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Impact of Mobility on the IoT MAC Infrastructure: IEEE 802.15.4e TSCH and LLDN Platform

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***Abstract*—Realizing the target of high reliability and availability is a crucial concept in the IoT context. Different types of IoT applications introduce several requirements and obstacles. One of the important aspects degrading network performance is the node mobility inside the network. Without a solid and adaptive mechanism, node mobility can disrupt the network performance due to dissociations from the network. Hence, reliable techniques must be incorporated to tackle the overhead of node movement. In this paper, the overhead of mobility on both IEEE 802.15.4e timeslotted channel hopping (TSCH) and low latency deterministic (LLDN) modes is investigated. These two modes can be considered as the MAC layer of the IoT paradigm because of their importance and resilience to different network obstacles. In addition, the set of metrics and limitations that influence the network survivability will be identified to ensure efficient mobile node handling process. Both TSCH and LLDN have been implemented via the Contiki OS to determine their functionality. TSCH has been demonstrated to have better node connectivity due to the impact of frame collision in LLDN. In addition, by neglecting the overhead of collision, the LLDN has been shown to have better connectivity and low radio duty cycle (RDC).**

***Index Terms*—IEEE 802.15.4e, TSCH, LLDN, Node mobility, Contiki OS.**

I. INTRODUCTION

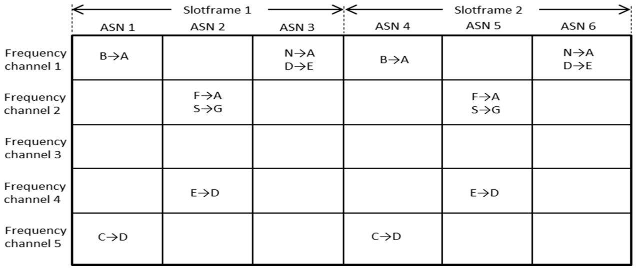
The evolution of the IoT concept is determined by multiple standardization tools that have shaped the infrastructure of the IoT paradigm. Regarding limited memory and low power devices as required for wireless sensor network (WSN), three basic components have formed the communication stack which will smoothly integrate these limited power devices with the internet. These three elements are the IPv6 protocol, the 6LoWPAN adaptation layer and the IEEE 802.15.4 standard. The IEEE 802.15.4 [1] standard defines the dominant physical and MAC layers of the IoT infrastructure. In addition, multiple industrial technologies that reside under the IoT umbrella have incorporated the IEEE 802.15.4 as the default physical and MAC components, e.g. WirelessHART, ISA 100.11a and WIA-PA. Hence, several contributions are made to optimize the performance of this standard and achieve a more coherent system. As a result, the first MAC amendment IEEE 802.15.4e [2] has been introduced that presents two important modes of operation, low-latency deterministic network (LLDN) and timeslotted channel hopping (TSCH). The LLDN is designed to support applications that emphasize high cyclic determinism and low latency reading aggregation. In the meantime, TSCH aims to provide network robustness and minimize the impact of collision while increases network throughput and extends the effective range of communication.

The emergence of such networks led them to be utilized into further, different sorts of application that each has different requirement with various challenges. Applications like health (wearable sensors) [3], cargos containers [4], automotive industry and airport logistics all share the aspect of also including mobile nodes. Therefore, the current standards and technologies must consider the overhead of node movement within the functionality of the network.

Prior to investigating the impact of node mobility, the type of node movement has to be addressed in order to define the appropriate approach to tackle the mobility issue. According to [5], the node mobility can be differentiated into two basic types, macro and micro mobility. Macro mobility refers to node movement between different network domains while the micro mobility indicates the node movement within single network domain. Hence, based on this classification, we can allocate the best elements (of IPv6, 6LoWPAN or IEEE 802.15.4e) to handle node movement. In the meantime, for several of the mentioned applications the mobility of the nodes can be managed through IEEE 802.15.4e MAC layer rather than incorporating the MIPv6 protocol to handle this issue. Hence, the overhead of the IPv6 protocol can be omitted, since such protocols have been seen to have high overhead over limited power devices [6]. Accordingly, the TSCH and LLDN modes will be under the scope to handle node mobility.

The impact of node mobility is basically influenced by the number of dissociation from the network that degrades node connectivity and causes several disruptions to the functionality of the network. Hence, in order to mitigate the overhead of dissociations, IEEE 802.15.4e MAC infrastructure must ensure a fast and smooth association mechanism to maximize connectivity and achieve better node throughput. In turn, the IoT paradigm can easily tolerate the existence of mobile nodes and realize efficient ubiquitous object networking.

The related work in the field has only focused on the mobility issue of either beacon-enabled or the beacon less modes [7, 8]. In addition, regarding the TSCH or LLDN, there



	ASN 1	ASN 2	ASN 3	ASN 4	ASN 5	ASN 6
Frequency channel 1	B→A		N→A D→E	B→A		N→A D→E
Frequency channel 2		F→A S→G			F→A S→G	
Frequency channel 3						
Frequency channel 4		E→D			E→D	
Frequency channel 5	C→D			C→D		

Fig. 1. TSCH slotframe structure

are no prior contributions that investigate the overhead of node mobility. In our previous work [9], we have addressed the impact of mobility for only the TSCH mode. Accordingly, the aim of this work is to investigate the overhead of node mobility over the infrastructure of both LLDN and TSCH modes while identifying the drawbacks that negatively impact the mobility management process. Both models have been implemented via the Contiki OS [10] through different deployment scenarios to study providing a reliable mobile node handling scheme.

II. LLDN AND TSCH DESCRIPTION

The IEEE 802.15.4e standard has introduced several techniques and enhancements in this amendment as the coordinated sampled listening technique (CSL), deterministic and synchronous multi-channel extension (DSME), LLDN and TSCH modes. In this section, we will focus on both LLDN and TSCH modes for their importance and crucial services that can influence positively the rise of the IoT concept.

A. Timeslotted channel hopping mode (TSCH)

This mode has gained a lot of interest in the research community due its robustness that achieved through a hybrid technique which based on both time and frequency channel diversity. Due to its importance and robustness, the IETF has formed a dedicated group (6TiSCH) [11] to integrate the IPv6 and the TSCH mode. The default routing protocol has been set to the RPL routing protocol.

The coordinator in the TSCH network assigns a dedicated timeslot for each node and when each timeslot elapses the frequency channel will be changed. The mechanism by which the nodes and the coordinator determine the recent frequency channel for the current timeslot is based on the channel offset and the number or of frequency channels and the number of the timeslot. Each timeslot has a unique number called the absolute slot number (ASN). Hence, the nodes can indicate the frequency channel of the current timeslot via:

$$PH_{channel} = Frequency_{List}\ [\mathrm{ASN} + CH_{Offset}\ \%\ N_{ch}]$$

Where $PH_{channel}$ is the physical channel, $Frequency_{List}$ is the list of the available frequency channels, CH_{Offset} is the channel offset and N_{ch} is the number of channels in $Frequency_{List}$. Accordingly, the coordinator assigns each node a link, which is a combination of time and frequency to facilitate transmitting readings without any collision. In the meantime, the coordinators periodically broadcast the enhanced beacons (EB) to indicate the existence of a coordinator and to determine the ASN value. This will inform the nodes that seek to join the network on the current sequence of channels for the upcoming timeslots. The TSCH network has defined what is called a slotframe (as depicted in Fig. 1) that contains a number of timeslots, corresponds to the number of nodes, and this slotframe will be repeated (but with different ASN and channels) in each time based on the period of transmission.

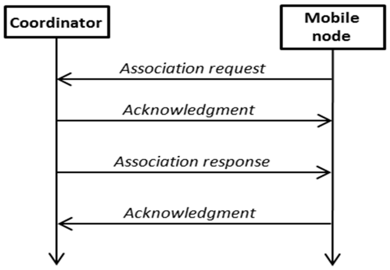


Fig. 2. FastA association mechanism

The timeslots in the slotframe structure is categorized into three types; TX (which is allocated for a specific node to transmit reading), RX (for sending information from the coordinator to the nodes and SHARED TX (that is the nodes are contending on to send requests or readings, the type of each timeslot will be defined through EB).

The mobile node that announces it status as 'orphan' will initiate the association process by scanning the available number of frequency channels in $Frequency_{List}$ for a valid EB. Once it detects an EB, it sends an association request to request a link with the coordinator. Although the standard has identified the association process in the TSCH mode as optional, this will introduce several issues since the standard assumes that an orphan node can be synchronized with a network through only listening to the EBs and hence, deduce the structure of the slotframe. However, the coordinator has also to be identified about the new node wishing to join the network and to allocate a dedicate TX slot or increase the number of SHARED TX. Thus, the TSCH can preserve its targeted functionality by providing reliable and collision-free communication. In the meantime, the mechanism of the association process can be carried out either through the default association process defined in [1] or through the fast association technique FastA (expressed in Fig. 2) which is described in [2].

B. Low latency deterministic mode (LLDN)

Several applications in the industry require deterministic systems to ensure low delay data aggregation services. Based on this, the IEEE 802.15.4e has presented the LLDN mode that according to the standard, within less than 10ms the coordinator must be able to collect data from 20 devices. The LLDN can accomplish this task by relying on two important features in its structure. These two specifications are; (i) reduced MAC frame header through eliminating the addresses field in the frame header and keeping only one byte for the frame type and two bytes for the FCS. The coordinator can identify the ID of the node through the slot number that the node is being transmitting on. (ii) Each node has a defined slot in the superframe for which they are the 'slot owner' and thus, they do not need to contend on the medium prior to transmission. This will ensure low delay and guaranteed transmission. The LLDN mode has classified the network

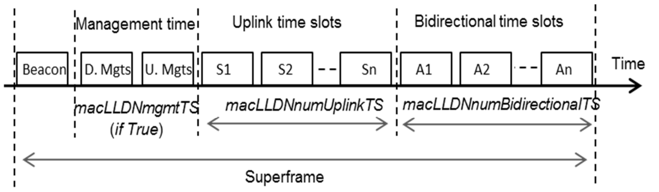


Fig. 3. LLDN superframe structure

lifecycle into three different transmission modes, ‘discovery’, ‘configuration’ and ‘online’ state.

The general superframe structure (as indicated in Fig. 3) is composed of one beacon slot, two management slots, *macLLDNnumUplinkTS* slots for regular reading transmission, *macLLDNNumRetransmitTS* slots for refreshing faulty transmissions and *macLLDNBidirectionalTS* slots used as either uplink or downlink (marked by the coordinator). The *macLLDNnumUplinkTS* value is set as default to 20 but can be variable based on the number of nodes attached to the coordinator.

The coordinator is responsible for defining the current transmission mode through identifying this through broadcasted EBs. The discovery state is invoked during the initialization of the network and over adding new nodes to the network. The node that seeks to join the network has to scan for EBs that indicates discovery state. The configuration state is required to synchronize the nodes that managed to communicate with the coordinator during the discovery state and show their willingness to join the network. The coordinator at this stage needs to allocate each node a dedicated slot and replies to each configuration request. The nodes that finalize their configuration during the configuration state can commence transmitting readings during the online state once the coordinator confirms the current state as the online state.

During the beacon slot, the coordinator announces the EB that indicates the current transmission state and the number of slots and their sizes plus marking the existence of bidirectional and retransmission slots. In addition, the LLDN is based on the concept of group acknowledgment that embeds an ACK bitmap either in the beacon or is transmitted separately in a single frame. There are two management timeslots one of which is uplink (sending requests form the nodes to the coordinator) and one downlink (where the coordinator replies back to the nodes that has requested). The next slots in the superframe are unidirectional uplink timeslots where the nodes are sending their regular readings to the coordinators; the number of theses slots is determined by the value of *macLLDNnumUplinkTS*. Within this field, the coordinator can allocate a specified number of uplink slots as retransmission slots. Hence, the number of slots to send readings is (*macLLDNnumUplinkTS* - *macLLDNNumRetransmitTS*) and *macLLDNNumRetransmitTS* slots are allocated for the nodes to retransmit their readings if the group ACK bitmap has marked their transmissions were unsuccessful.

The LLDN has defined a specific superframe structure for each transmission state. The superframe in the discovery and configuration states is the same which composes only a beacon slot and two management time slots. The superframe in the online state is formed from only the beacon slot and the uplink slots (*macLLDNnumUplinkTS*). The *macLLDNmgmTS* has been set to FALSE and *macLLDNBidirectionalTS* is set to zero. The association process in the LLDN network starts by the orphan node that will scan for a discovery EB. Once it managed to identify a discovery EB, it sends a request called discovery response frame during the uplink management slot. The coordinator upon the reception of this request, it will respond in the next superframe (during the downlink management slot) with an ACK message as in Fig 4. Next, the node has to wait and scan for the configuration state, once it determined an EB that indicates a configuration state, it will send a request for configuration called configuration status frame. The coordinator then replies with the required configuration parameters in the next superframe (over the downlink slot) by what is called configuration request frame message. After configuring a node successfully, the node can commence sending readings during the allocated slots within the uplink field and only within the online superframes.

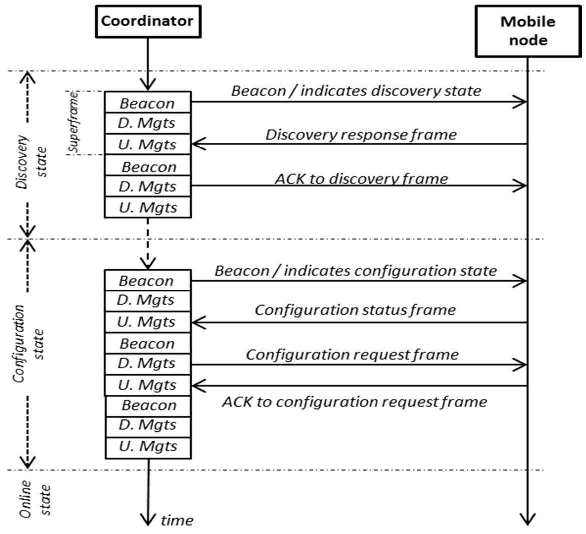


Fig. 4. Association procedure in LLDN network

III. MOBILITY ISSUES AND CONSIDERATIONS

In this section we will address the possible challenges that affect network performance with regards to nodes movement. In addition, we will set the possible approaches that mitigate the overhead of node mobility in order to realize better network connectivity and functionality. Table I simplifies the potential issues that are caused by the node mobility and degrade network availability.

For the TSCH network, the standard did not define a specific association scheme and hence, the default association process will be either the ordinary approach defined in [1] or FastA [2]. The FastA has low waiting association time since it relies on only four messages rather than six as in [1]. Nevertheless, the mobile node has to perform the passive scan which has the most impact on the association time caused by the concept of channel hopping. The TSCH and according to the channel hopping strategy has to change frequency channel for each timeslot and thus, the EB will broadcast on a different channel at each time. Therefore the maximum waiting time prior to receive a valid EB is ($N_{ch} \times SF_D$), where SF_D is the slotframe duration. The second issue here is the TSCH has no defined beaconing policy, which is a drawback by what the node can’t determine the existence of coordinator in the moving perimeter.

TABLE I
CHALLENGES AND APPROACHES FOR LLDN AND TSCH MODES

TSCH			LLDN		
Issue	**Impact**	**Approach**	**Issue**	**Impact**	**Approach**
Multiple frequency channels	Increase the scanning time	Fixing beaconing transmission to a single channel	The mobile nodes are limited to associate only during the discovery state	The mobile nodes will be disconnected during the whole online state period	Facilitate the association process by forcing the coordinator to accepts association requests during the online state
Undefined beaconing mechanism	Mobile nodes can't detect the existence of coordinator	Provide beaconing strategy as in LLDN or beacon enabled mode	The LLDN has no defined approach to change between the states	The nodes will stay in a single defined state	Setting the duration of each state based on the mobility metric of the nodes
Undefined timeslots management scheme	Mobile nodes added/deleted will change the number of timeslot; means changing ASN value and desynchronization	Systematic approach that inform the nodes about any changes in the slotframe structure to keep ASN value consistent	The nodes are obligated to transmit only during the online state	During the discovery and configuration states, the node can't send readings which will increase the latency of data	Omit the discovery and configuration states while modifying the online state to accept association requests and configure nodes
Undefined mechanism that defines the existence of SHARED TX slots	Mobile nodes association; lack of these slots will prevent mobile nodes from associating to the network	Ensures the existence of SHARED TX slots in each slotframe while determining the number of slots based on the mobility metric	Star topology network and single hop communication	Needs for high number of coordinators to cover the entire deployment area	Facilitate the network infrastructure to include multihop tree network where even the leaf nodes can accept associations

Moreover, the TSCH does not have a timeslot allocation scheme such that a new associated node determines its link. In the meantime, due to the existence of mobile nodes, there will be several associations and dissociations from the coordinator and hence, the slotframe structure will be changing each time. Node deletion and addition to the slotframe will change the sequence of the ASN and thus, the frequency channel will be changed that the current node will not be able to communicate with the coordinator due to channel mismatch. Therefore, the TSCH must define a scheme by which smoothly add or delete timeslots in the slotframe without affecting the existed nodes. Thus, the nodes can easily determine any change in the ASN sequence and keep ASN consistency with the coordinator.

Regarding the LLDN mode, categorizing the LLDN lifecycle into three states has complicated the association to the network. The mobile node can only associate through contacting the coordinator first during the discovery state, then the node has to wait until the coordinator announces the state of configuration. During the online state, which is the longest period in the network lifetime, the orphan node can't request association since the management timeslot *macLLDNmgmTS* is set to FALSE. This maximizes waiting time which will completely be dependent on the interval between each two discovery states. In the meantime, increasing the number of discovery and configuration superframes on the count of online superframes will degrade network throughput. This is caused by blocking the already existed nodes from transmitting their readings during discovery and configuration superframes and hence, nodes have to wait till the beginning of online state.

Another important issue is the lack to a valid mechanism by which to control the duration of each state over other states. The network administrator has to set the number of each superframe and make a trade-off between the number of the three superframe types. Increasing the number of online superframes will maximize the dissociation time. Meanwhile, reducing the number of online superframes will minimize network throughput but increases node connectivity.

Moreover, the topology of the LLDN network, which is based on tree infrastructure, also causes a problem to the mobility management process. Based on the star topology, only the coordinator has the ability to accept associations while supporting multihop infrastructure can increase the number of access points where the leaf nodes can also accept associations. In addition, it will maximize the coverage area of the network since even the leaf nodes here will act as coordinators to facilitate mobile node association.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
OS	Contiki 2.6.1
Scattering area size	240m×240m
Microcontroller	MSP430
Transceiver	CC2420
Mobility model	Random waypoint
Nodes' speed range	1-4 m/s
Payload size	20 Bytes

IV. IMPLEMENTATION AND ANALYSIS

Determining the impact of node mobility is achieved through testing the functionality of both modes of operation within a real test platform. This is carried out via implementing the TSCH and LLDN modes within the Contiki OS. Two important parameters are evaluated, which are the RDC of the sensor nodes (that contribute the energy consumption) and nodes connectivity. In addition, two factors that affect the mobile node association process are considered in the analysis. These are the number of mobile nodes and the superframe /slotframe size (LLDN/TSCH). Table II demonstrates the depended parameters in our simulation. LLDN online superframe to discovery and configuration superframes ratio is 5 to 1. One of the drawbacks that degrades LLDN operation is the interference between the nodes (either coordinators or mobile nodes). This issue has no impact on the TSCH operation due to the principle of channel hopping. Therefore, in this analysis we have provided two cases for the LLDN deployment, one with interference and one where we have set the interference range to be coincide with the active range of the nodes.

Fig. 5 presents the RDC performance of the three scenarios, LLDN with interference (LLDN,In), LLDN without interference (LLDN,NoIn) and TSCH. The RDC here

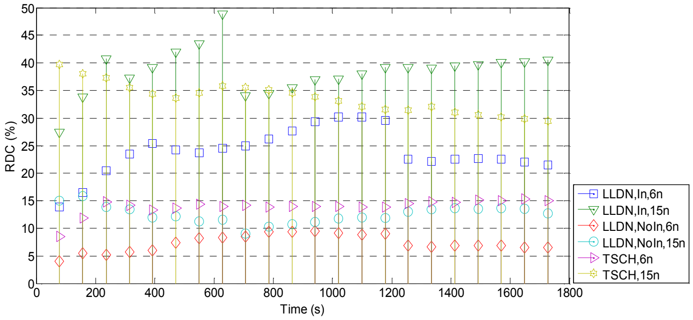


Fig. 5. RDC comparison between LLDN and TSCH, slotframe/superframe size =0.5s, transmission range=50m, no. of coordinators=9

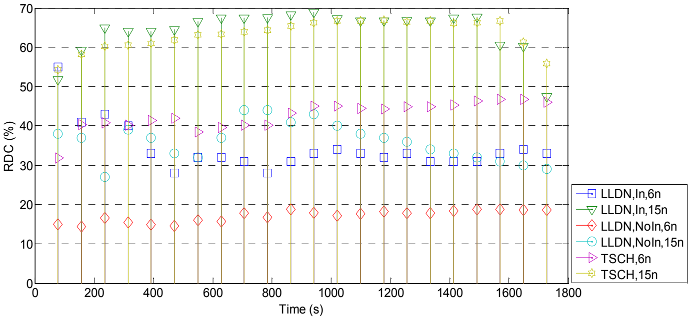


Fig. 6. RDC comparison between LLDN and TSCH, slotframe/superframe size =2s, transmission range=50m, no. of coordinators=9

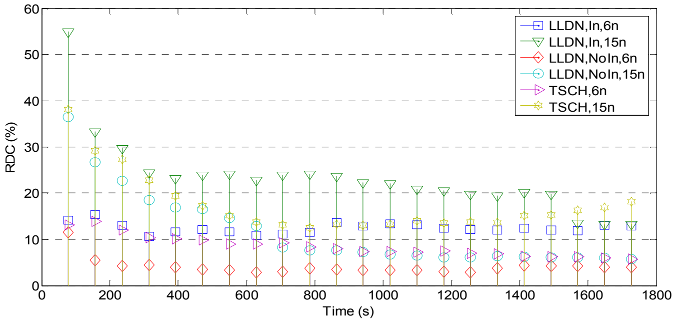


Fig. 7. RDC comparison between LLDN and TSCH, slotframe/superframe size =0.5s, transmission range=100m, no. of coordinators=4

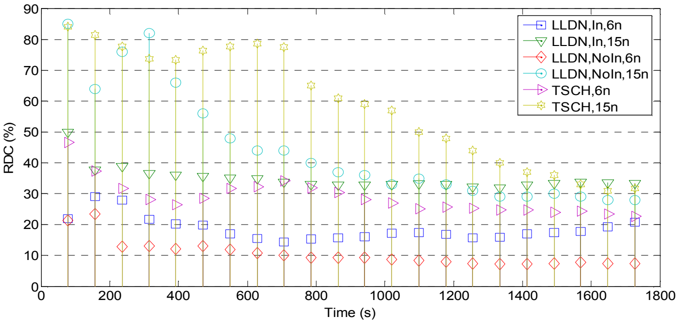


Fig. 8. RDC comparison between LLDN and TSCH, slotframe/superframe size =2s, transmission range=100m, no. of coordinators=4

corresponds to the total operation time of the transceiver (for the two states, transmitting and receiving) over total node's running time since deployment. For slotframe/superframe size of 0.5s, the TSCH has lower RDC than the default LLDN (with interference) for both cases of 6 mobile nodes (6n) and 15 mobile nodes (15n) as in Fig. 6. However, by increasing the number of nodes to 15n, the TSCH has an RDC that is slightly higher than the LLDN. This is influenced by the problem of contention between the mobile nodes and once a node fails to associate, it has to scan again and wait until it receives a valid EB on the channel which it scanning on. This waiting time is mainly influenced by the number of channels N_{ch} in the $Frequency_{List}$, which has been set to 16 (number of channels defined in the IEEE 802.15.4, 2.4 GHz). In the meantime, LLDN,NoIn shows better performance than TSCH and LLDN,In. Neglecting the impact of interference has minimized the probability of collision and the need again for retransmission of data or association requests. Finalizing the association process from the first attempt will cancel extra waiting time for the next EB on the fixed scanning channel (in the case of TSCH) or waiting till the discovery state (as in LLDN). Consequently, this minimizes the scanning time and in turn realizes lower RDC activity.

The mobile nodes incur lower RDC while increasing the transmission range to 100m as in Fig. 7 and 8, since the nodes reside longer time in the coordinator perimeter and hence, lower number of dissociations. By maximizing the transmission range of the sensor nodes, we gain the advantage of reducing the number of coordinators and thus, minimizing the impact of collisions. The only drawback will be during the network initialization phase where all the mobile nodes contend on the same time to associate and this can get worse especially when more nodes are located in the same coordinator perimeter. Hence, the RDC is at its peak through the initialization phase and then decreases as time passes. As the nodes running into the steady state of operation, the RDC declines since the nodes have already associated. In addition, even if the mobile nodes disconnected from the network, the nodes will easily associate again without the overhead of contention as during the initialization phase of the network deployment (since not all the nodes will be disconnected as the same time).

According to the RDC performance, we can visualize the ratio of connectivity, since lower RDC for mobile nodes, means better node stability and less association attempts and thus, high node connectivity. This can be indicated through investigating the relation between the RDC behaviour of both LLDN,In and LLDN,NoIn with the connectivity metric. Nevertheless, the TSCH has different aspect, since although it has higher RDC than LLDN,In for case slotframe size 2s, it has demonstrated better connectivity in several cases as compared to LLDN,In. This is caused by the LLDN association procedure where the nodes manage transceiver activity during discovery and configuration states by relying on the schedule that is indicated in the announced EBs of each state. Hence, LLDN realizes efficient radio utilization by determining when exactly to switch on or off radio. On the second hand, the TSCH has no specific association schedule and has no defined beaconing structure. In turn, although the TSCH shows higher RDC in some cases, but the RDC activity can't be used to deduce the connectivity. Therefore, TSCH shows to have better connectivity than LLDN,In (as in case 50m range 6n, 2s and 15n, 2s; case 100m range 6n, 2s). Fig 9 shows the percentage of time that a mobile node was connected to the network since deployment for transmission range of 50m while Fig. 10 corresponds to the connectivity with 100m range. As indicated earlier, TSCH demonstrates higher connectivity ratio in almost all scenarios as LLDN,In, but the LLDN,NoIn has the leading

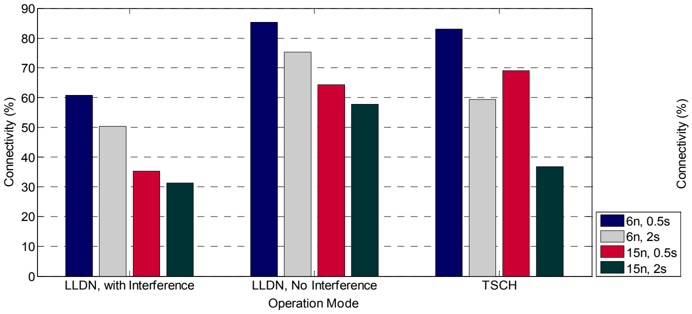


Fig. 9. Ratio of connectivity to the network, transmission range=50m, no. of coordinators=9

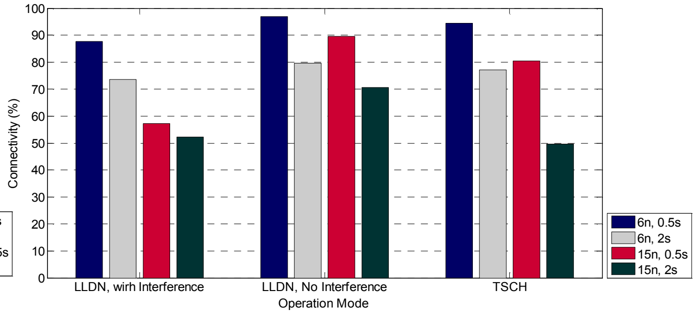


Fig. 10. Ratio of connectivity to the network, transmission range=100m, no. of coordinators=4

connectivity among them. This is traced back to the impact of collision caused by the inter-cluster interference (interference between adjacent clusters). Intra-cluster interference is negligible since the coordinator ensures that there is no overlapping between the assigned slots to the nodes in the cluster.

V. CONCLUSION

Node mobility is an upcoming challenge in the IoT context due to the lack of a defined and standardized protocol that manages mobile node associations and dissociations dedicated to low power devices. In this paper, a study that highlights the challenges which arise as a consequent of node movement has been presented. Two of the important IEEE 802.15.4e modes of operation have been implemented and tested against node mobility. The obstacles of each mode have been identified and possible approaches to tackle these issues have been indicated. Simulations show that TSCH has better connectivity but higher RDC than the default implementation of the LLDN. After neglecting the impact of interference, the LLDN shows better RDC and highest connectivity ratio than TSCH. The drawback with LLDN is operation on a single channel which incurred several collisions and in turn this complicates the association process and successful data transmission. Conversely, the defect with TSCH operating on multiple channels is that this complicates the association process caused by waiting a longer time to receive a beacon. The coordinator in TSCH announces the beacon on a different channel at each time and thus, the mobile node has to scan for a longer time until it receives the beacon on the relevant channel (or searching the whole available list of channels which means extra scanning time).

Hence, the best approach for the LLDN mode is to combine the concept of channel hopping and only to the uplink slots while fixing the beaconing to a single channel, where all the nodes adjust the scanning channel to it. In addition, the management timeslots in the LLDN have also to be set to a fixed channel that is known for all nodes prior to deployment. Moreover, facilitating the association process during the online state though activating the management slots will mitigate the overhead of waiting to associate until the discovery state.

Regarding the TSCH mode, the appropriate practice for tackling node mobility is by defining a beaconing strategy that sets the beacon structure which facilitates the association process. In addition, the beaconing has to be fixed to a single frequency channel that is predetermined by all the nodes prior to deployment and thus leads to a low scanning time.

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