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NCHR: A Non-threshold-based Cluster-head Rotation Scheme for IEEE 802.15.4 Cluster-tree Networks

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***Abstract*—The IEEE 802.15.4 standard specifies two network topologies: star and cluster-tree. A cluster-tree network comprises of multiple clusters that allow the network to scale by connecting devices over multiple wireless hops. The role of a cluster-head (CH) is to aggregate data from all the devices in the cluster and then transmit it to the overall personal area network (PAN) coordinator. This specific role of CH needs to be rotated among multiple coordinators in the cluster to prevent it from energy drain out. Prior works on CH rotation are either based on threshold energy levels or rely on periodic rotation. Both approaches have their respective limitations and, at times, result in unnecessary CH rotations or non-optimal selection of CH. To address this, we propose a non-threshold cluster-head rotation scheme (NCHR), which incurs minimal rotation overhead. It supports topological changes, node heterogeneity, and can also handle CH failures. Through simulations and hardware implementation, the performance of the proposed NCHR scheme is analyzed in terms of network lifetime, CH rotation overhead, and the number of CH rotations. It is shown that the proposed scheme boosts network lifetime, incurs less rotation overhead, and needs fewer CH rotations compared to other related schemes.**

***Index Terms*—IEEE 802.15.4, cluster-tree network, cluster-head rotation, energy conservation, network lifetime.**

I. INTRODUCTION

Energy efficiency is one of the primary design objectives of protocols for low-power, low-rate wireless networks [1]. It can be achieved both at the network level and at the device level by minimizing overhead, unnecessary energy dissipation, collisions, etc [2]. Synchronization, duty-cycling, and clustering techniques are known to reduce the energy consumption of individual devices and the network at large. The IEEE 802.15.4 standard [3] defines several physical layer protocols and medium access control (MAC) sub-layer options that provide low-cost communication for meeting low-power and low-rate requirements of such networks. The standard is widely adopted for various IP based networks, including Internet of Things (IoT) [4], [5] such as home automation, smart city [6], industrial monitoring and control [7], etc. It supports synchronization among network devices with the help of a superframe structure [3], which synchronizes the sleep schedule of a coordinator with its associated devices. Synchronization in peer-to-peer cluster-tree network topology is achieved using schemes like [8], [9]. Additional optimization of sleep schedules of devices is achieved through duty-cycling [10], [11]. To further boost energy savings, a cluster-tree network topology can be considered with a designated cluster-head for each cluster that is responsible for data aggregation and transmission. Such a network topology is shown in Fig. 1. A typical use-case can be an Industrial Internet of Things (IIoT) network, where devices are programmed to transmit data either periodically or to report an event. Clustering the devices is shown to facilitate efficient data acquisition. Basically, the devices within a cluster transmit data to the CH that in turn aggregates and transmits to the PAN coordinator (PANC).

A. Motivation

In an IEEE 802.15.4 cluster-tree network, a typical cluster is comprised of fully-functional devices (FFD) and reduced functional devices (RFD). The network of these devices forms a PAN. An FFD can assume the role of a PAN coordinator, a cluster-head (CH), or just act as a coordinator. On the other hand, an RFD always associates with a single FFD. The role of a CH is to aggregate data from all the devices in the cluster and transmit it to the PANC, thereby reducing the communication overhead. Due to its role as an aggregator, it drains energy faster compared to other devices. In addition, the CH is also involved in frequent data transmissions towards the PANC, which also results in higher energy consumption. Hence, the role of the CH needs to be frequently rotated among other coordinators to maximize the lifetime of the cluster and, in turn, the network.

B. Contributions and Organization

This paper presents a CH rotation mechanism, which is built on the premise that the network lifetime of a cluster is dependent on the lifetime of the CH coordinator. CH rotations

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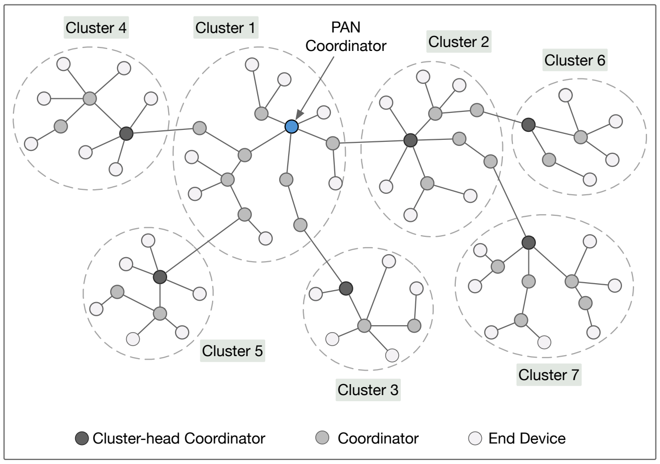

Fig. 1. Illustration of an IEEE 802.15.4 cluster-tree topology.

are carried out only if the selection of a new CH results in an improvement in network lifetime. The lifetime of a coordinator is computed based on residual energy levels, data aggregation cost, and transmission costs to the coordinator. Besides, the proposed mechanism is not bound by any threshold or time-specific periodic rounds for CH rotation. Also, the limitations of considering periodic rotations and thresholds for CH rotation are analyzed through simulations. The main contributions of this paper are summarized as follows.

- We derive an expression to compute the lifetime of a cluster by considering residual energy, CH rotation overhead, transmission costs to transmit towards a PAN coordinator, and aggregation cost from the associated devices.
- Based on the computed lifetime, a non-threshold cluster-head rotation (NCHR) mechanism is proposed that incurs very minimal CH rotation overhead.
- The proposed NCHR mechanism is analyzed for its handling of network topological changes (i.e., change in topology does not affect the CH rotation mechanism) and node heterogeneity. It can also handle CH failures. In addition, the effect of CH rotation on synchronization and duty-cycling is analyzed.
- Through simulations and test-bed implementations, the performance of the NCHR mechanism is evaluated in terms of network lifetime, CH rotation overhead, and the number of CH rotations.

The remainder of the paper is structured as follows. Section II briefly discusses several works related to CH rotation. The coordinator's lifetime is analytically computed in Section III, and the proposed CH rotation mechanism is described in Section IV. The performance results of the proposed mechanism are shown in Section V, and finally, the conclusions are drawn in Section VI.

II. Related Work

Organization of Wireless Sensor Networks (WSNs) into clustered architectures has been one of the prime approaches for scheming energy-efficient, robust, and highly scalable distributed networks [12]–[14]. In IEEE 802.15.4 networks, devices are constrained in terms of energy, memory, and processing capabilities. Thus, the selection of CH among coordinators in a cluster is one of the pivotal problems in such network applications and can severely affect a networks' energy dissipation.

In WSNs, LEACH [14] was initially proposed for the CH rotation mechanism. It is one of the first mechanism to employ clustering and CH rotation. Basically, the LEACH includes a distributed cluster formation, local processing to reduce global communication, and randomized rotation of cluster-heads. It is a TDMA-based mechanism with random CH selection having a local probability for homogeneous coordinator devices. The CH rotation is performed at every round, which is a predefined time interval. This ensures that every node is selected once as a CH. Also, the energy dissipation as CH is distributed equally among all the coordinators in the cluster.

Several works [15]–[28] based on LEACH have been proposed. These works have modified the original LEACH protocol and considered parameters like remaining energy and distance for the CH rotation. However, most of them rely on direct communication (single hop) between the CH and the PANC. These schemes primarily use a predefined threshold for selecting a new CH at each round, and extensive information exchange between the coordinators is observed, resulting in a high CH rotation overhead. Basically, LEACH-C [20] is an improved version of the LEACH mechanism where coordinators transmit their current location and residual energy to the PANC. Based on this information and a threshold energy value, the PANC selects a CH and notifies the cluster coordinators. Similarly, the authors in [21], [22] extend the LEACH stochastic CH selection algorithm by a deterministic component and by adjusting the threshold relative to the coordinators' remaining energy, respectively. The authors in [23] propose a distributed CH rotation mechanism that considers the distance between coordinators and the PANC to optimally balance the energy consumption among the coordinators in the cluster. T-LEACH [28] minimizes the frequent CH rotation of LEACH (at every round) by using the threshold of residual energy. In [17], the authors define a vice cluster-head (VH), a coordinator with the second-highest residual energy after CH. It serves as a secondary or backup coordinator for the role of CH. The VH is usually is in a sleep state and wakes up when the CH energy falls below a predefined critical value. Salem et al. [15] extends the LEACH protocol by selecting a CH according to the lowest degree of distance from the PANC in order to decrease power consumption in CH devices. The authors also list out several limitations of the LEACH protocol, a few of which are addressed through the proposed mechanism. In [16], the authors propose a Node Ranked-LEACH scheme based on a node rank algorithm that relies on both the path cost and the degree between the coordinators to select a new CH. The coordinators are ranked based on the distance, residual energy, and the degree. However, both [15], [16] assume direct connectivity between the CHs and the PANC, i.e., they are limited to single-hop communication.

In addition, the authors in [29] aimed to increase the transmission efficiency and network lifetime using Fuzzy logic as a means to select a new CH. Recently, Sarkar et al. [30] presented the implementation of CH selection by proposing a firefly algorithm with a cyclic randomization mechanism, which is an extension of the conventional firefly algorithm. In [31], the authors propose a residual-based LEACH (R-LEACH) scheme that considers both the initial and residual energy of the coordinators to compute an optimal number of CHs. The coordinators with the highest residual energy are selected as the new CH. Each CH communicates with the PANC either in the single-hop or multi-hop communication. The authors in [32] presents a mechanism that minimizes unnecessary data transmissions by the devices. CH rotation is based on the expected energy consumption of the coordinators that is estimated, taking into account transmission probabilities. Mahima et al. [33] proposed an Energy Harvesting-CH Rotation Scheme (EH-CHRS) for Green WSN that is based on an analytical double chain Markov model.

It is observed that the unreasonable and random selection of CHs may not result in optimal or minimal energy consumption by the network. Also, the aforesaid schemes do not consider the superframe parameters and the constrained nature of the IEEE 802.15.4 based devices, thereby not suitable in IEEE 802.15.4 networks. However, Tavakoli et al. [34] presents a CH rotation algorithm for the IEEE 802.15.4 networks with low overhead. It considers the residual energy of the coordinators but assumes a single-hop transmission to the PANC. This will not suffice for large-scale networks requiring multi-hop transmissions. Further, they consider a predefined threshold for packet count for every node that cannot be dynamically controlled. In addition, LAR-CH [35] sets a dynamic threshold for CH-rotation in order to reduce the premature battery drainage of CH nodes in WSNs. It considers the current load of the CH in terms of energy to compute the dynamic threshold. However, the work considers cluster splitting that may result in several small clusters in the network. Also, single-hop transmissions are assumed for both inter-cluster and intra-cluster communication, thus limiting the scalability of the network.

In view of this, we propose a CH rotation mechanism that addresses the limitation of the prior works by considering a multi-hop cluster-tree network topology. Besides, the proposed mechanism considers network lifetime without any pre-determined threshold and time-specific rounds for CH rotation. Recently, in [36], we have presented a preliminary version of the proposed CH rotation algorithm. The differences between this article and previous work [36] are as follows:

1) This paper provides a detailed description of the proposed CH rotation mechanism by discussing the support for dynamic topologies. In addition, support for node heterogeneity and dealing with CH failures are also discussed in the paper.
2) A comparison of the associated overhead with related schemes is presented. Also, the effect of CH rotation on synchronization and duty-cycling mechanisms is discussed.
3) We showcase the limitations of different CH selection strategies that are based on predefined rounds and pre-determined threshold values.
4) Finally, we present the experimental results of the proposed CH rotation algorithm using a test-bed in addition to the simulations.

TABLE I
MAIN NOTATION DEFINITION

Symbols	Definition
N	The total number of data transmitting devices in a cluster
$E_{\text{remaining}}$	The residual energy of a coordinator
$P_{\text{aggregation}}$	The power consumption on data aggregation
$P_{\text{transmission}}$	The power consumption on data transmission
$P_{\text{const-power}}$	The power consumption to carry out normal network operations
$P_{\text{CH-overhead}}$	The power consumption as an overhead to CH rotation
l	Length of a single frame
P_{rec}	Power consumed to receive a single frame
P_{tx}	The power consumed in transmitting a single frame
ϵ_{cost}	The aggregation cost computed cumulatively at each coordinator
$\epsilon_{\text{subtree-cost}}$	Aggregation cost of a sub-tree
C_i	The aggregation cost at a coordinator C_i
N_{tx}	The total number of frames received at a sub-tree
ζ	The lifetime of a CH
n_{child}	The total number of associated data transmitting devices
η	The rate of frame generation
N^i_{cluster}	The number of coordinators in the ith cluster

In the following sections, we describe the network model and present analytical expression for computing lifetime of a coordinator, which would later be used as an important parameter for the CH rotation.

III. NETWORK LIFETIME CALCULATION

A. *Network Model*

We consider an IEEE 802.15.4 cluster-tree network topology as shown in Fig. 1. To begin with, the first device in the network, called the PANC, initiates the network. The coordinators in the network are responsible for synchronizing the associated nodes through the transmission of periodic beacons. The network employs a synchronization and a duty-cycling mechanism to schedule transmissions and optimize nodes' sleep periods. The end-devices associate with a coordinator and all transmissions are routed through the parent coordinator. The network is divided into clusters comprising of coordinators and end-devices. According to the IEEE 802.15.4 standard, a CH is chosen randomly. The CH is responsible for data aggregation [3]. It aggregates data from all the nodes in the cluster, and further transmits towards the PANC, through other clusters. The main notations in this paper are summarized in Table I.

B. *Computation of Cluster Lifetime*

It is worthwhile to note that if the CH expires, the basic operations of transmissions and aggregation towards the next cluster will be halted and the entire cluster will be rendered orphaned in the cluster-tree topology. Thus, we define the cluster lifetime as the moment when the CH of a cluster expires. Moreover, a network is said to be functioning when it performs all its normal operations. Therefore, the lifetime of a CH or a cluster affects the network lifetime[1] Similarly, the lifetime of a coordinator is the time span from its deployment in the network to the time instant when its battery powers out. Now, the lifetime of a coordinator primarily depends on the following factors:

1) The residual energy of the coordinator.
2) The power consumed on the aggregation of data from all the associated devices.
3) The power consumed on the transmission of aggregated data to the next cluster coordinator.
4) Finally, a constant and continuous power is consumed by the coordinators to perform normal network operations. This includes mechanisms like synchronization, duty-cycling, cluster formation, association, dissociation, beacon management, PAN maintenance, overhead for various control, and ACK frames.

In addition to the above means of energy dissipation by the CH, $P_{\text{CH-overhead}}$ is consumed as an overhead to the CH rotation. It is consumed on account of transmitting control frames during the CH selection and rotation. Based on these, a CH lifetime expression is presented. Assume that each device generates regular data frames and transmits the data frames to its parent coordinator. Therefore, the power consumed on aggregation is expressed as

$$P_{\text{aggregation}} = \sum_{i=1}^{N} r_{n_{\text{child}}} \times P_{\text{rec}} , \tag{1}$$

where $r_{n_{\text{child}}}$ is the number of frames generated and transmitted by the n_{child}th device. For simplicity, we consider that all the devices generate data frames at a rate of η per unit time. Therefore, (1) can be re-written as

$$P_{\text{aggregation}} = \eta \times n_{\text{child}} \times P_{\text{rec}}. \tag{2}$$

Moreover, the aggregation cost from a coordinator C_i to another coordinator C_{ch} is expressed as

$$P_{\text{aggr-Ci-Cch}} = h_{\text{i}} \times P_{\text{aggregation}} ,$$

where h_{i} is the hop count from the sensing device (connected to the C_{i}) to the coordinator C_{ch}.

In a given cluster, as shown in Fig. 2, the total aggregation cost for a CH is the sum of aggregation at the intermediate coordinators and end-devices associated directly with it. Aggregation cost, ϵ_{cost} is computed cumulatively at each coordinator, as shown in Algorithm 1. Aggregation at subtrees are computed separately up to the root of the sub-tree, denoted by $\epsilon_{\text{subtree-cost}}$.

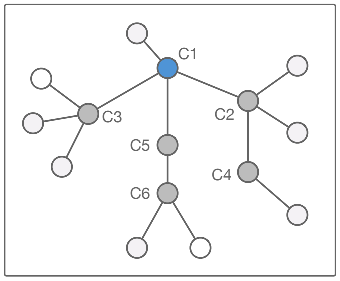

Fig. 2. Illustrative example.

Algorithm 1: Computing the aggregation cost

```
Set $\epsilon_{\text{cost}}(0) = 0$; $i = 1$;
while $i \neq hop(CH)$ do
    if $(subtree(i) == 0)$ then
        $\epsilon_{\text{cost}}(i) = \epsilon_{\text{cost}}(i-1) + \epsilon_{\text{local-cost}}(i)$;
    else
        $\epsilon_{\text{cost}}(i) = \epsilon_{\text{cost}}(i-1) + \big(\sum \epsilon_{\text{subtree-cost}} + child\big) + \big(N_{\text{tx}} \times (i-1)\big)$ ;
    end
end
```

An example: We consider an illustrative example (as shown in Figure 2) to understand the computation of total aggregation cost at coordinator C_6, which is to be transmitted to the present CH C_1. The aggregation cost, ϵ_{cost} is initialized to 0. At C_6, $\epsilon_{\text{cost}} = 2$, which is transmitted to its parent C_5, which in turn adds its local aggregation cost ($\epsilon_{\text{local-cost}}(\text{i}) = 2 \times 2 = 4$) to the previous ϵ_{cost}, totaling to $\epsilon_{\text{cost}} = 6$ and transmitted to C_1. The CH, C_1 has two sub-trees, namely, sub-tree(C_3) and sub-tree(C_2), where $\epsilon_{\text{subtree-cost}}(C_3)$ = 6 and $\epsilon_{\text{subtree-cost}}(C_2)$= 7, and child of CH =1. Hence, $\epsilon_{\text{cost}}(\text{i}) = 6+6+1+7+(7\times 2) = 34$. This term can be multiplied with the appropriate P_{rec} value to get the desired power consumption, i.e.,

$$P_{\text{aggregation}} = \epsilon_{\text{cost}} \times P_{\text{rec}}. \tag{3}$$

The above expression for $P_{\text{aggregation}}$ is used to compute the cluster lifetime. Then, the cost for transmitting the aggregated data to the coordinator in the next cluster that is h_{c} hops away, is expresed

$$P_{\text{transmission}} = \eta \times N \times h_c \times P_{\text{tx}}. \tag{4}$$

$P_{\text{transmission}}$ is the cumulative energy spent on transmitting and relaying data frames.

Afterward, the transmission cost is sent to the current CH along with the data frames. This transmission cost is computed by incrementing the hop count by one unit each time a data frame is passed to a parent coordinator. Finally, the lifetime can be expressed as

$$\zeta = \frac{E_{\text{remaining}}}{P_{\text{const-power}} + P_{\text{aggregation}} + P_{\text{transmission}} + P_{\text{CH-overhead}}}. \tag{5}$$

IV. PROPOSED CLUSTER-HEAD ROTATION MECHANISM

Algorithms like [37], [38] can be used to perform clustering prior to network initialization. Multiple clusters are formed by a group of coordinators involved in a common application/operation. Certain coordinators are randomly chosen as CH in each of the clusters as per the IEEE 802.15.4 standard. A synchronization mechanism [9] is used to schedule the transmissions between the devices.

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[1] It is the duration from network initialization to the instant when the network is unable to perform its normal operations.

Algorithm 2: NCHR: Non-threshold based cluster-head rotation

```
for each $i \in N^i_{cluster}$ do
    Collect $E_{\text{remaining}}$, $P_{\text{const-power}}$, $P_{\text{aggregation}}$, and $P_{\text{transmission}}$ ;
    Compute $P_{\text{CH-overhead}}$ ;
    Compute $\zeta$ using (5) ;
end
Find a device $i$ that has a longer lifetime than the current CH ;
if $(Lifetime_{CH} \leq Lifetime_i)$ then
    CH=$i$;
else
    Current CH continues;
end
```

A. Non-threshold cluster-head rotation (NCHR) Algorithm

In the proposed NCHR mechanism, the CH is responsible for computing the lifetime of the other coordinators. The CH collects the residual energy ($E_{\text{remaining}}$), power consumed on aggregation ($P_{\text{aggregation}}$) and transmission ($P_{\text{transmission}}$), and the constant power ($P_{\text{const-power}}$) values from the other cluster coordinators. These values are transmitted along with the data frames to the CH to minimize transmission overhead. The $P_{\text{CH-overhead}}$ is determined by accounting for the transmissions involved during the handover of the CH role. The transmission overhead depends upon the hop count between the current CH and the newly selected CH. Using (5), the cluster lifetime is computed for each of the coordinators in the cluster. Afterward, a device i with the longest lifetime among the coordinators in the particular cluster is identified (if available) by the CH. This is done by comparing its lifetime with that of the others. A device i is chosen as the new CH if it has a longer lifetime than that of the current CH. The current CH notifies this information to the rest of the coordinators through its broadcast beacons. The new CH acknowledges the new role as CH in its beacon frames. On the other hand, if no such device i is found, the current CH continues with its role. Therefore, the proposed NCHR mechanism chooses a new CH only if the cluster lifetime can be increased. *Algorithm* 2 is executed at each of the CH in the network.

B. Dynamic Topology and Node Heterogeneity

Note that due to a new device taking the role of a co-coordinator or malfunction of present coordinators, the network topology may change. The proposed CH rotation scheme supports dynamic network topologies, i.e., change in topology does not affect the CH rotation mechanism. Firstly, a new coordinator within a cluster is a participant in the proposed lifetime based CH rotation mechanism. It transmits its residual energy, $P_{\text{const-power}}$, $P_{\text{aggregation}}$, and $P_{\text{transmission}}$ to the CH like any other ordinary coordinator. The current CH computes the lifetime of this new coordinator along with the other coordinators within the cluster. The lifetime computation is independent of the number of coordinators in the cluster. Therefore, new coordinators joining a cluster will not affect the CH rotation mechanism. However, the associated overhead of computing the lifetime increases with the number of coordinators in the cluster. This overhead incurred by the CH is discussed in the next subsection. Also, in dynamic network topology, coordinators and end-devices may part with the network (that includes failures). Again, this does not affect the CH rotation mechanism, and only the available coordinators are involved in determining the lifetime and $P_{\text{CH-overhead}}$. If one or more associated end-device dissociates, the corresponding coordinator will have reduced $P_{\text{aggregation}}$ and $P_{\text{transmission}}$ values transmitted to the CH and the CH rotation mechanism remains unaffected.

Algorithm 3: NCHR: Handling a CH failure

```
$C_i, C_j \in N^i_{\text{cluster}}$, $C_j \in$ sibling of $C_i$;
if ($C_i$ detects $(C_i - CH)$ communication failure) then
    $C_i$ broadcast CH failure message;
    if ($C_j$ does not detect $(C_j - CH)$ communication failure) then
        $C_j$ responds to $C_i$ with CH ok message ;
        $C_i$ re-aligns with a new parent ;
    else
        if (no previous CH) then
            Randomly choose a CH;
        else
            CH = previous CH;
        end
    end
else
    Continue network operations;
end
```

The NCHR mechanism accommodates node heterogeneity. Firstly, heterogeneity among the devices is due to the different sizes of energy sources. The proposed mechanism allows heterogeneous coordinators to simply transmit their current residual energy to the CH, which in turn compute the lifetime based on all the requisite parameter values. Secondly, heterogeneity can arise from devices when the standard deviation of the packet generation is higher, perhaps due to the association of different sensors. The NCHR mechanism does not assume periodic and equivalent generation of data by all the coordinators in the cluster. The devices are allowed to transmit data as often as necessary. Also, each cluster executes the NCHR algorithm independently from the other clusters in the network.

C. Handling CH failures

A CH may fail either due to a device malfunction or if its energy gets depleted. As the proposed scheme always selects a coordinator as CH only if it enhances the overall network lifetime, the probability of CH failure due to energy depletion is rare. In other words, a CH usually relinquishes its role as the CH before its battery runs out. A CH failure is typically detected by its associated coordinators either if they fail to receive periodic beacons, or if multiple coordinators report

TABLE II
CH ROTATION OVERHEAD

CH rotation schemes	CH rotation overhead
Proposed NCHR	N^{i}_{cluster}
Tavakoli [34]	$N^{i}_{\text{cluster}} + 2$
LEACH [14]	$\left(2 \times N^{i}_{\text{cluster}}\right) - 1$

link failure to the CH (usually identified while transmitting data). In such a scenario, the previous CH (if such a CH exists) acts as an interim CH and further carries out the process of new CH selection. In order to achieve this, all coordinators that act as CH are required to maintain their status as previous CH till the cluster undergoes two CH rotations. Falling back to the previous CH to handle current CH failures avoids additional overhead in selecting a new CH among all the coordinators. Alternatively, if no such previous CH exists, a new CH is chosen at random. This can be carried out with the help of any of the random CH selection approaches [14], [39]. *Algorithm* 3 describes the mechanism of handling a CH failure. When a coordinator associated with the CH detects a communication failure (that may happen due to either of the two aforesaid scenarios), it initiates the *handling CH failure* process by broadcasting the `CH failure` message. On receipt, the other associated coordinators verify if a similar communication failure has been encountered by itself, and other associated coordinators (if any). If it is able to communicate with the CH, the sibling coordinator responds with a *CH ok* message. The initiating coordinator (on receipt of *CH ok* message) then undergoes a re-alignment mechanism with a new parent coordinator as specified in the standard. On the other hand, if the sibling coordinators also identify a communication failure to the CH, it is indeed concluded as CH failure, and the previous CH is chosen as the interim CH.

D. Effect on Synchronization and Duty-cycling Mechanisms

The CH rotation mechanisms do not directly affect the synchronization among the coordinators in the cluster. But if a CH fails, a part of the network may be disconnected, and the synchronization will be affected. However, the duty-cycle of a coordinator may be affected when the CH role is rotated. The CH is entrusted with added responsibilities of aggregation and transmissions of all other coordinators in the cluster. This demands a higher duty-cycle for the CH coordinator. The operational duty-cycling mechanism is invoked primarily to increase the active period and optimize the sleep period. But it is known that duty-cycling can potentially result in a loss in synchronization [9].

In the round-based CH mechanisms, periodic CH rotation in the cluster leads to frequent duty-cycling among the coordinators. Hence, the synchronization or the operational re-synchronization scheme will also be frequently invoked. The network will suffer from overhead arising from these two mechanisms. Similarly, the threshold-based approaches with frequent CH rotations also suffer from high synchronization and duty-cycling overhead. The NCHR mechanism reduces unnecessary CH rotations that do not contribute to increasing the cluster or overall network lifetime. Thus, the overhead incurred through duty-cycling and, in turn, the re-synchronization is significantly lower than other related schemes.

TABLE III
SIMULATION PARAMETERS

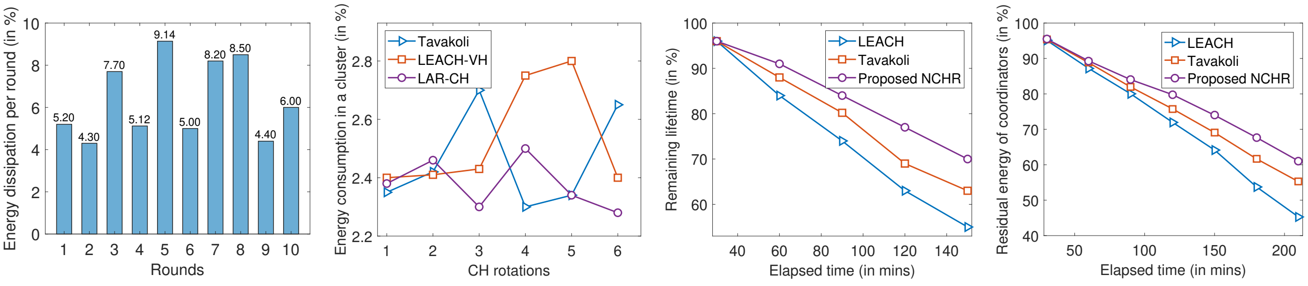
Parameters	Values
Frequency band	2.4 GHz
Maximum data rate	250 kbps
Number of nodes	11
Transmission radius	50 m
Coverage area	$1000 \times 1000\,\mathrm{m}^2$
Transmission time	600 s
Initial energy	1 J
Energy consumption to receive a frame	0.003 J
Energy consumption to transmit a frame	0.006 J
Energy consumption during sleep-state	0.000 030 J

E. Comparison of CH rotation overhead

The NCHR mechanism aims to lower the CH rotation overhead in the network. This is achieved by optimizing the number of selection of new CHs and optimizing the transmission of control messages for CH selection. The overhead is minimized by transmitting the CH selection information as a part of the beacon payload. Initially, the current CH has to retrieve the residual energy, $P_{\text{const-power}}$, $P_{\text{aggregation}}$ and $P_{\text{transmission}}$ from the data frames. Then the CH computes and compare the lifetime of the respective coordinator with its lifetime, and store the longest lifetime against the short address of the coordinator. This is done for all the coordinators in the cluster, and finally, the coordinator with the longest lifetime is chosen as the new CH. The current coordinator computes the lifetime for N^{i}_{cluster} coordinators using (5). Therefore, the CH rotation overhead (computational) for the proposed mechanism equals to N^{i}_{cluster} with no significant transmission overhead.

We compare the CH overhead of the NCHR mechanism with LEACH [14] and the scheme proposed by Tavakoli et al. [34]. LEACH adopts a periodic CH rotation policy involving all the coordinators in the cluster. Each coordinator computes a randomized number until it becomes a CH once every *P* rounds (determined in prior). That is, initially N^{i}_{cluster} coordinators are involved in computing the random number, which decreases by 1 after every round of CH selection. The selected CH broadcasts an advertisement message (transmission overhead) to all the other N^{i}_{cluster} coordinators using CSMA/CA. Computational overhead is distributed among the ordinary coordinators rather than solely on the current CH. Therefore, a significant CH rotation overhead (twice to that of NCHR) is incurred through the LEACH mechanism.

On the other hand, [34] relies on a threshold of packet count, after which the current CH handover the role to the coordinator with the highest reported energy. For this, CH keeps a count of the packet received from each of the coordinators, and when the number of packets received from a single coordinator goes beyond the threshold, a CH handover



(a) (b) (c) (d)

Fig. 3. (a) round versus energy dissipation, (b) energy consumption during CH rotations among different schemes, (c) lifetime versus elapsed time, and (d) residual energy versus elapsed time.

occurs. At this moment, the CH sends a handover ACK frame to the next prospective CH, which in turn transmits a handover notification back to the old CH, thereby accepting the CH role. Similar to the proposed mechanism, the computational overhead for CH rotation in [34] is borne by the current CH and is equal to N^i_{cluster}, for storing the packet count of each node. However, an extra transmission overhead of two transmissions per round is incurred through the exchange of CH handover. Table II summarizes the total overhead incurred (computation and transmission) per CH rotation by the considered schemes.

V. Results and Discussion

In this section, we present the performance of the proposed scheme using both simulations and experiments carried out on a test-bed.

A. Simulation Results

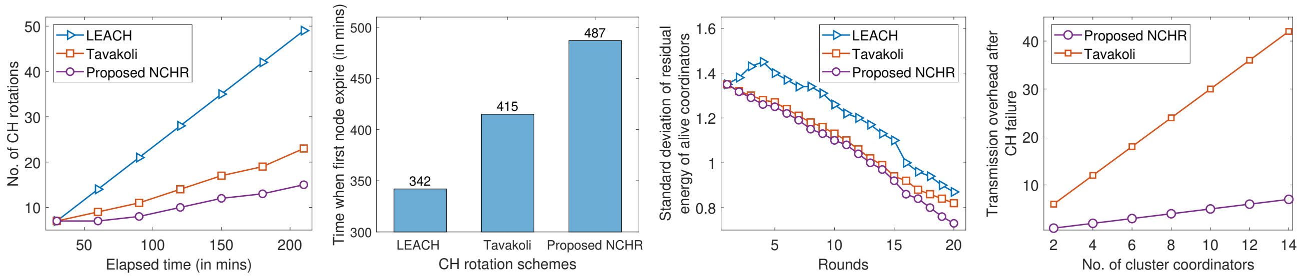
The network simulator NS-2.34 [40] is used to evaluate the performance of the NCHR mechanism in comparison to other CH rotation schemes. Parameters employed in the experiments are listed in Table III. We consider an IEEE 802.15.4 based cluster-tree network topology comprising of a total of 71 nodes (among them, 31 coordinators and 40 end-devices) forming 7 clusters. The network is set-up over an coverage area of $1000\,\mathrm{m} \times 1000\,\mathrm{m}$. We consider the $2.4\,\mathrm{GHz}$ frequency band that provides a maximum data rate of $250\,\mathrm{kbps}$ [3]. Besides, a transmission radius of $50\,\mathrm{m}$ is chosen to provide sufficient reliability to the transceiver with optimum energy consumption [41]. We have used a two-ray ground radio propagation model and IEEE 802.15.4 PHY and CSMA/CA for MAC sub-layer in our simulation. The 802.15.4 CSMA/CA has provision for ACK as well as re-transmissions in the wpan model in NS-2.34. The above settings are adopted from [9]. The simulations are averaged over 30 different runs.

1) Predefined Rounds for CH Rotation: Prior works [14], [21], [22], [34] based on this strategy primarily rotate the CH at each round. The duration of the round is chosen in prior and is fixed. At every round, a new CH is essentially chosen, either based on residual energy or purely in a randomized manner. Herein we show that it may not always be optimal to rotate the CH role after a fixed interval of time or wait until the next round to select a new CH. This is due to the fact that the cost associated with aggregation and transmission to the next cluster varies from one coordinator to another owing to its location and the traffic flow through it.

In our experiment, the role of CH is rotated periodically among all the coordinators in a cluster. The residual energy and lifetime of the current CH and the previous CH is recorded at the end of every round. From Fig. 3(a) it can be observed that not every rotation results in an increase in network lifetime. The duration of the round also plays an important role as smaller rounds result in frequent rotations, and increases the overhead. On the other hand, longer rounds can lead to a situation where a CH drains out more than what is ideal, resulting in network disconnectivity. Fig. 3(a) shows that CH rotation in round 3 is unnecessary as it leads to the selection of a new CH that lowers the network lifetime of the cluster. Similar inference can be made on rounds 5, 7, and 8 with a round duration of 1 hour. Also, as the network activity progresses, CH needs to be frequently rotated. This is because a coordinator may not possess sufficient energy to continue its role as a CH with longer round timings. Therefore, the duration of the round is an important parameter that needs to dynamically adjusted for efficient CH rotation.

2) Threshold for CH rotation: Approaches based on the concept of threshold select a new CH whenever certain monitored parameters breach the considered threshold. These thresholds can be on the residual energy of the CH, the number of transmitted or received frames, the duration for which a coordinator can be a CH, etc. The choice of the threshold and the predefined value set is an important criterion that needs to be considered for optimal CH rotation. It is worthwhile to note that threshold-based schemes are generally combined with predefined rounds for CH rotation. This addresses the problem of frequent CH rotation. However, since the threshold cannot be dynamically controlled, the CH rotation may still be sub-optimal.

We compare threshold-based approaches adopted by Tavakoli [34], LEACH-VH [17], and LAR-CH [35] to analyze the optimality of CH selections. We have considered threshold and other related parameter values as per [17], [34], [35]. Although new CHs are selected at less frequently compared to pure round-based approaches; however, it still suffers from sub-optimal CH selections. CH rotation of a coordinator due to



(a) (b) (c) (d)

Fig. 4. (a) CH rotations versus elapsed time, (b) comparison between different schemes when first node expires, (c) comparison of the standard deviation of residual energy of nodes alive, and (d) dealing with CH failures.

exceeding the threshold value (number of transmissions [34]) can result in higher energy consumption by the new CH, as observed from Fig. 3(b). In all the considered schemes, one or more CH selections results in higher energy consumption in the cluster compared to the previous CH in the respective scheme. For residual energy based threshold, a lower threshold limit results into a single coordinator acting as a CH for a longer period of time, which in itself contradicts the initial motivation for CH rotation. In addition, adhering to threshold requirements (relative residual energy) may not be feasible as a rotation might be necessitated before the scheduled rotation.

3) Proposed NCHR mechanism: We compare the remaining network lifetime of clusters between LEACH [14], Tavakoli [34], and the proposed NCHR schemes for an IEEE 802.15.4 cluster-tree topology (as shown in Fig. 3(c)). Although [34] is suited for single-hop cluster topologies, we extend the scheme by allowing CHs to transmit the aggregated data to the next CH instead of the PANC. The lifetime of the current CH is considered as the cluster lifetime. LEACH uses a probabilistic approach to choose a CH among the coordinators in a particular cluster, resulting in the selection of a new CH at each round. It does not compare and consider the associated overhead of the current CH with the new CH; hence, it may result in a sub-optimal selection in terms of network lifetime. [34] chooses the coordinator with the highest remaining energy among coordinators when the considered threshold is exceeded by the current CH. The coordinator with the highest residual energy may have high transmission, and aggregation overhead and hence may not be the optimal choice. Such a selection may in-fact, result in higher energy consumption by the coordinators in the particular cluster. On the other hand, the NCHR mechanism selects a new CH whenever such a CH rotation increases the lifetime of the cluster. A significant increase (15% and 7% over [14] and [34], respectively) in the lifetime is achieved with the proposed mechanism.

Next, we compare the average residual energy of coordinators of a cluster for the aforesaid schemes. In [14], all the coordinators of a cluster act a CH at least once in its lifetime. Although this should equally distribute the extra overhead (in terms of energy) among the coordinators, a poor choice of CH can result in excess power consumption by the cluster coordinators. [34] addresses the aforesaid issue by introducing a coordinators' threshold of frame reception prior to CH rotation. This lowers the frequency of CH selection and the associated overhead. Also, as only the coordinator with the highest residual energy is chosen as next CH, instead of a random coordinator, it extends the cluster lifetime. In the NCHR mechanism, the current CH is responsible for identifying a coordinator for the CH role that optimizes the energy consumption of the cluster and improves the cluster lifetime. Thus, unnecessary CH rotations are avoided in this scheme. From Fig. 3(d), we observe that at initial network time, the average residual energy of the coordinators is similar in all the considered schemes. However, an improvement of 6-10% in average residual energy is observed in deploying the proposed mechanism. Optimal energy consumption within a cluster is achieved through an optimal choice of CH. Additionally, coordinators dissipate excess energy in terms of transmission overhead if a sub-optimal CH is selected. Both [14], [34] allow the selection of CH without considering the implications on the overall cluster lifetime. [34] takes into account only the highest residual energy of a coordinator as a threshold for selection. However, the proposed NCHR scheme addresses this by choosing a CH that specifically results in longer cluster lifetime. This is achieved by considering the aggregation and transmission costs while computing the lifetime.

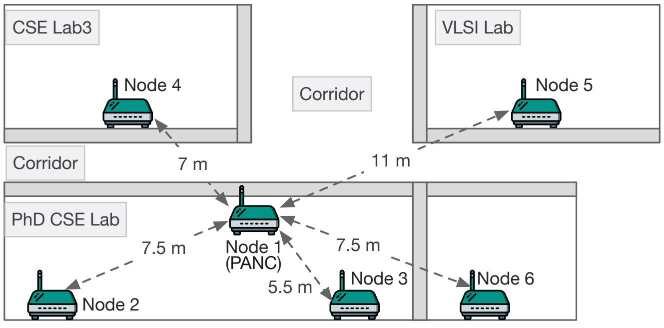
CH rotations are associated with additional overhead, as discussed in subsection IV-E. Frequent such rotations result in excessive power consumption with the exchange of control frames and transmission of messages. Fig. 4(a), shows the total number of CH selections in the network over a fixed period of time. LEACH randomly selects a CH rotation in each round, i.e., a new CH is chosen at each of the clusters in every round. Therefore, we observe a higher number of CH rotations in the network over the considered time. In [34], only when the number of frames received from a single coordinator reaches a predefined threshold, a new CH is chosen based on the highest residual energy. Thus, the total number of CH rotations are low compared to LEACH. On the other hand, the NCHR mechanism is observed to have the least number of CH rotations as it is not constrained by any pre-determined threshold and/or fixed time interval for CH rotation.

Finally, we investigated the advantage of the proposed NCHR mechanism by comparing the time in which the first node expires to that of the other considered schemes. Fig. 4(b) shows the comparison among the considered schemes with regard to the time when the first coordinator in the cluster expires. The performance of the NCHR mechanism can be attributed to its inherent nature of identifying and selecting a CH that improves the cluster lifetime, thereby optimizing the lifetime of the individual coordinators in the cluster. LEACH has the least time for the first node to expire as sub-optimal CH selections result in excessive energy consumption (in aggregation and transmissions) by the selected CH. Thus, an imbalance in power dissipation within the coordinators is observed, resulting in a few of the coordinators expiring prematurely compared to other coordinators. In [34], CH rotations are neither random nor necessarily after a fixed period of time. Hence, unnecessary CH rotations are minimized, and the role of the CH is awarded based on the highest remaining energy to address the power imbalance among the coordinators. Balancing among the coordinators' lifetime is further discussed in the next subsection.

4) Balancing Coordinators' Lifetime: As discussed earlier, the CH drains excessive energy compared to the other coordinators in the cluster. The balance can be usually restored by rotating the CH responsibilities among the other coordinators [34]. To analyze the uniformity in the energy drain of a CH and coordinators in the network after each round, we evaluate the energy balancing effect of different schemes. We consider equal duration of a round for both LEACH and Tavakoli schemes. As NCHR is not based on rounds, we record the residual energy over the same elapsed time. The standard deviation is computed from the recorded residual energy values of all the functioning coordinators. Statistically, a low standard deviation value signifies that the coordinators' residual energy are close to their average, i.e., uniformity in residual energy. In fact, the lifetime of the coordinators will be very close to each other, and coordinators will expire their battery power around the same time.

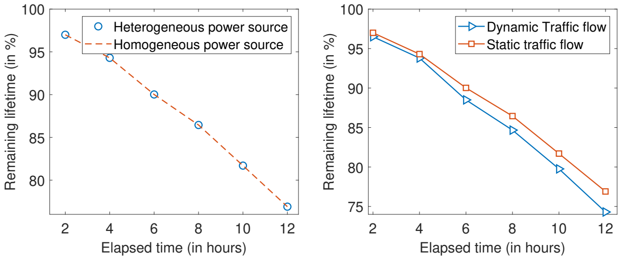
Fig. 4(c) shows the comparison of standard deviation in residual energy levels. A linear decrease indicates the balancing property of a CH rotation mechanism. It can be observed that the LEACH tends to increase at first, which indicates that it does not have any balancing effect. But as the number of functioning coordinators drops, LEACH shows a linear decrease. However, both Tavakoli and NCHR show a linear behavior from the start, which showcases the effect of balancing energy consumption achieved by the two schemes. The balancing property of NCHR is better compared to Tavakoli as it selects the CH that maximizes the network lifetime. In a network of heterogeneous power sources, the balancing effect will be more prominent.

5) Handling Cluster Head Failures: In case of a CH failure, the proposed scheme either entrusts the previous CH with the role of an interim CH or a new random CH is chosen if no such previous CH exists. Herein, we analyze the performance of the proposed scheme in comparison to that proposed by Tavakoli et.al [34]. The parameter chosen for comparison is transmission overhead to detect a CH failure, and select the interim CH. Fig. 4(d) shows the number of additional transmissions required by the two schemes, respectively, to achieve this. For increasing number of coordinators in the cluster, we observe that the overhead of NCHR is considerably lower compared to that of [34]. This is because only the associated coordinators of a CH are involved in detecting a CH failure, and further choosing a interim CH. As only such associated coordinators exchange messages, the transmission overhead is limited. But, according to [34], all such orphaned coordinators have to realign themselves to new cluster that incurs higher transmission overhead. It also involves reporting to the PANC, and messages exchanged (association request/response mechanism of the standard) for aligning to a new parent in a neighboring cluster.



(a)

Fig. 5. Test bed setup (layout).



(a) (b)

Fig. 6. (a) Performance under heterogeneous power sources and (b) Performance under dynamic traffic.

B. Implementation of the proposed CH rotation mechanism in a test-bed setup

The proposed CH rotation scheme is validated with the help of a small test-bed, which comprises of six Raspberry Pi (RPi-Model:3B) devices, each equipped with an Openlabs RPi 802.15.4 radio [42]. The radio model (containing Atmel AT86RF233 chip-set) is IEEE 802.15.4 compliant for transmissions. An external battery is used as an energy source for the RPi. For sensing and data collection, DHT22 temperature and humidity sensors are used. Linux wpan-tools have been used for our implementation. The test-bed is set up as shown in Fig. 5(a). Node 1 is $7.5\,\mathrm{m}$ away from Node 2 and Node 6. The respective distance between Node 1 with Node 3, Node 4 and Node 5 are $5.5\,\mathrm{m}, 7\,\mathrm{m}$ and $11\,\mathrm{m}$. The superframe parameter $\mathtt{BO}$ and $\mathtt{SO}$ are set to 8 and 3, respectively. The power consumption of the transceiver is available in the datasheet [43].

In the experiments conducted, heterogeneous power sources and traffic flows are considered for the devices. The primary objective is to measure the performance of the proposed CH rotation mechanism in a dynamic and heterogeneous environment. Fig. 6(a) and Fig. 6(b) illustrate the network performance in terms of network lifetime. Although the devices are equipped with different power sources, the proposed NCHR mechanism is able to choose a new CH that improves the lifetime of the cluster. No effect of the heterogeneous power sources is observed in the experiment. In the dynamic traffic scenario, the proposed mechanism adapts its CH selection (if required) with changing traffic load. However, this leads to an increase in the number of CH rotation in the cluster. Due to low CH rotation overhead, an increase in the number of CH rotations has little effect (2.6%) on the overall power consumption of the cluster.

VI. CONCLUSION AND FUTURE WORK

This paper presents a non-threshold based CH rotation scheme for IEEE 802.15.4 cluster-network topologies. The proposed mechanism uses lifetime as the sole criterion for selecting a new CH. This selection is subject to the condition that it improves the network lifetime. This CH rotation process is in contrast to other existing schemes that are either based on predefined threshold energy levels, or periodic CH rotations. Therefore, the number of CH rotations are low, and the corresponding overhead is minimal. To assess the performance of the proposed NCHR mechanism, experiments have been conducted by simulation as well as on a test-bed setup. Unlike [14], [34], the proposed mechanism is highly scalable as multi-hop transmissions from one CH to another is permitted. An increase of 7% to 15% in the lifetime is achieved with the proposed NCHR mechanism compared to other related schemes. It supports topological changes, node heterogeneity, and can also handle CH failures.

As the proposed scheme computes network lifetime using parameters received from all the coordinators in the cluster, failure to receive values from certain coordinators (due to collision or interference) may result in the selection of a sub-optimal CH. The loss of frames due to collisions can be considerably reduced by using an appropriate synchronization scheme. Also, during frequent transmissions/high data-traffic in the cluster, the CH repeatedly computes identical cluster lifetime values for a cluster coordinator. These unnecessary computations can be minimized by computing the lifetime at periodic intervals (predefined set of beacon intervals [3]). In addition, experiments to further analyze the inter-dependencies of CH rotation scheme with synchronization and duty-cycling schemes need to be conducted. Finally, we also plan to consider the network topologies wherein the CH is entrusted with extra responsibilities of synchronizing the entire cluster coordinators. In such networks, the synchronization overhead will have to be considered prior to CH rotations.

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