the obtained radio-on percentage with respect to traffic load variations. Both S-MAC variations succeed in keeping the radio-on operation at low levels. The comparatively increased radio-on performance (~12% higher) that FP-MAC algorithm presents, can be interpreted by the increase in collided packets that are retransmitted (Fig. 11b). The modified exclusion mechanism introduced in FP-MAC (back-off mechanism plus the overhearing avoidance trick) behaves similar to the RTS–CTS handshake procedure resulting in a 25% and a 11% increase in the number of collisions when compared to S-MAC and T-MAC, respectively, in addition to avoiding the RTS–CTS complexity. FP-MAC algorithm's overall performance though is very satisfying if we also consider its achieved average MAC delay. Fig. 12a shows that S-MAC at 10% duty cycle without adaptive listening presents the highest latency and has about twice the average latency than that of S-MAC with adaptive listening. However, even with the adaptive listening mechanism, S-MAC does not reach T-MAC's and FP-MAC's latency performance. Since the adaptive listening mechanism cannot guarantee the immediate transmission at each hop, if a node fails to receive a CTS from the intended receiver after a RTS transmission, it has to wait for one sleep cycle which increases the overall end-to-end delay. On the contrary, the fast periodic operation of

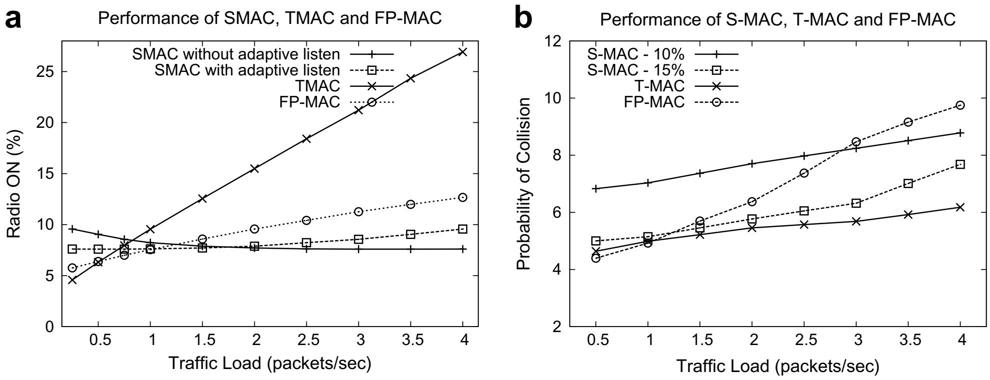


Fig. 11. (a) Radio on percentage and (b) probability of collision with respect to traffic load variations (*corner sink* traffic).

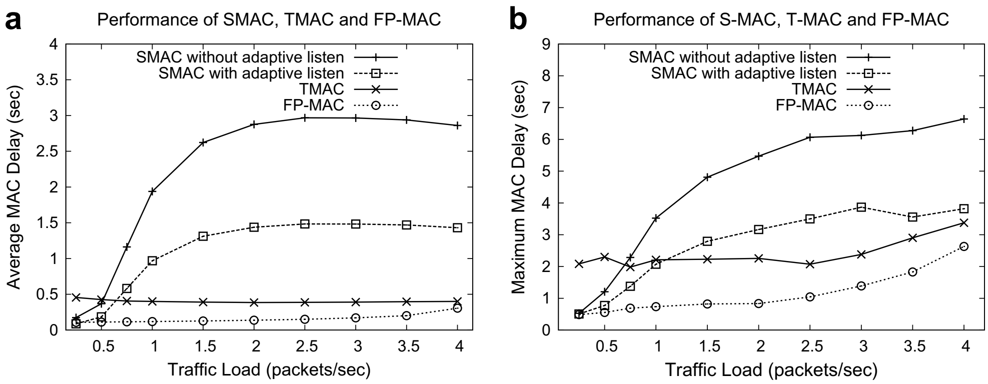


Fig. 12. (a) Average MAC delay and (b) maximum MAC delay with respect to traffic load variations.

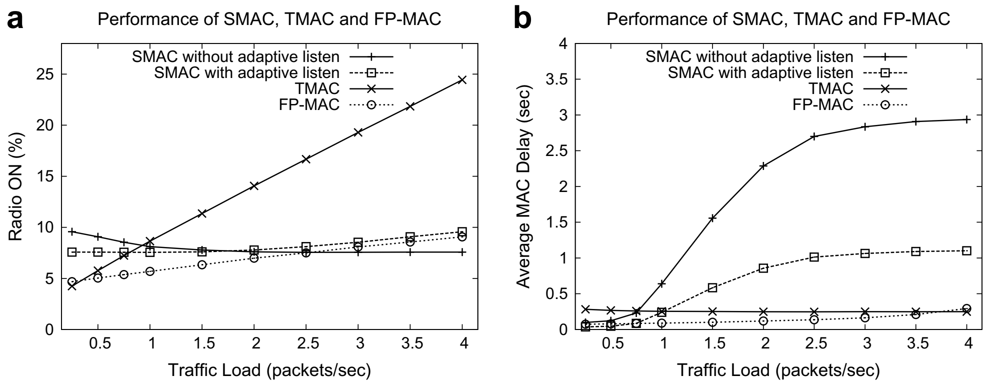


Fig. 13. (a) Radio on percentage and (b) average MAC delay with respect to traffic load variations (*center sink* traffic).

FP-MAC maintains both the average (Fig. 12a) and the maximum (Fig. 12b) end-to-end delay at the lowest levels.

The maximum MAC delay, which is a critical performance parameter to several delay intolerant sensor network applications, incorporates the effect of the path length on the latency performance. Thus, Fig. 12b dictates that FP-MAC is more robust and mainly less affected by the number of hops between the source nodes and the sink.

In the *center sink* traffic scenario shown in Fig. 6c (the sink is located in the center of the 3 by 5 grid topology), we also applied a *sink-type* communication pattern. The smaller number of hops to the sink compared to the previous case (*corner sink* traffic) lowers the access delay. Moreover, since more nodes, i.e. 4, are able to deliver packets towards the sink, this results in both improved energy and latency performance to all the algorithms under test (see Fig. 13a and b). The depicted results, however, clearly indicate that FP-MAC presents the best overall and un-traded performance.

6. Conclusions

In this paper, a new MAC algorithm, namely FP-MAC, which is closely coupled to the IEEE 802.15.4 physical layer is presented. FP-MAC enhances energy conservation and reduces delay in wireless sensor networks. The algorithm is capable of using small period values by decreasing the actions that a node needs to perform at the beginning of every communication period and by incorporating a variable radio-on operation. Moreover, the introduced differences in nodes' scheduling positively acted upon reducing the delay. As a result, the obtained benefits from our proposal are the maintenance of low radio-on time, which translates into low energy consumption, and low mean delay in a wide range of network topologies and traffic conditions. This stable network performance, in terms of the above metrics, makes feasible the efficient implementation of FP-MAC algorithm in a wide range of applications. As it is shown in the results section, depending on the traffic conditions the MAC protocols under test trade-off energy and delay, thus requiring different periods in order to keep both metrics low. In a real implementation, however, where traffic varies in time, real-time period adaptation is an option that is best to be avoided, because it injects enormous complexity. FP-MAC succeeds in keeping system's complexity to a minimum level without requiring a constant reconfiguration of the period, but simply a wise application-related setup.

Acknowledgements

This work was performed within the framework of the project PENED 2003 (Grant No. 636), co-financed by European Union-European Social Fund (75%) and the Greek Ministry of Development-General Secretariat for Research and Technology (25%).

References

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: a survey, Computer Networks 38 (4) (2002) 393–422.

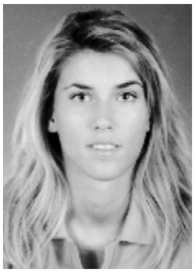
[2] 802.15.4™-2003, ieee standard for information technology-part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), 2003.

[3] ZigBee Alliance, <http://www.zigbee.org>, version 1.0 (Apr. 2005).

[4] A. Wheeler, Commercial applications of wireless sensor networks using zigbee, IEEE Communications Magazine 45 (4) (2007) 70–77.
[5] H. Edgar, J. Callaway, Wireless Sensor Networks: Architectures and Protocols, CRC Press, 2003.
[6] I. Demirkol, C. Ersoy, F. Alagoz, MAC protocols for wireless sensor networks: a survey, IEEE Communications Magazine 44 (4) (2006) 115–121.
[7] B. Hull, K. Jamieson, H. Balakrishnan, Mitigating congestion in wireless sensor networks, in: Proc. of the 2nd international conference on Embedded networked sensor systems (SenSys 04), New York, USA, 2004, pp. 134–147.
[8] F. Bennett, D. Clarke, J.B. Evans, A. Hopper, A. Jones, D. Leask, Piconet: Embedded mobile networking, IEEE Personal Communications Magazine 4 (5) (1997) 8–15.
[9] W. Ye, J. Heidemann, D. Estrin, An energy-efficient mac protocol for wireless sensor networks, in: Proceedings of the 21st International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2002), vol. 3, New York, NY, USA, 2002, pp. 1567–1576.
[10] S. Singh, C. Raghavendra, PAMAS: Power aware multi-access protocol with signalling for ad hoc networks, ACM SIGCOMM Computer Communication Review 28 (3) (1998) 5–26.
[11] IEEE, Wireless medium access control (MAC) and physical layer (PHY) specifications. ANSI/IEEE Standard 802.11, 1999 edition, 1999.
[12] A.Woo, D.Culler, A transmission control scheme for media access in sensor networks, in: Proc. of the ACM/IEEE International Conference on Mobile Computing and Networking, Rome, Italy, 2001, pp. 221–235.
[13] J.H.J. Polastre, D. Culler, Versatile low power media access for wireless sensor networks, in: Proc. of the 2nd ACM Conference on Embedded Networked Sensor Systems (SenSys), Baltimore, MD, 2004, pp. 95–107.
[14] W. Ye, J. Heidemann, D. Estrin, Medium access control with coordinated, adaptive sleeping for wireless sensor networks, IEEE/ACM Transactions on Networking 12 (3) (2004) 493–506.
[15] T.V. Dam, K. Langendoen, An adaptive energy-efficient MAC protocol for wireless sensor networks, in: The 1st ACM Conference on Embedded Networked Sensor Systems (Sensys03), Los Angeles, USA, 2003, pp. 171–180.
[16] G. Lu, B. Krishnamachari, C.S. Raghavendra, An adaptive energy-efficient and low-latency mac for data gathering in wireless sensor networks, in: Proc. of 18th International Parallel and Distributed Processing Symposium (IPDPS'04), 2004, p. 224a.
[17] P. Havinga, G. Smit., Energy-efficient TDMA medium access control protocol scheduling, in: Proc. of the Asian International Mobile Computing Conference (AMOC 2000), 2000, pp. 1–9.
[18] A. Sridharan, B. Krishnamachari, Max-min fair collision-free scheduling for wireless sensor networks, in: IEEE International Conference on Performance, Computing, and Communications, 2004, pp. 585–590.
[19] V. Rajendran, K. Obraczka, J.J. Garcia-Luna-Aceves, Energy-efficient, collision-free medium access control for wireless sensor networks, in: Proc. ACM SenSys'03, New York, NY, USA, 2003, pp. 181–92.
[20] L. van Hoesel, T. Nieberg, H. Kip, P. Havinga, Advantages of a TDMA based, energy-efficient, self-organizing mac protocol for WSN, in: Proc. of the IEEE 59th Vehicular Technology Conference (VTC 2004), vol. 3, 2004, pp. 1598–1602.
[21] C. Zhihui, A. Khokhar, Self organization and energy efficient TDMA MAC protocol by wake up for wireless sensor networks, in: Proc. of Sensor and Ad Hoc Communications and Networks IEEE SECON 2004, pp. 335–341.
[22] I. Rhee, A. Warrier, J. Min, L. Xu, Drand: distributed randomized tdma scheduling for wireless ad-hoc networks, in: Proc. of the Seventh ACM MobiHoc'06, 2006, pp. 190–201.
[23] J. Zheng, M.J. Lee, A Comprehensive Performance Study of IEEE 802.15.4, IEEE Press Book, 2004.
[24] G. Lu, B. Krishnamachari, C. Raghavendra, Performance evaluation of the ieee 802.15.4 mac for low-rate low-power wireless networks, in: Workshop on Energy-Efficient Wireless Communications and Networks (EWCN'04), 2004.
[25] E. Callaway et al., IEEE Communications Magazine 40 (8) (2002) 70–77.
[26] J. Reason, J.M. Rabaey, A study of energy consumption and reliability in a multi-hop sensor network, SIGMOBILE Mobile Computing and Communication Review 8 (1) (2004) 84–97.
[27] Chipcon AS SmartRF© CC2420, preliminary datasheet (rev. 1.2). Available from: <http://www.chipcon.com/files/cc2420> data sheet 1 3.pdf (2004).
[28] I. Ramachandran, A.K. Das, S. Roy, Analysis of the contention access period of ieee 802.15.4 mac, ACM Trans. Sen. Network 3 (1) (2007).
[29] A. Varga, The OMNeT++ discrete event simulation system, in: European Simulation Multiconference (ESM'2001), Prague, Czech Republic, 2001.
[30] K. Langendoen, Medium Access Control in Wireless Sensor Networks, in: H. Wu, Y. Pan (Eds.), Practice and Standards, vol. 2, Nova Science Publishers, Inc., 2007.

Ioannis Gragopoulos received his Diploma degree from the Department of Electrical and Computer Engineering in Aristotle University of Thessaloniki in 1993 and his Ph.D. Degree from the same institution in 1999. He has worked in several telecommunication companies as a research and development engineer of computer networks, fleet management and global positioning systems as well as navigation. From 2004 up to now he has been working as a researcher (Grade D) at the Institute of Informatics and Telematics of CERTH. He has participated in various research programs and his interests focus in the field of wireless telecommunication networks and telematics and especially in wireless sensor networks, medium access and routing protocols and in global positioning and navigation systems. Email: grag@iti.gr.

Ioannis Tsetsinas received his Diploma degree from the Department of Electrical and Computer Engineering in Aristotle University of Thessaloniki in 1997. He has worked in companies an engineer in computer networks and in research institutes as a research and development engineer of wired and wireless telecommunication networks. From 2004 up to now, he has been working as an associate researcher at the Informatics and Telematics Institute of CERTH. He has participated in various research programs and his interests focus in the field of wireless sensor networks, medium access protocols and navigation systems. Email: tsetsinas@iti.gr.



Eirini Karapistoli received her Diploma degree (with honors) from the Department of Electrical and Computer Engineering in Democritus University of Thrace in 2005 and has been awarded with a scholarship from the Greek State Scholarship's Foundation during her undergraduate studies. Currently, she is pursuing a Ph.D. Degree at the Department of Electrical and Computer Engineering in Aristotle University of Thessaloniki and she is working as an associate researcher at the Informatics and Telematics Institute of Thessaloniki. She is also a student member of the IEEE. Her research interests lie in the area of wireless communications, wireless ad hoc and sensor networks, and optimization of communication networks. Email: ikarapis@ieee.org.

Fotini-Niovi Pavlidou received the Ph.D. degree and the Diploma in Electrical Engineering from the Aristotle University of Thessaloniki (AUTh), Greece, in 1988 and in 1979, respectively. She is with the Department of Electrical and Computer Engineering at AUTh engaged in teaching in the areas of Mobile communications and Telecommunications Networks. Her research interests are in the field of mobile and personal communications, satellite communications, multiple access systems, routing and traffic in networks and QoS studies for multimedia applications over the Internet. She is participating in many national and international projects (Tempus, COST, Telematics, IST) and she has been chairing the European COST262 Action on.Spread Spectrum Systems and Techniques for Wired and wireless Communications.. She has served as member of the TPC in many IEEE/IEE conferences and she has organized/chaired some conferences like, the IST Mobile Summit 2002, the 6th International Symposium on Power Lines Communications-ISPLC2002, the International Conference on Communications-ICT1998. etc. She is a permanent reviewer for many IEEE/IEE journals. She has published more than 100 papers in refereed journals and conferences. She has served as guest-editor for special issues in many journals. She is a senior member of IEEE, currently chairing the joint IEEE VT&AES Chapter in Greece. Email: niovi@auth.gr.