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Mobility Aware Framework for Timeslotted Channel Hopping (TSCH) IEEE 802.15.4 Sensor Networks

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***Abstract*—Ubiquitous object networking has sparked the concept of the Internet of Things (IoT) which defines a new era in the world of networking. Realization of this concept needs to be addressed by standardization efforts that will shape the infrastructure of the networks. This has been achieved through the IEEE 802.15.4e, 6LoWPAN and IPv6 standards that formalize the communication pattern between different types of devices within the IoT world. In addition, the IEEE 802.15.4 standard, which can be considered as the backbone of the IoT structure, has presented the timeslotted channel hopping (TSCH) that can achieve a high reliability through time and frequency diversity. Although the aforementioned standards provide a coherent and diffused system that achieves the concept of smart world, several implications tackle these standards to achieve an optimized performance and reliability. Node mobility can be considered as the delimited factor for realizing a fully connected network, especially with the inclusion of TSCH mode that will complicate the association process of the mobile nodes, this caused by the frequency hopping mechanism. In this paper, we investigate the mobility impact over the TSCH sensor network whereas a Markov chain model is presented to determine the parameters that affect mobile node association process. Secondly, we provide a proposed mobility-aware MTSCH management protocol that will facilitate the mobile nodes association and minimize the latency incurred by leaving the nodes dissociated from the network. TSCH and the proposed MTSCH techniques have been implemented and evaluated within Contiki OS. The proposed MTSCH manages to reduce the radio duty cycle (RDC) of the mobile nodes by an average of 30% while increasing the connectivity of the nodes by 25%. Moreover, cluster heads (CHs) managed to save energy by a ratio of 14%.**

***Index Terms*—IEEE 802.15.4e, TSCH, mobility, Markov chain, Contiki OS.**

I. INTRODUCTION

THE IEEE 802.15.4 [1] standard can be considered as the de-facto physical and MAC infrastructure of the IoT paradigm, which is dedicated for low power wireless devices. Memory and power constrained devices such as wireless sensor networks (WSN) are the largest contributor of information that feed the global world network of resources. The IEEE 802.15.4 standard has taken its place into the IoT infrastructure with the emergence of the 6LoWPAN [2] layer which acts as the linchpin between the 802.15.4 and the IPv6 protocol. Hence, low power devices, like the sensor network, finally become a member within the IoT cloud. The media access control (MAC) of the 802.15.4 utilizes two modes of communications, non-beacon mode and beacon-enabled mode. Moreover, the nodes within the personal area network (PAN) are differentiated in two types, reduced function devices (RFD) and full function devices (FFD) [3].

The optimization process led to the introduction of several amendments to this standard that incorporate several extra functions and enhancements like the IEEE 802.15.4e MAC amendment [4]. The basic contribution of this amendment is the addition of three modes of operations, timeslotted channel hopping (TSCH), deterministic and synchronous multi-channel extension (DSME) and low-latency deterministic networks (LLDN). In addition, it presents the coordinated listening mode (CSL) that sample the listening time to save energy. Furthermore, the standard has introduced a new association mechanism called the fast association (FastA) while inserting another type of beaconing named the enhanced beacon (EB) which will contain the information element field (IE). IE includes relative information to the designated process that the EB called for. The TSCH mode can be considered as a hybrid mode of both time-division multiple access TDMA and frequency-division multiple access FDMA techniques, this mechanism will provide robustness and high reliability. While the timeslotting process reduces the nodes' radio duty cycle (RDC) and saves energy, the frequency hopping will mitigate the effect of channel fading and maximize the network reliability. Moreover, due to frequency diversity, more than one node can utilize the same timeslot which maximizes the network capacity [5]. This mode has gained a high attention within the research community due its importance within industrial automation and thus, the IETF has formed a new group with task to enable IPv6 on top of TSCH mode and is dedicated for low-power lossy networks (LLNs) [6]. The 6TiSCH workgroup consider only a static schedule scenario while relying on the routing protocol for LLN (RPL [7]). The nodes within the TSCH network are fully synchronized and each node in the network has a specific timeslot that is used to exchange information with the adjacent nodes. Although TSCH can be considered as a power efficient technique, it

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maximizes latency as compared to CSL [8]. The nodes are initially synchronized via listening to advertised EBs while maintaining the schedule through slotted communications with neighbors. Although the standard does not indicate how the EBs are will be advertised, it describes the structure of the EB. In like manner, the standard has not described the timeslot allocation scheme by which the node will be assigned a timeslot [5, 9].

In order to obtain a fully connected mobile TSCH network, the 802.15.4 TSCH mode must provide the following services:

1) The mobile nodes must be able to determine the frequency channel that EBs are being advertised on. Thus, minimizing the waiting time for association and reducing the packet loss.

2) Since the standard does not indicate how the TSCH network should be constructed [5, 6], the TSCH must provide an approach that defines how the EBs will be broadcast; which nodes broadcast and when to broadcast (period of transmission).

3) The TSCH has to define an allocation scheme by which the nodes will have dedicated links. For two adjacent FFDs' personal operating space (POS) (or clusters) that have the same channel offset, the absolute slot number (ASN) sequence values will be the same and thus, the links will collide. This issue has to be considered by the allocation scheme.

4) The IE must indicate any alteration that might occur in the slotframe structure which is caused by deletion/ addition of new nodes that leave/join the FFD.

The aim of this work is to investigate the impact of node mobility over a TSCH network. A Markov chain model is presented to analyze the parameters that influence the nodes association process. Accordingly, a mobility-aware MTSCH model is proposed that tackles the overhead of nodes movement within TSCH network. The basic approach of the proposed MTSCH is the introduction of the concept of passive beacons.

The passive beacons utilize the acknowledgement (ACK) messages, sent by FFD devices, to announce the existence of FFDs. These passive beacons will be transmitted based on a randomized fashion on a fixed channel. Thereby, each FFD will select a random time reference, picked up from a predefined time window in order to mitigate the probability of collisions with other ACK messages. Both of TSCH and MTSCH have been implemented within Contiki OS [10] to investigate the nodes mobility overhead for the two models. MTSCH shows improved nodes connectivity and a reduction of nodes' RDC which in turn led to minimize the energy consumption.

The rest of this paper is structured as follows. An introduction to nodes mobility, TSCH structure and related work is given in section II. Mobility impact and a Markov chain model are presented in section III. The proposed MTSCH is discussed in section IV while the details of implementation and analyses are demonstrated in V. Finally, conclusion and outcomes are indicated in section VI.

II. NODES MOBILITY, TSCH AND RELATED WORK

Mobility in the IoT context is a crucial concept due to the inclusion of sensor networks in different sorts of industrial application, where mobile nodes will exist. Mobility has a significant impact on network performance, by handling node mobility efficiently it is possible to preserve network availability and maintain a fully connected network. Hence, node mobility can be managed in three different approaches, through IPv6 protocol (Mobile IPV6), the 6LoWPAN layer or the IEEE 802.15.4 standard. Managing node mobility from inside IPv6 (either through MIPv6 or Proxy MIPv6) can increase the overhead and degrade the network performance. Within the IoT context, mobility can be categorized into two folds, network mobility (edge router movements / connection to the Internet) and node mobility (node movement). Moreover, the nodes mobility can be classified into two categories, macro and micro mobility. The micro mobility corresponds to the nodes movement inside a PAN (single network domain) while with the macro mobility the nodes move between different networks (different network domains) [11]. Accordingly, the burden of managing mobility within the network layer can be omitted via adopting a link-layer approach to handle mobility, while network mobility can be dealt with through PMIPv6 or NEMO protocols that will easily take place inside the edge router.

On the other hand, the 6LoWPAN does not indicate any mechanism to handle mobility and suggests leaving this issue to routing protocols [12]. Thus, 802.15.4 is the key solution to manage mobility, but unfortunately the standard has no clear approach to tackle mobility problems. Although 802.15.4 has defined association and dissociation techniques, which permit the nodes to join and leave the PAN, the association process is the key problem for mobility [13, 14]. In reality, this issue is also affected by the increased latency incurred through relying on the CSMA/CA which increase backoff time prior to transmission [15].

With all these issues and the lack of a defined approach that can be standardized for the IoT cloud, TSCH complicates the case by introducing the concept of channel hopping. The diversity of frequency channels will let the EBs be advertised on several channels and thus, the mobile nodes have to deduce on which channel the EB is being broadcast.

Regarding TSCH structure, the communications between the nodes within the TSCH network is defined by what is called a link, which is a combination of time and frequency, where each node has a dedicated or shared slot of time and channel frequency. The channel frequency is calculated by relying on the absolute slot number (ASN) which acts as a counter for each elapsed timeslot and each slot has a unique ASN value.

P_Channel = Frequency_List[(ASN + Channel_Offset) % F_{ch}]

Where, the P_Channel represents the physical frequency channel that a node will use for communication and the Channel_Offset is a predetermined value that the nodes are configured with prior to initialization or during the association phase.

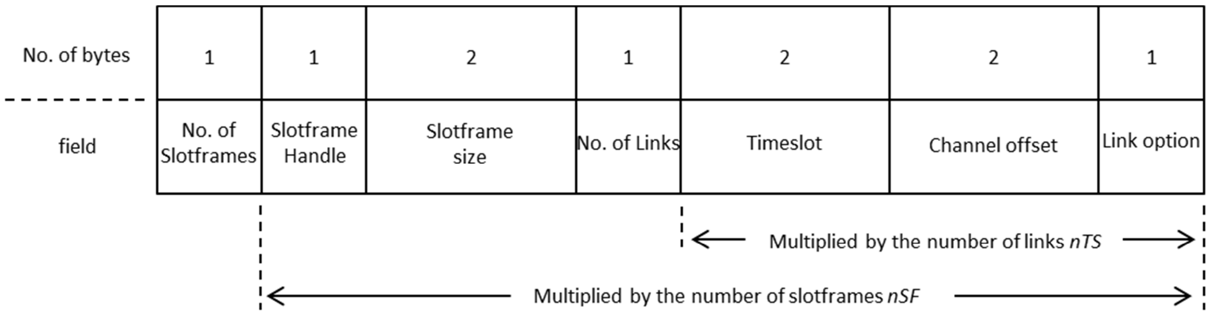


Fig. 1. IE elements of EB for TSCH

The Frequency_List contains the list of the available frequency channels while the F_{ch} value represents the number channels in the list.

The 802.15.4e defines the information element (IE) that will be included in the EB which includes the required information for a node seeking to join the network. The IE can define the number of slotframes and the number of links per slotframe in addition to the channel offset as in Fig. 1 and is preceded by five bytes ASN value and a one byte join priority field. Moreover, the above fields are followed by a *macTimeslotTemplate* which describes the format of a single timeslot and is up to 25 bytes. This can be omitted to ensure not exceeding the *aMaxPHYPacketSize*, but must be presented in the network initialization and for every association_request reply. Finally, the IE defines the hoping sequence information that also can be omitted to prevent exceeding the *aMaxPHYPacketSize.* The value *nSF* corresponds to the number of slotframes while *nTS* is the number of timeslots in each slotframe (Table I presents related symbols and the their corresponding definitions). Hence the FFD can advertise EB in every *ebP* time. *ebP* can be expressed as in (1) where *T* corresponds to the timeslot duration (approximated to 10µs [16]):

$$ebP = \sum_{i=1}^{nSF} \sum_{j=1}^{nTS} T_{ij} \tag{1}$$

Hence, in order to reduce the waiting time for a mobile node wishing to join a network, we must reduce the number of defined slotframes, *nSF,* since reducing *nTS* can negatively affect the association. Decreasing *nTS* leads to reduce the number of available shared slots that are required to accommodate the mobile nodes and permit communication with a FFD.

The related work section will focus on recent enhancement processes that have been carried out regarding TSCH mode. There is a lack of effort towards investigating mobility issues for TSCH. The main mobility related contributions were focusing on the mobility within IEEE 802.15.4 beacon-enabled modes such as [13, 14, 17-20].

Duglielmo *et al.* [21] investigate the problem of not defining an advertising algorithm by the 802.15.4e standard, hence the authors present a random-based advertisement algorithm. Accordingly, they investigate the impact of the number of channels used by advertisers over the joining time for a node seeking to associate a TSCH network. The random-based advertisement model is, according to the authors, derived from [22]. The presented model aims to reduce the impact of collisions caused by advertising two or more EBs on the same link and thus, each advertiser will commence broadcasting EBs based on a probability (P_{eb}) that is derived locally according to specific network conditions (i.e., the number of neighbors). In turn, this technique will minimize the probability of collision since each advertiser has different P_{eb}.

TABLE I
SYMBOLS AND DEFENETIONS

Symbol / Abbreviation	Definition
F_{ch}	number of frequency channels
nSF	number of slotframes
nTS	Number of timeslots
ebP	EB announcement duration
T_s	settle time
$P_{eb}(sf)$	probability of receiving at least one EB
$P_{(ts_n)}$	probability of receiving an EB in a given slot index
$Peb(sfi)$	probability of receiving an EB on a slotframe
σ	probability of leaving a POS
D_{RSSI}	distance of the mobile node from a FFD
R_{dBm}	maximum transmission range of a FFD
β	Probability of gaining a free SHARED TX link
sh	number of shared links
E_m	expected number of mobile nodes entering a POS
A_n	number of existed nodes
L_D	number of dedicated links
φ	probability of receiving an acknowledgement
η	probability of a FFD accepts an association request
ε	number of available time slots
$\overline{E_m}$	Number of mobile nodes that migrated out the POS
Re	number of association requests
θ	channel error rate

Vilajosana *et al.* [23] model the energy consumption of the TSCH network and provide an experimental validation based on nodes running the OpenWSN [22]. The paper provides analyses of the overhead for both the scheduling process and control signal on energy consumption. The analyses are based on classifying the source of energy consumption for each slot type: Rx, Tx, off and idle listening slots. The experimental validations are performed on two types of hardware, GINA and OpenMote-STM32 platforms.

Stanislowski *et al.* [16] emphasize the problem of clock-drift and its impact on the TSCH network that requires tight synchronization between communicating nodes. The authors present an adaptive synchronization technique that permits each node to calculate with neighbors its clock drift and based on the information, each node will periodically performs internal rectification to track its neighbor's drift. This mitigates the desynchronization problem effect on the communicating nodes. The analyses were based on the GINA mote platform and running OpenWSN stack.

Zhou *et al.* [8] investigate the performance of both the TSCH and CSL techniques and compared between them regarding the energy consumption and latency. The analyses, were based on nodes running the Contiki OS [10] utilizing the MSP-EXP430 and CC2520 transceiver. The results show that while the TSCH has less energy consumption than the SCL, the CSL has much less latency than TSCH.

Barcelo *et al.* [24] provide an extension to the 6TiSCH stack RPL routing in order to support node mobility utilizing a position-aware routing approach. The routing process is divided into two parts, default RPL routing among the static nodes and the proposed position-aware routing technique between mobile and static nodes. The static nodes, which are considered as the anchor points in this work, are location-aware nodes while the mobile nodes with unknown positions. The technique shows an improvement, over some of existed geographic routing algorithm, and robustness to positioning inaccuracies.

Palattella *et al.* [25] present a traffic aware scheduling algorithm (TASA) that manages the distribution process of slots and channels to the nodes within the TSCH network. The TASA is a centralized approach and dedicated for static multihop network and targeting to achieve high parallel transmissions with a reduced number of channels. The process by which TASA allocates links is determined by two important factors, the network topology and data-traffic load. Hence, the objective is maximizing the throughput and minimizing latency. The presented work, which is an amendment to previous work for the authors in [9], shows how the TASA could be incorporated into the IoT stack.

XU *et al.* [26] introduce a delay-aware resource allocation (DARA) model which carry out a resource allocation service for multi-camera TSCH networks. The concept of resources in the TSCH network is interpreted in terms of links. Unlike the previous works, which require cross-layer information to allocate resources, DARA requires only limited statistical information as a packet delay-deadline. The presented work ensures not to exceed the delay-deadline limit for transferring a video while preserving video quality. This is achieved through providing a slot weighting mechanism which is dependent on the video coding technique, video content and specific application requirements. Moreover, it assigns each sensor node an index that follows some parameters. Based on the indexing, the sensor with the largest index will get the current timeslot. Hence, minimizing the delay and preserving video quality.

Du *et al.* [27] present an adaptive TSCH (A-TSCH) that provides a blacklisting technique which selects the best channel with less interference to hop over. Hence, the channels with high noise will be eliminated from the channels hopping list. The A-TSCH has been analyzed and shows an improvement over the default TSCH.

III. MOBILITY IMPACT ON THE TSCH NETWORK

The association process in the TSCH network starts by scanning the available channels for advertised EBs. Although the channel hopping can be seen as an advantage by letting the EB be broadcast on a different channel in every period [28], but this will maximize the mobile waiting time to receive a valid EB. Once a node has received an EB, it will synchronize to the network based on the IE parameters. Then, the node should commence the association process, which is either the default association process depicted in [1] or the FastA approach presented in [4].

In this work, the terms CH, parent and coordinator will always have the same meaning and refer to FFD device. In a similar manner, the terms non-CH, mobile node and child are referring to RFD devices.

According to 802.15.4e, sending an association request is optional in the case of TSCH mode. Hence, to maintain synchronization, a mobile node can rely only on an advertised EB. Based on this approach, the FFD will be unaware of any mobile node seeking to join the network (cluster). On the other hand, to achieve full connectivity, FFD device has to be alerted (through association request) regarding a node wishes to join the network. The FFD task here is to provide the required resources for handling the new mobile node through allocating a dedicated link or adding new SHARED TX link.
To sum up, the association request can't be optional in TSCH mode.

The timeslots (links) in TSCH are classified into three types (identified via the link option field), TX link, RX link and SHARED TX link. For a node wishes to join FFD, it has to send its association request during a SHARED TX link and then receives the association information during the RX link or SHARED link.
Hence, the association process is completely dependent on the existence of a SHARED TX link in a slotframe and whether this link is free or busy (occupied by an already exited member or accessed by another mobile node). In the presence of a SHARED TX link (linkoptions bitmap set shared transmission), the node performs a clear channel assessment (CCA) to check whether the link is idle. In the case of CCA failure (did not receive a valid acknowledgment), the node has to invoke the TSCH-CA backoff mechanism seeking to reduce the number of collisions that may occur. Unlike the CSMA-CA, the TSCH backoff waiting is determined in terms of shared links rather than the *aUnitBackoffPeroid*. So, each FFD must maintain an adequate number of shared slots that simulate the number of mobile nodes entering the POS of a FFD in a given slotframe period. Hence, the mobile nodes join the network immediately without any given delay.

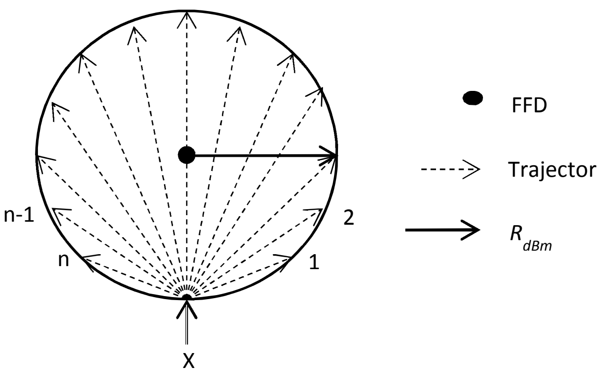


Fig. 2. Possible trajectories of a mobile node in a POS

In order to determine whether a node will join a network or not, we must estimate the time that a node will settle in a given POS and the required time to associate with a FFD.

Fig (2) presents the possible trajectories that a mobile node may follow when entering a POS at a given point x. Here, we assume that in each POS, a mobile node will move at a constant speed and direction. The probability of traveling in a given trajectory is $1/n$ and uniformly distributed. Thus, the expected settle time T_s elapsed in a POS of a FFD that has a transmission range R at a given dBm is approximately given by:

$$T_s = \frac{\sum_n t_n}{n} \tag{2}$$

Where, t is the settle time of a given trajectory and n is the number of possible trajectories in a POS.

Expected settle time cannot be defined as the connectivity time to a FFD, since this time will be divided into two parts, the requesting association time (time required to associate with the FFD) and join time or associated time (time by which the nodes can transmit readings to the FFD).

The behavior of the TSCH can be modeled via a Markov chain that depicts the possible states a mobile node can encounter to join a TSCH network. The modeling is based on the three fundamental stochastic processes which are the slotframe index (by which a node receives a valid beacon), the status of the slotframe and the status of the node. The index of timeslot ranges from ts_1 to ts_i and corresponds to which timeslot a node receives an EB. The timeslot status varies between the conditions of a shared timeslot and ranges from *Ac* (the node has received an acknowledgment to its transmission), *B* (the time slot is busy due to the usage by other new mobile nodes or already existing nodes, relying on the SHARED TX slots) and *nAc* (the node has not receive any ACK message). Node status can be either *Or* (the node is orphan and is disconnected from network), *R* (the node's association request has been rejected due insufficient resources of the FFD), *Ac* (the node's association request has been accepted) and finally *J* (the node is joining network). Fig. 3 depicts the transition probabilities of the Markov chain model for the possible states within a TSCH network.

The probability $P_{eb}(sf)$ of receiving at least one EB within a slotframe *sf* composed of *nTS* will follow a binomial

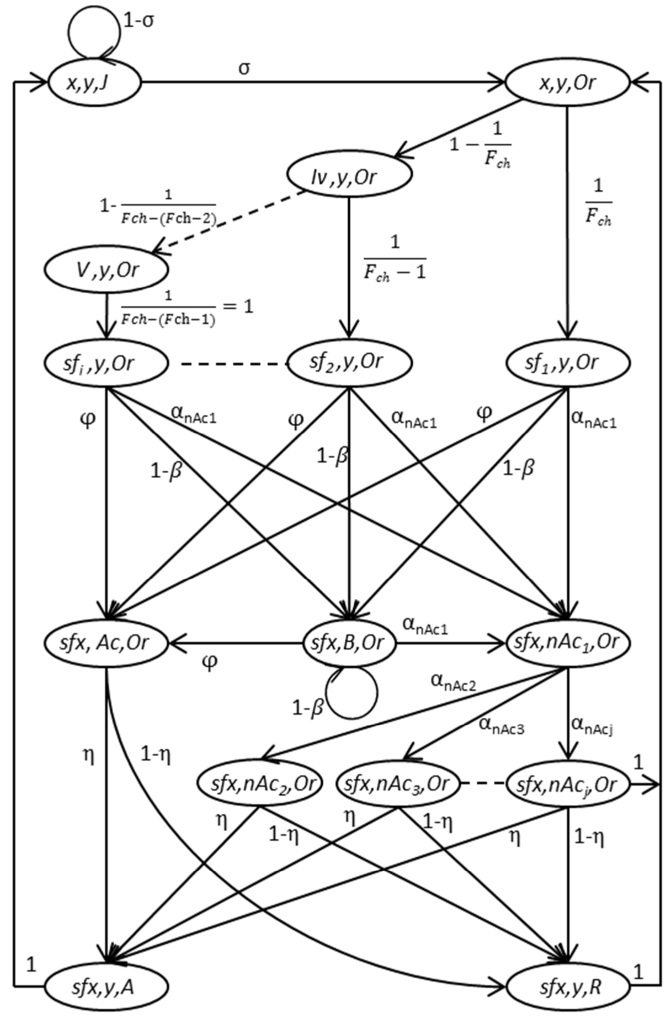


Fig. 3. Transition probabilities for a mobile node in TSCH

distribution and is given by:

$$P_{eb}(sf) = \sum_{j=1}^{nTS} \binom{nTS}{j} \left(\frac{1}{F_{ch}}\right)^{j} \left(1 - \frac{1}{F_{ch}}\right)^{F_{ch}-j} \tag{3}$$

Where F_{ch}, is the number of available frequency channels that the TSCH hopped over. Moreover, with the case of a network where the mobile nodes require an association time larger than the settle time in a POS, the probability (P_{eb}) that a mobile node receives an EB in a given slot index ts_n is:

$$P_{(ts_n)} = \frac{\left(1 - \frac{1}{F_{ch}}\right)^{ts_n - 1}}{F_{ch}} \qquad ts_n = 1,2,3, \ldots. \tag{4}$$

Note here, the difference between ts_n and ts_{n+1} is always dependent on the period of EB transmissions and the slotframe size (in links) where their maximum trial is i that correspond to the number of available frequency channels.

The sequence of which timeslot a mobile nodes receives an EB is not only contributing the delay by which a node can join a network, but also maximizes the RDC and hence, increase the energy consumption.

However, our simulations verify that the mean settle time will may always be larger than the required time for association.

$$T_s > T_{as} + T_{con} + T_{ma}$$

Where T_{as} is the required time for a mobile node to associate with a coordinator once it receives an EB. T_{con} is the time where the status of the node is connected and T_{ma} is the time to indicate the node is disconnected due to missing ACK messages (which depends on the number of missed ACK messages to announce the node as orphan and start scanning for EBs).

Thus, the coordinator or CH will always complete its period of channel hopping while the node is in its POS. In turn, the transmitted EB may always be advertised on all the available frequency channels while a mobile node is in POS. Hence, the probability $P_{eb}(sfi)$ that a mobile receives an EB on a specific frequency channel in a given slotframe i is:

$$P_{eb}(sfi) = \frac{1}{F_{ch} - (i-1)} \cdot \prod_{z=0}^{i-2} 1 - \frac{1}{F_{ch} - z}, for \;\; i \neq 1 \tag{5}$$

The probability (σ) of leaving a POS is based on the position of a node regarding FFD position and whether it is moving inside or outside the POS:

$$\sigma = \begin{cases} \frac{R_{dBm} - D_{RSSI}}{2R_{dBm}}, & RSSI_{t+1} < RSSI_t \\ \frac{R_{dBm} + D_{RSSI}}{2R_{dBm}}, & RSSI_{t+1} > RSSI_t \end{cases} \tag{6}$$

Where, D_{RSSI} is the distance of the mobile node from a FFD based on the RSSI of the received ACK messages from the FFD. R_{dBm} is the maximum transmission range of FFD at a given dBm transmission power.

In order to address the probability (β) that a mobile node will gain a free SHARED TX link, we have to identify the relevant parameters that a FFD can provide, as: number of shared links sh, expected number of mobile nodes (E_m) entering a POS at a given sf, number of attached nodes (A_n) to the FFD (children, non-CH) and number of dedicated links (L_D).

$$\beta = \frac{sh}{E_m + (A_n - L_D)}, \quad \text{for } L_D \leq A_n \tag{7}$$

Moreover, the probability (φ) that a mobile node receives back an acknowledgement is:

$$\varphi = 1 - (\alpha_{nAc1} + (1 - \beta)) \tag{8}$$

In addition, the probability (η) that a FFD accepts an association request is dependent on the number of available time slots (ε) that a FFD can additionally allocate without compromising the node lifetime, $\overline{E_m}$ the mobile nodes that migrated out of the POS within the same sf, Re is the number of association requests and the channel error rate (θ).

$$\eta = \left(1 - \frac{Re}{\overline{E_m} + \varepsilon}\right) \theta \tag{9}$$

The transition probabilities of the possible states that a mobile node can encounter during the association process now can be easily derived. The probability of a SHARED TX slot being blocked is presented in (10) while the probability of a SHRED TX slot is free and the request has been sent correctly is indicated in (11).

$$P(sf_x, B, Or|x, y, Or) = \left[1 - \frac{sh}{E_m + (A_n - L_D)}\right] \cdot \left(\sum_{n=1}^{x} \frac{1}{F_{ch} - (n-1)} \cdot \prod_{z=0}^{n-2} 1 - \frac{1}{F_{ch} - z} + 1\right) \tag{10}$$

$$P(sf_x, Ac, Or\,|x, y, Or) = \left(1 - \left(\alpha_{nAc1} + (1 - \beta)\right)\right) \cdot \left[\sum_{n=1}^{x} \frac{1}{F_{ch} - (n-1)} \cdot \prod_{z=0}^{n-2} 1 - \frac{1}{F_{ch} - z} + 1\right] + P(sf_x, B, Or|x, y, Or) \tag{11}$$

In accordance, the probability of transmission failure within a SHARED TX slot is:

$$P(sf_x, nAc_1, Or\,|x, y, Or) = \alpha_{nAc1} \cdot \left(\sum_{n=1}^{x} \frac{1}{F_{ch} - (n-1)} \cdot \prod_{z=0}^{n-2} 1 - \frac{1}{F_{ch} - z} + P(sf_x, B, Or|x, y, Or)\right) \tag{12}$$

Hence, the probability of failure to join after several backoff SHARED TX slots is:

$$P(sf_x, y, R)\,\big|\,x, y, Or) = \left(1 - \left(1 - \frac{Re}{\overline{E_m} + \varepsilon}\right)\theta\right) \cdot \left[\sum_{l=1}^{j} P(sf_x, nAc_1, Or).\alpha_{nAcl} + P(sf_x, Ac, Or)\right] \tag{13}$$

Finally, the probability that a mobile node will join a network is indicated in (14):

$$P(sf_x, y, J) = \eta \left(P(sf_x, Ac, Or) + \sum_{l=1}^{j} P(sf_x, nAc_1, Or).\alpha_{nAcl}\right) \tag{14}$$

Once a node gets into the nAc state, it will not return to B state since the FFD has a sufficient shared links. Thus, from states nAc_i, the node will either be directed to j or to Or states.

IV. M-TSCH PROTOCOL FOR MOBILE SENSORS NETWORK

The concept of MTSCH is basically dependent on embodying the concept of beaconing that is adapted in the default 802.15.4 beacon-enabled mode. Here, we introduce the principle of passive beacons by which the nodes can determine whether they have left a POS and to identify the presence of a FFD in a new area they have moved to. Therefore, the MTSCH relies on the ACK messages that a FFD replies to a node in order to validate a successful transmission. Hence, the ACK messages are acting as passive beacons which announce the presence of a FFD. Instead of obligating FFD nodes to

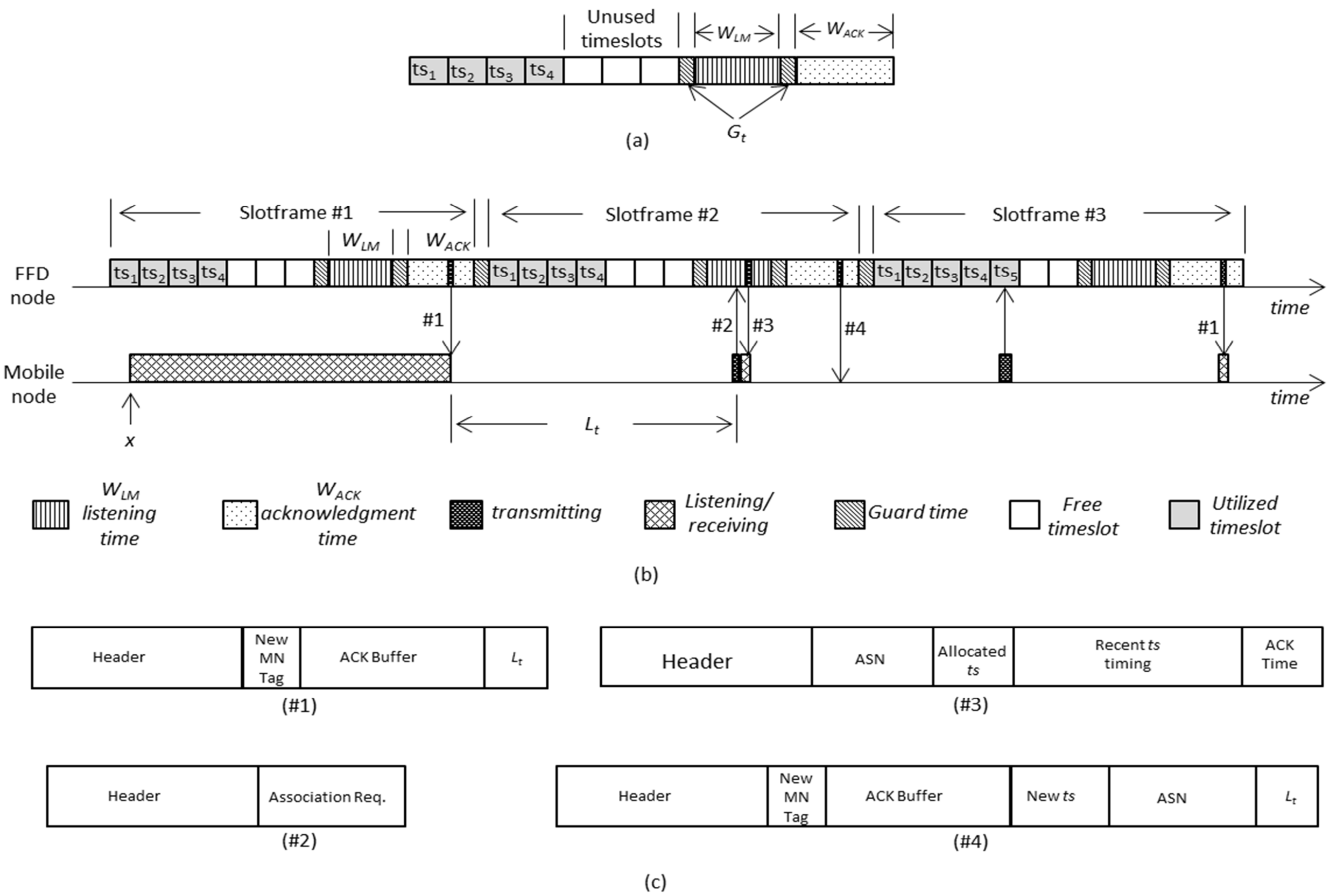


Fig. 4. MTSCH mechanism to accommodate mobile

reply for each transmission individually and to utilize the ACK message in the sake of acting as beacons, the ACK message of the TSCH is to be modified. Each FFD has to respond, at the end of each slotframe, only once to verify a successful transmission for all the members. This concept resembles the concept of group ACK used in LLDN mode. In addition, each ACK will indicate:

1. The time that a FFD will listen for any mobile node (radio is ON for receiving association requests).
2. The nodes that whose transmissions were correctly received.
3. Whether a modification has occurred in the cluster or not (due to join/leave a mobile node).

All the ACK messages will be transmitted on a fixed frequency channel (F_{ACK}) while omitting this channel from the Frequency_List that the TCSH network hopping over. Hence, the mobile nodes that seek to join a network have to scan only one channel which will save time and energy. Moreover, the FFD has to reply only one ACK for all the members which will save time by (ut):

$$ut = \sum_{m=1}^{A_n - 1} TxAck_m \tag{15}$$

Each slotframe gains extra free time g_t that contributes the additional resources which are affecting the number of mobile nodes that can be handled as in (8). Where g_t can be expressed as:

$$g_t = \sum_{m=1}^{A_n} (TsRxOffset + TsTxAckDelay + TxAck)_m \tag{16}$$

For a mobile node that determines it has been disconnected from the network (invalid ACK) at time x in Fig. 4, the node shall switch its radio ON and starts a passive scan for ACK message on frequency channel F_{ACK} (message #1 in Fig. 4). Once the mobile node detected an ACK message, it will determine the L_t time that is presented in the last field of the ACK frame and corresponds to the time by which a FFD will switch its radio ON to listen for any association request from a mobile node. For MTSCH, the waiting time (w) of a mobile node seeking to join a FFD will be $0 < w \leq 2sf$. Thus, with MTSCH, the mobile node can join a FFD with only two successive slotframes and commence sending readings within the third slotframe.

After time L_t, the mobile node transmits its association request and waits for time tp (time required by a device to respond to a request) and then receives the association reply (message #3) that identifies the synchronization parameters required for a

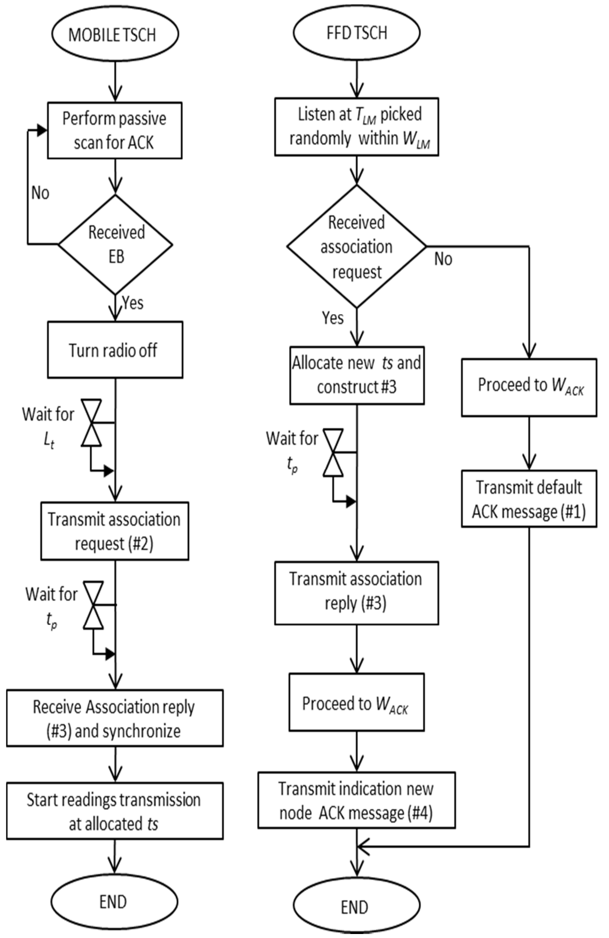


Fig. 5. Handling association flowchart for FFD and RFD

mobile node to join a network. This message contains the ASN, allocated *ts* by which the node can transmit its readings within a slotframe schedule, recent timing slots in order to let the mobile node know exactly when to increment the ASN and keep its schedule synchronized with the network and finally the ACK time which depicts the time by which the FFD will transmit its ACK message to the nodes.

The FFD node has to identify any change to the cluster by transmitting as usual the ACK, but this time another ACK format is included that comprises the new *ts* field and identifies *ts* timing of the new mobile node that joined the network. This will let the existed nodes in the POS (or cluster) to know exactly when to increment the ASN and prevent desynchronization.

The slotframe structure within TSCH is slightly altered by dividing the *sf* period into three parts. The first part is the usual timeslots part that composes dedicated links and SHARED TX links. The second part is called W_{LM} section which the FFD listens for association requests. The third piece is W_{ACK} part where the FFD send an ACK message (passive beacon) by which the existing members (connected to FFD) determine whether their transmissions were successfully received. Each FFD will pick up a random time (T_{LM}) within W_{LM} to open its radio ON for small duration of time and listen to any association request. In the same way, each FFD selects

TABLE II
SIMULATION PARAMETERS

Parameter	Value
OS	Contiki 2.6.1
Nodes' running time	1700s
Scattering area size	400m*400m
No. of mobile nodes	6, 9,12 and 15
No. of CHs	9 and 5
Transmission range	50m, 70m and 100m
Microcontroller	MSP430
Transceiver	CC2420
Mobility model	Random waypoint
Nodes' speed range	1-4 m/s
Slotframe period	0.5s, 1s and 2s
Payload size	20 Bytes

a random time (T_{ACK}) within W_{ACK} period to transmit the ACK message. The last field of each broadcast ACK message is always containing L_t, that is:

$$L_t = (sf - T_{ACK}) + T_{LM}$$

Dependency on randomization within a predefined time window shows improved performance by reducing the probability of collision and this has been demonstrated through our previous work in [29].

The mobile node can also keep its radio ON within L_t to determine if there is any other FFD beaconing with higher RSSI to ensure more settle time. Fig. 5 shows the flow chart that demonstrates the tasks for both of a FFD device and a mobile node in the TSCH network.

Finally, the mobile node is able to start transmitting readings at the allocated timeslot. Including the timings in message #3 and #4 rather than the number of nodes can be seen here as an obligatory task, since there is a case that a FFD has to assign a *ts* which has been released by a node that migrated the cluster, like *ts* 1 or 2 or 3 as in Fig. 4. Hence, the nodes here in the cluster (POS) will increment the ASN each time new *ts* is started.

V. IMPLEMENTATION AND ANALYSIS

The analysis will emphasize on three important aspects that determine the network lifetime and availability, which are: RDC, energy and association time (the total time that a mobile was connected to the network).

In order to observe the real performance for both of TSCH mode and the proposed MTSCH scheme, the two models are implemented within the Contiki OS [10] and simulated through Cooja network simulator [30].

The test-bed platform for each sensor node is composed of the MSP430 microcontroller and CC2420 transceiver. Different scenarios have been adapted in the simulation process to investigate the impact for each of number of mobile nodes, slotframe interval (EB period) and transmission range. Powertrace tool [31] has been utilized to assess the performance of the two models. In addition, since the periodic transmission is considered to be more substantial for determining applications [15], the nodes are programmed to transmit periodically based on the slotframe duration. Table II indicates the basic parameters of the simulation.

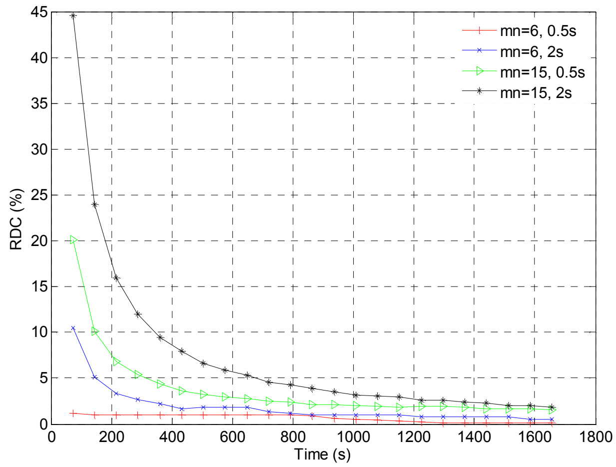


Fig. 6. RDC of static TSCH network

Several deployments are considered within the Contiki OS implementation. These deployments are changing each time by varying the number of mobile nodes (*mn*), transmission range of the sensor nodes (for both of CH and Non-CH) and slotframe duration (*sf*). Moreover, in order to handle mobility, both TSCH and MTSCH are configured to accommodate only a single association request in each slotframe. Hence, the TSCH has a single SHARED TX slot in each slotframe while the MTSCH will respond only to a single request per slotframe.

In order to assure that advertised EBs are hopping over the entire frequency channels sequence. Either the number of timeslots within a slotframe should set to be prime [28], or the number of frequency channels F_{ch} should also set to be prime [9]. Therefore, seeking to guarantee that EBs are broadcast over the whole channels sequence and since the number of links within a slotframe can't be adjusted due to mobility, the number of utilized frequency channels in the available frequency hopping list F_{ch} is set to 13.

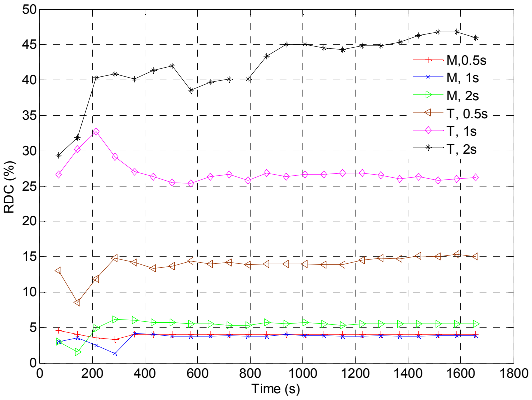
Before investigating the overhead of mobility over the TSCH network, the performance of TSCH regarding static sensor nodes have to be evaluated to show how clearly the mobility can degrade nodes' performance. Fig. 6 presents a simple example of the real outstanding performance of a TSCH network regarding static nodes. The average RDC for *mn*=6 and *sf*=0.5s is 0.56% and for *sf*=2s is 1.15%. Here, the RDC is representing the average radio operating time over the sensor running time.

Fig. 7(a) depicts the RDC for both of MTSCH (labeled M) and TSCH (labeled T) regarding six mobile nodes and at a transmission range of 50m. On average, the RDC of TSCH is 13% for slotframe duration *sf* of 0.5s and increasing while maximizing *sf* to reach 44% for 2s. This due to the impact of maximizing the *sf* duration that increases the waiting time for the mobile node to receive an EB, whereas the RDC is supposed to be decreased due to maximizing the transmissions interval. On the other side, the MTSCH has a RDC of 4% for *sf* of 0.5s and 3.6% for *sf*=1s. In case of *sf* is 2s, although the RDC must be reduced, the RDC has raised to 5.5% since the waiting time for a valid EB has a greater impact on the RDC than the effect of increasing the transmission intervals. This case has been repeated with other scenarios as in Fig 7(b), (c) and (d). Accordingly with TSCH, the RDC is increasing each time the *sf* or *mn* is increasing. While with MTSCH case, the RDC is decreased when maximizing *sf* to 1s and raised when *sf* is increased to 2s whenever the *mn* is maximized.

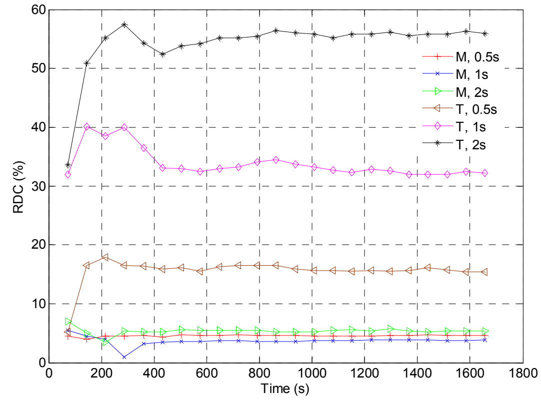
Looking to the FFD (CH) side, the MTSCH also managed to reduce the RDC of FFD devices due to relying on a single ACK for all the nodes within the POS rather than individual ACK for each member. The FFD within MTSCH spent 13,620 mJ after running for 1,700s, *sf*=0.5s and *mn*=9 and range 50m (Fig. 8(a)). In accordance, the FFD within TSCH consumed 21,594 mJ for the same period of running time and simulation parameters. By increasing the number of mobile nodes, the MTSCH performed slightly better than TSCH, where it consumes 49,199mJ against 49,257mJ for TSCH regarding 15 nodes, *sf*=1s and range 100m (Fig. 8(d)). Thus, the greater impact of the MTSCH, regarding FFD, will be achieved when increasing the number of EB announcements (shortening *sf)*.
Referring to the total energy consumption of all transceivers' states, the non-CH nodes of TSCH have consumed 26,578mJ for *mn*=6, *sf*=1s and at a transmission range of 50m (Fig. 9(a)). Similarly the MTSCH has depleted 4,207mJ when increasing the *sf* to 2s (Fig. 9(d)), the TSCH has a total of 46,423mJ while MTSCH has spent 6,105mJ. The next step is to increase the transmission range and determine the impact, which is set to 70m, the TSCH incurred 12,612mJ for *sf*=1s while MTSCH is 2,998mJ. Maximizing *sf* to 2s, led to increase the energy consumption for both of the models, where the TSCH consumed 25,936mJ and MTSCH 4,120mJ. The final selected range of transmission is 100m, where the energy consumption is dramatically reduced as compared to 50m transmission range. The energy consumption of TSCH has been reduced to 12,306mJ in the case of *sf*=1 and to 23,201 for *sf*=2 (Fig. 9(c)). In addition, MTSCH minimized it consumption to 2,355mJ for *sf*=1s and to 2,624mJ for *sf*=2s (Fig. 9(f)).

It's clear how the mobility has a great overhead upon the TSCH network and how it increases the RDC and energy consumption. Back to Fig. 6, the average RDC for *mn*=6 and *sf*=0.5s is 0.56% and for *sf*=2s is 1.15%. Hence, the RDC has jumped from 0.56% and 1.15% to 13% and 44% for *sf*=0.5s and *sf*=2s respectively.

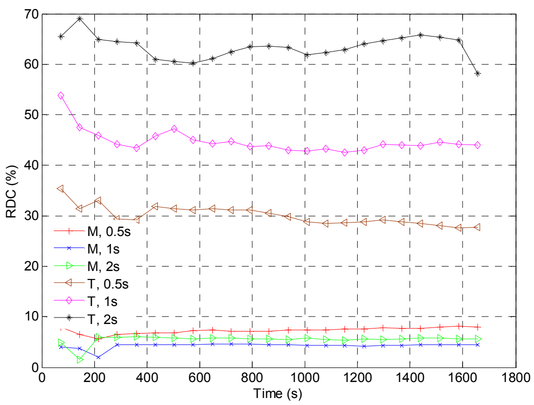
The third important part that has been evaluated is the associated time (connected time), by which the total amount of time that a mobile node was connected since deployment. By maximizing the associated time, both the availability and packet delivery ratio will be increased. To shed light on this part, Fig. 10 indicates the percentage of associated time for each network scenario. It can be seen that the MTSCH improved the connectivity from 82.9% to 95.9% for *mn*=6 and *sf*=0.5s and at range of 50m. Fixing to the same range, MTSCH raises the connectivity from 69% to 91.9% and from 36.7% to 84.7% for *sf*=0.5s and *sf*=2s respectively, each with *mn*=15 nodes. Meanwhile, by shifting the transmission range to 70m, the TSCH has a percentage of connectivity equal to 90.6% and MTSCH lifts it up to 97.3% for *mn*=6 and *sf*=0.5s. Similarly, increasing *mn* to 15 with *sf*=2s, TSCH has 43.9% connectivity while MTSCH managed to achieves 85.7% of connectivity.



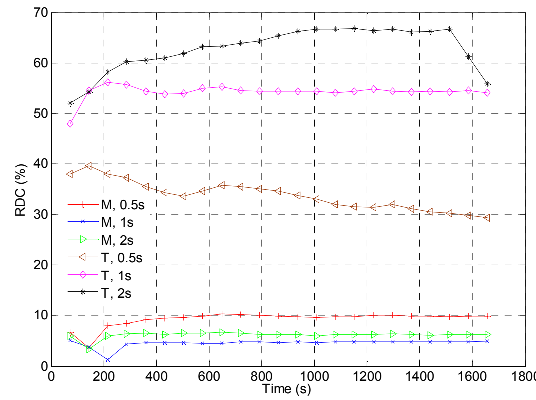
(a) *mn*=6



(b) *mn*=9

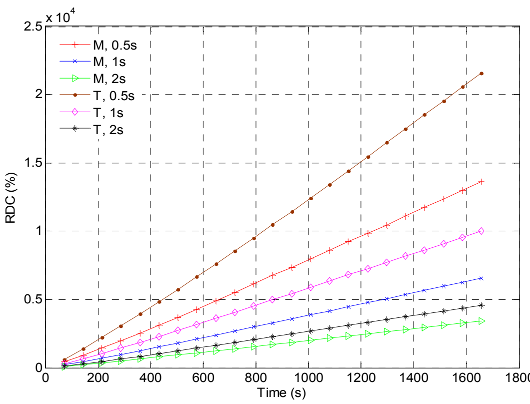


(c) *mn*=12

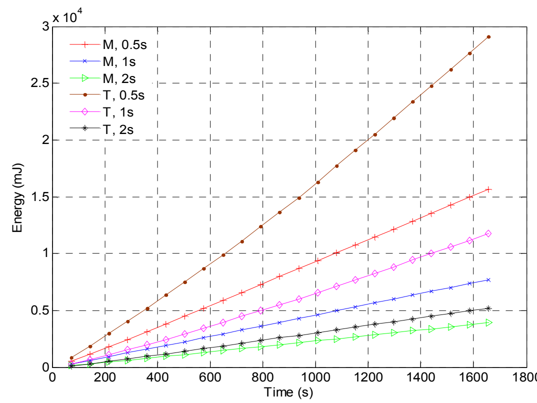


(d) *mn*=15

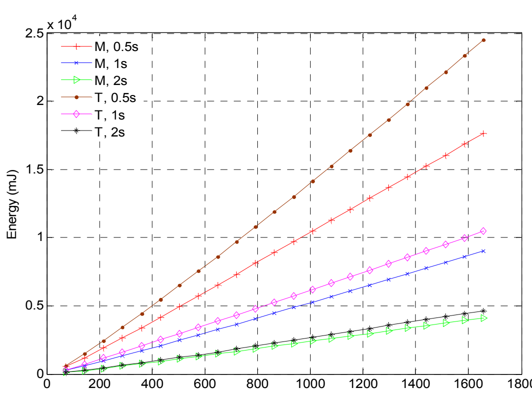
Fig. 7. RDC for non-CH nodes with range=50m



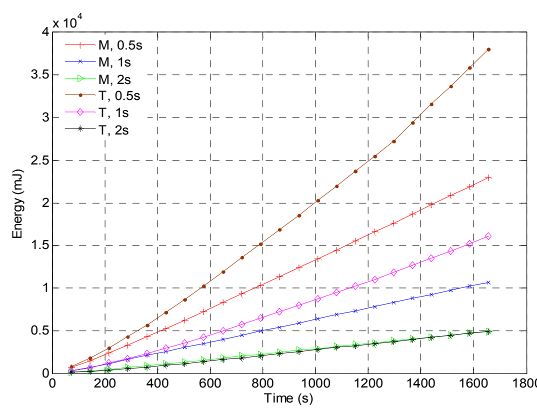
(a) *mn*=9, range=50m



(b) *mn*=9, range=100m

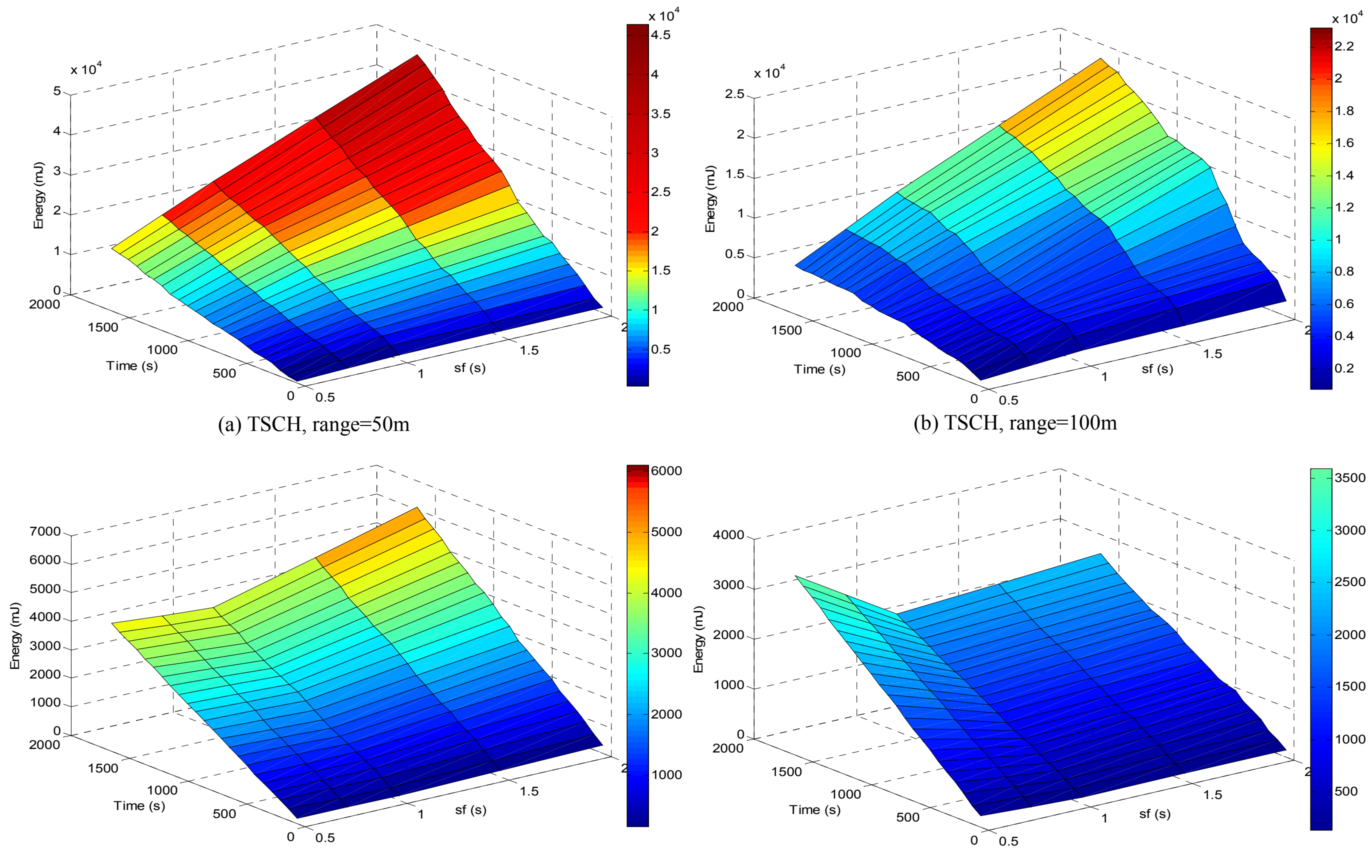


(c) *mn*=15, range=50m



(d) *mn*=15, range=100m

Fig. 8. Energy consumption of CH nodes



(a) TSCH, range=50m (b) TSCH, range=100m

(c) MTSCH, range=50m (d) MTSCH, range=100m

Fig. 9. Energy consumption of non-CH nodes, *mn*=6

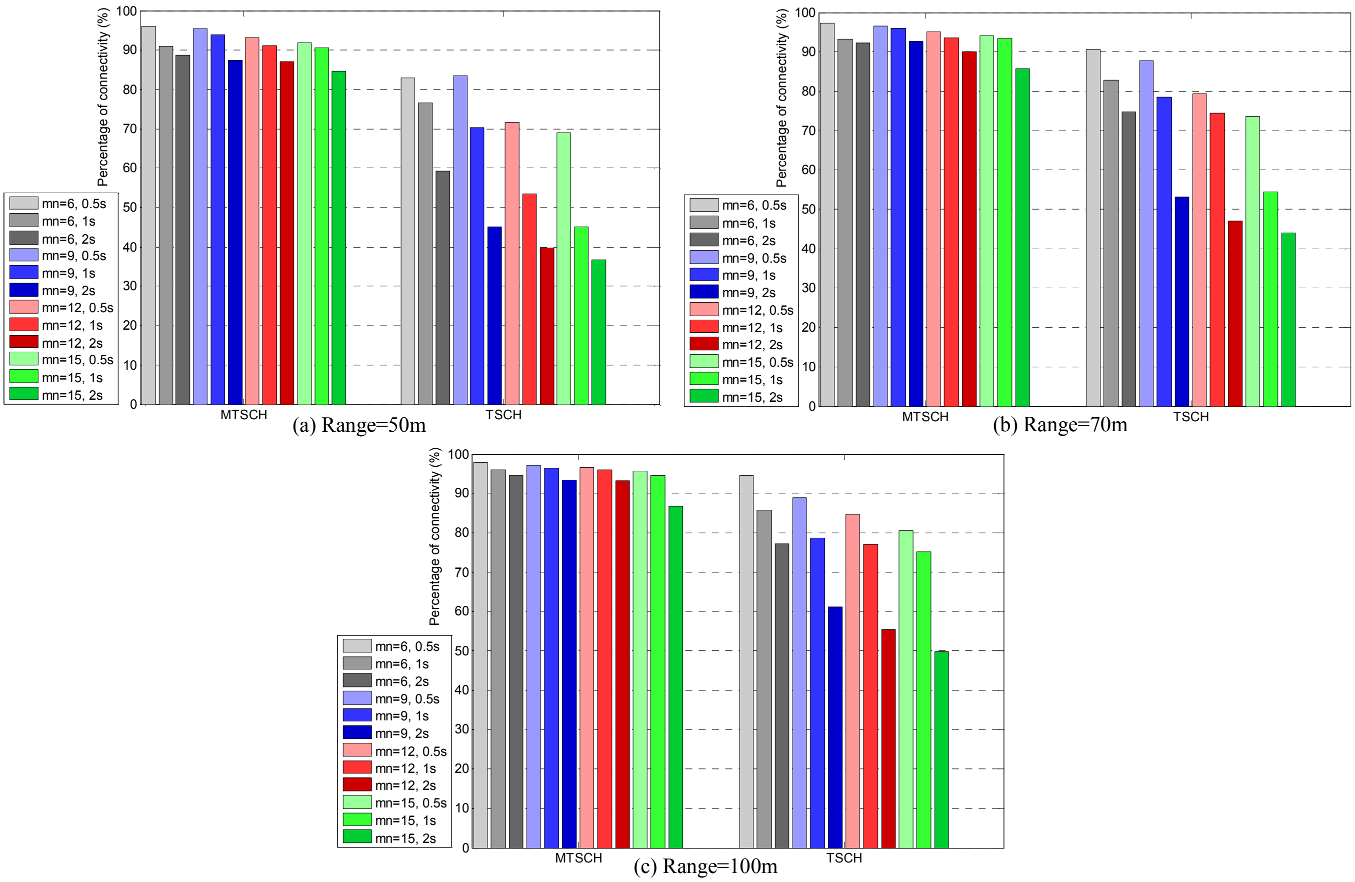
Furthermore, setting transmission range to 100m, both TSCH and MTSCH show there best performance as compared to previous ranges. At *mn*=15 and *sf*=2s, MTSCH boosts node connectivity from 49.7% to 86.7%. Finally, Fig. 11(a) and (b) present the whole picture of the RDC performance for mobile nodes with respect to different transmission ranges, *sf* and *mn*. The MTSCH managed to reduce the RDC of TSCH from 7% to 3% in the case of *mn*=6, *sf*=0.5s and transmission range of 50m. Similarly, for the worst application scenarios, the MTSCH has RDC of 9.4% and the TSCH is 31% regarding *mn*=15, *sf*=0.5s and transmission range=50m. In addition, the RDC has been reduced form 50% to 4% for *mn*=15, *sf*=2s and at a transmission range of 100m.

VI. Conclusion

The conducted analyses show the real impact of node mobility upon a TSCH network. The overhead incurred by the impact of increased listening time while scanning for a valid EB that is required to conduct an association. According to the implemented TSCH within the Contiki OS and the observed performance, we can formulate the possible factors that affect the overall WSN network services with the presence of mobile nodes, such as:

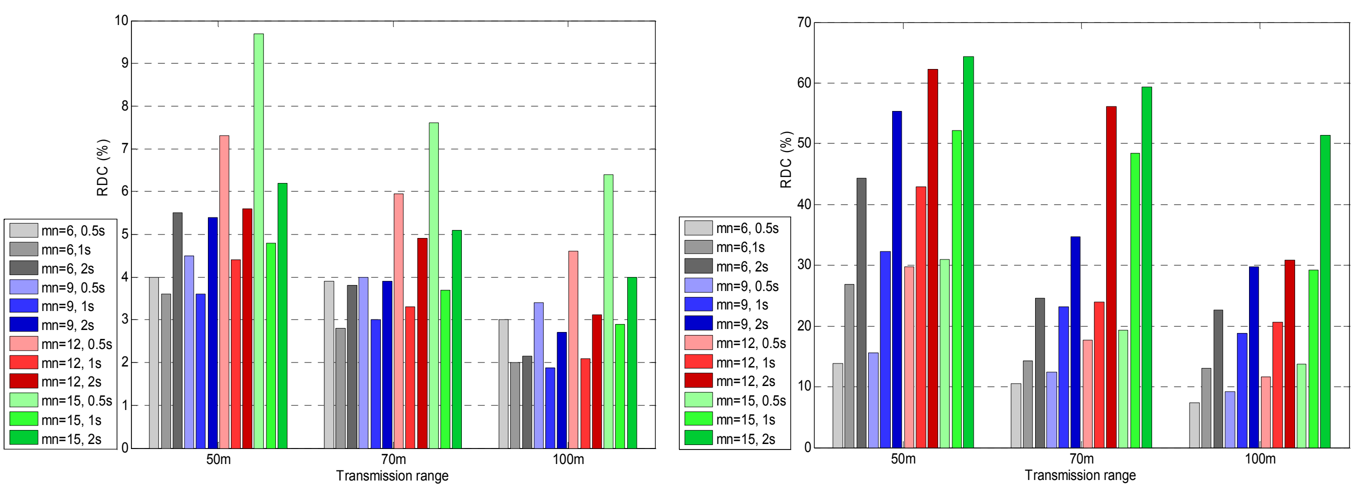
- Mobility patterns of the sensor nodes.
- Nodes movement speed.
- Number of FFD devices in a given mobile node POS.
- Transmission range for both FFD and RFD devices.
- Settle time that is determined by the possible trajectory of the mobile node within a given FFD POS and the transmission range.
- Number of SHARED TX slots in each slotframe that can accommodate mobile nodes association's requests.
- Number of mobile nodes in a single FFD POS.
- Number of frequency channels available for hopping.
- FFD deployment pattern in the scattered area of sensor nodes.

The proposed MTSCH framework proves that it can provide WSN mobility service with low overhead on both of FFD and RFD nodes. Different implementation scenarios show the gain by reducing RDC of the mobile nodes and ranges between, on average, 7% to 50% for 6 to 15 mobile nodes respectively. The MTSCH enhanced the connectivity metric (percentage of time the node is associated to the network) of the nodes by reducing the listening time or waiting for a valid EB. The MTSCH increased mobile nodes connectivity time by a ratio of 10% (*mn*=6) to 50% (*mn*=15) for 50m transmission range while it improves the connectivity by a ratio of 3% (*mn*=6) and 36% (*mn*=15) for 100m range. On the other hand, after running the nodes for 1,700s, the MTSCH reduces FFD energy consumption (for *mn*=9 and range=50m) by 7,000mJ and 1,200mJ for 0.5s and 2s *sf* durations respectively. In addition, MTSCH achieves a saving in energy (for *mn*=15 and range 50m) averaged to 18,000mJ



(a) Range=50m (b) Range=70m (c) Range=100m

Fig. 10. Percentage of time associated to the network



(a) MTSCH (b) TSCH

Fig. 11. Average RDC of non-CH nodes

(*sf*=0.5s) and 600mJ (*sf*=1s). Hence, the advantage of implementing MTSCH to support nodes mobility has influenced the performance of all the nodes within the network, FFD and RFD. Furthermore, the proposed MTSCH overcomes the problem of advertising EBs and the impact of collision by defining a randomized period W_{ACK}. The FFD nodes can listen and deduce T_{ACK} of the adjacent FFD devices and thus, selecting a different T_{ACK} time within this window. This ensures that the closet one hop devices will avoid collisions.

Finally, two issues exist in the implementation of TSCH and have been identified through the implementation within the Contiki OS. These are the handling process of the dedicated links in the presence of mobile nodes that imposes the dynamic nature on the allocations process. Hence, the abandoned links have to be utilized and reallocated again to new mobile nodes entering the POS. the second problem is the variations in the number of slots that lead to change the sequence of the ASN, which in turn existing nodes must be informed to maintain synchronization with the network. Therefore, after each join process, if the new mobile node has not utilized an abandoned link, the FFD must inform the existed nodes regarding the addition of new timeslot which will affect the ASN sequence. Thereby, the existed nodes within cluster shall maintain synchronization with the FFD.

References

[1] "IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)," *IEEE Std 802.15.4-2011 (Revision of IEEE Std 802.15.4-2006),* pp. 1-314, 2011.

[2] G. M. N. Kushalnagar, and C. Schumacher, "IPv6 over lowpower wireless personal area networks (6LoWPANs): overview, assumptions, problem statement, and goals,," *IETF, RFC4919,* 2007.

[3] I. R. N. Salman, and A. H. Kemp,, "Overview of the IEEE 802.15. 4 standards family for low rate wireless personal area networks,," *in 7th International Symposium on Wireless Communication Systems (ISWCS), York,UK,* Sept. 2010.

[4] "IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer," *IEEE Std 802.15.4e-2012 (Amendment to IEEE Std 802.15.4-2011),* pp. 1-225, 2012.

[5] M. R. Palattella, N. Accettura, X. Vilajosana, T. Watteyne, L. A. Grieco, G. Boggia, *et al.*, "Standardized Protocol Stack for the Internet of (Important) Things," *IEEE Communications Surveys & Tutorials,,* vol. 15, pp. 1389-1406, 2013.

[6] D. Dujovne, T. Watteyne, X. Vilajosana, and P. Thubert, "6TiSCH: deterministic IP-enabled industrial internet (of things)," *IEEE Communications Magazine, ,* vol. 52, pp. 36-41, 2014.

[7] T. W. a. R. D. Team, "RPL: Routing protocol for low power and lossy networks,," *in Netw. Working Group Internet Drafts,* July 2009.

[8] Z. Jianwei, A. E. Xhafa, R. Vedantham, R. Nuzzaci, A. Kandhalu, and L. Xiaolin, "Comparison of IEEE 802.15.4e MAC features," in *IEEE World Forum on Internet of Things (WF-IoT),*, 2014, pp. 203-207.

[9] M. R. Palattella, N. Accettura, M. Dohler, L. A. Grieco, and G. Boggia, "Traffic Aware Scheduling Algorithm for reliable low-power multi-hop IEEE 802.15.4e networks," in *IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC),*, 2012, pp. 327-332.

[10] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki - a lightweight and flexible operating system for tiny networked sensors," in *29th Annual IEEE International Conference on Local Computer Networks, ,* 2004, pp. 455-462.

[11] Z. Shelby and C. Bormann, *6LoWPAN: The wireless embedded Internet* vol. 43: John Wiley & Sons, 2011.

[12] C. Gomez, E. Kim, D. Kaspar, and C. Bormann, "Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing," *IETF, RFC 6606,* 2012.

[13] C. Chaabane, A. Pegatoquet, M. Auguin, and M. Ben Jemaa, "Energy optimization for mobile nodes in a cluster tree IEEE 802.15.4/ZigBee network," in *Computing, Communications and Applications Conference (ComComAp),*, 2012, pp. 328-333.

[14] P. Sthapit, Y.-S. Choi, G.-R. Kwon, J.-Y. Pyun, and S.-s. Hwang, "Fast Association Scheme over IEEE 802.15. 4 based Mobile Sensor Network," in *The Ninth International Conference on Wireless and Mobile Communications ICWMC* 2013, pp. 179-184.

[15] G. Anastasi, M. Conti, and M. Di Francesco, "A Comprehensive Analysis of the MAC Unreliability Problem in IEEE 802.15.4 Wireless Sensor Networks," *IEEE Transactions on Industrial Informatics, ,* vol. 7, pp. 52-65, 2011.

[16] D. Stanislowski, X. Vilajosana, Q. Wang, T. Watteyne, and K. S. Pister, "Adaptive synchronization in IEEE802. 15.4 e networks," *IEEE Transactions on Industrial Informatics,,* vol. 10, pp. 795-802, 2014.

[17] K. Zen, D. Habibi, and I. Ahmad, "A new algorithm to improve mobile sensor node connectivity based on link quality indicator," in *IEEE Region 10 Conference (TENCON)*, 2009, pp. 1-6.

[18] W.-S. F. Bashir, Baek Sthapit, P. Pandey, D. Jae-Young, Pyun, "Coordinator assisted passive discovery for mobile end devices in IEEE 802.15.4," in *IEEE Consumer Communications and Networking Conference (CCNC),*, 2013, pp. 601-604.

[19] Y. Min-Chieh and L. Jenq-Shiou, "Adaptive weighted scheme for improving mobile sensor node connectivity in IEEE 802.15.4 networks," in *IEEE Network Operations and Management Symposium (NOMS),*, 2012, pp. 968-973.

[20] M. Al-Jemeli and F. A. Hussin, "An Energy Efficient Cross-Layer Network Operation Model for IEEE 802.15.4-Based Mobile Wireless Sensor Networks," *IEEE Sensors Journal, ,* vol. 15, pp. 684-692, 2015.

[21] D. De Guglielmo, A. Seghetti, G. Anastasi, and M. Conti, "A performance analysis of the network formation process in IEEE 802.15. 4e TSCH wireless sensor/actuator networks," in *IEEE Symposium on Computers and Communication (ISCC), ,* 2014, pp. 1-6.

[22] T. Watteyne, X. Vilajosana, B. Kerkez, F. Chraim, K. Weekly, Q. Wang, *et al.*, "OpenWSN: a standards-based low-power wireless development environment," *Transactions on Emerging Telecommunications Technologies,* vol. 23, pp. 480-493, 2012.

[23] X. Vilajosana, W. Qin, F. Chraim, T. Watteyne, C. Tengfei, and K. S. J. Pister, "A Realistic Energy Consumption Model for TSCH Networks," *IEEE Sensors Journal,,* vol. 14, pp. 482-489, 2014.

[24] M. Barcelo, A. Correa, X. Vilajosana, J. Lopez Vicario, and A. Morell, "Novel Routing Approach for the TSCH Mode of IEEE 802.15.14e in Wireless Sensor Networks with Mobile Nodes," in *IEEE 80th Conference Vehicular Technology (VTC Fall), ,* 2014, pp. 1-5.

[25] M. R. Palattella, N. Accettura, L. A. Grieco, G. Boggia, M. Dohler, and T. Engel, "On optimal scheduling in duty-cycled industrial iot applications using ieee802. 15.4 e tsch," *IEEE Sensors Journal, ,* vol. 13, pp. 3655-3666, 2013.

[26] J. Xu, Y. Andrepoulos, Y. Xiao, and M. van der Schaar, "Non-Stationary Resource Allocation Policies for Delay-Constrained Video Streaming: Application to Video over Internet-of-Things-Enabled Networks," *IEEE Journal on Selected Areas in Communications,,* vol. 32, pp. 782-794, 2014.

[27] D. Peng and G. Roussos, "Adaptive time slotted channel hopping for wireless sensor networks," in *4th Computer Science and Electronic Engineering Conference (CEEC), ,* 2012, pp. 29-34.

[28] M. P. a. L. G. T. Watteyne, " Using IEEE802.15.4e TSCH in an IoT context: Overview, Problem Statement and Goals," *IETF Draft, draft-ietf-6tisch-tsch-06,* 2015.

[29] Y. Al-Nidawi, S. Naveed, and A. H. Kemp, "Mesh-Under Cluster-Based Routing Protocol for IEEE 802.15.4 SensorNetwork," in *Proceedings of 20th European Wireless Conference EW; ,* 2014, pp. 1-7.

[30] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt, "Cross-Level Sensor Network Simulation with COOJA," in *Proceedings of 31st IEEE Conference on Local Computer Networks, ,* 2006, pp. 641-648.

[31] J. E. A. Dunkels, N. Finne, and N. Tsiftes, "Powertrace: Network-level power profiling for low-power wireless networks," *Technical reoprt T2011:05, SICS,,* 2011.