Real-Time Communication Approach in Wireless Sensor Networks Applied for Smart Home

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Summary
In this paper, we propose a Real-Time Communication Tree Building approach (RT-CTB) for critical Sensor Networks (WSN). This approach aims to provide communications between sensor nodes that respect of real-time constraints with the prediction of the communication delays as well as improving the Sensors Network Lifetime (SNL) of these networks in order to have maximum longevity. The building of the real-time communication trees is done periodically depending on the load and the remains energy in each sensor. This approach is applied for Smart Home where the existence of the events that require that the information should reach the base station before the delay such as the fire. The simulation results show that our RT-CTB approach is better than non-real time approaches. We have compared our results to other works and we have proved the efficiency of our approach in terms of energy and delay.

Key words:
Wireless sensor networks, real-time, communication tree, delay, lifetime, smart home.

1. Introduction

Wireless Sensor Networks (WSN) are deployed in many domains and applications such as detection, smart home, smart cities, environmental monitoring, etc. [1][2]. These networks are composed by sensor nodes, which are able to collect and to transmit the environmental data autonomously [3]. However, the control of energy consumption by the sensors, the maximization of their Sensors Network Lifetime (SNL) are the most major problems [4][5]. In this paper, we are interested to solve these problems in critical real-time applications where the respect of the delay constraint is imperative (e.g. the fire detection in homes, the medical applications to monitor the critical patients at their home, etc.). These applications require hard real-time communication between sensors. Severe constraints on the node in WSN make it hard to support real-time communications [6]. To deal with the impact of traffic over wireless link, usually higher priority is given to real-time traffic by reporting to non-real-time one to minimize the contention on shared medium [7][8] or contention-free scheme is usually employed in WSN [9]. Recently, the wake-up radio approach in MAC (Medium Access Control) protocols has enabled the sensor node to put its main radio in a deep sleep mode to conserve energy in the network [10][11][12]. Based on the above motivation, most of the research takes different approaches to focus on application-specific property. Moreover, some literature and one special issue were published and organized recently. For example, RAP [13] (real-time communication architecture for large-scale sensor networks) architecture attracts the researcher's interest. It is a soft real-time communication architecture for large-scale sensor networks. RAP provides convenient, high-level query and event services for distributed micro sensing applications. A scalable and lightweight network stack supports a location-addressed communication model. The authors propose and evaluate a new packet scheduling policy called Velocity Monotonic Scheduling (VMS). This scheduling policy takes care of both time, distance constraints, and prioritizes packets based on that. We observe that this policy is particularly suitable for communication scheduling in sensor networks in which a large number of wireless devices are seamlessly integrated into a physical space to perform real-time monitoring and control [14]. With RAP VMS, a real-time packet gets higher priority if it has delayed and has a long path to reach the destination. Therefore, this protocol helps to reduce the end-to-end miss ration. In fact, RAP is a very interesting approach for soft real-time communications, but it is not applicable in the hard real-time with deadline guarantee, which is the context of our work. Whereas, SPEED (stateless protocol for real-time communication in sensor networks) [15] protocol is designed to provide soft deadline guarantees for real-time packets in sensor networks. It uses a Geographic Forwarding (GF) mechanism based on local information exchange. For this, each node maintains its neighbor node's information such as the geographic distance and average delay to each neighbor. This information can lead to maintain the desired delivery speed [16]. If there is no neighbor node that can support the desired speed, it probabilistically drops packets to regulate the workload. This protocol can significantly reduce the end-to-end deadline missing of packets by using techniques proposed by the authors such as feedback control. It uses GF as the routing protocol and it uses feedback control at the network layer to divert traffic in case of congestion. The SPEED routing protocol is improved by integrating it into RAP architecture [13] and extending to MMSPEED [17] to support different velocities and level of reliability for multiple probabilistic

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QoS guarantee in WSNs. However, with SPEED no real guarantee is given since the congestion cannot be predicted. Thus, time latency cannot be predicted and real-time constraints cannot be reached. For that reason, SPEED is not suitable, also, for hard real-time applications. Whereas, IEDF [18] is one of the best scheduling algorithms that address the hard real-time system. The authors in [18] consider a hexagonal cellular structure as the unit of the network. The sensors are distributed inside each cell and have a router at the center of the cell. The router has two transmitters: one for intra-cell communication and one for inter-cell communication. IEDF allows a frequency channel to each cell that is different from its neighbors; seven channels are enough to avoid any interference between neighbors. Inside a cell, each node knows which its neighbors are and which are the characteristics of the messages that each one intends to send. However, this solution does not present studies and analysis of the Sensors Network Lifetime (SNL), which is the most important concern of sensor networks. Further, the router nodes have important treatments and communications relative to the other nodes, which will lose quickly their energy before the others and consequently the Sensors Network Lifetime (SNL) will be short. In addition, this solution does not optimize energy consumption. Thus, IEDF is not a complete approach for real-time sensor networks. The authors in [19] define the Sensors Network Lifetime (SNL) as the time until the first node dies. They model the Sensors Network Lifetime (SNL) by a linear program. Their goal is to maximize this NL by defining a routing protocol based on the tree structure. With regard to the energy conception, this protocol determines the optimal route of each sensor node to reach the sink. These authors deploy two types of routing algorithms, the first is centralized and the second is distributed. In the centralized routing protocol, the sink node has all information about the network state. Thus, it is able to compute, at each instant, the optimal route by applying linear programming. Consequently, this centralized approach will increase the time to calculate a route. The technique of the distributed routing protocol is a local method in which the neighbor stations exchange messages of the traffic and network state, in order to update their routing tables. This protocol tries to obtain an optimal Sensors Network Lifetime (SNL) (i.e. maximum value), by running periodically this distributed routing protocol to be adapted to the energy consumption changes. The elaborated routing table makes an inverse tree path to sink. This tree represents the communication between nodes to sink. It is made periodically for load balancing and to optimize paths with regard to power consumption. Also, 'SINEM' [19][20] proposed an analysis of real-time constraints to get a real-time guarantee. The authors in [19][20] propose an efficient approach for energy optimization, but the real-time constraints are secondly taken with less importance. So, real-time concerns are inefficiently optimized.

Most of the presented protocols are with a probabilistic guarantee, which makes them not suitable for hard real-time context. Whereas, the proposed deterministic protocols suffer from restrictive assumptions. Only SINEM [19][20] solution seems to be adequate to real-time deterministic QoS guarantee with energy consumption optimization. That's why we inspired from SINEM [19][20] load balancing technique to build our approach.

The rest of this paper consists of the following sections. In Section 2, our real-time communication tree building approach is presented. In Section 3, an analysis of the energy cost and the Sensors Network Lifetime (SNL) is given. The simulation and results are illustrated in Section 4. Finally, Section 5 concludes the paper.

2. Our Real-Time Communication Tree Building Approach (RT-CTB)

In this section, our aim is to provide communications that respect the real-time constraints with the prediction of the communication delays as well as improving the Sensors Network Lifetime (SNL) of these networks in order to have maximum longevity (see Fig. 1). For that, we have proposed our Real-Time Communication Tree Building approach (Called RT-CTB) which transforms our initial graph into real-time trees periodically.

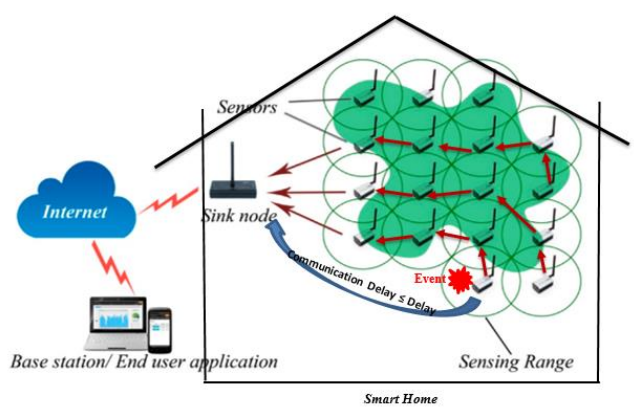

Fig. 1 Real-Time Sensor Networks used in Smart Home.

2.1 Description

The proposed RT-CTB approach aims to propose a global strategy to reduce energy consumption and communication's delay. Our approach is based on the transformation of the graph network to a real-time communication tree while respecting the required delays.

After that, a load balancing is performed by switching the traffic on different paths that help some nodes not losing quickly their energy compared to others. It should be mentioned that the paths are built by the creation of the real-time communication tree. The construction of the tree is done dynamically relative to the weakening of energy knowing that our sensor network is assumed that the nodes are fixed and that there is no addition of additional nodes. Moreover, during our work, we do not deal with the technique of charging batteries. Once the energy level of the piles of nodes decreases, the tree is reconstructed according to the new values of the energy cost. From the initial graph of the network, the communication tree is determined by optimizing the energy consumption while respecting the constraints of the periods. The construction of the communication tree is done node-by-node starting by the Sink node (called SN). Each node added to the tree is selected as being the one having the minimum energy cost and respecting the real-time constraints (see Eq. 1). The building-tree algorithm selects the node that consumes less energy in order to not converge quickly to empty energy and therefore to extend the Sensors Network Lifetime (SNL) of the nodes and the network. The periodic construction of trees depends on the SNL. In other words, there will be no generation of communication trees once we have reached the Sensors Network Lifetime (SNL) of the wireless sensor network. This condition should be verified in order to not dissipate energy and to generate useless trees. Our proposal is to find paths, at the SN, which minimize the consumptions of global energy.
A node Nj is chosen if the Consumed Cumulative Energy (noted CCEj) on the path to the SN is minimal. We must be sure that the selected node will not modify the real-time constraints. So, starting from a node Ni, we choose a Child Node (Called ChN) Nj (the added node) to join the tree if it satisfies the following Eq. (1):

$$\begin{cases} CCEi = Minh \in neighbor(i)\ (CCEh) + Cj \\ TTN\ (i) + TTL\ (i, j) \leq D) \end{cases} \quad (1)$$

Where, C_j is the Cost interpreting the Remaining Energy of the node N_j, CEC_h is the Consumed Cumulative Energy from the node *SN* to the node *h*, $TT_N(i)$ is the data Transmission Time of the node N_i and $TT_L(i,j)$ is the Transmission Time of the Link between nodes N_i and N_j. *D.* represents the deadline.

2.2 Example of RT-CTB

In order to explain the aim of our previously described RT-CTB approach, we take the graph of the network shown in Fig. 2. This graph is composed of six wireless sensor nodes having energy costs noted Ci relative to the node Ni. In the course of time, the energy level decreases for the intermediate nodes solicited in the communications, we then realize a load balancing to solicit other sensor nodes and consequently other nodes. The trees will be generated by our approach. In the case of Figure 2, there is a construction of three communication trees. For the first generated tree (tree 1), note that nodes 1 and 2 are connected directly to node 0 (Sink Node) because our algorithm chooses the shortest path based on the cost of energy. According to the same strategy, the nodes 3 and 4 are connected to node 2, but they can also be connected to node 1. Finally, node 5 can be linked to the node 4.

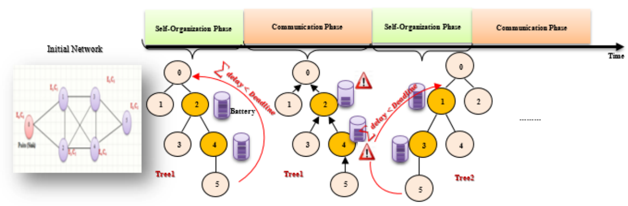

Fig. 2 Different phases of the real-time communication tree building.

After a given period, the remaining energy will change for all sensor nodes. In this case, a rebuilding of the tree will be necessary to take into account the new values of the remaining energies of the nodes (the case of the second communication tree). It should be mentioned that the rebuilding is done in the same way as before. As in the first tree (tree 1), node 2 is the most solicited, its energy is considerably decreased. The generation of tree 2 allows the load balancing by changing the association of the nodes 3 and 4 to the parent node 2 to the new parent and intermediate communication node 1. The traffic passing through node 2 is then alleviated. Using the same process of load balancing and energy consumption, the other trees will be defined. Generated trees are retained provided that the real-time constraint is verified. For example, in the first tree, node 5 must verify that the cumulative delay in communication from node 5 to the NS (node 0) is lower than the defined deadline in each sensor node. Our network goes through two phases: Self-Organization phase and Communication phase. During the first phase, the communication tree-building algorithm will be executed at the Sink Node (SN) in a distributed manner. Once the trees are built, the sensor nodes go through the second phase during which they will exchange their data (see Fig. 2).

2.3 RT-CTB Algorithm

Our algorithm builds a real-time communication tree by adding all the nodes from the original network graph starting by the SN. Firstly, each node of the graph is considered the node that will be connected to the parent node of the real-time communication tree. Subsequently, if this child node is connected to the real-time tree, it will be considered as a parent node (as being a treated node) that will initiate connection messages to other neighboring nodes untreated (candidates to be children nodes) of the graph. The addition of the untreated node (child node) is done in two phases of control message exchanges:

- The parent node sends a message (Ms) to its neighbors for soliciting the child node. This message contains information on energy accumulated at the SN, the node address and its deadline. The energy accumulation is computed within each sensor node that has received the Ms message while starting by the SN. The untreated neighbor nodes (the candidate nodes to be children) will reply by sending a confirmation message (noted Mc) to the parent node to establish a parent relationship with it. The child node can then receive a solicitation message from the different parent nodes and then choose the best one to ensure minimal cumulative energy and delay guarantee. This choice only will be notified to the concerned parent node.
- We propose an algorithm that interprets the communication phases to build a real-time communication tree from the network graph. The parent node task is called Request-child-links. The child node task is called node-child response.

Algorithm 1 Make_Child_Links ()

```
{***Child node solicitation to link***
Ms.energy_cost=cumulative_energy_cost_of_this_node();
Send_broadcast (Ms);
***Receive all the confirmation messages (Mc) from Children nodes***
Start_timer (Δt);
***Δt is the worst time interval required to get all Mc from neighbor's children nodes***
j=0;
Do {if (receive(Mcj))
{ j++;
AddToSet(Mcj, {Mc});
}} Until (expired_timer(Δt));
***get the maximum set of children nodes that verifies real-time constraints (Deadline)***
***SMe is the set of nodes that verifies real-time constraints and SMne set of nodes that does not verifies***
***R is the worst response time of each child node which depends on the allocated timeslot and the number of children nodes (equations 2–7) ***
R = Get_max_ set_nodes_verifies_deadlines ({Mc}, timeslot (), &SMe, &SMne);
***send the established link confirmation message Me and negative confirmation message Mne***
For (m in SMe)
{Me.destination = m.node_address;
Me.source=actual_Node();
Me.Cumulative_Communication_time = m.Cumulative_Communication_time + R;
Send(Me);}
For (m in SMne)
{Mne.destination = m.node_address;
Mne.source = actual_Node();
Send(Mne);}
end procedure Make_Child_Links
```

Algorithm 2 Child_Node_Response ( )

```
{*** Receive the child node solicitation message from parent node***
Start_timer (Δt);
***Δt is the worst time interval required to get all Ms from neighbors children nodes***
j = 0;
Do {if (receive(Msj))
{j++;
AddToSet (Msj, {Ms});
}} Until (expired_timer(Δt));
endLoop=false;
Do {
*** from the parent link solicitation, we choose the one with the minimum of cumulative energy cost
Ms*=Accept_parent_solicitation_with_min_energy_cost ({Ms});
***send a confirmation message (Mc)***
Mc.source = actual_node_address( );
Mc.destination = Ms*.source;
Send (Mc);
***Wait for the confirmation established link message (Me) after the verification of the real-time constraints by the parent node***
Receive (m);
If (m is confirmation_established_link_message)
***m is the Me message
{***add this child node to the communication tree***
***Add_link_to_parent_node_of_tree(m.source, m.destination);
Change_node_state_to_parent (actual_node());
Cumulative_Energy_cost_of_this_node+=Ms*.energy_cost;
endLoop=true;
} Else {***m is Mne message (negative confirmation message,the link can be made due to the real-time constraints which cannot be met. Remove the corresponding node to m from the set {ms} of potential parent nodes to link.***
removeFromSet({Ms}, m);
```

28: }} Until (endLoop or Ms=Ø);
29:}end Procedure Son_Node_Response

2.4 Example of establishing a Sensor Parent Node 1-Sensor Child Node 3 link (SPN1-SCN3)

To explain the aim of our approach and the real-time tree building algorithms, we assume the example of two nodes; Sensor Parent Node 1 (noted SPN1) and Sensor Child Node 3 (noted SCN3). Fig. 3 presents the necessary exchanges to execute the proposed approach.

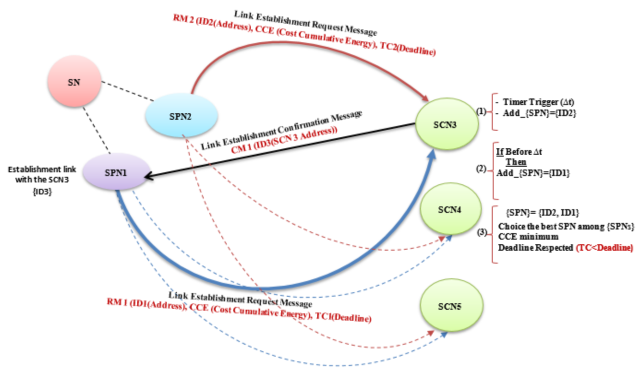

Fig. 3 Link establishment between SPN1-SCN3.

To validate the execution of a WSN real-time application, we propose a mathematic model to predict the Sensors Network Lifetime (SNL) and to respect the real-time constraints.

3. Analysis of the Energy cost and Sensors Network Lifetime constraints

During our work, we consider that the Sensors Network Lifetime (SNL) is the earliest time instant at which any of the sensor nodes in the network fully depletes its battery [20][21][22]. We compute this time in the worst-case situation. Whereas, the energy (cost) is provided by the same formula (2) used by SINEM's works [19][20]. As energies are initially given with different values, we would like to normalize the calculation of the cost of energy in the interval [0, 1]. Value 0 means that energy is full and value 1 means that energy is empty (see Eq. 2).

$$EC_i = t * \frac{P_{tx}(g_i + f_i) + P_{rx} f_i + p_s g_i + K}{TBE} \qquad (2)$$

Where EC_i is the Energy Cost of the node i at time t, P_{tx} is the energy spent in transmission of a packet, g_i is the packet generation rate (its unit is: packets/second) at node i, f_i is the packet forwarding rate, P_{rx} is the energy spent in reception of a packet, and f_i is the packet forwarding rate at node i. We consider that the Sensors Network Lifetime (SNL) expires when the EC_i is equal to 1. In this case, the energy is empty. Otherwise, if the maximum of the Energy Cost is less than 1, the network is still correctly working according to the energy (see (3)).

$$Max_{i \in set-of-nodes}\{EC_i(t)\} \pi 1 \qquad (3)$$

The maximum value of the cost becomes equal to 1, at the moment t when the Sensors Network Lifetime (SNL) is reached. Thus, the SNL is expressed as follow:

$$SNL = \{t | Max_{i \in set-of-nodes}\{EC_i(t)\} = 1\} \qquad (4)$$

Seeing that our routing algorithm generates a set of real-time communication trees. The building is made periodically to achieve the load balancing and we give a lower bound of the worst-case Sensors Network Lifetime (SNL) for different generated real-time trees. The worst tree is that it minimizes the SNL:

$$SNL \geq \underset{Tree \in L_{Tree_i}}{Min} \{t | Max_{i \in set-of-nodes}\{EC_i(t)\} = 1\} \qquad (5)$$

Where L_{Tree} {$Tree_1$, $Tree_2$, $Tree_3$, ….$Tree_n$} is a set of generated real-time trees and n is the number of the tree.

4. Simulation and Results

The purpose of our simulations is to evaluate our Real-Time Communication Tree Building approach (Called RT-CTB) with regard to the Sensors Network Lifetime (SNL) as well as the real-time guarantee. Our energy cost model is inspired by SINEM works [19][20] that uses the Berkeley Mica sensors components. Consequently, we take the packets transmission rate equal to 50 kbps. The packets generation rate for each node is 0.03 per second, which is a typical value for traffic light applications. The battery power is chosen as being the value of two batteries, which can supply 2200 mAh at 3V, for all nodes except the sink node (with no energy constraint). In our simulations, the energy cost in the transmission of one packet (Ptx) is 0.92 mJ. To receive one packet (Prx), the energy cost is 0.69 mJ. Finally, the energy cost in the listening to the channel (K) is 29.71 mJ/sec. We execute a set of simulations, developed in C++ language based on equations of Section 3, in order to evaluate our proposed approach. We begin by simulations dealing with energy spent and, after that, we consider the respect of the deadline and we compare our results by SINEM approach.
The aim of our simulations is to analyze the Sensors Network Lifetime (SNL) and the energy cost of each node depending on the time progress and the real-time tree-rebuilding period. During our simulations, we consider the same network graph presented in Fig.2, where

all the nodes have the same initial energy or Cost (i.e. C0 = C1 = C2 = C3 = C4 = C5). Furthermore, we assume that the overhead of the real-time tree building is neglected and the time interval of direct transmission (between two neighbor nodes) is equal to 10 UT (Unit of Time) which depends on the network flow and the packet size. In Fig.4, we illustrate the variation of Sensors Network Lifetime (SNL) relative to the period of the real-time tree rebuilding. This figure demonstrates two stages. The first one shows that when we increase the period of real-time tree rebuilding, we obtain a linear decrement of the SNL. Furthermore, whether we have more load balancing (short period of real-time tree rebuilding), the energy cost will be more shared by nodes and consequently the SNL increases. Whereas, the second stage (when rebuilding period is up to 350 UT) shows a limit in the Sensors Network Lifetime (SNL). This behavior proves insufficient of load balancing period to share the energy cost between sensor nodes. At this stage, there will be no improvement in the Sensors Network Lifetime (SNL).

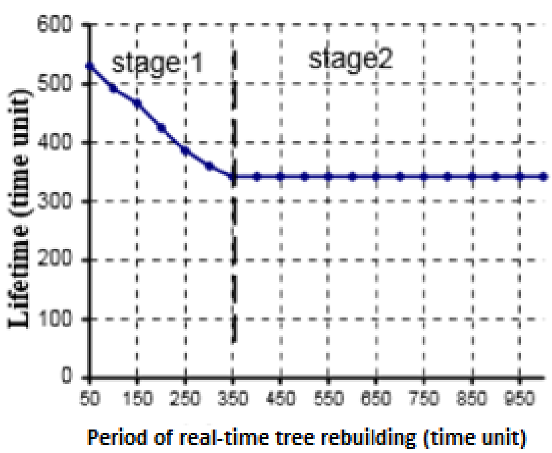

Fig. 4 Variation of the Sensors Network Lifetime (SNL) vs. period of real-time tree rebuilding.

Fig.5 shows the variation in energy cost vs. the time. The load balancing, between nodes 1 and 2 (see generated real-time trees in Fig.2), ensures that the energy cost is shared between them, otherwise the node 1 will waste its energy quickly. The same for sensor nodes 1 and 2 which consume more energy than the others since they are closest to the sink node and ensure the communication forward for other sensor nodes. Thus, all the communications pass through either sensor node 1 or sensor node 2. In the second level, sensor nodes 3 and 4 consume less energy because they represent the second and the third level of the real-time tree, respectively. The sensor node 5 consumes less energy than the other sensor nodes since it is not an intermediate sensor node. It consumes only the energy of its communications.

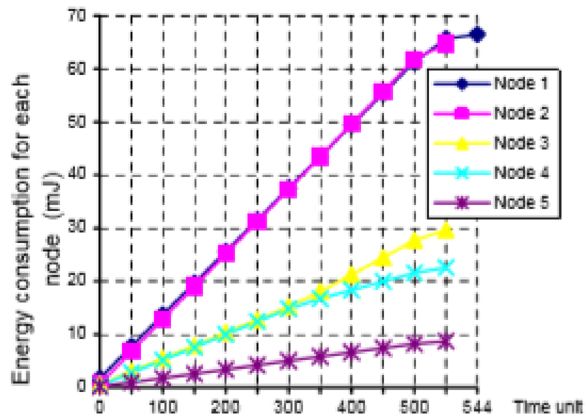

Fig. 5 Node's energy consumption change.

Furthermore, we prove the efficiency of our RT-CTB approach by determining the maximum number of sensor nodes which can support compared to SINEM approach [19][20] with respecting the real-time constraints. For this reason, we modify the deadline values of all sensor nodes and we insert the same value for all and check the number of nodes that can be supported (Fig.6). We distinguish that, for the deadline equal to 1000, our RT-CTB approach can support more than 35 sensor nodes in the network, while SINEM approach cannot support more than 12 sensor nodes. Therefore, our RT-CTB approach is more efficient than SINEM approach for real-time communications. This efficiency is proven by finding real-time communication trees guarantying real-time constraints. The SINEM approach is based on a global guarantee. It means that the real-time constraint is verified globally after the generation of real-time communication trees depending on energy optimization. If one of the generated trees does not respect real-time constraints, the global guarantee will be not possible and it rejects other correct trees. Thus, our RT-CTB algorithm remains more functional and finds more real-time solutions.

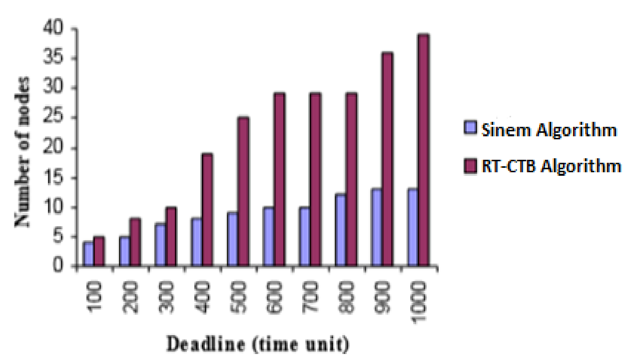

Fig. 6 Variation of the number of nodes vs. Deadline

Finally, we prove that our RT-CTB approach is more efficient in terms of a real-time guarantee than SINEM approach by varying the deadline and checking the real-time solutions generated by both. For this reason, we consider that all the sensor nodes use a global TDMA (Time Division Multiple Access) and we take the same graph network in Figure 2 than SINEM approach. In this case, all sensor nodes have deadlines equal to 100UT, except sensor node 2 with value 50 and a variable deadline for sensor node 1 (noted: d1). We check the deadline guarantees of our RT-CTB approach by report SINEM approach. This comparison is given in Table 1.

Table 1: Comparison between the guarantee of RT-CTB and SINEM approaches vs. deadline variation

Deadline(d_1) / ***Guarantee***	***20***	***30***	***40***	***50***	***60***	***70***	***80***	***90***	**100**
RT-CTB	✓	✓	✓	✓	✓	✓	✓	✓	✓
SINEM	✗	✗	✗	✗	✓	✓	✓	✓	✓

The results show that SINEM approach does not find a real-time solution under the deadline value 50. Whereas, our proposed RT-CTB approach always finds real-time solutions. It means that the capacity of real-time guarantee is better for our approach since we take into consideration the two constraints at the same level: energy and real-time.

5. Conclusion

In this paper, we proposed a Real-Time Communication Tree Building Approach (RT-CTB) which aims to build, periodically, real-time trees from an initial graph network for load balancing. In this case, the sensor nodes will share similarly the energy cost and get paths within pre-defined deadlines. Our proposed approach is distinct to SINEM approach by combining at the same time energy consumption and real-time constraints. In order to get a real-time guarantee, we proposed a mathematical formula of the Sensors Network Lifetime (SNL) and an analysis of the energy cost. The efficiency of the proposed RT-CTB approach is proven compared to SINEM approach in terms of real-time guarantee.

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