Adaptive Global Reclustering in MWSNs

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***Abstract*—Energy conservation is crucial for clustered wireless sensor networks (WSNs) due to the bounded energy at sensor nodes. Energy conservation is achieved mainly through load balancing, which is realized with reclustering in frequent time intervals called rounds. Although in clustering the round duration is typically fixed throughout the network lifetime, the use of a dynamic round duration based on energy exhaustion at sensor nodes has also been proposed. Even though many attempts have been made to determine the round duration dynamically, all of them focus on WSNs. However, in mobile wireless sensor networks (MWSNs), apart from energy exhaustion, packet loss due to node mobility is also an important issue to be considered in the case of dynamic round duration. To investigate the problem of the calculation of the dynamic round duration in MWSNs, in this work we evaluate the applicability of an existing recluster triggering scheme initially proposed for WSNs, which is adaptive to energy consumption at cluster-heads (CHs). We also propose a new scheme, the lost ratio reclustering (LRRC), which provides adaptivity to the percentage of mobility-induced packet losses at each CH. Furthermore, the case of reclustering in fixed time intervals is also considered. Simulation results show the effectiveness of the LRRC scheme in increasing the packet delivery ratio (PDR) and reducing the clustering energy overhead.**

***Index Terms*—clustering, global reclustering, mobility, lifetime**

I. INTRODUCTION

WIRELESS sensor networks (WSNs) comprise a number of nodes collecting and transmitting data to the base station (BS). Longevity is one of the most critical issues in the design of WSNs and it mainly depends on energy conservation due to limited energy at sensor nodes. Up to now, clustering is the most popular solution achieving energy efficiency [1]. Clustering organizes nodes into clusters, where in each cluster the cluster-head (CH) receives data packets from the other cluster members (CMs) -i.e., the non-cluster-heads (non-CHs)- and then it aggregates the data and transmits the result to the BS. Data aggregation in CHs decreases the number of relayed packets resulting in a significant energy saving. However, since the CHs have many responsibilities, such as data gathering, aggregating and transmitting/forwarding, their energy is depleted faster compared to the non-CHs [2].

For further energy efficiency, reclustering takes place in order to achieve energy load balancing and avoid premature death of the CHs [1], [2]. Generally, reclustering can be categorized into *localized* and *global* [3], [4], [5]. In *localized* reclustering, either a CH's re-election is performed in a part of the network, [4], or the CH role is rotated among the CMs of a static cluster [3], [5], [2], [6] . In contrast, *global* reclustering affects the whole network and the decision for the next full-network reclustering is taken either by BS in a centralized style, or by CHs in a distributed fashion. Concerning *global* reclustering, the majority of clustering protocols specify clustering to be triggered periodically in the beginning of fixed time intervals, called rounds. This approach is known as the round-based policy (RBP) [3], [7], [8]. LEACH [9] is the most well-known protocol using RBP.

Although RBP clustering approaches aim at load balancing, they cannot provide the best performance in terms of energy conservation and network lifetime. This is because reclustering in predetermined fixed time intervals ignores the network status. To overcome this shortcoming, in the literature of static WSNs, there are few works studying the adaptation of the round duration to the network conditions, which in general specifies the *adaptive* reclustering. Particularly in [8], [7], [10], [11], the round duration is dynamically determined based on a criterion that considers the energy decrease at CHs, while in [12] the round duration is decided based on the number of alive nodes. Concerning the decision of the next reclustering time, in [10], [12], [11], it is made by BS via a centralized approach, whereas in [7], [8] in a distributed fashion among CHs. As for mobile WSNs (MWSNs), node mobility randomly and dynamically changes the network topology and results in frequent connection losses. Therefore, *adaptive* reclustering should also take into account the node mobility besides the residual energy decrease in MWSNs. Considering *adaptive* reclustering in MWSNs, there is only one work, [13], and in contrast to the aforementioned works, it focuses on *localized* reclustering, where nodes in the boundary of a cluster can change cluster membership when it is necessary based on the prediction of nodes' locations.

In the literature of MWSNs, there are several mobility-aware clustering protocols, which consider node mobility in CH selection phase, and all of them employ fixed round duration according to RBP. Nevertheless, as the topology changes during a round, it may be not optimal for a node to continue attaching itself to the current cluster due to the increasing communication distance, which results in extra energy consumption during transmission and reduction in packet delivery ratio (PDR), [13]. [13] proposes an *adaptive* reclustering method for MWSNs which is *localized*, whereas in this work we investigate *adaptive global* reclustering in MWSNs. More specifically, [13] considers *adaptive localized* reclustering both from CH and non-CH points of view and after the initial formation of clusters the time for cluster re-formation is not specified. Instead, a periodical rotation of CH role inside a cluster is considered and additionally, the non-CHs in the boundaries of a cluster are allowed to recluster themselves to the optimal clusters due to node mobility whenever it is necessary. Contrary to [13], in this

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work we investigate the *global* reclustering for MWSNs, where all nodes participate in cluster formation. The latter is executed after a time interval that dynamically changes based on the condition of the sensors , therefore the reclustering is *adaptive*. Moreover, the membership declaration is employed in order to manage the non-CHs' disconnections from CHs due to node mobility. The proposed approach can be adopted by all mobility-aware RBP protocols as a stand-alone reclustering method. On the contrary, [13] proposes a *localized* reclustering method, which could be applied to a clustered network in synergy with *global* reclustering. Another difference between this work and [13] is the unrealistic assumptions considered in the latter. Specifically, although the consideration of energy is crucial for the modeling of sensor networks, the energy of nodes is not taken into account in [13]. Also, the duration of simulations is fixed. In contrast, in this work we consider the limited node lifetime due to the exhaustion of its energy and run the simulation up to time that the death of the last node occurs. In summary, the contributions of this work are:

- we evaluate the applicability of an existing energy-aware *adaptive* recluster triggering scheme, already proposed for WSNs, on MWSNs.-*Case study 1*
- we propose a new recluster triggering scheme, which is *adaptive* to the percentage of mobility-induced packet losses at each CH.-*Case study 2*
- the proposed *adaptive* recluster triggering schemes schedule cluster formation independently of the clustering algorithm, so they are compatible with all existing mobility-aware RBP protocols. The proposed schemes can be applied to mobility-aware RBP protocols and enhance the performance of the latter taking into account the network parameters.

The rest of the paper is organized as follows: Section II presents the papers proposing *adaptive* reclustering either in static or in mobile WSNs. Section III presents the proposed round duration schemes under node mobility. Section IV describes the simulation results and finally Section V concludes the paper.

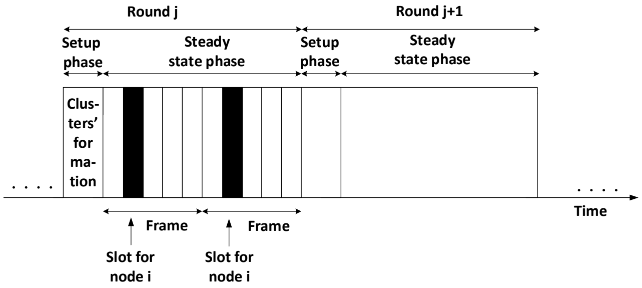


Fig. 1: Round structure in RBP

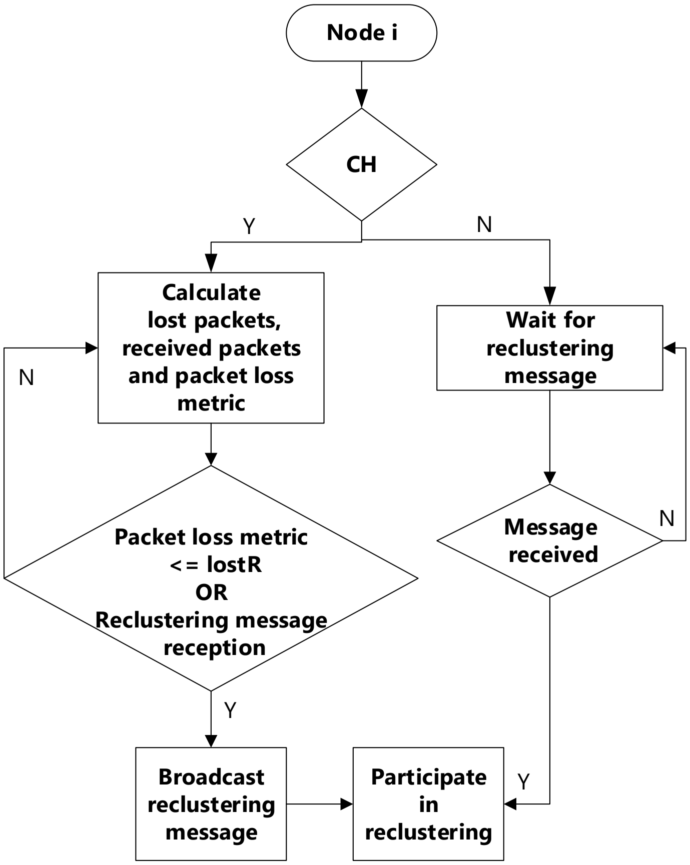
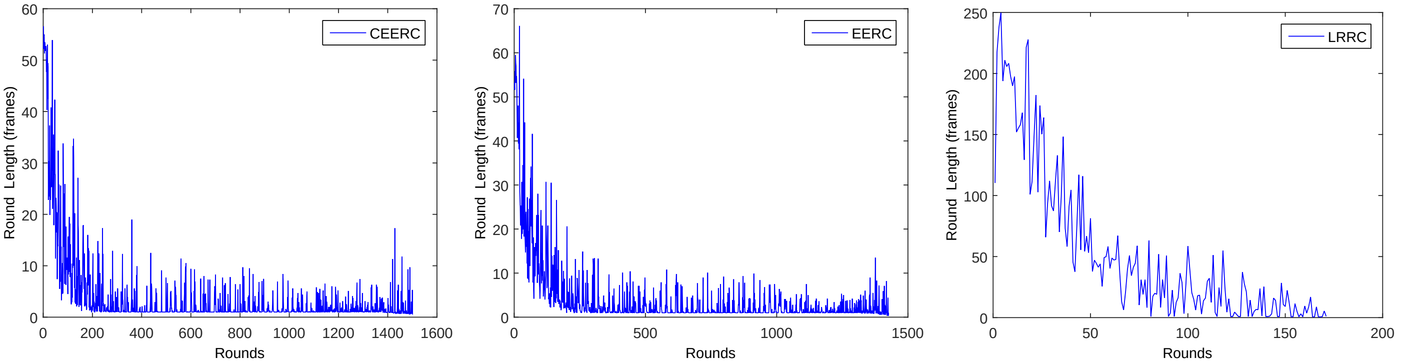


Fig. 2: Flowchart of the LRRC

II. RELATED WORK

From the consideration of the network conditions viewpoint, reclustering can be categorized into *static* and *adaptive*. *Static* reclustering takes place after constant time intervals ignoring the network conditions, whereas *adaptive* reclustering is triggered based on the variation of the network conditions. *Static* reclustering includes the previously described RBP approach. Particularly regarding RBP, as shown in Fig. 1, the network lifecycle is divided into predefined fixed time periods, which are called rounds. Each round starts with a setup phase, which organizes nodes into clusters, and then a steady state phase follows, which collects the sensed data to the BS. The steady-state phase is partitioned into a number of frames, where non-CHs transmit the sensed data packets to their CH during their allocated timeslots. Below, we review the existing related works considering *adaptive* reclustering, which also belong to either *global* or *localized* category.

To begin with, the majority of research papers focus on *global* reclustering and as already mentioned, all of them refer to static WSNs. Particularly in [7], [8], the network operation is divided into hyper rounds (HRs) and each HR is further divided into rounds. In the setup phase of the first round of every HR, CHs are elected based on their current residual energy. In both [7] and [8], the number of rounds per HR varies throughout the network lifetime and it is decided in a distributed manner among CHs. In [7], each CH computes its HR length based on its residual energy and the distance from the sink using fuzzy inference system (FIS), while in [8], each CH decides reclustering in the upcoming round whenever its residual energy falls below a threshold. The CHs agree about the next reclustering time through a signalling exchange and choose the shortest HR length as *global* HR length. Contrary to [7] and [8], in [11], [10], [12], the decision of the next reclustering time is taken by BS in a centralized way. In [11], the reclustering time is decided in advance by



(a) (b) (c)

Fig. 3: Length per round vs rounds for scenarios, 50% mobile nodes, $R_b = 10kbps$, $RF = 0.8$, $lostR = 0.05$, $v \in [1, 20]m/s$, pause time $\in [0, 5]s$: (a) CEERC (b) EERC (c) LRRC

BS based on an energy prediction model. In [10], the BS calculates the round length for each cluster based on the corresponding CH's current energy. In [12], the reclustering is adaptive to the number of alive nodes. More specifically, the round length is proportional to the number of alive nodes and in order to avoid very short round lengths, after the death of half nodes, the round length remains constant for the rest of the network lifetime. Lastly, in [14], the reclustering rate is determined beforehand using an analysis of the energy consumption. Specifically, the reclustering rate is expressed as a function of the maximum cluster radius and network lifetime and thereafter the relationship of the two aforementioned parameters is derived through an energy consumption analysis.

Regarding *localized* reclustering in static WSNs, in [4], the authors examine *localized* reclustering for large-scale sensor networks. The network is partitioned into concentric rings and then each ring is further divided into different parts, forming fan-shaped clusters. Reclustering is *adaptive* to energy and it is done only on each concentric ring. When the energy of a CH falls below the threshold, it passes its role by broadcasting a head-selection message, which is received by the nodes inside a ring. Receiving this message, the nodes compete for being new CH. In [15], reclustering is *adaptive* to the received signal strength. During the rounds of the network operation, the non-CHs which reside at the boundary of the cluster are allowed to switch their cluster and join the CH of a neighboring cluster with stronger signal than that of its current CH. In [16], reclustering is performed locally when a CH consumes a significant part of its residual energy. Although the network operation is divided into rounds, not all nodes participate in the setup phases. At the end of a setup phase, every CH calculates its current residual energy and whenever the latter falls below a percentage of its initial energy, the CH informs its CMs of participating in the setup phase of the next round. However, the nodes whose CHs have adequate energy do not participate in the setup phase and they wait until this period finishes. Finally, in [13], *localized* reclustering for MWSNs is proposed based on node's location prediction. Specifically, non-CHs periodically estimate their current location through a particle filter algorithm, predict their locations of the next time interval based on the mobility model and transmit their locations along with their IDs to the corresponding CH. Each CH forwards the information to the non-CHs in the boundary regions of the corresponding cluster. If reclustering is necessary a boundary node transmits a join message to the CH of the optimal cluster.

Lastly, an hierarchical scheme, which includes both *global* and *localized* reclustering, is proposed in [3]. The lifecycle is hierarchically divided into global hyper rounds (GHRs) and each GHR contains some local super rounds (LSRs), which are further divided into a number of rounds, for each cluster. *Global* reclustering is executed at the end of every GHR. As mentioned in [3], *global* reclustering is in general *adaptive*. Specifically, the authors refer that the CHs can monitor the variations of LSRs and when the LSR length in a region is very short compared to other areas, *global* reclustering is scheduled by CHs. Furthermore, the length of GHR can be dynamically determined based on the network conditions. When a CH finds that the condition has been satisfied, the decision of the next *global* reclustering is taken in a distributed way among CHs and the reclustering is triggered at the upcoming setup phase. As for *localized* reclustering, it is energy *adaptive* and only clusters whose CHs' energy falls below a threshold perform reclustering at the end of the cluster's current LSR.

In this paper, we focus on *adaptive global* reclustering in MWSNs. So *localized* reclustering falls beyond our interest, because we mainly investigate the determination of the dynamic round duration.

III. PROPOSED ROUND DURATION SCHEMES

To evaluate the effect of the *adaptive global* reclustering on the network performance, we employ LEACH-MF as baseline clustering protocol, [17]. LEACH-MF falls into the category of RBP, thus it employs fixed round duration. In the evaluation approach, the setup phase of LEACH-MF is identically adopted, while the method of recluster triggering is varied. Futhermore, the *adaptive localized* reclustering scheme proposed for MWSNs in [13] is unreasonable to be adopted here. This is because the method of membership declaration, which specifies cluster membership change, is inherited here from LEACH-MF. More specifically, to avoid packet losses due to node mobility, membership declaration allows a non-CH to join a new cluster in case of not receiving a request from its current CH for data transmission during 2 consecutive frames.

A. Mobility-aware clustering algorithm

In this paper, for clustering task, we employ the LEACH-MF clustering algorithm currently proposed in [17]. LEACH-MF adopts the well-known LEACH protocol with an extension to mobile nodes using FIS. More specifically, as LEACH-MF is based on LEACH, it falls in the category of RBP approach and its execution is divided into rounds. Each round starts with the set-up phase in which the most appropriate nodes are elected to act as CHs. The suitability of a node as CH is evaluated by FIS, which introduce the current residual energy, the moving speed and the pause time of nodes as fuzzy descriptors during the CH selection process. The output variable is a crisp number in the range $[0, 1]$ which denotes the chance of a CH candidate. The operation of the LEACH-MF algorithm is briefly described in 3 stages:1) CH selection, during which a node generates a random number and if this number is larger than a threshold, the node becomes CH candidate. All CH candidates compute their chances, i.e., crisp numbers, using FIS and they advertise their chance in their neighbourhood. If the chance of a CH candidate is larger than the chance values of the other neighbouring CH candidates, the CH candidate elects itself as CH. 2) Cluster formation, during which an elected CH broadcasts a CH-message. A non-CH receiving multiple CH-messages selects the closest CH to join and transmits a join request message to the latter. After the completion of cluster formation, each CH transmits its TDMA schedule to its CMs. 3) Data transmission, in which the non-CHs transmit data packets to their CH in the scheduled timeslots. To avoid packet losses caused by node mobility, the authors employ the membership declaration method, which is initially proposed in [18].

It is worth to mention that in cluster formation, we have used two transmission ranges; the inter-cluster and the intra-cluster ranges as specified in [19], [20]. The inter-cluster range represents the maximum communication distance among CHs used in message transmissions, while the intra-cluster range represents the aforementioned distance between a CH and its CMs. The intra-cluster range is also referred as cluster radius. The ranges are determined by the transmission power level of a node and this can vary in order to achieve inter or intra cluster communication [20]. According to [19], the inter-cluster range controls the number of clusters that satisfy network coverage and it is usually two times greater than the intra-cluster range.

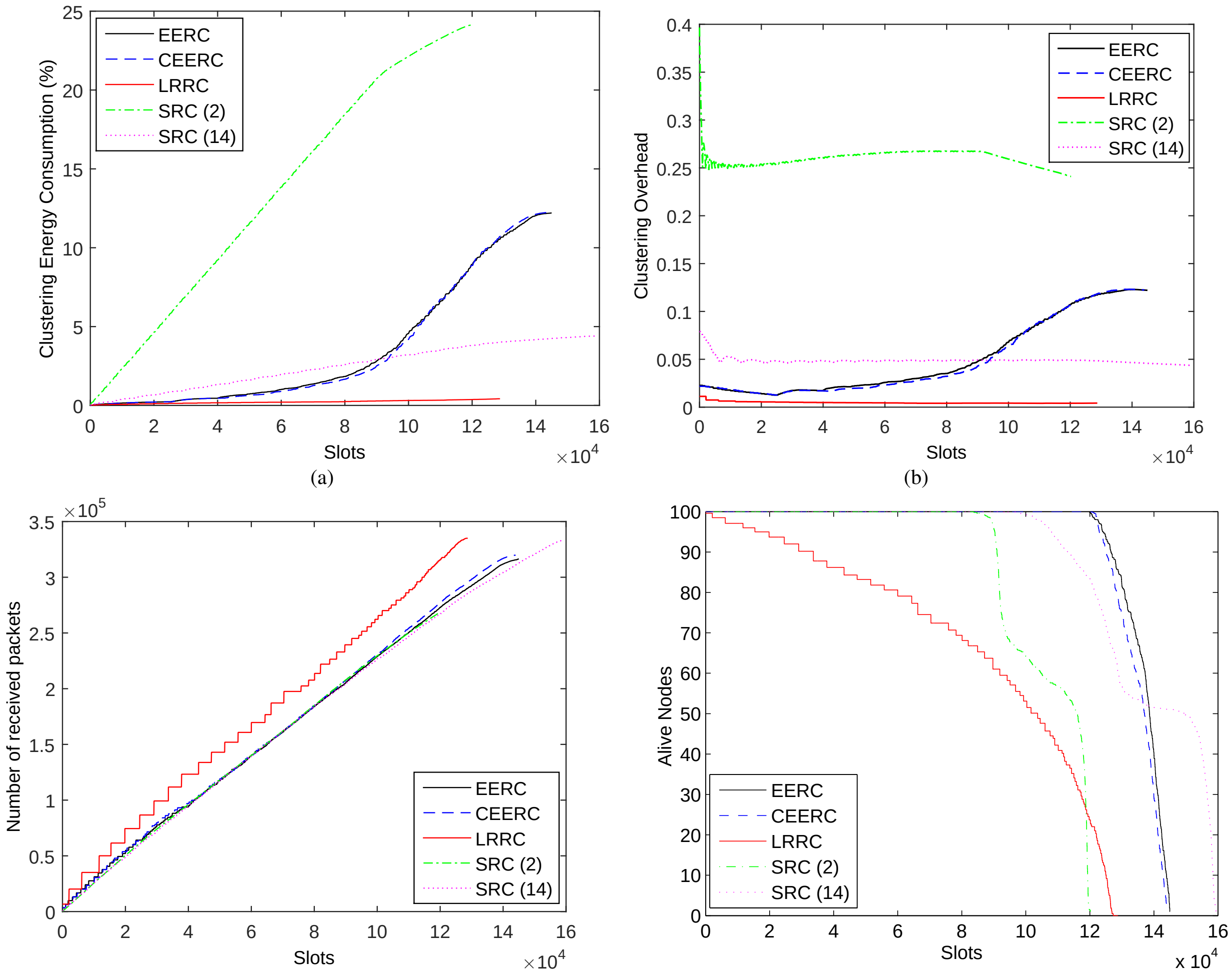
B. Recluster triggering schemes

1) Case study 1:

- EERC: The energy efficient reclustering (EERC) scheme employs the residual energy of CHs in comparison with that of CMs in order to schedule reclustering. This scheme was initially proposed in [8] for WSNs and it is described as follows: after the CH selection stage at the end of the setup phase of an HR, each non-CH sends its current residual energy to the chosen CH along with the join message. Then, each CH calculates the mean of its CMs' residual energy $\overline{E_{CM-init}}$ and lastly each CH determines its energy threshold as $E_{th} = RF \times \overline{E_{CM-init}}$, where RF, $0 \leq RF \leq 1$, is the reclustering factor and it is fixed throughout the network lifetime. In [8], the authors vary the RF value and show by simulations that the best lifetime is achieved for $RF = 0.8$. For this reason, RF is set to 0.8 in the rest of the paper. Each CH observes its residual energy and whenever the latter falls below its threshold the CH broadcasts a message for the next clustering to its neighbouring CHs. Afterwards, every CH informs its CMs to perform the next setup phase, i.e., reclustering, in the following round. The authors employ a clustering algorithm that selects CHs only based on the metric of residual energy. Based on this selection, the authors present an analysis for the HR length computation. Nevertheless, the extracted analytical formulas are not validated with comparison to simulation results. The authors state that the proposed recluster triggering scheme does not depend on the clustering algorithm, so we examine this scheme together with the LEACH-MF clustering algorithm in MWSNs.
- CEERC: The current energy efficient reclustering (CEERC) scheme is almost identical with EERC and their only difference is that in CEERC, the energy threshold is recomputed after each of the sequential frames dedicated for data transmission, while in EERC, the threshold is computed once per HR at the end of the setup phase. Particularly regarding a CH, initially in the setup phase, the CH receives the current residual energy of its CMs and computes the energy threshold similarly to EERC. However, in each frame of the steady state phase, each non-CH transmits its current energy amount along with the data packet. So each CH considers the energy of the current CMs for the computation of the threshold at the end of every frame of the steady state. The CEERC scheme is proposed because the CMs of a cluster change during a round. More specifically, as already mentioned, the membership declaration is employed and according to which the nodes may change cluster membership during the steady state phase of a round. Nevertheless, as seen later, simulation results reveal not much difference on the behavior of the EERC and CEERC schemes probably because of the uniformity of nodes' energy. Particularly, the initial energy of all nodes is equal, the nodes are initially uniformly dispersed and move randomly in the network area. As for the CHs, their energy decreases faster compared to non-CHs. However, in CH selection, only nodes that have not been recently CHs for 20 consecutive rounds can be elected as CHs in the current round and this results in not sharp decrease of nodes'energy in general.

2) Case study 2:

- LRRC: In the lost ratio reclustering (LRRC) scheme, each CH calculates a packet loss metric as the complementary of the PDR metric. PDR is defined as the ratio of the successfully received packets at a CH to the sum of the aforementioned packets and lost packets because of node mobility. More specifically, at the end of every frame, each CH calcuates the lost data packets, the received data packets and it computes the



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

Fig. 4: Performance metrics vs slots, 50% mobile nodes, $R_b = 10kbps$, $RF = 0.8$, $lostR = 0.05$, $v \in [1, 20]m/s$, pause time $\in [0, 5]s$: (a) clustering energy consumption (b) clustering overhead, (c) number of received packets at BS, and (d) number of alive nodes

packet loss metric as the percentage of the lost data packets. A CH can calculate the lost data packets, since it schedules slots dedicated to CMs for data packet transmission in every frame. In the steady state phase of a round, each CH computes the packet loss metric in every frame and whenever the latter falls below $lostR$ the CH sends a message for reclustering to its CMs and to the other CHs. The other CHs inform their CMs about the reclustering. Then reclustering is performed in the set-up phase of the upcoming round. The decision of the next reclustering time is taken in a distributed manner. Fig. 2 shows the steps followed by a CH or a non-CH according to LRRC. To evaluate the effect of $lostR$ on the LRRC's behavior, several values of $lostR$ are tested for 90% mobile nodes. In LRRC, the condition that triggers reclustering is only based on the percentage of lost data packets at each CH, so the effect of $lostR$ on the LRRC's behavior can be clearly revealed under a high percentage of mobile nodes. When $lostR$ takes the values $\{0.3, 0.2, 0.1, 0.05, 0.005\}$, PDR takes the values $\{0.5818, 0.5548, 0.5457, 0.5373, 0.5297\}$, whereas clustering overhead takes the values $\{0.0242, 0.0058, 0.0032, 0.003, 0.0028\}$ respectively. As observed, the increase of $lostR$ results in the increase of not only PDR but also clustering overhead. If $lostR$ increases over 0.3, the reclustering takes place very frequently, almost in every frame. In the rest of the paper, $lostR$ is considered fixed and equal to 0.05.

To evaluate the efficiency of the proposed round duration schemes, we also consider *static* reclustering (SRC), which signifies RBP. Particularly, we examine the cases that there are 2 and 14 frames per round. The two cases are denoted as SRC(2) and SRC(14) respectively.

To validate the accuracy of the LEACH-MF implementation in this work, we present some results regarding the cluster formation. Specifically, table I presents the mean and the standard deviation of clusters up to the round that half nodes remain alive (HNA). The results are demonstrated for the 4 recluster triggering schemes and enhance the validity of the LEACH-MF implementation in this work. LEACH-MF, [17], gives 4.5 average number of clusters with 0.73 standard deviation. Slight differences in our values compared to [17] are probably due to the use of the inter-cluster transmission range during the advertisement phase in cluster formation.

IV. DETERMINATION OF PACKET LOSS METRIC FOR LRRC

According to LRRC, whenever the packet loss metric (PLM) at one of the CHs falls below $lostR$ the reclustering is executed in the setup phase of the upcoming round. Therefore, in order to determine PLM, we examine one cluster. Also for simplicity of the analysis, the following assumptions are made:

- The CH is stationary.
- To consider the data packet transmissions from new nodes joining the examined cluster using membership declaration, a constant number of the aforementioned nodes, N_c, is assumed in a frame.
- The nodes that join the cluster using membership declaration are not disconnected from this cluster.

Let N denote the total number of nodes and k the expected number of clusters, thus the expected number of nodes in one cluster is N/k.

After cluster formation the CH (node j) transmits the TDMA schedule to its CMs at time $t = 0$. The CH is static, so based on [19] its position is

$$(x_j, y_j) \tag{1}$$

and the position of a non-CH node i is

$$(x_i + v_i cos\theta_i t, y_i + v_i sin\theta_i t) \tag{2}$$

where $i \in [1, \frac{N}{k} - 1]$, (x, y) is the initial position, v is the velocity and θ is the moving direction.

The transmissions between the CH and a non-CH node i are successful, if the following condition holds, [19]:

$$(x_j - x_i - v_i cos\theta_i t)^2 + (y_j - y_i - v_i sin\theta_i t)^2 \leq R^2 \tag{3}$$

, where R denotes the cluster radius. Given the (x, y), v and θ, the connection time T_i between the CH and node i can be computed solving the inequality (3).

Let l denote the data packet size and R_b the transmission bit rate, thus l/R_b denotes the slot duration. Also, let n_i denote the number of the dedicated slot for a non-CH node i in a frame of the steady state phase, [19]. Assume that we examine the $K - th$ frame after the setup phase. The non-CH node i transmits successfully in the examined frame if:

$$\left(n_i + K\left(\frac{N}{k} - 1\right)\right)\frac{l}{R_b} \leq T_i \tag{4}$$

Let R_i a random variable (RV), indicating a transmission failure in the dedicated slot n_i, $i \in [1, \frac{N}{k} - 1]$. So R_i can be determined as follows:

$$R_i = \begin{cases} 1, \ if \ \left(n_i + K\left(\frac{N}{k} - 1\right)\right)\frac{l}{R_b} > T_i \\ 0, \ otherwise \end{cases} \tag{5}$$

Finally PLM is computed as follows:

$$PLM = \frac{\sum_{i=1}^{N/k-1} R_i}{\frac{N}{k} - 1 + (K-2)N_c} \tag{6}$$

TABLE I: Validation of the employed Clustering algorithm

reclustering scenario	SRC(2)	SRC(14)	EERC	CEERC	LRRC
avg clusters	4.797	4.79	4.882	4.831	4.904
st. deviation	0.71	0.698	0.672	0.673	0.712

According to membership declaration, a non-CH joins a new cluster, if it does not receive a request from its current CH for data transmission during 2 consecutive frames. Also, we examine the $K - th$ frame after the setup phase in a round and for this reason Nc is multiplied by $(K - 2)$ in (6).

V. PERFORMANCE EVALUATION

This section evaluates the performances of EERC, CEERC and LRRC compared to that of SRC. Different from SRC, where the round duration is fixed and predetermined, EERC, CEERC and LRRC determine the round duration dynamically based on the network conditions. To compare the performance of these schemes, simulations are conducted using MATLAB. In the experimental setup, initially, 100 sensor nodes are uniformly distributed in a $100m \times 100m$ network area, whereas the inter-cluster and intra-cluster communication ranges equal $50m$ and $25m$ respectively. The percentage of mobile nodes varies in the range $[10, 100]$. The mobile nodes roam around the fixed network area according to the random waypoint (RWP) mobility model. According to RWP, a mobile node randomly picks a constant velocity value from $[1, 20]m/s$ and when the node reaches the destination point, it waits for a pause time randomly selected in $[0, 5]s$. The BS is stationary and similarly to literature [17], [7], [8], [3], the BS is located at the position $(50, 175)m$, which is outside the network area. The data and control packet sizes are 4000 and 200 bits respectively. The initial energy of each node is $2J$ and the first-order radio model has been employed to model the energy dissipation between 2 devices similarly to [17]. The parameters used in simulation experiments are described in table II. To consider the randomness of the nodes' placement and movements, the simulations were run 10 times similarly to [7]. For all experiments, the demonstrated results are obtained by averaging the results of the 10 independent simulation runs.

Initially, the behavior of the recluster triggering schemes is evaluated over the simulation time from the round length, clustering energy consumption, clustering overhead, number of received packets at BS and alive nodes perspectives. Next, the network performance from the perspectives of PDR, average energy consumption per packet and clustering overhead is investigated versus the variation of the percentage of mobile nodes, velocity and transmission bit rate.

A. Dynamic Network Behavior

The results in this subsection show the dynamic behavior of the recluster triggering schemes during the simulation time. In Figs. 3a-3c, the dynamic changes of the round length are depicted over the simulation time, rounds, for the CEERC, EERC and LRRC schemes respectively. In CEERC and EERC, where the next reclustering time is determined based on CHs' energy sufficiency, the length is long at the beginning of the simulation time because of CHs' high energy amount. As time passes, nodes' residual energy decreases, so reclustering takes place in shorter time intervals. Although the length decreases initially over the time, the behaviour is not clearly in the steady state. This is due to the fact that the CHs are elected based on not only the residual energy but also the mobility according to LEACH-MF. As described in Section III-B-1, the mechanism of EERC is initially proposed in [8]. In [8], the HR length is more clearly descending compared to Figs. 3a-3b and this is because the CHs are elected only based on their residual energy in [8]. On the contrary, in our approach, the suitability of a CH depends also on its velocity and pause time and therefore nodes with lower residual energy may be selected as CHs. This results in more up and downs in the round length in Figs. 3a-3b. In Fig. 3c, the reclustering time is determined by LRRC, which triggers reclustering based on the lost ratio. Although the decision criterion is not energy related, the round length has also a decreasing behavior over the time similarly to Figs. 3a-3b. This is reasonable, since as time passes nodes die, therefore clusters have fewer CMs which result in fewer successful transmissions and so higher lost ratio at each CH. Additionally, the round length in LRRC gets much higher values compared to CEERC and EERC. This occurs because of higher number of packet transmissions.

In Figs. 4a- 4d, comparative simulation results are presented over the simulation time for the 4 recluster triggering schemes. Since a round has different duration in frames based on the recluster triggering scheme, the time is converted into slots for fair comparison among the schemes. Fig. 4a presents the percentage of the initial energy dissipated in the clustering process, while Fig. 4b the ratio between the energy consumed for clustering and the total energy consumed- i.e., clustering overhead. As shown in Figs. 4a-4b, LRRC results in the minimum energy dissipated in clustering compared to EERC, CEERC, SRC. This is expected, since LRRC gives larger round durations and therefore fewer reclusterings compared to EERC and CEERC (see Fig. 3). SRC(2) gives the highest clustering overhead due to the short constant round duration of 2 frames. EERC and CEERC attain less clustering overhead up to $9.4*10^4$ slots compared to SRC(14). Afterwards, clustering overhead grows larger because reclustering is triggered in shorter time intervals due to further reduction of CHs' residual energy. Fig. 4c shows the total number of received packets at BS. LRRC gives the largest number of successful packet transmissions over the simulation time at the cost of the smallest last node dies (LND) lifetime, which particularly occurs at $1.288*10^5$ slots. Lastly, the number of alive nodes during the simulation time is depicted in Fig. 4d. This figure shows that LRRC is less efficient than EERC, CEERC and SRC from the network lifetime perspective in general. On the contrary, EERC and CEERC give the largest first node dies (FND) time, while SRC(14) the largest LND. Generally, it is observed that EERC and CEERC have almost identical behavior over the simulation time (Fig. 4).

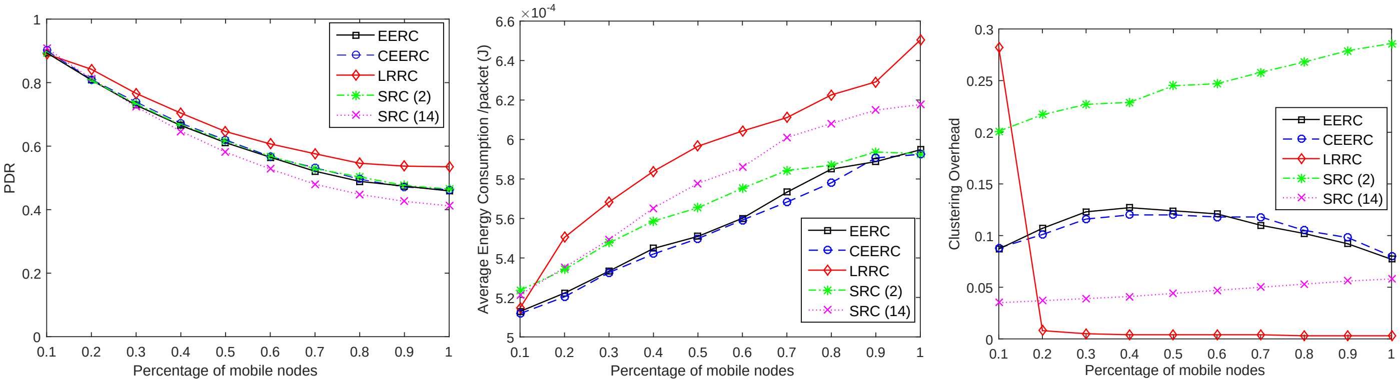
B. Performance under network parameters

The results presented in this subsection are obtained in the end of simulation time for each value of x axis variation.

1) Percentage of mobile nodes: Performance metrics with respect to the percentage of mobile nodes for different recluster triggering schemes are illustrated in Fig. 5. The ratio of the successfully received packets to the total transmitted packets -i.e., PDR- is depicted in Fig. 5a. As shown, LRRC outperforms the other schemes from the PDR perspective as the percentage of mobile nodes varies in $[0.2, 1]$. LRRC retains a higher PDR value compared to the other schemes. This is reasonable because it triggers reclustering based on an acceptable percentage of lost packets at a cluster, $lostR$. When the percentage of mobile nodes equals 0.1, SRC(14) slightly outperforms the other schemes and thenceforth its performance worsens. SRC(14) has a relatively large round duration, which cannot achieve high PDR as the number of mobile nodes further increases. EERC, CEERC and SRC(2) give similar PDR. Next, the average energy consumed for a successful data packet transmission is demonstrated in Fig. 5b. Generally, the average energy per packet increases as the percentage of mobile nodes increases. This is reasonable, since the number of successfully transmitted data packets decreases, while the CHs consuming the same energy because of data aggregation transmit fewer data packets to BS. In Fig. 5c, the clustering overhead is depicted for all schemes. It is noteworthy that LRRC attains large clustering overhead only when the percentage of mobile nodes equals 0.1 and thereafter the clustering overhead is extremely low. This can be explained, since when the percentage of mobile nodes equals 0.1, the number of lost data packets at a CH is low, which further results in lower value for the complementary of PDR. The latter falls frequently below the threshold, $lostR$, resulting in many reclusterings throughout the network operation and thus the clustering overhead is increased. So it is revealed that the performance of LRRC depends on some network parameters. Finally, SRC(2) gives the highest clustering overhead compared to others (except LRRC for 0.1 percentage of mobile nodes) due to fixed short round duration.

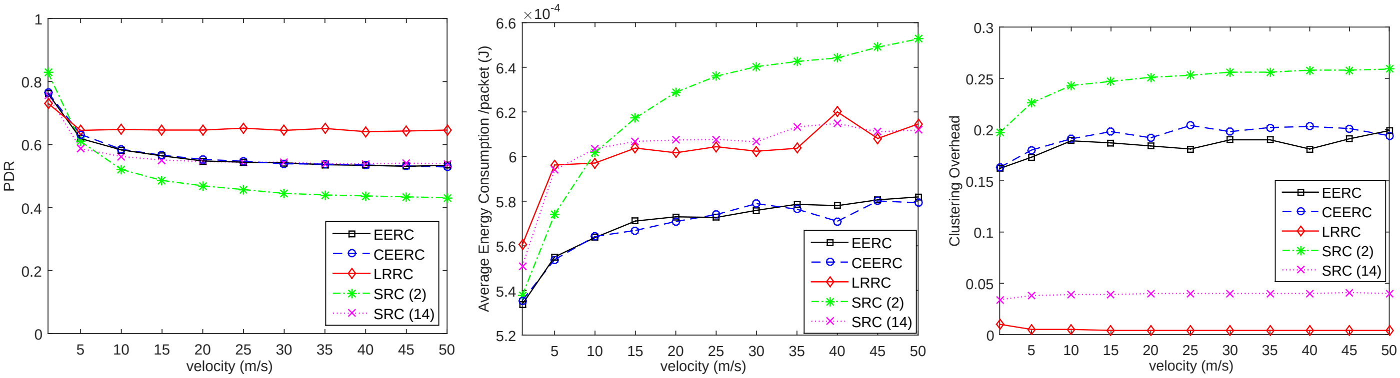
TABLE II: Simulation Parameters

Parameters	**Values**
Network	
nodes number (N)	100
expected number of clusters	5% of N
network area	(0,0)-(100,100)m
BS location	(50,175)m
data packet size	4000 bits
control packet size	200 bits
Transmission bit rate (R_b)	10 kbps
inter-cluster range	50 m
cluster radius	25 m
Energy model	
$E_{elec}^{TX}/E_{elec}^{RX}$	50 nJ/bit
E_{mp}	0.0013 pJ/bit/m^4
E_{fs}	10 pJ/bit/m^2
E_{da}	5 nJ/bit/signal
d_{th}	$\sqrt{E_{fs}/E_{mp}}$
Mobility model	
percentage of mobile nodes	[10, 100]%
velocity (v)	[1,20] m/s
pause time	[0,5] s
Reclustering	
RF	0.8
$lostR$	0.05



(a) (b) (c)

Fig. 5: Performance metrics vs percentage of mobile nodes,$R_b = 10kbps$, $RF = 0.8$, $lostR = 0.05$, $v \in [1, 20]m/s$, pause time $\in [0, 5]s$: (a)packet delivery ratio (PDR) (b) average energy consumption (c) clustering overhead

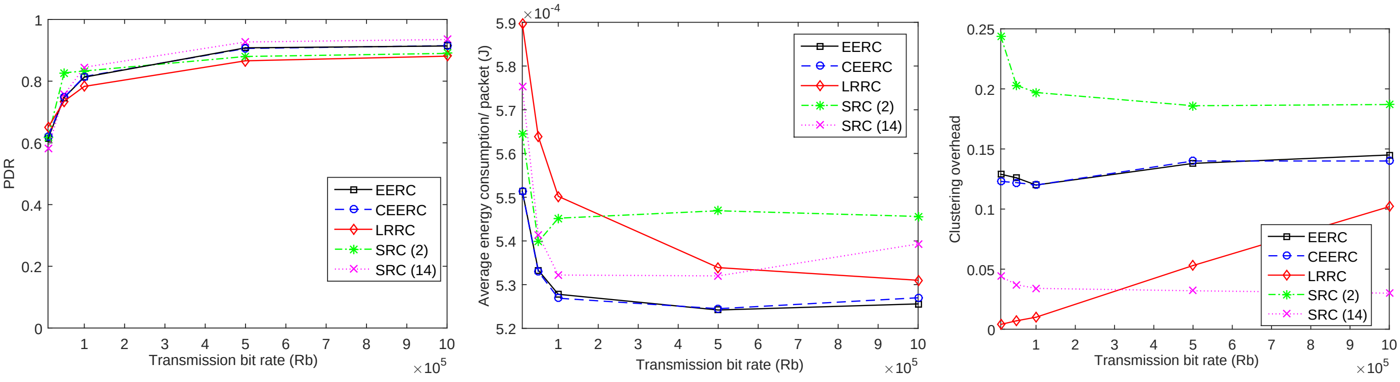


(a) (b) (c)

Fig. 6: Performance metrics vs percentage of mobile nodes, 50% mobile nodes, $R_b = 10kbps$, $RF = 0.8$, $lostR = 0.05$, pause time $\in [0, 5]s$: (a) packet delivery ratio (PDR) (b) average energy consumption (c) clustering overhead

2) Velocity: In this experiment, the velocity of mobile nodes is varied with 50% mobile nodes. In contrast to the properties of RWP, where velocity is chosen randomly within a range, the velocity in this experiment is constant in order to evaluate clearly the effect of the velocity on the performance of the recluster triggering schemes. The performance metrics versus the velocity are depicted in Fig. 6. As shown in Fig. 6a, LRRC outperforms the other schemes, when $v \in [5, 50]$. Generally, LRRC triggers reclustering based on an acceptable ratio of lost packets, which results in higher PDR compared to the other schemes. However, in the case that v equals $1m/s$ this behavior is reversed and more specifically SRC(2) attains the highest PDR value. CEERC, EERC and SRC(14) perform almost in the same way. Interestingly, Fig. 6b shows that the average energy consumption per successful packet transmission strongly depends on the node's velocity. For constant percentage of mobile nodes and equal to 50%, the average energy consumption has an ascending behavior with the velocity, since the transmission distance increases as the velocity increases resulting in more energy consumption. Particularly EERC and CEERC give the lowest energy consumption in the whole range of the velocity variation. In SRC(2), when $v \in (10, 50]$, more energy is consumed compared to the other schemes. Finally, Fig. 6c shows the clustering overhead. As expected, LRRC results in the lowest overhead. Also, for LRRC and SRC(14), overhead remains almost constant regardless of the velocity value.

3) Transmission bit rate: In the related literature, [17], [8], [7], [3], the transmission bit rate (R_b) is not specified. For this reason, we vary the transmission bit rate in the range $[10kbps, 1Mbps]$. This range is selected because 10kbps and 1Mbps are used in the literature of WSNs in general. In Fig. 7a, it is observed that PDR increases with the increase of R_b. This is logical, since the slot size is directly affected by R_b. More specifically, the slot size equals the ratio of the data packet size to R_b. Therefore the slot size decreases with the increase of R_b. However, the velocity ranges in $[1, 20]m/s$ regardless of the R_b variation. This results in a slower movement of nodes as R_b increases. Consequently, the latter results in the increase of PDR. In Fig. 7b, the average energy consumption per packet decreases as R_b increases. The consumed energy for a successful packet transmission and reception from a non-CH to a CH remains constant with the increase of R_b. However, a CH transmits more packets to the BS consuming the same energy because of data aggregation, which results at the decrease of the average energy consumption. As for the clustering overhead illustrated in Fig. 7c, in SRC(2) and SRC(14), it decreases as R_b increases. This is expected because the consumed energy for clustering remains constant due to fixed round duration, while the energy consumption for data packet transmission increases because of more successful packet transmissions. In CEERC and EERC, the clustering



(a) (b) (c)

Fig. 7: Performance metrics vs transmission bit rate (R_b), 50% mobile nodes, $RF = 0.8$, $lostR = 0.05$, $v \in [1, 20] m/s$, pause time $\in [0, 5] s$: (a) packet delivery ratio (PDR) (b) average energy consumption (c) clustering overhead

overhead increases, since the transmission of more packets results in higher energy consumption at a CH. A CH's energy falls sooner below the threshold, which triggers reclustering in shorter time intervals. Lastly, in LRRC, clustering overhead clearly increases with the increase of R_b. This occurs as the complementary of PDR falls sooner below $lostR$ because of more packet transmissions and thus more reclusterings take place throughout the network lifetime.

To sum up, simulation results show that the varying parameters affect the behavior of the recluster triggering schemes from the perspective of network performance. Specifically LRRC, which is proposed in this paper, can achieve the highest PDR besides the lowest clustering overhead compared to the CEERC, EERC and SRC schemes in the case of average to high nodes' velocity under an average to high percentage of mobile nodes. Regarding this worst-case scenario from mobility point of view, the effectiveness of LRRC is revealed, since it triggers *global* reclustering *adaptive* to packet losses at each CH. Furthermore, for the first time in the related literature, this paper examines the effect of the transmission bit rate on network performance of clustered MWSNs. Simulation results show that the aforementioned effectiveness of LRRC is hidden under high transmission bit rate because the nodes' movements are very slow compared to packet transmissions.

VI. CONCLUSION

This work investigates the dynamic round duration in MWSNs considering EERC, CEERC, LRRC and SRC, which are *global* recluster triggering schemes. EERC determines the round duration based on the energy consumption at CHs and was initially proposed for WSNs. This work evaluates the applicability of EERC on MWSNs. CEERC is proposed in this work as a variation of EERC and it takes into account the current residual energy of nodes for the computation of the energy threshold at a cluster. LRRC proposed in this work is adaptive to the percentage of data packet losses at each CH, which stem from node mobility. Concerning SRC, it employs constant round duration and in order to examine the effect of round duration on system performance, the cases of 2 and 14 frames per round are considered, namely SRC(2) and SRC(14). To evaluate the network performance and the network lifetime under these recluster triggering schemes, simulations are conducted versus the simulation time, the percentage of mobile nodes, the nodes' velocity and the transmission bit rate. To conclude, the percentage of mobile nodes, the nodes' velocity and the transmission bit rate affect the behavior of the LRRC, EERC, CEERC and SRC schemes in terms of various performance metrics. So the CHs should take into the aforementioned parameters in order to decide which scheme to employ for reclustering. In case of high transmission bit rate, the CHs should employ SRC(14). For low transmission bit rate and low percentage of mobile nodes, the CHs should employ EERC or CEERC. On the other hand, if the percentage of mobile nodes is not low, LRRC gives the best system performance in the case of average to high nodes' velocity. As for SRC(2), it results in high clustering overhead in all cases, thus it is not a good choice in general.

Lastly, future work can explore the behavior of CEERC compared to EERC in the case of unequal initial energy of nodes and also investigate a condition that triggers reclustering based on signal strength in clustered MWSNs.

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