Strategies to extend the lifetime of a sensor network based on a hierarchical routing algorithm.

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1 - Introduction

Wireless Sensor Networks (WSN) are used to measure environmental variables in order to supervise different kinds of surroundings and activities. WSN are integrated in industrial, medical, agricultural, for environment preservation or intelligent ambient creation applications, among others. In many of these applications the acquisition of the variables of interest must be done in hostile or faraway environments, what makes very difficult the wiring and periodic attention of the measurement devices [1].

The nodes that constitute a WSN are able to process the collected data and collaborate with their neighbours in order to transmit them towards the base station(s) (sink). These networks organize themselves to auto-adapt to changing topologies, and they work under strong energy restrictions, trying to maximize their lifetime [2] [3].

Energy consumption in a WSN must be analysed making compatible different approaches because each node includes several software modules (SW), which implement communication protocol layers, supported by a hardware platform (HW). A network is made up of a set of nodes, and it is not enough to minimize their energy independently but it is important to balance the network workload, otherwise its connectivity will be spoiled. This work deals with the reduction of consumption that can be obtained in a WSN from its routing mechanism, analyzing the behaviour of CLUDITEM [4][5], a hierarchical algorithm for periodic data acquisition based in clusters.

A sensor network consumes energy doing three activities: environmental parameters measuring, information processing and communication among devices to get the data reach the base station. The consumption associated with communication tasks among the nodes was considered as the main reason for available energy exhausting in each device, as it is stated in most of the publications in this area [6]. Because of this, for the system lifetime analysis and algorithm parameter calculation, consumptions associated with measuring and processing was not taken into account. Node transceivers, which are considered as the unique consumption source, can assume one of the following states: transmission, reception, listening and turned off. In transmission, the node has won access to the medium and sends information to the network. In reception, it detects the arrival of a message sent by a neighbour. In listening, the node keeps analysing the medium. And when the node is turned off, it performs no work, consuming the minimum energy [7]. Therefore, for the analysis done, consumptions associated with the transceiver states and the correspondingly time that the node remains in each state were taken into account, accordingly with the role assumed by the node and the algorithm working stage in which it actually is.

CLUDITEM contributes to prolong the network lifetime based on two main aspects:

- To turn off the nodes transceivers as much time as possible, because lifetime is directly related with the devices activity time.
- To balance the network workload, achieving similar clusters structures with rotation and uniform distribution of the clusters headers (CH) in the area under study.

The rest of this paper is organized as follows: in section two, works related with the present one are reported; section three deals with routing algorithm generalities and in section four the metrics used to evaluate performance are defined. Section five shows simulation results and finally, in section six, conclusions are achieved and future work lines are set out.

2 - Related works

Cluster-based hierarchical routing algorithms provide important advantages for WSN regarding its scalability and efficiency in communication between nodes [8]. Consequently, several algorithms have been developed with these features, as mentioned in [9], [2] y [10]. CLUDITEM divides the area under study in a virtual grid, whose use was proposed by Al-Karaki en [11]. This author developed an algorithm where the clusters correspond to the grid divisions, and the header role is rotated among grid members based on their remaining energy. However, in CLUDITEM, when CH are rotated, clusters are defined again and nodes from other grid divisions may be incorporated [12].

The lower protocol layers are based on IEEE 802.15.4 standard, widely used in WSN [1] [6]. In Deliang's work [13], media access control (MAC) protocols are classified in four categories. The first includes the protocols based on contention that compete for the channel use, oriented to the solution of conflicts, but expensive from the point of view of consumption [14]. The second one groups the protocols that use a kind of TDMA scheme, assigning time slots to each node that needs to send data, of course, collisions free. In third place are the hybrid protocols, like IEEE 802.15.4, which combine the advantages of the two previous categories. At last, protocols of related layers are considered because they constitute a very promising research area [15]. CLUDITEM incorporates for its MAC layer the IEEE 802.15.4 in beaconless mode, recommended for multi-hop networks as reported in [16]. The network routing structure is responsibility of CLUDITEM, and in this sense the importance of inter and intra-cluster interferences were considered, concerning to information loss, for the cluster-based hierarchical algorithms [17]. Therefore, CLUDITEM includes a TDMA scheme to prevent the loss of messages because of collisions in the cluster definition phase and also in the phases corresponding with the process of sending measurements to the base station (sink) [4]. There are just few works regarding algorithms based in clusters that combine routing information with some media access mechanism in order to improve the system performance. The algorithm presented in [14] includes clusters with a star topology, and the slot allocation is done by the sink and the clusters headers, which must know the complete network topology. Also [17] is a centralized algorithm that requires many control messages to organize the transmissions, increasing the traffic in the network.

CLUDITEM combines CSMA/CA without slots in the MAC layer with a TDMA scheme defined at routing level. It is a simple, distributed algorithm that only utilizes local node information to organize the data transmission, minimizing the number of control messages in order to reduce the network traffic and the energy consumption. However, the definition of measurement transmission slots increments the time that the devices must stay in activity, and consequently also the energy consumption rises. In this sense, a work was done with the aim of achieving a TDMA scheme that allows a balance between the admissible information loss and the time the nodes must keep their transceivers active, as reported in [4].

3 - Algorithm generalities

CLUDITEM is a cluster-based hierarchical routing algorithm that performs periodic data acquisition, sending useful information to the base station in each measurement period (T). Network nodes are all identical, in respect of resources and initial energy; they are manually distributed once, are fixed and are identified by an ID. The base station is unique and it is located outside the area under supervision, which is divided in a virtual grid with the aim of achieving a uniform distribution of the clusters headers.

This algorithm was developed for environmental supervision applications where the periodic measurement of environment variables is very used. A sensor network working under this algorithm remains constituted by nodes with two different roles, cluster headers (CH) and ordinary nodes (ON), which communicate using radiofrequency. The nodes which assume the task of CH are more demanded regarding energy consumption; hence, a rotation technique was added to the role of CH in order to balance the workload of the network.

CLUDITEM operation is divided in three well differentiated phases. The first handles the establishment of routing tree, which is described in detail in [5] and [18]. The second phase manages the sending of data to the sink, deeply analysed in [4], and during the third phase, the devices remain in low consumption state. These phases are repeated periodically, maximizing the duration of the third with the aim of prolonging the system lifetime.

The definition of the routing structure is repeated every X measurement rounds. If the headers keep their roles too much time, they get exhausted and disconnections in the network arise. I X is too small, considerable energy is consumed in reassembling the routing tree. Therefore, there is an X value that balances the network energy consumption, which was analytically obtained in [5].

3.1. Phase of establishment of routing tree

The routing scheme is defined in two levels. The first level sets the structure of each cluster. Each cluster is defined choosing at first its CH. The headers nominate themselves, following a type of TDMA scheme, by means of cluster structure message (CS). Ordinary nodes adopt a header and choose a link node (LN). Inside the cluster, the communication is multi-hop and ordinary nodes have a level defined by the number of jumps they are separated from its CH. To define the cluster structure, each ON which hears the CH nomination resend this CS message with the necessary information to make possible others nodes can choose them as their LN.

Message type	Chosen CH	Emitter	Emitter level

Fig. 1. CS message format

The format of a CS message is shown in Fig. 1. Strategies were defined in order to achieve balanced clusters in deepness and number of members. The ideal situation corresponds to a unique header per virtual grid division, but it is admitted more than one nomination because of the conclusions obtained from the detailed analysis of the cluster definition presented in [18].

The second level of routing scheme takes care of CH tree definition, which is responsible for sending the aggregated data down to the base station. The phase is initiated with a message sent by the sink. The clusters headers which hear this message assume the level 1 in the tree and resend it, putting its ID and level, so other headers may adopt them as LN in order to send aggregated messages. This level is considered critical because a failure in it may produce disconnected sub-networks which affect seriously the functioning of the network [5].

3.2. Phase of data sending

Data sending towards base station is performed in two stages: in the first, the ordinary nodes send their data to its cluster header and, in the second, the CH utilise the headers tree in order to send to the sink an aggregated message, which summarize the information collected by the cluster they coordinate. This phase takes place after the definition of the routing tree in the case of a reconfiguration round, or at the beginning of the T period of information collection in a round for the exclusive transmission of measurements.

In each data collection period T, ordinary nodes send the performed measurements to their CH making use of a data message whose structure is shown in Fig. 2. The sending of the values measured by each ON is performed according to a TDMA type scheme. This criterion is adopted in order to reduce the occasional collisions which could arise if several nodes sent their information at the same time.

The intra-cluster communication is multi-hop, for this reason each node which receives a message sent by a neighbour verifies if its own ID matches up with the link node field of the data message, places its own LN in that field and resends the message immediately. The origin of the data is important in order that the sink knows how many nodes report to each CH and this one uses it to define the aggregated message.

Type of message	Data origin	Nodo de Enlace	Data

Fig. 2. Data message format.

In the stage of sending the aggregated data, each CH process the messages sent by its clusters members concatenating the received measurements. There are others aggregate functions, some more simple and economical, like the average, the maximum or minimum value of data. Concatenation, chosen because of the requirements of the applications, is a more expensive function but it allows the obtaining of significant benefits in relation to energy consumption, as He et al. have proved in [19].

Type of message	Data origin	Nodo de Enlace	Aggregated data

Fig. 3. Aggregated data message format

The aggregated information of each CH is sent to its LN in the headers tree, using the message structure shown in Fig.3, with the aim of making it arrives to the base station. Ordinary nodes don't participate in these activities and they sleep until the next T period. The headers which hear the circulating message compare its ID with the value of its LN field. If they match up, they resend it to its own LN, otherwise it discards it. If any CH is disconnected from headers tree, it sends its aggregated message with a help code in the link node field. Every header which hears an aggregated message containing this help code resends it to its LN. In this way, the aggregated messages of the CH without link reach the base station, which is the responsible of filtering eventual repetitions.

3.3. Phase of low consumption of the devices

Once the stage of sending the aggregated data is finished, all the CH enter in a low consumption state, in the same way the ON did when the stage of data sending was finished, waiting for the fulfilment of data acquisition period T. When this happens, if the necessary X rounds for headers rotation have been accomplished, a new routing tree definition starts, otherwise a new data sending phase begins.

4 - Metrics related to the energy consumption

The consumption values for the CC2420 transceiver, which was taken in order to define the parameters of the energy model in simulation, are summarized in Table 1 and they make clear that the most significant consumption belongs to the listening state. This happens because the power consumed by the transceiver in this state is similar, even higher, to the corresponding to the reception and transmission states, and the listening state is assumed by the nodes most of the time they are active. In this regard, the time that the devices stay awake is fundamental in the definition of the energy they consume.

The configuration rounds are longer than the exclusive data sending rounds and besides, the headers stay active more time than the ON in all rounds, hence the following metrics were considered in order to analyse the network consumption:

- Node consumption by role and round type
- Remnant energy of the devices when the network lifetime is over
- Network outage due to unfulfilled quality of service (QoS) when X varies.

Definition	Parameter	Value
Antenna Gain in transmission	G_t	0 dB
Antenna Gain in reception	G_r	0 dB
Antenna height in transmission	h_t	0,33 m
Antenna height in reception	h_r	0,33 m
System loss	L	0 dB
Wavelength	λ	1,25 e^{-01} m
Frequency	freq	2,40 e^{+09} Hz
Intracluster transmission power	tx_power_EC	0,00000316 W
Intercluster transmission power	tx_power_ACH	0,001 W
Reception threshold (sensitivity)	RXThresh	3,16 e^{-13} W
Intracluster transmission consumption	tx_consume_EC	0,01516 W
Intercluster transmission consumption	tx_consume_ACH	0,03067 W
Consumption in reception	Pr_consume	0,03528 W
Consumption in listening	P_idle	0,03528 W
Consumption in off	P_sleep	0,000000144 W

Table 1. Radio model parameters and consumption in each transceiver state

The quality of service requirement for the applications chosen is defined based on an admitted percentage of loss of messages. The network lifetime ends when 5 measurement rounds are performed under the established QoS.

The nodes that assume the CH role are the most demanded with respect to energy consumption, but its situation should be balanced in relation with the ON because of the mechanism of role rotation. Therefore, it was decided to analyse the remaining energy in the whole network at the end of a complete rotation of CH in order to asses if the technique included into the algorithm is effective to balance the situation of the devices.

Another considered aspect was the calculation of the optimum moment of network reconfiguration (X), considering that each node consumes its energy in full when a complete rotation of the roles is done. Therefore, the operation of the algorithm was simulated with the established parameters for the theoretical calculation, changing only the X value, and the obtained results were analysed.

5 - Simulation results

The behaviour of the algorithm was analysed using NS2 v2.31, a discrete events simulator focused to the analysis of network communication protocols. CLUDITEM was incorporated to the NS2 environment as an agent at routing level and it was integrated with the lower layers of the protocol.

The simulation scene was defined as an area of 136 meters square, divided in 9 identical cells with 16 nodes spaced 12 meters apart in each cell, and with the base station in the outside of the area under supervision [4].

Table 2 shows the values adopted for simulation. The intra and inter cluster transmission slots were adjusted based on the logs files from previous results and they were used for defining the duration of the measurements sending phases, taking in each case a safety factor. The period until the next data collection round was adopted in 25 seconds, based on the requirements of the applications of interest.

Definition	Parameter	Value [sec]
Duration of cluster definition phase	T_CLUSTER_ASSEMBLE	1,0
Duration of CH tree definition phase	T_TREE_ASSEMBLE	0,1
Transmission period of a single datum until the CH	T_SLOT_DATUM	0,02
Duration of intracluster transmission phase	T_SEND_DATA	0,8
Transmission period of a single aggregated data until *sink*	T_SLOT_AGGR	0,1
Duration of CH transmission phase	T_SEND_MSG_AGGR	3.0
Period until the next measurement round	T_ROUND	25,0

Table 2. Values for the algorithm operation timing in simulation

Average and maximum consumption values of the devices were obtained as results, as shown in Table 3, where it can be appreciated that the values classified by role and round have little dispersion in each category. Also, it is shown that the consumption of CH, as expected, is significantly higher than ON, which emphasizes the importance of the role rotation mechanism in order to balance the workload among the devices.

Node role and round type	Average consumption [W]	Maximum consumption [W]
ON in a round without reconfiguration	0,028182	0,028192
ON in a round with reconfiguration	0,069103	0,069479
CH in a round without reconfiguration	0,134007	0,134024
CH in a round with reconfiguration	0,174927	0,175217

Table 3. Consumption according to node role and round type.

In Table 4, the value X=17 corresponds to the optimum moment of network reconfiguration theoretically obtained for an initial energy of 12 joules and the parameters values of the chosen transceiver. The achieved results clearly show that the theoretical calculation of X is certainly the most suitable, because if its value is increased or decreased the network goes out of service before, because of not to fulfil the established requirements. The major differences that take place when lowering the X value are attributed to the fact that the nodes have the opportunity to nominate themselves a greater number of times. The CH role is more demanding with respect to consumption and therefore it is expected that they exhaust their supplies of energy, causing early network disconnections. When X is increased, the nodes which assume the CH role do that for a large number of rounds, which also has a negative impact in their supplies. Consequently, the theoretical value, for the initial energy adopted and the time scheme defined, achieve the best balance for the rotation of the roles, giving a longer system lifetime.

Simulation	**Out of service round X = 15**	**Out of service round X = 16**	**Out of service round X = 17**	**Out of service round X = 18**	**Out of service round X = 19**
1	255	266	*277*	274	267
2	254	266	*277*	274	268
3	253	266	*277*	274	268
4	255	266	*277*	274	268
5	254	266	*277*	274	268
6	255	266	*277*	274	266
7	255	266	*273*	271	267
8	255	266	*277*	274	268
9	255	266	*278*	274	268
10	255	266	*278*	274	267

Table 4. Network outage round for different X values.

The analysis continued with the optimum value of X=17 and focused on the remaining energy in the 10 associated simulations, once the network came out of service in the round shown in Table 4. The achieved results are reported in Table 5 and they show that the total residual energy in the system is small and approximately the same for every simulation.

Simulation	**Total remaining energy [J]**
1	201,018036
2	210,745063
3	201,435832
4	213,520508
5	213,163628
6	208,352504
7	202,242503
8	215,757158
9	212,008508
10	213,441527

Table 5. Network remaining energy when it comes out of service because of QoS breach.

This situation is coherent with the objective of balancing the workload in the network. However, it does not give information with respect to the individual state of the nodes. For this reason, the remaining energy of each device was analysed next, making clear that, in every simulation, four node groups could be defined, with each node retaining a very similar remaining energy, as shown in Table 6.

Simulation	Group 1		Group 2		Group 3		Group 4	
	Qty. of nodes	Group average energy [J]	Qty. of nodes	Group average energy [J]	Qty. of nodes	Group average energy [J]	Qty. of nodes	Group average energy [J]
1	3	3,4968	108	1,6991	6	1,1704	27	0,0000
2	4	3,4961	111	1,6988	7	1,1701	22	0,0000
3	1	3,4962	111	1,6989	8	1,1701	24	0,0000
4	4	3,4962	114	1,6989	5	1,1711	21	0,0000
5	5	3,4692	111	1,6707	10	1,0364	18	0,0000
6	2	3,4966	113	1,6991	8	1,1700	21	0,0000
7	4	3,4958	106	1,6987	7	1,1704	27	0,0000
8	4	3,4968	116	1,6991	4	1,1682	20	0,0000
9	4	3,4689	113	1,6710	9	1,0349	18	0,0000
10	2	3,4686	118	1,6710	9	1,0357	15	0,0000

Table 6. Node groups classified by remaining energy when the network comes out of service.

The nodes situation of each group identified in Table 6 can by summarized as shown below:

Group 1: Formed by a reduced set of nodes which never assumed the CH role during the network lifetime, hence they consumed the least energy during operation. This situation was foreseen due to the defined conditions for headers nomination, which could not be met in some reconfiguration rounds.

Group 2: Constituted by the majority of the nodes, which complied with the header role just one time during a complete reconfiguration round (17 rounds of measurements sending).

Group 3: Composed of just a few nodes which assumed the CH role in a complete reconfiguration round the first time, but they nominated themselves a second time in the last reconfiguration of the network lifetime, so that, in this opportunity, they complied with the responsibilities of the role only by 4 o 5 measurement.

Group 4: These nodes complied with the header role in two complete reconfiguration rounds. For this reason they exhausted their energy, although the network accomplished the QoS requirements, finishing its lifetime in subsequently rounds, after a complete rotation of CH role.

The presence of the sets of nodes identified through the analysis of the remaining energy is coherent with the working hypothesis that was proposed during the development of the algorithm. The ideal situation of only one CH per cell, which performs its role during a complete reconfiguration round, is the situation of the majority of the network devices. Nevertheless, the potential nomination of two headers per grid division was adopted taking into account the results obtained in [5]. This situation allows the existence of nodes which assume the more demanding role, regarding resources consumption, in more than one opportunity, producing that some small groups consume more than the average, even exhausting their resources completely. It is important to note that the devices in the same situation or group finish their operation with very similar remaining energy. This permits to affirm that the applied techniques to balance the workload become successful.

Conclusion

This work analyses the efficiency of the strategies implemented in CLUDITEM routing algorithm to prolong the network lifetime. Therefore, it reports the achieved results obtained using the characteristic of the devices of to turn off its transceivers and putting them into sleep mode where the energy consumption is minimal.

Besides, the energy consumption in the different operational phases is analysed, for the roles of CH an ON, as well as the verifications related to the definition of network lifetime.

The analysis of the simulation results permits to affirm that the strategies embodied in CLUDITEM in order to decrease the energy consumption and to balance the workload among the network members were successful, allowing the system to prolong its lifetime.

The tasks sequence that CLUDITEM implements in its different work phases requires that the clocks of the devices are synchronized. The current version of the algorithm does not include a clock synchronization mechanism, thus, for the timing of the tasks, a maximum clock time drift was assumed, which assures that the activities are carried out in the appropriate time. There are currently a set of synchronization schemes for WSN with different characteristics and associated implementation costs. Therefore, it is planned as future work to analyse those schemes to select the best suited for CLUDITEM characteristics, in order to incorporate it into the design.

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