Energy Optimization For Mobile Nodes in a Cluster Tree IEEE 802.15.4/ZigBee Network

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***Abstract*—IEEE 802.15.4 proposes a cluster-tree topology to organize a network and to support energy efficient data routing. In this paper, we propose a new approach to manage mobility by adapting this topology. Our approach is based on the link quality indicator (LQI) metric. It aims at anticipating the loss of the association between coordinators and mobile nodes. Hierarchical addresses are attributed to coordinators regarding their position in the network. Then, a speculative algorithm is proposed to choose the next coordinator of association. In this paper, we focus on the consumed energy average and the changing coordinator procedure delay average of moving nodes in the network.**

Keywords: *IEEE 802.15.4/ZigBee, cluster-tree, mobility, LQI, energy consumption*

I. INTRODUCTION

Wireless sensor networks widely use IEEE 802.15.4 due to its low energy consumption, low cost and small size. This protocol is not initially designed for applications that require mobility. The mobility management in IEEE 802.15.4 is, as a consequence, not properly taken into account. In this paper we propose to enhance IEEE 802.15.4 to efficiently handle mobility. Our approach allows a mobile node to move through the cells in a heterogeneous cluster tree network where coordinators have both IEEE 802.15.4 wireless and wired connections. This approach uses the hierarchical addressing algorithm to attribute addresses to coordinators regarding their geographical position. To reduce energy, a speculative algorithm is defined in order to choose the next coordinator for association. Cell change is triggered based on the link quality indicator (LQI). Results obtained in simulation with NS-2 show that energy consumption can be reduced by a factor of three using our approach compared with IEEE 802.15.4 standard protocol.

The remainder of this paper* is organized as follows: In Section II, we provide an overview of the hierarchical topology and addressing necessary for describing our scheme as well as mobility management used in IEEE 802.15.4. Parameters considered in mobility management are introduced in Section III. Section IV reviews several studies and enhancements proposed previously. In Section V, we present our approach, and in Section VI, we present the performance evaluation of the proposed approach. Finally, Section VII concludes our paper by pointing out some possible future research directions.

II. IEEE 802.15.4/ZIGBEE STANDARD

A. *Overview of the standard protocol*

ZigBee [2] relies on the IEEE 802.15.4 specification [1] to define the physical and the mac layers. An overview of IEEE 802.15.4 is available in [3]. The network and the applicative layers are defined according to the ZigBee specification. ZigBee defines three topologies: star, mesh and cluster tree. In each kind of topology, a unique coordinator must be defined. If many IEEE 802.15.4 PANs are present in the same area, each one has to be defined by a unique identifier called a PAN Id. The beacon mode can only be used in a star or a cluster tree topology. In both topologies, a node wishing to transmit a message to another node has to transmit it first to its coordinator which handles the transmission to the destination node. In a cluster tree topology, each cluster has its own coordinator and its unique PAN Id. All clusters of a same network use the same transmission channel. In this topology, a hierarchical address is assigned to each node of the network, so that hierarchical routing protocol can be used [9]. This addressing mode is used in the presented approach. The attribution of hierarchical addresses is based on three parameters: (i) the maximum number of children per parent (C_m), (ii) the maximum number of ZigBee routers (R_m) between these children and (iii) the maximum depth (L_m) of the cluster tree network. At a given depth d, a function called $C_{skip}(d)$ (given in (1)) is used by a node M to calculate the address A_n (following (2)) of its n[th] children. Node addresses are distributed by their parent located at depth d.

$$C_{skip}(d) = \begin{cases} 1 + C_m * (L_m - d - 1) & \text{if } R_m = 1 \\ [1 + C_m - R_m - C_m * R_m^{\,L_m - d - 1}]/[1 - R_m] & \text{otherwise} \end{cases} \quad (1)$$

$$A_n = \begin{cases} A_{parent} + C_{skip}(d) * R_m + n & \text{for leaf nodes} \\ A_{parent} + C_{skip}(d) \times (n - 1) + 1 & \text{for other routers} \end{cases} \quad (2)$$

B. *IEEE 802.15.4 mobility management*

During movement, a node can leave the coverage area of its PAN and enter into an area of another one. Mobility in IEEE 802.15.4 is handled in a very basic way.

* This work is supported by the French National Research Agency (ANR) project GRECO bearing reference ANR-2010-SEGI-004-04.

A loss of association with a coordinator requires an orphan scan operation during which the node looks for its current coordinator. This procedure is triggered if the node fails to listen to four consecutive beacons of its current coordinator. If this step fails, the node, next, begins a new association procedure by making an active or a passive scan. For each scanned channel, if a coordinator is discovered, the mobile node saves its corresponding parameters into a PAN descriptor structure. This structure contains some parameters of the beacon frame such as the PAN Id, the logical channel, the coordinator address and the LQI value of the received beacon. At the end of this scan, the node chooses a coordinator from a list of discovered coordinators for association and sends an association request (assocRqt) using the CSMA/CA protocol. As it can be seen in Fig. 1, when the node receives an association request acknowledgment (Ack) from the coordinator, a macResponseWaitTime timer is set to wait for the processing of the association request. The *macResponseWaitTime* is a mac attribute defined in the IEEE 802.15.4 specification as "the maximum time, in multiples of *aBaseSuperframeDuration*, a device shall wait for a response command frame to be available following a request command frame". When this period expires, the node sends a data request command to the coordinator. Then, the coordinator sends an association response (AssocRsp). The node is considered to be associated with the PAN when an association response (AssocRsp) that contains a new network address and a status indicating a successful association is received.

A communication between different PANs coordinators is not possible unless they belong to the same cluster tree or if they define a common transmission channel. In both cases, the performance of the network is not optimized. In fact, a cluster tree topology presents two major problems. First, the collision probability is high since all nodes transmit on the same channel. Second, the IEEE 802.15.4/ZigBee standard does not specify how to synchronize a cluster tree network. Changing to a common transmission channel requires additional controls to synchronize coordinators as well as maintain nodes associated to these coordinators. In this paper, we consider that different wiredly connected PANs can form a unique heterogeneous network composed of star PANs. All coordinators are connected to a coordinator called a superCoordinator through a wired connection. Messages between nodes that do not belong to the same PAN Id can then be routed through the superCoordinator.

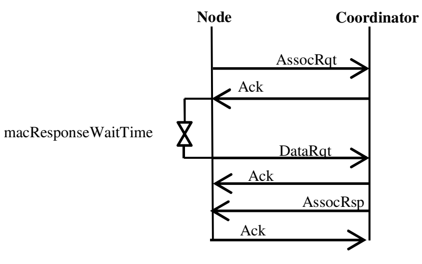

Figure 1. Association procedure in IEEE 802.15.4

Coordinators that are neighbors do not use the same channel so that synchronization between coordinators is not required any more.

III. PARAMETERS TO BE CONSIDERED IN MOBILITY MANAGEMENT

When a packet is received by a node, its link quality LQI can then be determined. The IEEE 802.15.4 standard defines the LQI as an integer ranging from 0 to 255. However, the calculation of the LQI is not specified in the standard. The LQI measurement is a characterization of the strength and/or quality of a received packet. IEEE 802.15.4 specifies that the measurement may be implemented using receiver energy detection (ED), a signal-to-noise ratio estimation (SNR), or a combination of these methods. The use of the LQI metric by the network or application layers is not specified in the standard as well. Although the calculation of the LQI is not specified in the standard, its definition implies that it depends on the distance between the receiver and the sender.

In this study, mobile nodes do neither send nor receive data packets from other nodes. We only consider the case where nodes receive beacons from their coordinator. As a consequence, the only information on the LQI is obtained at the receipt of the beacon frame. Therefore, a low beacon interval (BI) is used in our use cases (table I) so that the number of received beacons is enough to handle mobility.

The frame number of the received beacon also depends on the speed of mobile nodes. Actually, if the speed of a mobile node moving away from its coordinator is increased, LQI values of received packets at the same instant decrease more rapidly. In other words, the synchronization with the coordinator is lost more rapidly.

Our approach was implemented using the NS-2 simulator version 2.34. This version has been extended by integrating a hierarchical routing protocol [9]. The implementation of IEEE 802.15.4 in NS-2 has also been adapted in order to simulate different WPANs star topology, where each WPAN uses a distinct frequency. These changes also allow having both wired and IEEE 802.15.4 wireless interfaces for a same node. In NS-2, the LQI is calculated based on the received signal strength and the signal to noise ratio. A packet is received only if its LQI is equal to or greater than 128. Value 127 is considered to be the worst value in case the packet is not received. The table I summarizes the setup for the different simulations.

TABLE I. SIMULATION SETUP

BI (no inactive period)	245.76 ms
Distance between two consecutive coordinators	25 m
Routing protocol	Zbr [9]
RF transceiver	CC2420
Transmission power	0 dBm
Propagation model	Two-ray-ground

IV. STATE OF THE ART FOR MOBILITY MANAGEMENT IN CLUSTER TREE WSN

Several studies have investigated mobility management in IEEE 802.15.4. In [5], a comparison of mobility scenarios was made in IEEE 802.15.4 networks by varying some parameters, such as the type of communicating nodes, their number and their speed. This study shows that mobility is highly dependent on network topology. Moreover, network performance decreases when the number of mobile nodes is increased or when the node is moving fast. These studies do not cover the cases where many coordinators are present in the same area and when each one is transmitting on a different channel. The most important aspect of mobility management is the association procedure which is costly in terms of time and energy due to the scan phase and the mechanism of CSMA/CA [7]. Authors in [6] show that the CSMA/CA itself has some shortcomings and contributes to the decreased response of the system. Therefore, they propose a simplification of the association procedure for reducing conflicts and the number of retransmissions. This involves changing the association response of the coordinator node from an indirect to a direct mode. The proposed method, thus, reduces the risks of collision, the time required for association and the corresponding energy consumption. In conclusion, the more the number of channel access is reduced, the better the mobility is managed. Extending the range of a network usually consists in using many nodes and letting them communicate via multi hop. Previous studies have shown that using multi hop increases the probability of losing synchronization frame between the different nodes [11]. In [10], authors investigated the possibility of extending the network and reducing channel access conflict by using multi frequencies in the same network. However, the mobility case was not considered.

V. AN ENERGY EFFICIENT IEEE 802.15.4 MOBILITY MANAGEMENT

In IEEE 802.15.4, a node will typically do an orphan scan and an active scan when it moves away from its coordinator area. As it will be shown later on, these scans are costly in terms of both power consumption and latency. In order to minimize these costs, our approach proposes to anticipate the cell change before the loss of connection. For that, we modified IEEE 802.15.4 for handling mobility efficiently. Note that the objective is to reduce the energy consumption of mobile end devices since coordinators are considered to be on power supply.

A. Enhanced changing cell procedure

In order to anticipate the change of cell, our approach uses the LQI metric. As shown in Fig. 2, the decision of changing to a new coordinator is based on an $LQI_{threshold}$. The Fig. 2 illustrates how messages are exchanged between mobile node and coordinators during an enhanced change of cell. When a mobile node M receives a beacon frame with an LQI lower than the $LQI_{threshold}$, it informs its coordinator C1 by sending an LQI notification (lqiNot) message. This frame contains the LQI value of the last received beacon. If the lqiNot is successfully received by C1, it has first to acknowledge the request of the mobile node.

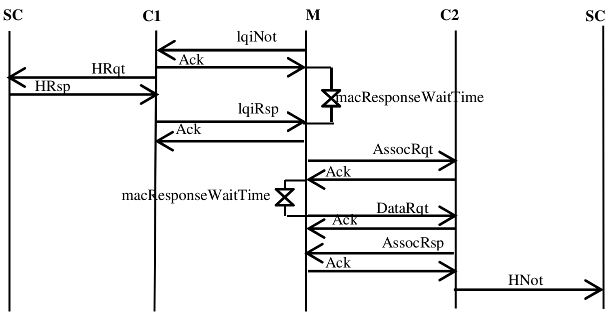

Figure 2. Timing in the changing cell procedure

If the maximum number of lqiNot frame sending trials is reached (fixed to four tentatives in simulations) without receiving the acknowledgment frame (Ack), it is considered that the mobile node has left the coverage area of its current coordinator. Next the node begins an active scan. If the acknowledgment is received, M sets a *macResponseWaitTime* timer to wait for the response from its coordinator C1. After sending the acknowledgment, C1 sends a handover request (HRqt) to the superCoordinator SC which chooses the new PAN for association. The choice of the next coordinator is based on a speculative algorithm detailed in section B. SC answers to C1 with a handOver frame (HRsp) containing the new association PAN Id, the address of the next coordinator (C2), as well as the next logic channel identifier. Then, the coordinator C1 sends to the mobile node M an LQI response (lqiRsp) frame which contains the information sent by SC. The mobile node M starts, then, an association procedure to synchronize with C2. Unlike [6], the association procedure is not modified. If the association procedure ends successfully, C2 sends a handover notification (HNot) to SC that contains the new address of the corresponding mobile node. However, if the procedure fails at any of these steps, the IEEE 802.15.4 standard procedure will be performed starting with an active scan. Notice that the orphan scan is no longer performed.

B. A speculative algorithm for selecting a coordinator

The algorithm of selection of the new coordinator is based on the knowledge of the geographical distribution of coordinators. In this paper, we consider as an example a multi-road with a set of geographically aligned coordinators (Fig. 3). Successive coordinators of the same road are separated by 25 meters. A coordinator is initialized when the superCoordinator attributes an address to it and a channel on which it has to communicate. The initialization of coordinators is organized in relation to their geographical location so that coordinators belonging to the same road have successive addresses. The superCoordinator may have an IEEE 802.15.4 interface and be a coordinator. In this case, it may permit association for end devices. To avoid the case where the superCoordinator attributes to an end device an address that is between two-coordinator addresses, coordinators addresses are attributed decreasingly starting from the highest hierarchical address attributed to the first initialized coordinator (n=1 in (2)) to the lowest address attributed to the last initialized coordinator in the network.

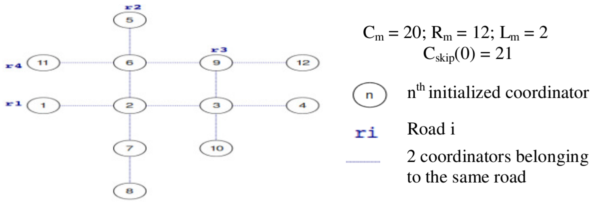

Figure 3. A multi-road network

The address attribution method infers that the last coordinator of a road i must be initialized before the first coordinator of the road i+1. In the example illustrated in Fig. 3, the address of the node 5 of r2 has lower address than its predecessor node 4 of r1. If a coordinator from a road i+1 has already an address because it belongs to another road (e.g node 2 in Fig. 3), the first address is preserved. Let A_0 define the address of the superCoordinator and let A_n be the n^{th} initialized coordinator. Addresses are given following (4) which is obtained by replacing *n* in (2) by *n'* of (3).

$$n' = R_m - n \qquad (3)$$

$$A_n = A_0 + C_{skip}(0) \times (n'-1) + 1 \qquad (4)$$

where n' corresponds then to the n^{th} initialized coordinator. Let Rt_m be the maximum number of roads in the network. An R_m-by-Rt_m Nt matrix is a matrix of the superCoordinator used to describe the network in order to choose the new coordinator of association. Columns of the Nt matrix correspond to the roads in the network.

$$Nt[i,j] = \begin{cases} n & \text{if the } n^{th} \text{ coordinator exists} \\ 0 & \text{otherwise} \end{cases} \qquad (5)$$

Our speculative algorithm favors the movement of nodes on the same road. By default, it is supposed that N nodes move from the coordinator having the highest hierarchical address to the coordinator having the lowest hierarchical address. The choice of the coordinator is based on the previous coordinator of association and on the current road of the mobile node. If the address of the previous coordinator is higher than the address of the current coordinator, the direction of movement is supposed to be changed. Let hist be a vector of size N containing the value of the previous coordinator of association for each mobile node M. Let rd be a vector of size N that corresponds to the current road of a mobile M. The hist and rd vectors are located in the superCoordinator which updates them at the end of each new successful association. The algorithm of selecting the new coordinator is as follows:

```
j = rd[M]
if (hist[M] == Nt[i+1,j] and hist[M] != 0 and i >=1)
then    return Nt[i-1,j]
else if Nt[i+1,j]!= 0
    then return Nt[i+1,j]   // e.g. at the first cell changing
    else return Nt[i-1,j] //e.g. the last coordinator of a road
    end if
end if
```

The choice of the next coordinator of association is done according to the Nt matrix. Nt[i,j] corresponds to the entry of the Nt matrix that refers to position i of the current coordinator of M in the current road j. The first condition in the proposed algorithm consists in verifying that the direction of the movement is not the default direction and the current coordinator is not the first one of the road. The second condition consists in applying the default direction. The last case arrives when the node reaches the limit of the network.

VI. Evaluation of the Proposed Approach

In our experiments, the $LQI_{threshold}$ and mobile node speed have been varied in two different use cases. The superCoordinator does neither send beacon frames nor permits mobile node association. Nodes speed has been varied from 1 to 7 m/s. Nodes are considered to be in an ideal environment, without noise and where the signal quality is only affected by the distance and interferences caused by transmitting nodes that are present in the network.

A. *Single-road use case*

As illustrated in Fig. 4, in this use case the network is composed of one superCoordinator (node 0), three aligned coordinators (C2, C3 and C13 in red) that form a horizontal road, and 12 mobile nodes (in green). The corresponding Nt matrix for this single-road use case is the following:

$$Nt = {}'(1 \;\; 2 \;\; 3 \;\; 0 \;\; .. \;\; 0).$$

Before nodes start to move, all of them are associated and LQI value of each received packet is the highest value 255. Mobile nodes move in the coverage area of the three coordinators. In this study, the simulation duration has been fixed to 300 seconds and $LQI_{threshold}$ is varied from 127 to 250. The procedure of changing cell is considered to be successful if all nodes do not perform a scan while changing cell procedure. All nodes move only once, each one of them follows a horizontal path parallel to the single road. Nodes initially associated to C13 (resp. C3) move to the C3 (resp. C13) coverage area. Nodes initially associated to C2 move to C13 area. The next coordinator of association is, then, properly chosen. The failure of the procedure is only due to packet loss. Fig. 5 presents results of the successful rate of changing cell procedure depending on $LQI_{threshold}$ value and on speed value Vi which is set up to i m/s. Relying on these results, we consider that the $LQI_{threshold}$ values can correspond to three zones whatever the node speed.

a) *Zone 1*: The mobile node is close to the next coordinator. Therefore, synchronization with its coordinator may be lost before the $LQI_{threshold}$ is reached. Moreover, in this case, if the $LQI_{threshold}$ is reached, the lqiNot and the lqiRsp frames may not be successfully received. The success rate decreases when the speed increases.

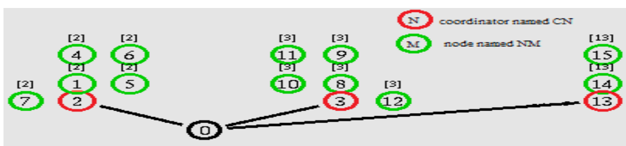

Figure 4. Single-road use case for different $LQI_{threshold}$

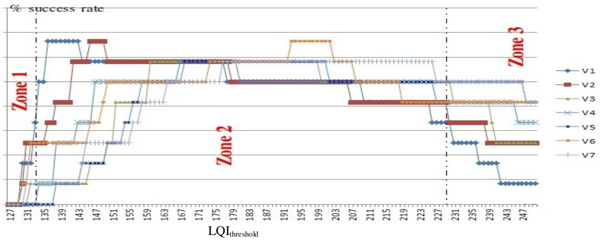

Figure 5. Success rate vs. $LQI_{threshold}$ and speed

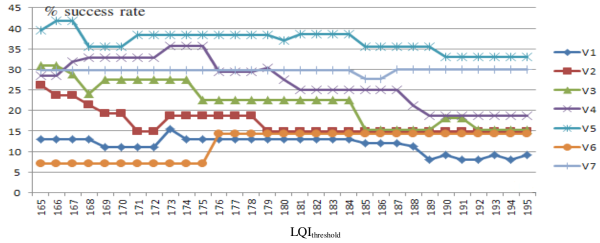

Figure 6. Success rate vs. $LQI_{threshold}$ and speed

b) *Zone 2*: A mobile node is close enough to its current coordinator when it communicates with it. The probability that lqiNot and lqiRsp frames are successfully received is better than in the zone 1. At the receipt of lqiRsp, a node may be close enough to the next coordinator to communicate with it. When $LQI_{threshold}$ is between 164 and 206, the success rate is greater to 50% whatever the speed.

c) Zone 3: The node is close to its current coordinator. The probability that lqiNot and the lqiRsp frames are successfully received is higher than in the first zone. However, since the node is close to its current coordinator, messages related to the association procedure may not be successfully received. In this zone, the success rate increases when the node speed decreases.

B. Multi-road use case:

The geographical organization of the multi-road use case is as described in Fig. 3. The network is composed of a superCoordinator (node 0), 12 coordinators and 7 mobile nodes (node 13 to19). The superCoordinator and the mobile nodes are not shown on Fig. 3. The Coordinators are grouped into 4 roads (r1, r2, r3 and r4). The corresponding Nt matrix for this multi-road use case is the following (only the first 5 representative lines and the first 4 representative columns of the matrix are presented):

$$Nt = \begin{pmatrix} 1 & 5 & 9 & 11 \\ 2 & 6 & 3 & 6 \\ 3 & 2 & 10 & 9 \\ 4 & 7 & 0 & 12 \\ 0 & 8 & 0 & 0 \end{pmatrix}.$$

All mobile nodes are associated before they start to move. They start moving at a constant speed 70 seconds after the beginning of the simulation. Each node follows a trajectory parallel to a road and may turn several times. If it turns, its current direction or its current road is changed. Node trajectories are set randomly without any spatial or temporal dependency. The simulation takes 400 seconds. As in the first case, we have performed simulations in order to determine the successful rate of changing cell for mobile nodes having different speed. The $LQI_{threshold}$ is set to values going from 165 to 195. This corresponds to the zone 2 previously mentioned. As shown in Fig. 6, the successful rate of changing cell procedures is lower than in the first use case. However, this result was expected because nodes move randomly and the geographical organization of the network is more complex. Nevertheless, it can be observed that even in this more complex use case, the successful rate may be up to 40% for a speed of 5m/s.

C. Simulation results related to energy and delay

In the enhanced changing cell approach, the optimization of energy consumption of mobile nodes is based on the LQI metric. The objective of the approach is to reduce the energy consumption and changing cell delay in comparison with the original IEEE 802.15.4 protocol. The delay of a changing cell procedure is calculated from the time a node receives the last beacon to the time that it is successfully associated with a new coordinator. Let the initial node energy be the energy when a node sends an lqiNot or when it begins to make a scan just after a beacon receipt. The energy consumption of a node is the difference between the initial energy and the final energy corresponding to the energy at the end of the procedure. Table II summarizes results obtained by applying the procedure to the first scenario (Fig. 4). Table III shows results obtained in the second scenario (Fig. 3). Speed values are expressed in m/s. Energy is expressed in mJ and delays in second. For each speed and all $LQI_{threshold}$ values, both the average energy consumption and the average delay for all changing cell procedures are computed. In the Single-road scenario $LQI_{threshold}$ varies from 127 to 250 and in the multi-road scenario $LQI_{threshold}$ varies from 165 to 195. The first line of both tables represents the maximum average energy consumption for the different $LQI_{threshold}$ values. The last two lines in both tables show respectively the percentage of gain in energy and in delay corresponding to each fixed mobile node speed compared to the IEEE 802.15.4 standard procedure.

As it can be observed, in the single-road use case, our new approach reduces up to 70.42% the average energy consumption of mobile nodes while the average delay can be decreased up to 73.9%. In the multi-road use case, results in table III show that we can reduce up to 58.17% the average energy consumption of mobile nodes and the average delay can be decreased up to 49.75%. Of course, in a multi-road configuration, the probability of success for changing cell is lower than in the single-road use case. In fact, although the number of mobile nodes is reduced (6 instead of 12), nodes are moving randomly over a longer duration. As a consequence, the probability that they access the medium simultaneously is greater; thus, increasing the number of collisions and backoff periods. Moreover, the probability to get a wrong next coordinator of association (i.e. wrong next coordinator in the lqiRsp frame) is increased.

TABLE II. SIMULATION RESULTS FOR THE SINGLE-ROAD SCENARIO

Speed (m/s)	1	2	3	4	5	6	7
Maximum average consumed energy (mJ)	5.178	3.360	3.823	3.083	3.083	2.629	2.686
Average consumed energy (mJ)	2.947	2.573	2.657	2.468	2.257	2.143	2.027
Average consumed energy in the standard (mJ)	7.017	6.834	6.846	6.848	6.851	6.851	6.851
Maximum average delay (s)	8.77	6.223	6.327	6.185	6.185	6.185	6.185
Average delay (s)	5.296	4.790	4.874	4.446	4.341	3.92	3.677
Average delay in the standard (s)	14.088	14.088	14.088	14.087835	14.088	14.088	14.088
Gain in energy (%)	58	62.35	61.18	63.97	67.054	68.72	70.42
Gain in delay (%)	62.4	66	65.4	68.43	69.189	72.172	73.9

TABLE III. SIMULATION RESULTS FOR THE MULTI-ROAD SCENARIO

Speed (m/s)	1	2	3	4	5	6	7
Maximum average consumed energy (mJ)	55.41	38.624	34.682	30.81	62.802	28.341	22.836
Average consumed energy (mJ)	45.44	36.427	31.424	28.268	28.260	27.865	22.654
Average consumed energy in the standard (mJ)	80.27	61.649	43.475	39.374	30.539	66.62	23.547
Maximum average delay (s)	457.52	39.545	35.177	30.841	26.518	30.408	25.182
Average delay (s)	46.96	37.28	31.829	28.302	24.928	29.588	24.933
Average delay in the standard (s)	93.49	69.074	50.505	44.646	34.891	29.148	26.545
Gain in energy (%)	43.39	40.91	27.69	28.21	7.46	58.17	3.79
Gain in delay (%)	49.75	46.03	36.98	36.61	28.55	-1.51	6.07

When a node only moves from a coordinator zone to a neighbor coordinator one, the changing cell procedure will certainly successfully end by the association of the mobile node to the coordinator. In this case, if the mobile node's speed is high, it will be faster within the new coordinator area. Thus, changing cell procedure delay and consumption average energy will be lower. As a consequence, the gain in energy and delay is higher when the speed is higher. This explains results obtained in table II. However, when it enters many coordinator coverage areas while moving at a high speed, the node may begin a changing cell procedure with a coordinator and then leaves its coverage area before the end of the procedure. In this case, the gain in energy and delay is higher when the speed is lower as obtained in the second use case.

VII. CONCLUSION AND FUTURE WORK

This paper proposed a new approach for mobility management of IEEE 802.15.4 mobile nodes in a cluster tree topology. The approach was based on an $LQI_{threshold}$ value and on a speculative selection of the next coordinator. Simulations demonstrated that anticipating the cell change before the loss of connection coupled with the right selection of the next coordinator can reduce the energy consumption average of mobile nodes up to 70%. Thereby, an improvement of the speculative algorithm should be performed to take into account more historical information related to the node movement and to better involve the coordinator infrastructure. Moreover, since node speed has effects on delay and energy, the choice of $LQI_{threshold}$ would be adapted according to the characteristics of the node movement. In addition to that, we will evaluate the proposed approach for mobile nodes in communication and for some existing mobility models (e.g. Manhattan mobility model).

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