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Energy-Aware Link Scheduling Protocol for Wireless Sensor Networks

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Abstract By reducing interferences drastically, time division multiple access (TDMA) based approaches are considered one of the most efficient solutions to optimize resources' use. The existing protocols, however, address only the latency minimization without considering the waste of energy, which typically results from idle listening or frequent transitions of the radio module between sleep and active modes. Besides, only saturated systems are considered in these protocols, which may imply resources' underutilization in some practical use cases. In this paper, we present an energy-aware TDMA-based link scheduling protocol, named deterministic link scheduling protocol (DLSP), designed with the aim of achieving both low energy consumption and low latency in wireless sensor networks. DLSP takes advantage of the spatial reuse of interference-free time slots using conflict graphs. Unlike earlier studies that often considered saturated traffic, we propose to relax the saturation assumption in order to maintain good performance when some of the nodes have no data to send. Thus, we propose to define the following transmission periods: a period to send the own data of the nodes and a period to relay packets. The simulation results clearly show the effectiveness of the proposed protocol, in terms of latency and energy consumption, compared to existing approaches.

Keywords Wireless sensor network · Conflict graphs · Link scheduling · Discrete event simulation

1 Introduction

Wireless sensor networks (WSN) are gaining widespread popularity with the multiplication of the possible use cases in many fields. These networks, which support self-organization

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and self-configuration, offer, indeed, a convenient, infrastructureless data communication services for wireless sensors. Nevertheless, WSN are characterized by severe constraints on resources, like: energy, memory and processing. Moreover, the application domains of sensor networks are sometimes critical and often require real-time communications and guaranteed quality-of-service (QoS).

An optimal management of the radio resource will certainly prevent the loss of energy, which is generally due to collisions, idle listening or signalling overhead. Addressing such issue is, thus, critical to improve the communications' quality (i.e., reliability) while reducing the network latency.

Medium access control (MAC) protocols are generally discriminated into two big families: contention MAC protocols based on the carrier sense multiple access (CSMA) technique, and contention-free MAC protocols based on time division multiple access (TDMA) [1].

Contention-based protocols, which are more appropriate for the non-saturated traffic, are flexible and easily deal with frequent nodes' mobility. However, the protocols based on the CSMA mechanism do not eliminate packet collisions. Collisions often entail the retransmission of lost packets, which leads to an over-consumption of energy and increases the network latency.

The main objective of the protocols based on TDMA is to avoid collisions while maximizing resources use. This also allows to conserve the sensors' energy while minimizing the idle listening. Therefore, this requires at the same time highly synchronized nodes, which involves some waste of energy [2]. In terms of latency, the protocols using the basic TDMA don't offer advantage compared to contention-based protocols in a non-saturated traffic. To that purpose, multiple link scheduling protocols (i.e., TDMA-based protocols) have been proposed in the literature to address such issue. The spatial reuse of time slots was proposed as one of the most efficient technique to reduce the network latency. However, most of the protocols don't take into account the existence of empty slots in varying traffic conditions (i.e., sensors with no data packet to transmit during their time slot) [3].

In this paper, we propose a novel scheme achieving both low energy consumption and low latency in WSN. Conflict graphs theory is exploited to maximize the spatial reuse, while reducing the network latency. In this work, we have proposed to divide the data transmission period of each superframe into two intervals: a period to transmit the own sensors data packets, named personal data transmission period (PDTP), and a period to relay data packets, named data forwarding period (DFP). At the end of the first period, the parents are aware of both existing empty slots and filled slots. At the start of the second period, a signalling slot is introduced to prevent parent nodes from listening during empty slots. This technique conserves energy of sensors and reduces the latency in the network. At each period of time, contiguous slots are assigned to the child nodes, of a particular parent, with the objective to avoid frequent transitions of the parent's radio module between active, idle and sleep modes.

The remainder of this paper is organized as follows: Sect. 2 presents the related work. Section 3 describes the proposed link scheduling protocol. Section 4 presents the simulation results and the performance analysis of the proposed protocol. The paper conclude in Sect. 5.

2 Related Work

Designing a proper MAC protocol is one of the most important ways to save energy of the wireless sensor nodes. MAC protocols can be, generally, discriminated into two families: *deterministic MAC protocols*, based on TDMA and *contention-based MAC protocols*, based on CSMA [4].

Contention-based MAC protocols are clearly the widest deployed access technique in today's wireless local area networks (WLAN). These protocols are, indeed, resilient as they don't really require stringent and global synchronization of the wireless nodes, which clearly simplifies the MAC layer's design. However, despite the proven effectiveness of such protocols in terms of throughput, they weren't conceived with the energy constraints in mind. In this way, many solutions have been proposed in the literature to address the energy conservation problem in contention-based WSN [5,6]. In such approaches, the wireless sensors keep listening for possible packets' reception involving energy waste due to idle listening. Moreover, the hidden station and exposed station problems are not completely solved, in these networks, even when using the Request To Send/Clear To Send mechanism [7].

In opposition to contention-based MAC protocols, the TDMA time-frame is divided into time slots to be assigned to the wireless sensors. Since a node is globally synchronized in such approaches, the collisions and the idle listening can be reduced significantly. This allows maximizing the energy savings with the cost of increasing the latency. In fact, the station willing to transmit has to wait for its time slot to send data. This increases the latency in the case of non-saturated traffic. Thus, many research works have been proposed to achieve lower end-to-end latencies when using TDMA-based schedulers [8–11]. These protocols can be classified into two categories: *centralized protocols* and *distributed protocols* [12].

2.1 Distributed Approaches

The traffic adaptive medium access (TRAMA) protocol, proposed by Rajendran et al. in [6], was one of the earliest deterministic MAC protocols considering the energy constraint. This protocol assumes that the MAC frame is divided into time slots to be used by the wireless sensors for transmission/reception operations. The time slots allocation is achieved using a distributed algorithm considering the traffic load at each node. This protocol includes two more components assisting the algorithm to determine the sensors' state by exchanging two-hop neighbors information and their corresponding schedules. This clearly avoids wasting energy by avoiding both: collisions and idle listening during data exchange periods. However, the exchange of traffic information involves an excessive overhead without avoiding collisions during signalling periods. This may lead to an increased energy consumption in situations of overload. To improve this protocol, the authors proposed the flow-aware medium access (FLAMA) protocol in which the MAC frame is divided into two periods: random-access period and scheduled-access period [13]. The first period is used for time synchronization and for exchanging information about the traffic to be exchanged between neighbors. In the second period, the time is divided into time slots allocated using a distributed algorithm, which guarantees only one transmitter for a predefined slot in the two-hop neighborhood. This is responsible, however, of amplifying the hidden terminal and the exposed node problems as the capture effects are not considered. Therefore, FLAMA will need more slots to allow the scheduling of all the packets.

To reduce latencies while considering the energy constraints, Macedo et al. proposed, in [10], the Latency-Energy Minimization Medium access (LEMMA) protocol, which constructs a tree-based topology in which the time slots assignment is achieved using a distributed algorithm. Considering the interferences experienced by the nodes instead of the information about the n-hops neighbors, LEMMA supports more efficiently the spatial reuse of time slots. However, the proposed slots' allocation technique causes extra energy consumption due to the periodic activity's detection in the slots.

2.2 Centralized Approaches

Having a global view of the network state, centralized MAC protocols can optimize network resources by maximizing spatial reuse of the time slots and by minimizing overhearing (i.e., maximizing sleeping intervals). Without loss of generality, these protocols generally assume MAC frames divided into two periods: *active period (AP)* and *sleep period (SP)*. Some differences exist, however, in the definition of the AP.

The authors, in [8], proposed two centralized TDMA scheduling algorithms addressing the latency issue: a *Node-based scheduling algorithm* and a *Level-based scheduling algorithm*. These approaches reduce clearly the latency by finding out the minimum length of the TDMA superframe. However, the authors don't really consider the energy constraints of the wireless sensor nodes. In [14], the authors proposed a global time synchronized link (RT-Link) protocol, which is designed to improve throughput, energy consumption and latencies in the network. Just like the spanning tree algorithm, RT-Link, first, organizes the network topology into a tree. In order to establish an interference-free slot assignment, each sensor transmits the lists of its neighbors to the gateway (i.e., Portal). A heuristic algorithm is, then, used to perform slots allocation in such synchronized network. In [15], the authors proposed a TDMA-based scheduling protocol with the aim to achieve a reduced energy consumption while minimizing end-to-end delays from sensors to gateway. With this protocol, a node willing to transmit sends a *WakeUP* message, which is forwarded to all the nodes located in the path from the sensor to the gateway, using the CSMA/CA algorithm. Just after receiving this message, the gateway executes a centralized algorithm to establish an appropriate scheduling. The main feature of this protocol consists in achieving power savings under various traffic conditions while limiting the end-to-end delay. Nevertheless, the end-to-end delays are not minimized and signaling overhead remains important. In [9], the authors proposed a low latency MAC (LL-MAC) protocol assuming a tree-based topology in which the active period is divided into two intervals: a control interval and a data interval. To serve all the nodes in the different levels of the tree the data period is divided, first, into a number of subdivisions corresponding to the number of hops in the tree. Each subdivision is, then, divided into time slots subdivisions allowing each node in the tree to talk to its parent. Note that the parent, in LL-MAC, transmits packets only after receiving all the packets of its descendants.

There are still a couple of problems that must be solved in order to further improve resources use, while minimizing both delays and energy consumption. First, we propose a conflict graphs-based technique improving the spatial reuse of interference-free time slots. This impacts directly the size of the TDMA frame, which allows optimizing the latency. Second, we introduce a novel mechanism preventing parents from listening during empty slots in order to reduce energy waste and improve network lifetime.

3 DLSP: Deterministic Link Scheduling Protocol

There are, today, a variety of interesting TDMA-based medium access protocols addressing the issue of minimizing end-to-end network latency, whereas, in [16], the authors reported that the latency may be considered a secondary problem in sensor networks. This is for sure the case for non delay-constrained applications, but for applications requiring short delays this is not the case (e.g. fire detection, nuclear power plant, …).

In this paper, we consider that the WSN is organized into a logical tree rooted at the base station or the portal. The proposed centralized scheduling algorithm, named DLSA, exploits conflict graphs theory to maximize the spatial reuse of time slots. In this way, it

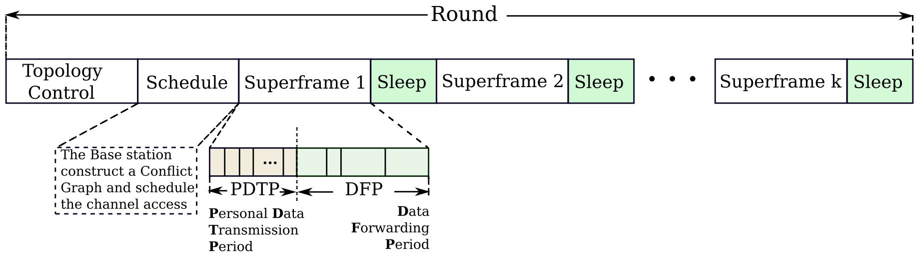

Fig. 1 DLSP superframe description

is supposed that the base station has a global knowledge of the network before starting the slots' allocation.

Deterministic link scheduling protocol is designed with the objective to realize a deterministic MAC protocol achieving both low latency and low energy consumption.

In order to reduce the latencies, the following solutions are proposed:

1. Assign one slot per sensor, so that, it can transmit its own data. The sensors in the vicinity of the sink transmit their packets rapidly in PDTP;
2. Each allocated slot is automatically reused by non conflicting sensors using the deduced conflict graphs.

In order to maximize the energy conservation, the following solutions are proposed:

1. Minimize the number of unnecessary transitions of the sensors' radio module between active and inactive modes (assigning contiguous slots);
2. Eliminate idle listening of the parents by using a signalling slot;
3. Eliminate the collision of data frames by using a TDMA-based technique and conflict graphs theory.

The operation of DLSP is divided into rounds as illustrated in Fig. 1. The parts of each round are described as follows:

Topology Control (TC) is used to update the information about network topology changes, which is generally due to new nodes joining the network or in case of nodes' mobility or disconnections. In our case, we assume static deployments with infrequent topological changes.

Schedule is the phase where the base station applies the scheduling algorithms and broadcast DLSP schedule to all nodes in the network.

Superframe k is the period reserved to transmit all data frames in the network to the base station, we divided this period into two parts:

> **Personal Data Transmission Period (PDTP)** is used by the DLSP to assign to each sensor one time slot, which is generally used by the node to transmit its own data packets.
>
> **Data Forwarding Period (DFP)** is used by the DLSP to assign to each parent as many contiguous slots as the number of its descendants. This period is used to allow packet forwarding.

Sleep Period, during this period, the sensors turn-off their radio module.

Note that our paper mainly focusses on the link scheduling problem. For more details about the synchronization and topology control problems one could consider the contribution of

Sivrikaya et al. [2]. Note also that the proposed approach is compatible with data aggregation techniques. In this case, the parent's allocated slots depend on its aggregation capacity not on the number of its descendants.

Before elucidating these techniques, we must first describe the considered topology while detailing the construction of the conflict graphs, which insures interference-free slots assignment.

3.1 Network Description

We model the network topology by a graph $G(V, E)$, where $V = \{s_0, s_1, \ldots, s_{N-1}\}$ represents the N wireless static sensors composing the network and E represents the wireless links, which are considered in the following to be symmetric.[1] These sensors are structured into a spanning tree connecting the root to all the other sensors. In our network, the tree's depth and the number of children by parent is not fixed but depends on the algorithm considered for creating the tree. Note that our objective is not to propose an improvement of the spanning tree algorithm for WSN. In fact, many solutions have been proposed to solve this problem (see [17,18] for more details).

We assume, in the following, that the base station is aware of the structure of the tree, in which the nodes are organized into levels (or hops), knowing that the base station is in hop 0. The clocks of the sensors are synchronized using a similar protocol than the one used in [9].

3.2 TDMA-Based Link Scheduling Protocol

In this section, we propose a link scheduling protocol using the TDMA principle. Our main objective is to minimize the TDMA frame size[2] in order to keep the overall network latency and the energy consumption minimized. The proposed centralized algorithm, which is executed at the base station level, firstly constructs a *conflict graphs*. This will clearly help in assigning efficiently the slots (i.e., spatial reuse) without conflicts (i.e., collision-free or interference-free). Then, the proposed scheduler allocates contiguous slots for the children of a particular parent to minimize frequent transitions of the sensors between *active* and *inactive* modes.

3.2.1 Conflict Graphs Construction

The conflict relationship between two different links is defined following the protocol interference model defined in [19]. All the different possible links' conflicts in wireless networks are considered in our study. A comprehensive summary about these configurations is presented in [11].

To illustrate the principle of DLSP, we consider a network of 10 wireless sensors (see Fig. 2) for more details. As explained above, the wireless sensors are organized into a logical spanning tree, with the base station, identified by 0, on the top. Two types of lines are used in Fig. 2: solid lines for data communication, and dashed lines to express the interferences existing between two sensors in case of simultaneous communications.

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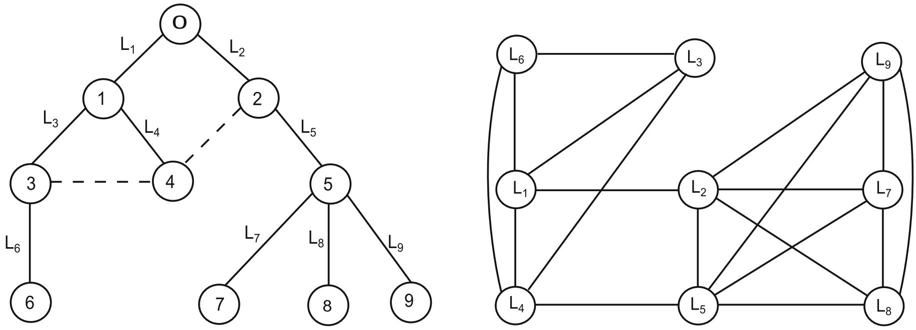
[1] Note that the existence of a link between two sensors indicates that their communications may interfere and hence may not transmit simultaneously.

[2] In our protocol the active period is divided into time slots of sufficient duration to allow each sensor to transmit its data.



(a) Network topology of G

(b) Conflict graphs CG corresponding to G

Fig. 2 Transformation from G to CG

Note that most of the protocols discussed in the related work section don't take into account the interfering links [18].

The conflict graphs corresponding to this network is represented by $CG(E^{'}, CL)$, where the set of vertices $E^{'} = \{L_1, \ldots, L_9\}$ represents the links in $G(V, E)$ and the set of edges (i.e. conflicts links CL) represents the possible conflicts existing between the different links in $E^{'}$. In the resulted conflict graphs, the interfering links are taken into account, even if they are not represented in CG.

3.2.2 Conflicts-Free Link Scheduling Algorithm

Our proposed protocol DLSP is composed of two sub-algorithms: deterministic link scheduling Algorithm 1 ($DLSA_1$) and deterministic link scheduling Algorithm 2 ($DLSA_2$). The first algorithm is designed to transmit the sensors' data packets and is performed during the first part of the active mode period that we called PDTP. The second algorithm is designed to relay the data packets to the base station and is performed during the rest of the active mode of each superframe period that we called DFP. All the variables we used in our algorithms are described in Table 1.

The $DLSA_1$ algorithm, described in the Algorithm 1, is executed by the base station, which is a powerful device with unconstrained energy supply, and significant computational capacity. This can correspond to the ZigBee coordinator (ZC) as defined in [20].

The main objective of $DLSA_1$ is to assign the minimal number of time slots required to transmit the sensors' data to their corresponding parent. This number determines the PDTP duration. First, based on the information received during the topology control period, the base station constructs the conflict graphs (CG). In the DLSA1 algorithm, the slots are allocated based on the set Com_L, in which the links are ordered according to their corresponding hop in the tree, in descendant order. To fully take advantage of the spatial reuse, we consider slots' allocation based on CG. In fact, when assigning a slot to a link L_i, the same slot is assigned to non conflicting links in Com_L using the same order. Then, another slot is used following the same process. This clearly allows optimizing the spatial reuse while having the minimal number of slots in the TDMA frame. Indeed, this opportunistic slot assignment mechanism allows the sensors close to the base station, for example, to transmit their data packets simultaneously with their indirect children without conflicts.

Table 1 Description of the variables

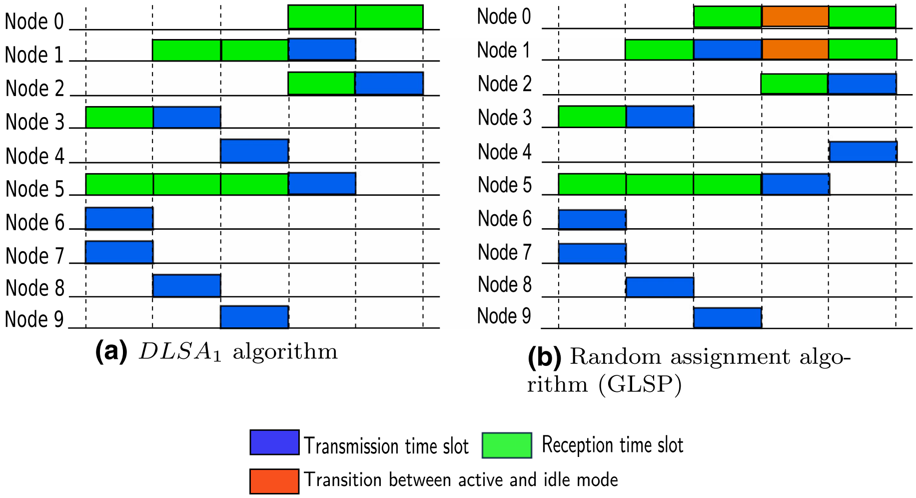
Variable	Description
$Sensor_{ID}$	The sensor identity
L_i	The link starting from the sensor i to its parent
TS_k	Time slot k
$Parent_s$	The parent of the sensor s
$G(V, E)$	The initial graph G
$A(V, E^{'})$	The spanning tree A
$CG(E^{'}, CL)$	The conflit graph GC
Com_L	The list of links in descending order according to their depth in the tree A
$Leafs$	The list of sensors leafs in the tree A
Ord_L	List of couples $< L_i, TS_{Li} >$ to schedule
Hop	The sensors' level in the tree
Nbr_Desc_s	The number of children of a sensor

Input: G(V,E), A(V,$E^{'}$);
Output: Ord_L, TS_t;
/* Initializations */
Hop ← maximum depth of A;
$TS_t \leftarrow TS_1$;
$Com_L \leftarrow E^{'}$;
$Ord_L \leftarrow \{\}$;
/* Conflict graphs construction */
Construction of the adjacency matrix corresponding to the CG;
/* Body */
while Com_L *!= {}* **do**
  Choose a link L_i in Com_L to schedule;
  $Ord_L = Ord_L \cup \{< L_i, TS_t >\}$
  $Com_L = Com_L - \{L_i\}$
  Remove all the nodes, in CG, in conflict with L_i (i.e., nodes directly linked to L_i in CG);
  if *CG contains a node* L_k *not ticked* **then**
    Choose a link L_k such as:
    $Sensor_k$ OR $Parent_{s_k}$ were/was active at time TS_{t-1};
    $L_i \leftarrow L_k$;
  else
    $TS_t \leftarrow TS_{t+1}$;
    Restore CG and removing the already scheduled nodes.
  end
end

Algorithm 1: $DLSA_1$

Minimum number of unnecessary transition
To minimize the nodes' transitions between active and inactive modes, which is a source of waste of energy, we constrained the assignment of a slot TS_i by both the state of the source and the destination at time TS_{i-1}, and by the sensors' level in the tree.

To well illustrate the minimum number of unnecessary transitions offered by DLSP, we have compared it with another algorithm that we have also proposed, it was called GLSP



(a) $DLSA_1$ algorithm

(b) Random assignment algorithm (GLSP)

Fig. 3 Deterministic link scheduling protocol vs random link scheduling protocol

(General Link Scheduling Protocol). GLSP, as DLSP, aims to minimize the number of slots in the TDMA frame, it uses the following advantages:

- Spatial reuse of the time slots and collision avoidance using the conflict graphs;
- Node-based scheduling technique as used in [8], in order to minimize the number of slots.

However, GLSP does not take into account the contiguous slots. Therefore, many transitions between active and inactive mode may appear. These unnecessary transitions cause a waste of energy.

It can be clearly seen from the considered example, in Fig. 3, that using $DLSA_1$, node 4 transmits its data at TS_3, as it is deeper in the tree and its parent (i.e., node 1) was in receive mode during TS_2, whereas sensor 1 can use slot TS_3 for transmission when using a random slots' assignment algorithm. As a consequence, $DLSA_1$ minimizes the number of unnecessary transitions of the sensors's radio module between sleep, idle and active modes (i.e., contiguous allocation of time slots) compared to a random allocation technique.

Note that $DLSA_1$ optimizes only the one hop slot assignment. To forward the packets from the sensors towards the portal while ensuring reduced latencies, we proposed $DLSA_2$, which is defined in the following section.

In order to reduce the global latencies, $DLSA_2$ considers multi-hop packets transmission into one TDMA frame. To ensure that multi-hop slots' allocation, it is assigned to each parent, in the tree, as many slots as the number of children. To optimize resources use, contiguous slots are allocated to the children of a particular parent.

Note that the leaves of the tree are not included in this algorithm as they are not implicated in packets' relaying operations.

As described above, $DLSA_1$ allows each sensor to transmit its own data, in opposition to $DLSA_2$ in which the sensors are assigned slots to relay the traffic of their children. The combination of the two algorithms allows minimizing the TDMA frame size (i.e., spatial time slots reuse), which directly impacts the end-to-end latency.

Figure 4 illustrates the behavior of the algorithms $DLSA_1$ and $DLSA_2$. In this figure, we can clearly see that the wireless sensors (e.g. sensor 1) do not have to wait for packets arrival

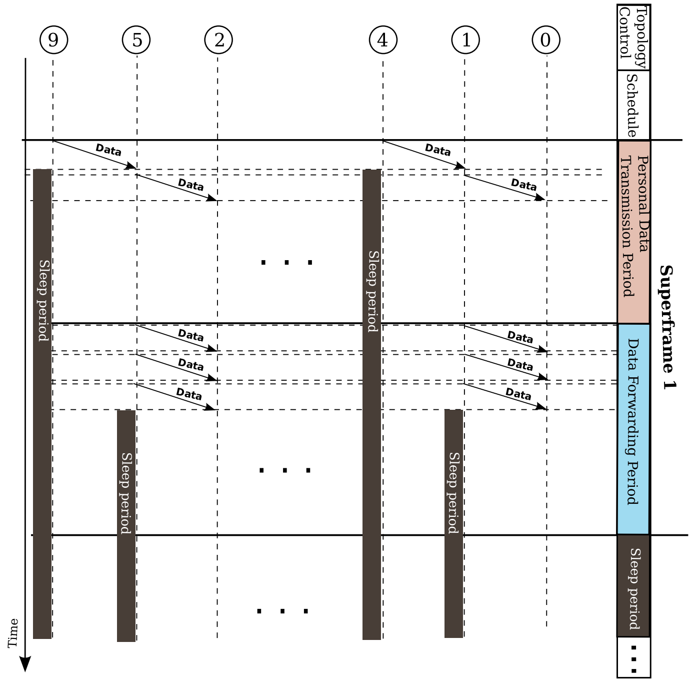


Fig. 4 Example of simultaneous transmission using both algorithms

from their descendants to send their own data to the sink. It, also, illustrates the time slots reuse when there is no conflict (e.g. sensor 1 and 5).

3.3 Energy Efficient Link Scheduling

Deterministic link scheduling protocol was initially designed with the objective to minimize latencies and energy consumption at the same time. As described above, this was realized by maximizing time slots' reuse (i.e., minimizing the TDMA frame length) and by allocating contiguous time slots for the children of a particular parent (i.e., minimizing switching between active, idle and sleep modes) as shown in line **5.** of Algorithm 2. However, in the case of sporadic traffic, the idle listening can not be avoided using such mechanism. In this way, we proposed to introduce a new technique consisting in signalling the presence of useful slots. A slot is useful if the sensor is supposed to use that slot to send its data, otherwise the slot will be considered empty.

We have illustrated in Fig. 5 the case of sporadic traffic, where the nodes 1, 3 and 5 (labeled with a red cross) have not transmitted a data to the $Parent_0$, but, the nodes 2 and 4 have transmitted a data to the $Parent_0$ in the PDTP.

The signalling slot is used just after the PDTP period (i.e., DFP period) to allow each parent to inform in turn its parent of the significant slots of his children ($Parent_0$ signals to its parent in Hop M-2 that there are only 2 active slots instead of 5 slots), the same operation is executed until reaching the base station. As the considered signalling frame is very small, the energy consumed when transmitting such frame is also small. This technique allows the parents to avoid energy waste due to idle listening of empty slots.

Input: G(V,E), A(V,$E^{'}$), Ord_L, TS_t;
Output: Ord_L;
$[Ord_L, TS_t] \leftarrow DLSA_1()$;
$A^{'} \leftarrow A - \{Leaf_s\}$ (i.e., reduction of A to $A^{'}$);
Hop $\leftarrow$ maximum depth of $A^{'}$;
$Com_L \leftarrow \{E^{'}\} - \{Leaf_s\}$;
4. Search in Com_L a link L_i of *Hop* that satisfies this condition:
$Sensor_i$ AND/OR $Parent_{s_i}$ active at time TS_t
5. $TS_{Li} \leftarrow TS_t + Nbr\_Desc_{s_i} * TS$;
6. $Ord_L = Ord_L \cup \{< L_i, TS_{L_i} >\}$;
7. $Com_L = Com_L - \{L_i\}$;
8. Search in Com_L the links L_x of *Hop* which can be activated simultaneously with L_i for each time slot TS of TS_{L_i} by using GC on $A^{'}$ to avoid cases of conflicts, favoring L_x satisfies the condition **5.**,
9. Schedule the L_x for each TS shared with L_x,
10. *If* there are still links of *Hop* not sequenced,
go to 8.,
else : Hop = Hop - 1, **go to 2.**;
11. *If* $Com_L = 0$, **finish**.

Algorithm 2: $DLSA_2$

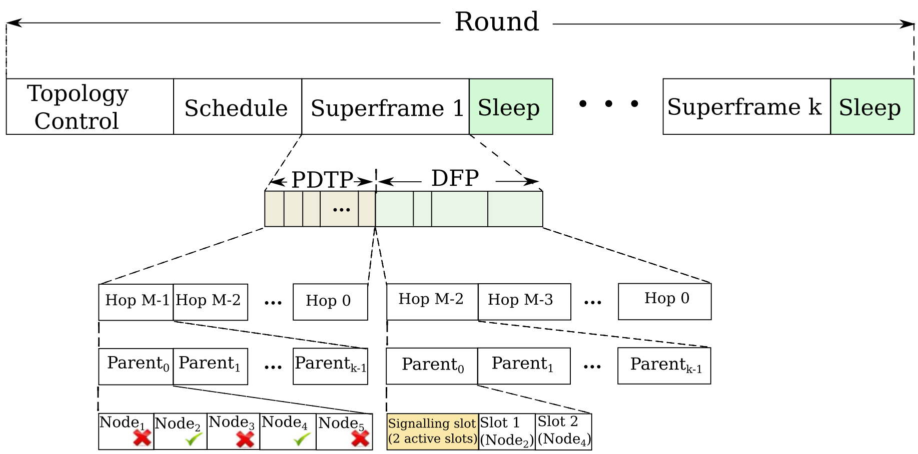


Fig. 5 Protocol scheme for energy conservation

Note that most of the existing deterministic protocols in the literature, have not explained how to avoid the idle listening in the case of a sporadic traffic.

The energy consumption by the wireless sensors during the round (see Fig. 1 for more details), in the case of fixed topology, can be given as follows:

$$E_{Round} = E_{TC} + E_{Schedule} + \sum_{i=1}^{k} E_{Sleep} + \sum_{i=1}^{k} E_{Superframe}. \quad (1)$$

Below, we detail the parameters of the Eq. (1): E_{Beacon} represents the energy consumed by the sensors to receive the beacon and by the parents to forward the beacon to their direct descendants. The energy consumed by each sensor in sleep mode is represented as follows:

$$E_{Sleep} = \sum_{i=1}^{Nbr\_Sensors} R_{Sleep\_Power} * Sleep_{Delay\_Sensor_i}. \tag{2}$$

where, $Sleep_{Delay\_Sensor_i}$ represent a sleep duration of the $sensor_i$.

$$E_{Superframe} = E_{Data\_Tr} + E_{Idle}. \tag{3}$$

where $E_{Superframe}$ is the energy consumed to transmit the data in the ith superframe. We have improved the two parameters of the Eq. (3) in different cases of traffic. The first, is the energy needed to transmit all the data (E_{Data_Tr}) to the sink, the second parameter is the energy consumed by the nodes in idle slots (E_{Idle}: appear only in sporadic traffic). The E_{Data_Tr} is calculated as follows:

(1) Regular traffic case: if all sensor nodes have data to transmit, the energy needed can be represented by the following equation:

$$\begin{aligned} E_{Data\_Tr} = {} & Nbr\_Sensors * E_{Tx} \\ & + \sum_{i=1}^{Nbr\_Parents} Nbr\_Desc_i * (E_{Rx} + E_{Tx}) \\ & + \sum_{j=1}^{Nbr\_Sensors} E_{Switch\_Sensor_j}. \end{aligned} \tag{4}$$

where $Nbr\_Sensors$, $Nbr\_Parents$, E_{Tx} and E_{Rx} represent, respectively, the number of sensors, the number of parents in the considered network, the energy consumed for transmissions which is equal to $E_{Tx} = R_{Tx\_Power} * P_{Delay}$ and the energy consumed for receptions which is equal to $E_{Rx} = R_{Rx\_Power} * P_{Delay}$. $E_{Switch\_Sensor_i}$ represents the energy consumed when switching between active and inactive states. It can be written as follows: $E_{Switch\_Sensor_i} = Nbr_{Switch\_Sensor_i} * Switch_{TxRx\_Power}$ DLSP aim to find the minimum number of radio switch of each sensor: $Min(Nbr_{Switch\_Sensor_i})$. However, GLSP does not take into account this constraint (Fig. 3)

(2) Sporadic traffic case: DLSP introduces signalling slot that will clearly allows reducing the idle listening periods. The energy consumption formula E_{Data_Tr} can be given as follows:

$$\begin{aligned} E_{Data\_Tr} = {} & Nbr\_Act\_Sensors * E_{Tx} \\ & + \sum_{i=1}^{Nbr\_Parents} Nbr\_Act\_Desc_i * (E_{Tx} + E_{Rx}) \\ & + \alpha * E_{Tx\_SignSlot} \\ & + \beta * E_{Rx\_SignSlot} \\ & + \sum_{j=1}^{Nbr\_Sensors} E_{Switch\_Sensor_j}. \end{aligned} \tag{5}$$

where $Nbr\_Act\_Sensors$, $Nbr\_Act\_Desc_i$, α and β represent respectively the number of sensors having transmitted their data during PDTP, the number of descendants of a particular parent i that have data to communicate, the number of parents which will consider the signalling slot (i.e., having inactive descendants), the number of parents having to receive the signalling slot (with $0 \leq \beta \leq \alpha \leq Nbr\_Parent$) and $E_{Tx\_SignSlot}$ the energy consumed to transmit a signalling slot is equal to $E_{Tx\_SignSlot} = R_{Tx\_Power} * SignSlot_{Delay}$, where the energy consumed to receive a signalling slot is equal to $E_{Rx\_SignSlot} = R_{Rx\_Power} * SignSlot_{Delay}$.

The E_{Idle} is calculated as follows:

$$E_{Idle} = \sum_{i=1}^{Nbr\_Sensors} Nbr_{Idle\_Slot\_Sensor_i} * R_{Idle\_Power} * TS_{Delay}. \tag{6}$$

where $Nbr_{Idle\_Slot\_Sensor_i}$ represents the number of empty slots that each parent must listen due to the scheduling algorithms (for example GLSP and LL-MAC). Also, DLSP allocates contiguous time slots for each parent in order to reduce the number of empty slots (i.e., $Min(Nbr_{Idle\_Slot\_Sensor_i})$) and by using a signalling slots, DLSP avoid the idle listening problem in the case of sporadic traffic.

4 Performance Evaluation

Having described the details of our proposed link scheduling protocol, which is named DLSP, we now direct our focus on evaluating its performance using computer simulations using MATLAB [21]. DLSP is compared to two protocols: (1) the LL-MAC protocol [9] and (2) the GLSP, which we have proposed with the main objective to minimize the number of time slots in the TDMA frame. These two approaches are considered for the following reasons. The LL-MAC protocol aims to reduce latency, it is, therefore, an ideal protocol to show the effectiveness of the proposed spatial reuse technique (using conflict graphs) in reducing the network's latency. Knowing that GLSP uses conflict graphs-based spatial reuse of time slots to ensure minimum network latency, it is, thus, a good candidate to see the improvement of DLSP in terms of link scheduling, signalling overhead and energy conservation. These protocols are simulated under non-saturated traffic and compared to DLSP, in order to show its ability to avoid wastage of energy due to idle listening and frequent transitions of the radio module between active and inactive states.

The simulations focus on the ability of our protocol to minimize: (i) the frame size (i.e., maximize time slots' reuse), (ii) the latencies and (iii) the overall consumed energy. In opposition to most of the existing contributions, we consider, in our performance evaluations, both communicating and interfering links.

4.1 Simulation Model

In this section, we present the simulation parameters, describe the envisioned network architecture and the test scenarios. We simulate a number of sensors (up to 200) placed uniformly in a plane of 800 m × 800 m. The sensing range and communication range of the sensors are assumed to be equal to 40 m. The whole simulation scenarios were run on a discrete event simulator developed in our laboratory. It is also assumed that all the nodes are synchronized. The deployed sensors are considered to be in one of the states: transmission, reception, idle or sleep.

First, we construct a complete graph connecting these sensors in function of the distance, then, we create a tree topology where the top of the tree is the sink. Also, we considered in our simulations the following traffic patterns: constant, sporadic and dense. The other key parameters used in the simulations are listed in Table 2 according to [14].

Table 2 Simulations parameters

Parameters	Symbol	Initial value
Max packet length	P_{Length}	127 bytes
Max packet transfert delay	P_{Delay}	4 ms
Signalling slot delay	$SignSlot_{Delay}$	0,1 ms
Radio transmission power	R_{Tx_Power}	52.2 mw
Radio reception power	R_{Rx_Power}	59.1 mw
Radio idle power	R_{Idle_Power}	1.28 mw
Radio sleep power	R_{Sleep_Power}	$3e^{-3}$
Switch to transmission/ reception state	$Switch_{TxRx\_Power}$	5 mw
Time slot duration	TS_{Delay}	4,5 ms
Battery capacity	$B_{capacity}$	2,500 mAh
Voltage	V	3.0 V

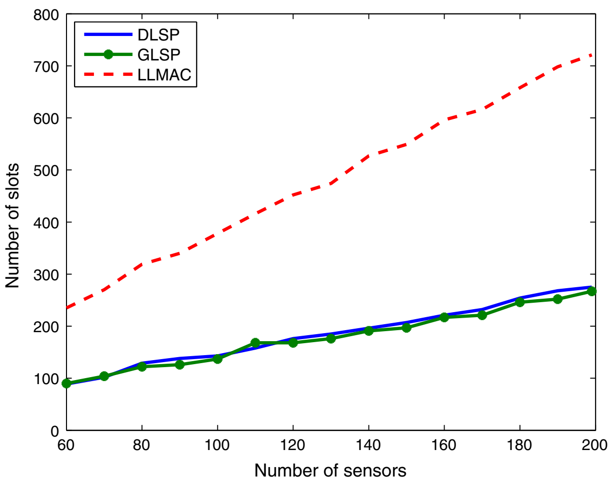


Fig. 6 The number of time slots of the TDMA frame

4.2 Simulations Results

4.2.1 Frame Length

Figure 6 illustrates the difference in term of slots number between DLSP, GLSP and LLMAC. We can see, from Fig. 6, that only a slight difference exists between DLSP and GLSP, which addresses only the minimization of the delay. In fact, our proposal is designed with the objective to realize the trade-off existing between latency and energy conservation. Hence, we consider in DLSP two periods of communications PDTP and RDP, which induce a very slight increase in the number of slots of the MAC superframe. Moreover, DLSP assigns time slots in a deterministic manner so as to avoid useless transitions between inactivity mode and activity mode. This may also induce a slight increase in the number of slots. Compared

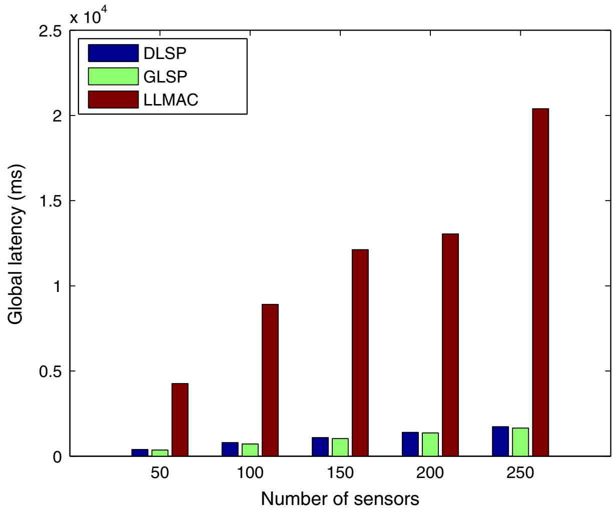


Fig. 7 Histogram of the global latencies

to LL-MAC, DLSP hugely reduces the size of the TDMA frame by reducing the number of time slots. This gain is essentially due to the spatial reuse of interference-free time slots.

4.2.2 Latency

Figure 7 shows the histogram of the global latencies for the different simulated protocols.

It can be clearly seen that DLSP offers lower latencies than LL-MAC (around 7 times lower). Lowering the latency is directly reflected from the efficiency of the spatial reuse of time slots. Thus, as observed in the previous sub-section, the GLSP improves slightly the latency compared to DLSP.

Latency of the Sink's Neighbors

Figure 8 shows the latencies of the sink's neighborhood.[3] We can clearly observe that DLSA outperform LL-MAC and GLSA.

This is a direct consequence of using $DLSA_1$ that focus on allocating time slots for the sensors' own data transmissions. Indeed, this avoids waiting for children's data, which reduces the latencies for these nodes. Note that the more the topology is big the more the impact of this mechanism is important.

Similar results can be seen in Fig. 9, which shows the latencies for sporadic traffic. It can be seen that DLSP improves the latencies for variable network conditions (e.g. the number of sensors that have data packet to transmit is variable). This is directly resulted from the differentiation between the transmissions during PDTP and DFP periods. In fact, using DLSP, the first bits of the PDTP period allow parents to have an idea about the forthcoming transmissions.

4.2.3 Energy Conservation

The simulation results in Fig. 10, shows the superiority of DLSP in term of energy conservation, compared to the other protocols. In fact, the proposed signalling packet, which is sent

[3] The sensors in the vicinity of the sink.

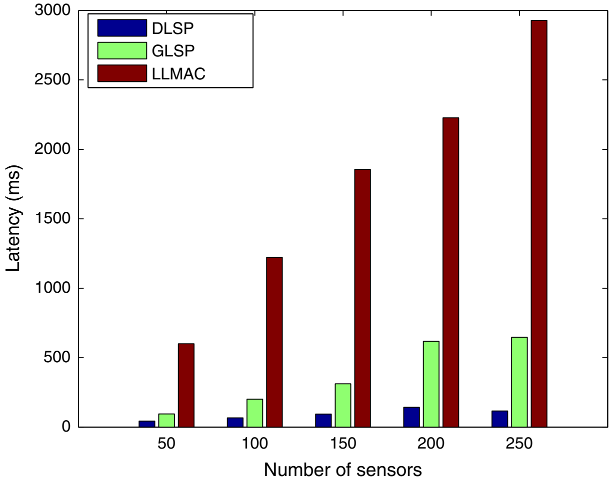


Fig. 8 Latencies' histogram of sink's neighborhood

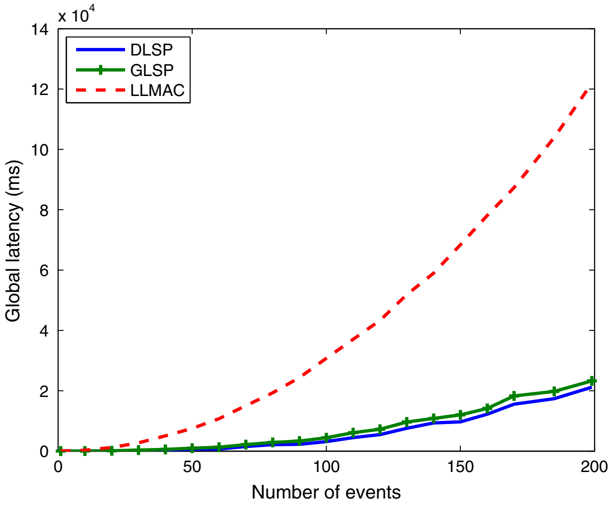


Fig. 9 Latencies for sporadic traffic

just after the PDTP, allow the parents to turn-off their radio module instead of staying into the listening mode during empty slots. This technique will allow the parent to conserve their energy during the Retransmission Data Period. We can also see that, the more the nodes have data to transmit the more DLSP is effective for both latency and energy conservation. DLSP clearly outperform LLMAC and GLSP.

5 Conclusion

In this paper, we have addressed the problem of minimizing both latencies and energy consumption in TDMA-based MAC protocols for WSNs. As a remedy, we have proposed two

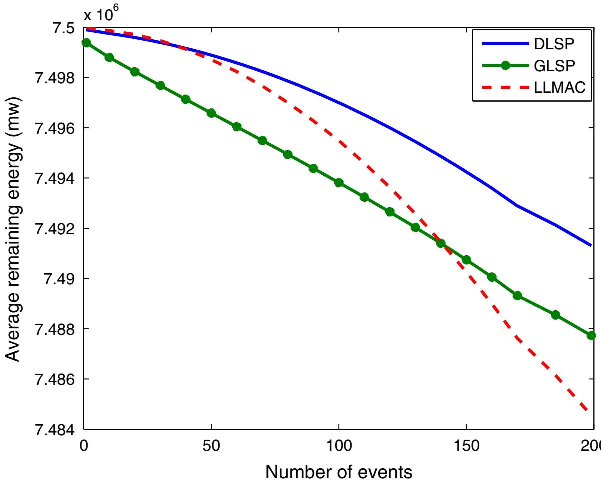


Fig. 10 Residual energy in sporadic traffic

centralized algorithms that assign a minimum number of time slots to all sensors with the aim to reduce the length of the TDMA superframe. The proposed DLSP protocol is different from conventional methods as it takes into account interfering links, while supporting sporadic traffic, in addition to the usual constant bit rate traffic. Using conflict graphs, the time slots' reuse is maximized. Further, the introduction of a signalling slot during the data period avoids useless listening, which directly impacts the energy conservation. Extensive simulations showed that DLSP considerably minimizes the latencies while reducing the energy consumption, compared to existing approaches.

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