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Performance Evaluation of IEEE 802.15.4 for Mobile Sensor Networks

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***Abstract*— The IEEE 802.15.4 standard medium access control (MAC) protocol for low rate wireless personal area networks (LRWPAN) is design mainly for static sensor networks and its capability to support mobile sensor networks has not yet been established. To the best knowledge of authors, this is the first paper that evaluates the suitability of IEEE 802.15.4 MAC in mobile sensor networks environment. We evaluate the performance based on node's speed and beacon order, and observe the effect on energy usage, packet delivery ratio and time required to associate with its coordinator. From the experiment we observe that the moving nodes experienced serious problems in association and synchronization and show results on energy usage, throughput , association and reassociation rate with different speeds of moving node. We also identify some key research problems that need to be addressed for successful implementations of IEEE 802.15.4 in mobile sensor networks environment.**

I. Introduction

Integrating node mobility features in wireless sensor networks (WSN) raises many new challenges to the research community. In WSN, node mobility is expected to facilitate numerous applications, from home healthcare and medical monitoring to target detection and animal monitoring. In particular, the issues regarding how significantly sensor mobility affects network performance at the Medium access control (MAC) layer level should be acknowledged. This is important in order to provide smooth flows of traffic in mobile sensor networks. The task of the MAC protocol is to efficiently manage the data transmission among nodes [1]. In sensor networks, MAC protocol should ensure that the association and synchronization process among nodes is in steady state without link failure. Although the standard MAC protocol IEEE 802.15.4 is proven to accommodate low data-rate and low power-consumption networks [2, 3], it should be evaluated for the mobile sensor network environment.

Permanent association is very hard to maintain when the nodes move frequently from one coordinator to another in mobile sensor networks. Because of the network's low range, nodes can lose neighbourhood information easily from the coordinator, this is called losing synchronization. In IEEE 802.15.4, when the node starts to lose its synchronization, it will send an orphan notification command to the coordinator and request for re-association. Within this period, the node does not receive any data from other nodes [4], which influence the throughput and network performance.

This paper evaluates the robustness of IEEE 802.15.4 in a mobile sensor networks environment. The objective is to investigate how the standard MAC performs in terms of throughput and node effective association time with its coordinator for mobile sensor networks. In this paper, the coordinator is static and only the nodes are modelled as moving. This is to ensure the accurate result when the node is out-of-range because of the distance from the coordinator. We evaluate the performance based on node's movement speed and beacon order and observe the effect on energy usage, packet delivery ratio and time required for a node to associate with its coordinator. We also look at the effect of node's speed when the node associates and reassociates with different coordinators.

II. Related Work

There are a number of papers in literature that focus on node mobility at MAC layer in WSN but none are concentrating on IEEE 802.15.4 for mobile sensor networks. In [5], the authors introduce MS-MAC where it is expected to outperforms S-MAC in terms of better throughput, less delay and more energy efficient in mobile sensor network environments. MS-MAC shortens the time required for the moving node to synchronize with its neighbourhood every time it moves to the new cluster. However, authors in [5] only concentrated on the design issues of MS-MAC and did not provide the detail of network performance.

MMAC [6] which follows the design of TRAMA [8] shows that its performance outperforms TRAMA in terms of energy-efficiency, delay and packet delivery ratio in mobile sensor networks. However, MMAC is a schedule-based MAC protocols while IEEE 802.15.4 is a contention-based MAC protocols. Furthermore, this paper [6] does not consider nodes with high speed and does not mention the percentage of moving nodes.

To the best of our knowledge, other papers on IEEE 802.15.4 are on static sensor networks [2,3,9,10]. The first performance evaluation of IEEE 802.15.4 [2] focuses on beacon-enabled mode for a star-topology networks. Authors in [9] simulates IEEE 802.15.4 performance on beacon-enabled and non beacon-enabled mode. Another related paper [10] focus on carrier sense with multiple access (CSMA) and analyses the performance limit of the slotted CSMA-CA in

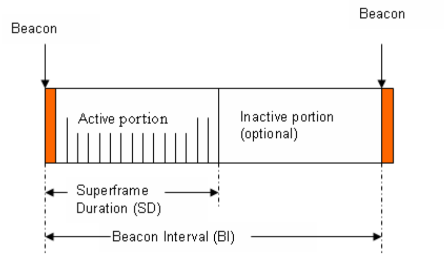

Fig. 1. Beacon interval and superframe structure

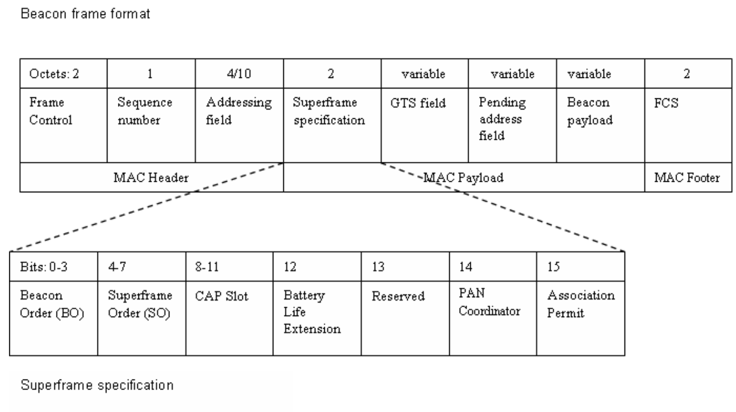

Fig. 2. Beacon frame format and superframe specification

IEEE 802.15.4. However, none of these papers evaluate the IEEE 802.15.4 performance in mobile sensor networks.

This paper concentrates on the performance of IEEE 802.15.4 in mobile sensor networks environment. We investigate the impact of changing beacon order (BO) on throughput, speed and energy for the moving node in a single-hop network. We compare the performance for various node speeds. We identify that the synchronization and association for the moving node is critical in beacon-enabled mode. We simulate some scenarios to show the results of node's association and reassociation rate, packet delivery ratio and energy level usage on IEEE 802.15.4 in mobile sensor networks.

III. Overview of IEEE 802.15.4 beacon-enabled mode

The IEEE 802.15.4 standard [4] defines both the physical and the MAC layer protocols for low data rate, low power consumption and low cost applications. The standard MAC protocol supports two operational modes, either beacon-enabled or non beacon-enabled. When using a beacon, the transmission is based on superframes slotted CSMA-CA. For the non beacon mode, the messages will be directly transmitted in an unslotted CSMA-CA.

Coordinators on a personal area network (PAN) can choose to operate on beacon-enabled mode or non beacon-enabled mode. Nodes attached to the beacon-enabled coordinator will receive beacon frames from the coordinator periodically depending on the value of beacon interval (BI). The BI defines the time between two consecutive beacon frames, which have an active and an inactive portion (Figure 1). The active portion, called superframe, is divided into 16 equally-sized time slots, during which frame transmissions are allowed, with the first slot assigned for beacon transmission. The beacon intervals are determined by two parameters which are known as beacon order (BO) and superframe order (SO). The beacon intervals are defined as follows:

$$BI = aBaseSuperframeDuration.2^{BO}$$
$$for\, 0 \leq BO \leq 14 \qquad (1)$$
$$BI = aBaseSuperframeDuration.2^{SO}$$
$$for\, 0 \leq SO \leq 14 \qquad (2)$$

In equation (1) and (2), *aBaseSuperframeDuration* is equal to 960 symbols which corresponds to 15.36ms [10]. Each symbol is equal to 0.016ms. The information regarding superframe specification in beacon frames is to ensure synchronization among nodes. The beacon frame format and superframe specification field are given in Figure 2. Node which receives the beacon frames can start transmitting data according to the CSMA-CA mechanism. Failure to receive a beacon frame a predetermined number of times results in losing synchronization and failure to transmit and receive data. However, node that loses synchronization (known as orphan node) can re-establish communication with its coordinator by sending an orphan notification command to the coordinator. The node will wait for a response from its coordinator and re-establish the link. However, if the node fails to receive any response from its coordinator in a predetermined period, it will start a new association procedure by listening to beacon frames from any other nearby coordinators.

The flow of node association and synchronization is given in Figure 3. The node association starts with an active scan procedure that scans all listed channels by sending beacon requests to all nearby coordinators. All the information received in a beacon frame will be recorded in a PAN descriptor. The results of the channel scan will be used to choose a suitable PAN. The node then sends a request to associate with the chosen coordinator. The node updates its current channel and PAN id while waiting for an acknowledgement from the coordinator. Upon receiving an acknowledgement, the node then waits for the association results. The coordinator will take *aResponseWaitTime* symbols (*32*aBaseSuperframeDuration, about 0.49 seconds)* to determine whether the current resources are available on the PAN in order to allow the node to associate. If sufficient resources are available, the coordinator then allocates a short address to the node and send an association response command containing a new address and a status indicating a successful association. If there are not sufficient resources, the node will receive an association response command with a failure status.

After the node associates with its coordinator, it will send a

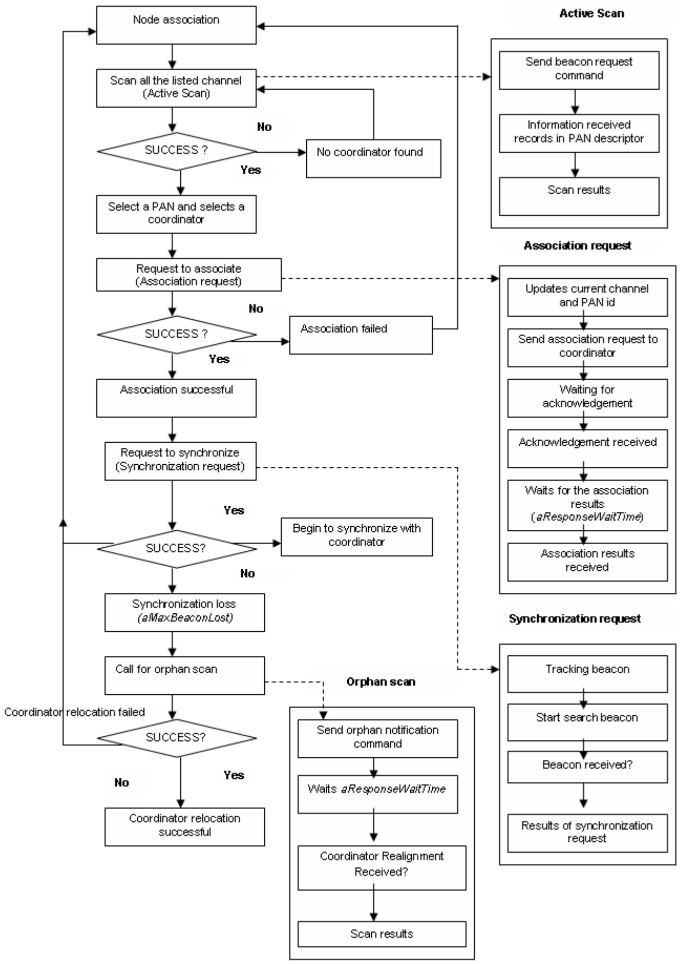

Fig. 3. Flow of node association and synchronization

request to synchronize and start tracking the beacons regularly. If the node fails to receive a beacon *aMaxLostBeacons* times (equal to 4 times), it may conclude that it has been orphaned. The node then has the option either to perform the orphan device realignment procedure or perform the association procedure. If the node chooses to perform an orphan device realignment, it will do the orphan scanning by sending an orphan notification command to relocate its coordinator. The node waits for *aResponseWaitTime* symbols to receive a coordinator realignment command. The coordinator that receives the orphan notification command will search its list looking for the record of that node. If the coordinator finds the record, it will send a coordinator realignment command to the orphaned node together with its current PAN id, MAC PAN id, logical channel and the orphaned node's short address. The process of searching the record and sending the coordinator realignment command takes within *aResponseWaitTime* symbols.

IV. IEEE 802.15.4 in Mobile Sensor Network

The implementation of non beacon-enabled mode in mobile sensor networks is not suitable because the non beacon-enabled mode does not send a beacon periodically, thus the node will assume its association is always preserved although it may have moved away from the coordinator and lost the link. If this happens, the moving node stops its attempt to associate with other coordinators because it does not consider itself an orphan node. Thus, it will be difficult for the nearest coordinator to detect this node.

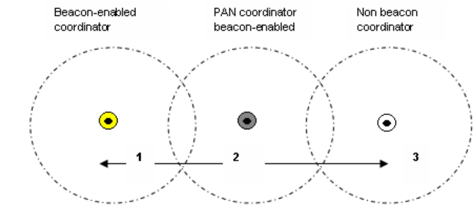

Fig. 4. Association weakness in non beacon mode

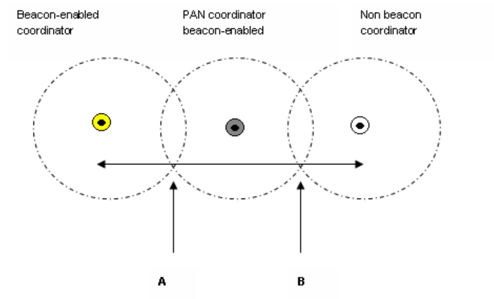

Fig. 5. Fast moving node lost synchronization

Figure 4 shows that the moving node at position 1 associates with the beacon-enabled coordinator. In position 2, it associates with the PAN coordinator which is also beacon-enabled and in position 3, it associates with the non beacon coordinator. The node will lose connectivity with the non beacon coordinator when it moves back to position 2, however, because of weak synchronization in non beacon mode, the node will not realize that it has moved out of range with its non beacon coordinator. In this case, it could not synchronize with any coordinator and could not be detected unless it is in range of the non beacon coordinator.

In beacon-enabled mode, a node considers itself an orphan when it does not receive a predetermined number of beacon frames from its coordinator. When the moving node moves further from its coordinator, it starts to lose synchronization. It then triggers the orphan device realignment procedure by sending an orphan notification to its original coordinator. If the coordinator does not reply after the node sends the orphan notification a predetermined number of times, the node then starts a normal association with the nearest coordinator. This often creates problems for a moving node because if it moves too fast, it will receive beacon from the nearest coordinator and try to associate but may not finish the association process.

In Figure 5 , the moving node will lose its synchronization when it is at position A. Then it starts to send orphan notification command and waits for the response from its original coordinator. When it fails to receive any response, it starts to associate with the nearest coordinator, which is a PAN coordinator. If it moves too fast, while waiting for the response from the PAN coordinator, it may be already at position B where it is out-of-range from the PAN coordinator. Therefore, it fails to associates with any coordinator.

V. Simulation results

There are three stages of experiments carried out to evaluate the suitability of IEEE 802.15.4 in the mobile sensor environment. We conduct our experiment using ns-2 simulator. The data rate is 250 kbps with 90 bytes of packet size. The simulation duration is 500 seconds for every experiments. We use Poisson traffic for all simulations.

The first experiment consists of one moving node and one coordinator. The coordinator and the node are setup to be 10 meters apart. The coordinator is not a PAN coordinator, so another PAN coordinator is positioned near the coordinator to start the network. The moving node will move back and forth from the coordinator with different speeds and beacon orders (BO). Figures 6 - 8 show the throughput, energy usage and association time for the moving node. Figure 6 shows the throughput when different speeds and different beacon orders are being set up. For a speed of 5 ms and 10 ms, the throughput drops slightly at BO = 5 and above. The fast movement of the node may cause some packet drops due to its position and weak signal from the coordinator. The energy usage in Figure 7 differs with the change of BO where lower BO consumes more energy because the node has to use its energy to receive more beacons from the coordinator. The different speeds do not show any difference in energy usage. The time required for the node to associate with the coordinator in Figure 8 is different for BO= 6 and above with different node speeds. For speeds of 0.2 to 1 ms, the movement of the node approaching the coordinator and PAN coordinator has confused the node and it ends-up receiving a beacon from the PAN coordinator instead of from the coordinator. It then associates itself with the PAN coordinator. This explains why the association time is shorter for speed 0.2, 0.5 and 1 ms. Nevertheless, for a node speed of 2 ms, it associates itself with PAN coordinator for beacon order 9 and 10. With speed 5 and 10 ms, the node associates with its own coordinator and not the PAN coordinator. This is because it moves too fast, which means it is not near to the PAN coordinator long enough before moving further from the PAN coordinator.From figures 6-8, it is evident that there is not much difference in throughput, energy usage and association time with beacon order less than 6 and node's speed less than 5 ms. However, BO= 6 and above are not suitable for mobile sensor networks especially in time required to associate because it delays the node's association time excessively.

The second experiment consists of 10 nodes moving and beacon order (BO) and superframe order (SO) varied from 0 to 10. There are 19 sensor nodes altogether, with 8 set to be coordinators and 1 PAN coordinator. 10 nodes are moving in a 50 x 50 m^2 area and these nodes change coordinators regularly while moving. Results from figure 9 shows that changing the beacon order to lower values such as 0, 1 or 2 decreases the throughput. This is due to the fact that the node orphans too frequently and is busy associating and re-associating itself rather than receives data.The results become stable for beacon order 3 and above. However, beacon order 5 and above create more delay in mobile sensor networks because the moving nodes that orphan and need to re-associate have to wait longer for the process.

Experiment 3 evaluates the association rate for a moving node where it changes coordinator regularly and does not stop moving. From this experiment, we observe that the moving node stops re-associating with any coordinator after the first few times it changes coordinators. The scenario becomes worse with higher speed. According to Figure 10, the node's active period is shorter with the increase in speed. This is because the node does not has enough time to receive beacons from the nearest coordinator due to its fast movement and its position. Figure 11 shows the reassociation rate for the same node with different speed. Nodes with higher speed are found to have a lower association rate. This is due to the lack of association efficiency when the moving node is changing coordinator but could not manage to synchronize with the coordinator because of its position and speed. Figure 12 shows that increasing the number of moving nodes results in more failure of reassociating. This is because the increase in the number of moving nodes increases the beacons lost and reduces the reassociation rate.

In this paper, the issue of node mobility at the MAC layer using IEEE 802.15.4 is elaborated and evaluated using ns-2. Different speeds of node do not have much impact on the throughput for one node and one coordinator as shown in experiment 1 because the node is always in the coordinator range without packet collision or hidden terminal issue. The decrease in throughput can be seen where more nodes are moving. The association efficiency is affected if the moving node has to change coordinators regularly. The faster the node's speed and the greater the number of moving nodes can deteriorate the node's synchronization because of an increase in number of beacons lost and packet collisions.

VI. Conclusion

We have found that IEEE 802.15.4 cannot maintain node's connectivity for fast moving nodes in beacon-enabled mode where the moving nodes change coordinators regularly. Although energy is not obviously affected compared to static networks, we have found a serious problem in the node's association with coordinators. The moving nodes stop re-associating after a few seconds and this becomes worse with higher speeds and when more nodes are mobile. The weakness in nodes' association, therefore, degrades the network performance due to the lack of synchronization with coordinators. More works are needed to address the association and beacon interval issues for successful implementation of IEEE 802.15.4 MAC in a mobile sensor networks environment.

When the node moves out of its coordinator range, it should start finding a new coordinator straightaway while

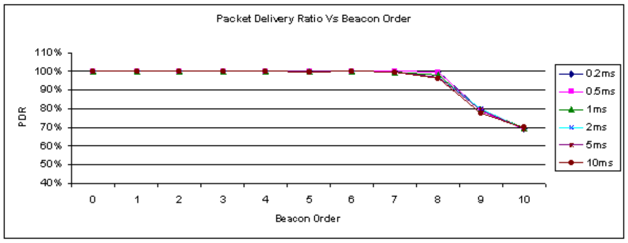

Fig. 6. Effect of node's speed on BO and PDR

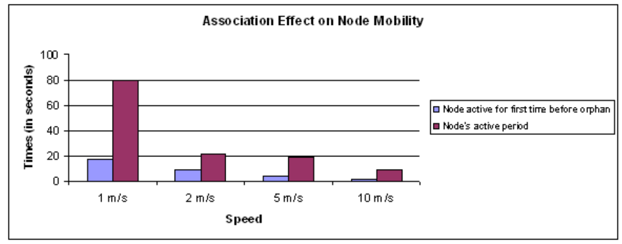

Fig. 10. Effect of node's speed on association with coordinator

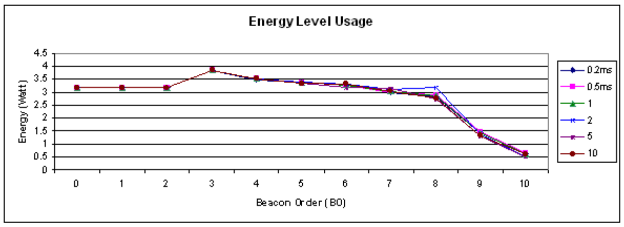

Fig. 7. Effect of node's speed on BO and energy usage

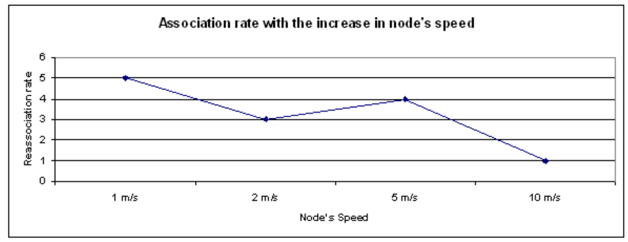

Fig. 11. Effect of node's speed on node association rate

it moves and not trying to send any orphan notification command. While sending an orphan notification saves some amount of energy compared to start a new association, this only gives advantage for static node which has a probability to receive a respond from its coordinator. Our future works will further investigate into possible solutions to improve the performances of IEEE 802.15.4 for mobile sensor networks.

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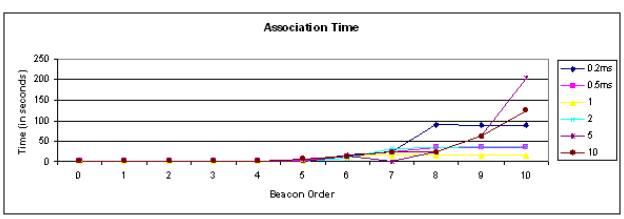

Fig. 8. Effects of node's speed on BO and association time

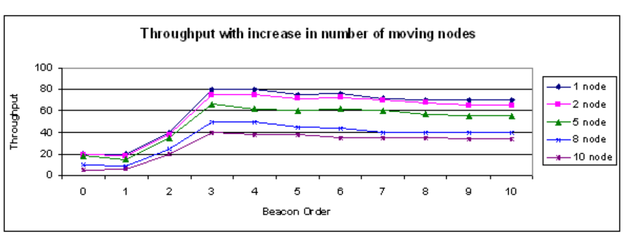

Fig. 9. Effects of number of nodes on BO and PDR

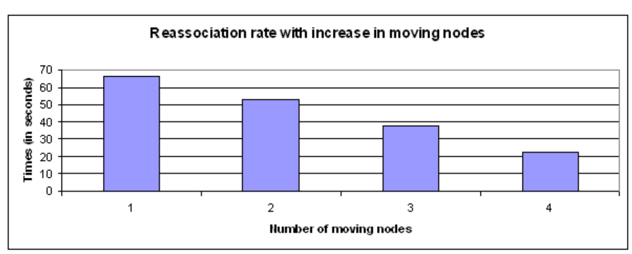

Fig. 12. Effect of number of nodes moving on association with coordinator