Balanced Clustering Approach with Energy Prediction and Round-Time Adaptation in Wireless Sensor Networks

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***Abstract*—This paper proposes three techniques to improve the energy efficiency of clustering protocols in wireless sensor networks (WSNs). The first technique reduces the periodic network re-clustering cost while distributing the load evenly amongst the nodes. The second technique adapts the rounds' durations to the cluster heads' (CHs) residual energy, and the third one ensures fair and spatially balanced distribution of CHs over the network. The proposed techniques are generic and may be applied to any centralized clustering protocol. Without loss of generality and for the purpose of performance evaluation, these techniques are implemented on TPSO-CR, one of the state-of-the-art clustering protocols. TPSO-CR, its enhanced version with the proposed techniques (ETPSO-CR) and the LEACH-C protocol are then extensively simulated and compared with various realistic topologies for both homogeneous and heterogeneous networks. The results demonstrate that the proposed solutions remarkably reduce and balance the total energy consumed in the network. Thereby, the time to the first node death is more than doubled in some scenarios. Further, we define several network lifetime metrics related to the nodes lifetime and network partition, which are used in the comparison. The results show improvement ranging from 25% to 76%. The total number of received data at the base station is also increased by more than 30% on average, and reaches 70% in some cases.**

***Keywords*-Wireless Sensor Networks; Clustering Protocols; Re-clustering; Data Routing; Energy Efficient Communication; Energy prediction; Load Balancing; Adaptive Round Time.**

I. Introduction

A Wireless Sensor network (WSN) consists of miniaturized low power computational nodes that are capable of sensing local environmental parameters and that cooperate to forward such information to a central base station (BS) [1]. WSNs have been applied in several real-world applications in different domains such as military [2], medical [3] and industrial [4]. Despite their numerous advantages, WSNs face a multitude of challenges including time synchronization [5], [6], network connectivity [7] [8] and connection impairment [9], network congestion [10] [11], communication range shrinkage due to adverse environmental conditions [12], reliable and efficient data acquisition [13], efficient data gathering [14] [15], misbehaving nodes problem [16], to name a few. Elongating the WSN lifetime remains the main concern shared by all the WSN applications, and it is more challenging in case of large-scale deployment where the use of physical topology does not ensure energy-efficient data transmission [17]. Topology control strategies have been proposed for this purpose. One category of these strategies is clustering, which consists in dividing the network into a number of groups called clusters. In each cluster, a particular node is designated as cluster-head (CH) [18], [19].

Numerous clustering protocols have been proposed in the literature [20], [21], [22]. These protocols provide solutions for optimized clustering in the election of CHs, and build upon the resulted cluster intelligent routing algorithm to prolong network lifespan. Centralized clustering solutions have proved their efficiency in producing high clustering quality compared to the fully distributed ones [23], and they allow to form balanced clusters through the complete view of the topology. This results in significant energy saving, and thus extending the network lifetime. However, the clustering raises the problem of unbalanced energy consumption amongst the nodes where the load will be concentrated at the CHs that are responsible for collecting data from their respective members, performing some data aggregation/fusion and forwarding meaningful data to a faraway BS. CHs become then, critical and bottleneck point in the network.

To avoid this problem and distribute the CH load between the sensor nodes (SNs), re-clustering is used in most of existing clustering protocols [23], [24]. That is, the network operation is divided into rounds and at the beginning of each one, nodes send messages containing their residual energy to the BS. Accordingly, the BS recalculates and broadcasts the optimal clustering scheme for the next round. Nevertheless, periodic re-clustering the whole network is energy consuming and lessens the network lifetime. The round duration is another important issue to consider. A long round-time may cause the fast depletion of CHs energy, while a short round-time results in a large waste of energy for frequent re-clustering. The majority of existing clustering protocols do not use thorough models or methods to set this duration but simply assign a static time to all rounds, independently of residual energy of CHs [25], [26].

In this context, the contribution of this paper is the proposition of techniques that enhance the energy efficiency of clustering protocols and, thus, prolong the lifetime of clustered WSNs. The proposed techniques permit to:

- Prevent the repetitive energy-consuming re-cluster process, while distributing the load evenly amongst the nodes;
- Adapt the round duration to the CHs residual energy;
- Ensure a fair distribution of CHs over the network.

The proposed approach is a general framework that applies to any centralized clustering protocol. Without loss of generality, and for the purpose of proof of concept and performance evaluation, we describe the implementation of the proposed techniques with the TPSO-CR protocol [24]. The simulation study confirms that resulted enhanced protocol (ETPSO-CR) clearly outperforms TPSO-CR in terms of network lifetime and successful packet delivery at the BS.

The rest of this paper is organized as follows. Section II summarizes some related work on clustering protocols. Section III presents the network and energy consumption models, followed by the description of the proposed techniques and the details of their implementation in a clustering protocol in Section IV. Section V holds simulation results and comparisons, while Section VI concludes the paper.

II. Related Work

Clustering in WSN is a topic that has been largely considered in the literature [27], and used in many applications [28]. LEACH [29] is one of the first canonical protocols. It uses a distributed probabilistic process to elect CHs. Each node chooses a random number between 0 and 1 and, accordingly, announces itself CH with a predefined probability. Several variants based on LEACH have been proposed recently such as HT2HL [30] that combines the operation of heterogeneous LEACH and a threshold-sensitive based policy for CH selection. LA-EEHSC [31] proposes a new learning automata based energy-efficient clustering scheme in which CHs are selected upon the weighted election probability of the nodes. LEACH-AP [32] develops a new distributed energy-minimizing cluster formation strategy based on affinity propagation. In [33], the fuzzy c-means (FCM) algorithm is used to change the LEACH protocol parameters in order to obtain the optimum number and locations of the CHs. In [34], the authors propose two clustering algorithms. The first algorithm focuses on energy efficiency of the SNs and load balancing between the CHs in terms of clusters' sizes, while the second one intends to optimize the energy efficiency of the SNs and the overall energy consumption by considering the CHs communication load. A multilevel minimized delay clustering protocol is proposed in [35] to extend the lifetime of the WSN and minimize the end-to-end delay through leveling and optimal selection of CHs. In [36], dynamic clustering is used to enhance the sensing efficiency by forming a two-level hierarchical cognitive radio network.

LEACH-C [23] is the first centralized clustering protocol that has been proposed to overcome the problems of random election and non-uniform distribution of CHs identified in LEACH. In this protocol, nodes send their values of residual energy and position information to the BS at the beginning of each round. Then the BS calculates the average energy of the network. Nodes with energy level higher than the average are eligible to compete for CH role in the next round. BS applies simulated annealing algorithm [37] on the eligible set of nodes to find the next round CHs.

In TPSO-CR [24], the authors propose two linear programming formulations to the clustering and routing problems. These formulations are then solved by two algorithms based on the particle swarm optimization [38]. The clustering algorithm selects CHs by considering energy consumption, cluster quality, and network coverage. The routing algorithm is developed with an energy-efficient fitness function to find the optimal routing tree that connects the CHs to the BS. In [25], CECP is proposed which uses a genetic algorithm [39] to find the optimal set of CHs. Nodes to be selected as CHs are those having residual energy higher than the average energy of the network, that are not outlier nodes, and that have the maximum sum of edges' weights in the modelled graph. The EBUC protocol [26] also uses an algorithm based on the particle swarm optimization but for another objective. The aim of EBUC is to deal with the hot-spot problem of multi-hop WSN for the purpose of balancing the energy consumption in the network. For this, the network is partitioned into clusters of unequal size. Clusters closer to the BS will have smaller size. This is to permit their CHs to preserve sufficient energy for ensuring the routing task. To minimize the energy dissipated by the CHs, EBUC adopts an energy-aware multi-hop routing algorithm between the CHs and BS.

LEACH-C, TPSO-CR and CECP enhance clustering quality by electing CHs that minimize energy dissipation, while the EBUC protocol considers balancing the total energy consumed in the network in the clustering process. However, all of these solutions suffer from the energy waste when re-clustering the whole network at the beginning of every round. To reduce this cost, Fixed-LEACH [40] has been proposed. LEACH-F is based on the LEACH-C protocol with the exception that clusters are formed only once, at the network initialization, and become fixed throughout the network lifetime. In addition, BS creates and broadcasts a schedule between the members of each cluster, which will be used to rotate the role of CH. In TCHE-WSN [41], the idea of avoiding frequent re-clustering by electing two CHs in each cluster has been investigated. The first CH collects data from its cluster members and transfers it to the second CH that aggregates the received data and transmits it to the BS. In addition, this protocol re-clusters the whole network every 100 rounds. In IEEHCS [42], re-clustering is not necessarily performed at every round. The residual energy of CHs are used to decide about local or global re-clustering. Local re-clustering reduces to changing the CHs within the clusters without affecting them.

LEACH-F, TCHE-WSN and IEEHCS rotate the role of CH within the cluster without changing the cluster membership. Consequently, nodes with small amount of remaining energy or that are far from the BS may be elected as CHs. Likewise, nodes may be assigned to some distant CH despite the existence of closer CHs. In those situations, nodes have to use a large amount of energy to communicate with their CHs or with the BS, which will have a negative impact on the network lifetime. To preserve the advantages of re-clustering with reduced costs, energy estimation based clustering protocols have been proposed. For instance, the authors in LEACH-CE [43] propose an energy prediction technique by defining a set-up phase that takes place in every eight rounds. In this phase, nodes send their energy information at the beginning of two successive rounds. Based on this information, BS can calculate the average of the energy consumed by CHs and member nodes in one round, and thus their residual energy. This energy estimation model is used in the upcoming eight rounds to avoid exchanging energy levels. Another energy estimation model is proposed in HMM-PSO [44]. This protocol also performs in rounds. In the set-up phase of the first three rounds, all nodes send information about their remaining energy level and location to the BS. Based on this information, BS estimates the energy consumed by each node and its residual energy using a hidden Markov model and particle swam optimization. Both LEACH-CE and HMM-PSO predict the energy consumed in each node based on its previous consumption. Nevertheless, energy consumption of nodes may differ from a round to another, relatively to the distance between a node and its CH and from CH to the BS.

The duration of each round is an important factor that significantly influences the performance of clustering protocols. The majority of existing clustering protocols have a constant round-time that is fixed by simulation. The work presented in [45], proposed a method to model the rounds' durations in a way that prevents early death of CHs. The key idea is that the rounds' durations should allow all nodes to act as CH once, and as non-CH in the other $(N/k-1)$ rounds, where N is the number of nodes in the network and K is the number of CHs. Another solution is proposed in [46], in which the round-time is calculated according to the number of nodes that are alive. In addition, the authors propose that upon the death of 50% of nodes, the round-time is fixed. The motivation behind this is that the remaining energy of nodes at that time will be very low, almost $10-20\%$ from initial energy. This protocol is also based on the idea that the rounds' durations should allow all nodes to act as CH once, and as non-CH in the other $(N/k-1)$ rounds. Nevertheless, this assumption is not necessarily significant since some nodes may have an unfavourable position that makes them inappropriate to act as CHs.

This paper proposes a new estimation-based re-clustering technique using the first order energy dissipation model. We model the round-time according to the CHs remaining energy. The proposed solution also includes a technique for ensuring a well-balanced distribution of CHs in every round.

III. Network and Energy Models

A. Network Model

We consider a WSN of N SNs and one base station (BS) that has unconstrained energy supply. Each SN has a unique ID. The SNs and BS are supposed stationary after deployment, and their locations to be known. We consider data logging applications, where all SNs generate data packets of the same length and at fixed rate. The sensed information in such application is highly correlated, thus CHs can aggregate the data. SNs are supposed to have the ability to reach the BS directly and to be equipped with power control capabilities to vary their transmission power.

B. Energy Consumption Model

The energy model presented in the following enables the BS to estimate residual energy at every node and avoid the need for periodic update of such information from the SNs. The principal sources of energy consumption in a SN are sensing, processing (calculation and data aggregation), radio communication. For the radio energy dissipation model, we adopt the model discussed in [23] and used in almost all-state-of-the-art protocols, such as [47], [48]. In this model, the energy consumed in transmission is proportional to the data size and the distance. The distance, d, separating the transmitter and receiver determines the channel model to use. If d is below a threshold, say d_0, then free space fs model is used; otherwise, multipath fading mp propagation model is considered. Eq. 1 and Eq. 2 draw the energy consumed in each case, respectively.

$$E_{tx}(l,d) = lE_{elec} + l\epsilon_{fs}d^2, if(d <= d_0) \tag{1}$$

$$E_{tx}(l,d) = lE_{elec} + l\epsilon_{mp}d^4, if(d > d_0) \tag{2}$$

Where E_{elec} is the energy required for running the transmitter and receiver electronic circuitry. l is the length of transmitted packet. ϵ_{fs} and ϵ_{mp} are the amplification energy in the free space and multipath fading models, respectively. d_0 is the crossover distance which is calculated using Eq. (3).

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \tag{3}$$

The energy consumed in the receiving mode, E_{rx}, is only proportional to the data volume. To receive l bits, a node consumes the following amount of energy.

$$E_{rx}(l) = lE_{elec} \tag{4}$$

IV. Proposed Solution

A. Solution Description

The proposed approach is centralized, where the clustering is carried out by the BS. Similarly to all dynamic approaches, the proposed one operates in rounds, each of which consists of two phases: (1) set-up phase, and (2) steady state phase. In the set-up phase, the BS calculates the optimal clustering scheme (set of CHs and their members) based on a heuristic or a meta-heuristic algorithm then informs the SNs. At the end of this phase, every node knows whether it is selected as CH or to which cluster it belongs. Thereafter, the network goes into the steady state phase which in turns is divided into a number of frames. In each frame, SNs perform periodical data gathering and send the collected data to their respective CH. CHs aggregate the received data and transmit it to the BS. The objective of a centralized clustering algorithm is to determine from a given topology the optimal clustering scheme. This has been proved to be a non-deterministic polynomial (NP)-hard optimization problem [49]. Meta-heuristic algorithms such as simulated annealing, genetic algorithm, particle swarm optimization, artificial bee colony [50], etc. are then used. Solving the clustering problem amounts to find the optimal set of CHs that optimizes a given fitness function. In general, the fitness function aims at minimizing the intra-cluster distance, balancing the energy consumption between CHs, producing clusters with unequal size, etc. In order to ensure a good distribution of CHs over the network, we propose to consider the distance between CHs as a factor to maximize in the clustering fitness function. In fact, maximizing the distance between all the elected CHs will result in properly scattered CHs across the network. In other words, the aim is to avoid that CHs will be concentrated in one area leaving the rest of the network uncovered. Further, when CHs are very close to each other, this may induce very crowded CHs and leaves other CHs almost without members, which leads to uneven energy consumption between CHs. In such situations, nodes will have to dissipate a large amount of energy to communicate with their distant CHs.

We also propose the adaptation of the round duration (round-time) to the residual energy of the selected CHs. This duration yields a trade-off; a long round-time may cause the fast depletion of CHs energy, while a short round-time results in a large waste of energy for frequent re-clustering. It thus must be carefully adjusted so as to prolong the network lifetime. The key idea is to use an energy threshold for each elected CH as a ratio from its residual energy. The appropriate value of this ratio will be determined empirically by simulation. Thus, after the generation of a clustering scheme at the beginning of each round, BS estimates the amount of energy that will be dissipated by each CH in the scheme for one frame. If the consumed energy of CHs is below their threshold, the CHs will be considered to have sufficient energy to perform their roles in the next frame. Consequently, the duration of the round will be increased by one frame. The BS repeats the same procedure until the consumed energy of one of the selected CHs reaches its threshold. This will border the round-time of the clustering scheme, which will be broadcast to the SNs. Consequently, the scheme ensures CHs will not consume more than their energy threshold, and sufficient energy will be left to enable them to act as members in the incoming rounds. Note that the energy estimation is based on the energy consumption model presented in Sec. III-B.

Moreover, to minimize energy dissipation, we propose an energy prediction based network re-clustering. Nodes send their energy and position information to the BS only in the set-up phase of the first round, while in the set-up phase of the following rounds, BS *estimates* the remaining energy of all nodes using the first order energy consumption model previously presented. The approximate energy consumed by a node in a round varies depending on its role (CH or members). This will be detailed in the next section. The BS then performs re-clustering throughout the network lifetime without any information sent from nodes.

The general approach proposed is summarized in the flowchart of Fig. 1. Note that we use here a general description that makes abstraction of the definition of the network lifetime, which captures any definition of the latter such as the first battery exhaustion of a node in the network, the exhaustion of a portion of nodes (e.g., half, all), etc.

B. Implementation in Clustering Protocol

For the proof of concept and to assess the efficiency of the proposed techniques, we have implemented them on the TPSO-CR protocol [24]. However, these techniques remain general and apply to any centralized clustering protocol. We call the resulted new version ETPSO-CR for Enhanced Two-tier Particle Swarm Optimization protocol for Clustering and Routing in WSN. As presented in Sec. II, TPSO-CR performs both clustering and routing based on the meta-heuristic PSO. This latter is a population-based stochastic optimization method that inspired by the social behaviour of birds [51]. PSO maintains simultaneously various candidate solutions (particles) in the search space and optimizes an objective function by evaluating the fitness of each particle. Particles are characterized by velocities and positions that are initialized with random values. At each optimization iteration, t, every particle, i, updates its velocity, V, and position, X, in such a way to converge towards the optimal solution. The formulates of updating both velocity and position are given in Eq. 5 and Eq. 6, respectively. As the algorithm progresses throughout iterations, each particle exploits its best discoveries in the past, say $pbest_i$, and the best discoveries of the entire population, say $gbest$, to approach the global best solution. w is a weight factor that specifies the velocity of the particle. c_1, c_2 are the learning factors and r_1, r_2 are random numbers in the interval $[0, 1]$. For detailed description on how PSO is used for clustering in TPSO-CR, we refer to [24]. The presentation in the following will be limited to the modifications we add to TPSO-CR.

$$V(t+1) = wV(t) + c_1 r_1 (pbest_i(t) - X(t)) + c_2 r_2 (gbest(t) - X(t)) \quad (5)$$

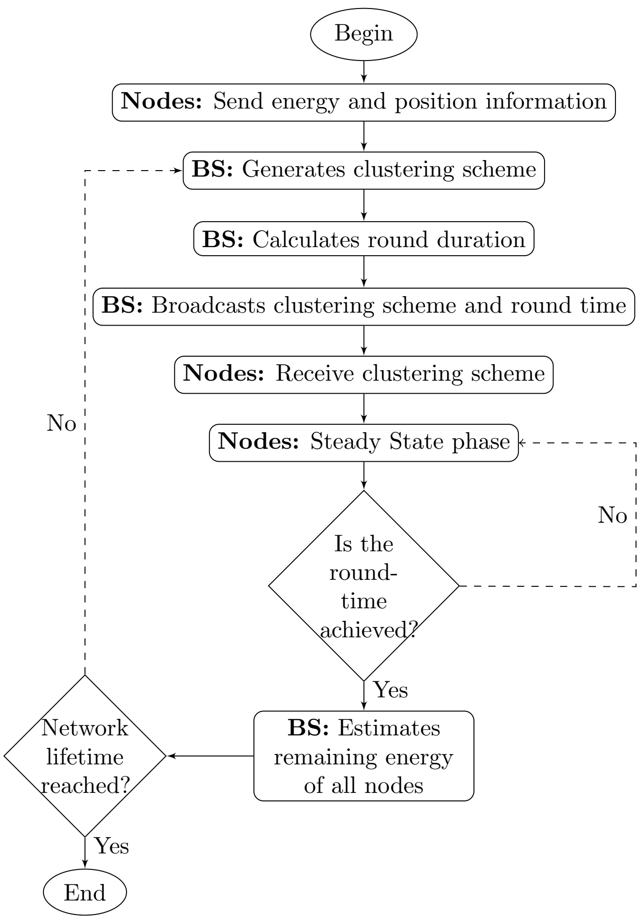

Figure 1. Flowchart of the proposed approach.

$$X(t+1) = X(t) + V(t+1) \quad (6)$$

As seen in the previous section, the first proposed technique aims to ensure a fair distribution of CHs over the network in order to extend the network lifetime. The idea is to additionally consider the distance between CHs as a factor to maximize in the clustering fitness function. To test this technique, a factor is added to the clustering fitness function of TPSO-CR. This factor represents the sum of the RSSI values between all the candidate CHs. Since the TPSO-CR objective function is a minimization problem and the RSSI returned is always a negative value, the selected CHs will have a maximum distance between each other. This means that these CHs are not close and they occupy different regions, which permits their burden to be quite balanced and contributes to the network lifetime extension. The new proposed fitness function of ETPSO-CR C_p is given in the following equation,

$$C_p = wc_1 EE_p + wc_2 CQ_p + wc_3 NC_p + wc_4 DCH_p \quad (7)$$

where EE_p represents the energy efficiency of the particle p, CQ_p is the cluster quality of the particle p, and NC_p indicates the network coverage of the particle p. For more details on how to calculate each of these factors, we refer to [24]. The new proposed factor, DCH_p, represents the distance between the candidate CHs of the particle p, which is computed using Eq. 8. wc_1, wc_2, wc_3 and wc_4 are weight coefficients that define the contribution of each sub-objective in the main clustering fitness function.

$$DCH_p = \sum_{k=1}^{K} RSSI_{CH_{p,k}} \quad (8)$$

TPSO-CR also proposes a fitness function to find the optimal routing tree that jointly optimizes the following criteria: i) saving energy $EE(a)_p$, ii) balancing energy $EE(b)_p$, and iii) maximizing link quality LQ_p. Detailed description of these factors may be found in [24]. Additionally, we consider another factor, denoted ω_p, in the routing fitness function to minimize the number of hops to reach the BS, i.e. size of routes between the nodes and the BS. This is achieved by minimizing the sum of a candidate relay nodes in a particle p, which permits the minimization of the overall amount of energy dissipated in the routing process. The new routing fitness function, R_p, and the formula of the new factor are given in Eq. 9 and Eq. 10, respectively.

wr_1, wr_2, wr_3, and wr_4 are weight coefficients that define the contribution of each sub-objective in the main routing fitness function.

$$R_p = wr_1 EE(a)_p + wr_2 EE(b)_p + wr_3 LQ_p + wr_4 \omega_p \quad (9)$$

$$\omega_p = \sum_{\forall rn_i \in r} rn_i \quad (10)$$

where $r = \{rn_i\}$ is the set of relay nodes in the particle p.

On the other hand, both re-clustering and adaptive round-time are based on energy estimation. Energy consumption of a node, v_i, in round, k, is highly dependent on the role played by this node therein. In TPSO-CR, a node may act as i) simple member, ii) CH, iii) member and relay, iv) CH and relay. Let represent the unit of time by the time frame. In each frame, a member node collects and sends data to its CH. CH receives data from its members, performs some data aggregation and transmits the processed data to the BS. Since TPSO-CR proposes a multi-hop routing algorithm, a member/relay or a CH/relay node has the task of ensuring data packet routing in addition to its role as a member or CH. Consequently, the energy dissipated in a time unit by a member node, v_m, a CH, v_h, a member/relay node $E_{v_{m/r}}$, and CH/relay node $E_{v_{h/r}}$, after one time frame are respectively calculated using Eq. 11, Eq. 12, Eq. 13, Eq. 14.

$$E^1_{v_m} = E_{sen} + E_{tx}(l, d) \quad (11)$$

$$E^1_{v_h} = E_{sen} + \lambda_h E_{rx}(l) + E_{agr} + E_{tx}(l, d) \quad (12)$$

$$E^1_{v_{m/r}} = E^1_{mem} + (E_{rx(l)} + \delta E_{tx(l,d)}) \quad (13)$$

$$E^1_{v_{h/r}} = E^1_{CH} + (E_{rx(l)} + \delta E_{tx(l,d)}) \quad (14)$$

where E_{sen} and E_{agr} are the energy spent in sensing and data aggregation, respectively. λ_h is the number of members of CH, v_h. δ is the number of packets relayed by node v_i. $E\_tx(l, d)$ and $E\_rx(l)$ are calculated trough the first order model, as explained in Sec. III-B. Accordingly, the consumed energy of any node, v_i, in a round, k, is then given by,

$$E_{c_{v_i}}(k) = E^1_{v_i} t_k \quad (15)$$

where t_k is the round duration, i.e, time of the round in terms of number of frames. Consequently, the expected remaining energy of node, v_i, may be obtained using Eq. 16.

$$E_{re_{v_i}}(k) = E_{re_{v_i}}(k-1) - E_{c_{v_i}}(k-1) \quad (16)$$

The proposed dynamic round-time calculation technique is presented in algorithm 1, to which we refer in the following. The BS runs this algorithm at the beginning of each round, k, to calculate its duration. The algorithm takes as inputs the ratio of energy discussed in Sec. IV-A, ρ, the round, k, and the vector of CH residual energies $E^k_{re}(CH_i)$, $i \in \{1 \cdots h\}$, where h is the number of CHs. It attempts to approach the optimal round duration, t_k. After initializing all entries of the vector V to 0, the algorithm calculates for every elected cluster, CH_i, a threshold, γ_i, proportionally to its residual energy (line 5). In line 6, the energy required by CH_i to satisfy the generated scheme for one time frame, $E^k_c(CH_i)$, is estimated using Eq. 12 or Eq. 14, depending on whether the node is a simple CH or CH and relay, respectively. The residual energy of that node is then calculated and saved in $\widehat{E}^k_{re}(CH_i)$, which is then compared to the threshold γ_i. If it is higher than the γ_i, the round duration in terms of number of frames of the cluster-head CH_i, V_i, is increased by one frame. This process is repeated until that the remaining energy of that CH reaches its threshold (loop in lines 8 throughout 12). In line 12, the minimum value amongst all the generated round duration values is chosen as the final round duration such that to ensure the residual energy of each elected CH does not exceed its respective energy threshold.

Algorithm 1 Dynamic round-time calculation algorithm

```
1: Input: ρ, k, E^k_re(CH_{i∈{1···h}})
2: Output: t_k

3: V_{i∈{1···h}} = 𝟘
4: for (each elected Cluster-Head CH_i) do
5:     γ_i = ρ E^k_re(CH_i)
6:     Estimate E^k_c(CH_i) using Eq. 12 or 14
7:     Ê^k_re(CH_i) = E^k_re(CH_i) − E^k_c(CH_i)
8:     while Ê^k_re(CH_i) > γ_i do
9:         V_i = V_i + 1
10:        Ê^k_re(CH_i) = Ê^k_re(CH_i) − E^k_c(CH_i)
11:    end while
12: end for
13: t_k = min_{i∈{1···h}} (V_i)
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V. SIMULATION STUDY

A. Setting and Comparison Metrics

To assess the performance of the proposed approach we have conducted an extensive simulation and compared TPSO-CR protocol, its enhanced version ETPSO-CR and the LEACH-C protocol. Simulations have been carried out using the NS3 Network Simulator [52]. Different realistic network topologies generated via the GenSeN tool [53] have been investigated. Two classes of WSNs have been considered,

i) homogeneous networks where all the sensor-nodes have the same amount of initial energy; and ii) heterogeneous networks with different initial energy values that have been picked up randomly. Each class consists of three different network densities, 100, 200, and 300 SNs, and random deployment over a sensing field of $100X100m^2$ has been used. Values of other simulation parameters are given in Table I. Moreover, the PSO parameters of clustering and routing algorithms for the TPSO-CR are fixed as in [24], while for those related to ETPSO-CR, we empirically set them after extensive simulations to specify the optimal values that maximize the network lifetime. In particular, the parameter "wr1" is used in TPSO-CR as a weight for advantaging CHs when selecting relay nodes, which may result in the construction of long routes with the default value (0.33). It is set to 0 instead, to prevent this problem.

Parameters	**Values**
Node Deployment Area	$100mm$
Number of nodes	100, 200, and 300 SNs
Base Station Position	$(50, 50)$
Initial Energy (E0)	Homogeneous: $0.25Joule$
	Heterogeneous: between 0.15 and $0.25Joules$
Transmission Energy (E_{elec})	$50nJoule/bit$
Propagation Energy ($freespaceE_{fs}$)	$10pJoule/bit/m^2$
Propagation Energy ($multipathE_{mp}$)	$0.0013pJoule/bit/m^4$
Data Aggregation Energy (Eda)	$5pJoule/bit/signal$
Threshold distance (d_0)	$87meters$
Packet Size	$800bits$

Table I
SIMULATION PARAMETERS

The obtained results are presented hereafter and organized in three subsections. The first one discusses the clustering and routing quality of TPSO-CR and ETPSO-CR protocols, to demonstrate the gain obtained by the modification of the TPSO-CR clustering and routing objective functions. The second one focuses on comparing the performance of the TPSO-CR, ETPSO-CR and the LEACH-C protocols in homogeneous networks. The comparison metrics include: 1) the average energy consumed on the network throughout the network lifetime, 2) the first node death (FND) as the time interval from the start of the network operation until the death of the first node, 3) the half node death (HND) as the time interval until the death of half of the nodes, 4) the first network partitioning (FNP) as the time when the first partitioning takes place in the network, i.e., a subset of nodes become disconnected from the BS, 5) the maximum network lifetime (MNL). In TPSO-CR and ETPSO-CR, MNL is represented by the last network partitioning (LNP), which is the time of the last node in the network gets disconnected from the BS [54]. Since LEACH-C is based on direct communication, no FNP or LNP can be defined. Consequently, the MNL is represented by the last node dies LND which is the time interval until the death of the last node in network, 6) The number of alive nodes over time, and 7) the total number of packets received at the BS are also considered in the comparison. The third part presents comparison of the three protocols in heterogeneous networks where nodes have different initial residual energy values. The same metrics are used as in the comparison with homogeneous networks. Note that each point of the simulation results presented in following plots is the average of no less than 25 simulation runs, and the average results are presented with error bars of 95% confidence interval.

B. Clustering and Routing Quality

The well-balanced distribution of the CHs is one of the factors that reflects the clustering quality. On the other hand, the routing quality is evaluated according to the length of the generated routes (number of hops). Fig. 2 and Fig. 3 illustrate cluster schemes of TPSO-CR and ETPSO-CR, respectively, for the same topology. It can be observed from the first figure that CHs in TPSO-CR are not fairly distributed in the network, as some CHs are concentrated in one region (C1, C2 and C3). This leads to some unclustered nodes (nodes represented by dashed sets), and unbalanced clusters' sizes. For instance, the size of the cluster C4 is more than five times larger than that of the cluster C3. Further, the TPSO-CR scheme yields on long routes. For example, data from C1 has to pass through the CHs of the clusters C2 and C3 before reaching the BS. This is because the TPSO-CR routing fitness function favours CHs as better candidates to act as relay nodes. Fig. 3 clearly shows that the quality of the clustering scheme is improved in ETPSO-CR, which produces balanced clusters and properly dispersing the CHs over the network. This is achieved by introducing the balancing factor on the TPSO-CR clustering fitness function. Moreover, since the criterion used in TPSO-CR for a member-node to join a CH is the distance, the balanced-distribution of the CHs across the network enables every member node to join a near CH, which results in an equilibrated clusters' sizes. More importantly, Fig. 3 shows that the ETPSO-CR protocol ensures a better network coverage where all nodes are clustered. This figure also demonstrates that the routing quality is enhanced in the ETPSO-CR protocol. The means of the generated routes' lengths in TPSO-CR and ETPSO-CR, which are captured at the first round of the network operation, are illustrated in Fig.

4. It is clearly shown that the generated routes in ETPSO-CR are always shorter than those of TPSO-CR for the different considered network densities and for both homogeneous and heterogeneous networks. This is justified by the factor added to the routing fitness function by ETPSO-CR, as well as the elimination of the $EE(a)_p$ factor in the routing fitness function (See Sec. IV-B) which allows to reduce the number of relay nodes and thus the routes' size. Not that LEACH-C is not included here in the comparison as it does not use multi-hop routing.

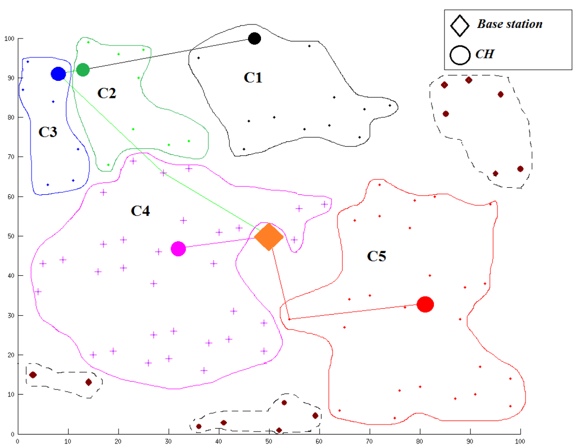

Figure 2. Clustering and routing quality in the TPSO-CR protocol for a network of 100 nodes.

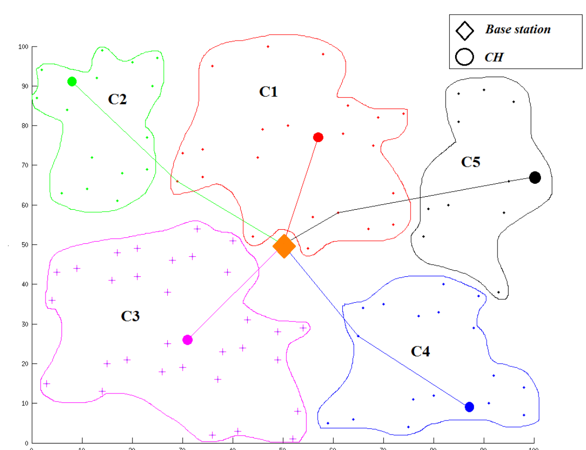

Figure 3. Clustering and routing quality in the ETPSO-CR protocol for a network of 100 nodes.

C. Comparisons in a Homogeneous Network

1) Network lifetime: Figure 5 depicts the network lifetime assured by TPSO-CR, ETPSO-CR, and LEACH-C for homogeneous networks of 100, 200 and 300 nodes. The lifetime is represented by three metrics, FND, HND, and MNL (Described in Sec. V-A). Compared to TPSO-CR, ETPSO-CR prolongs the FND by an average of 38.97%, the HND by 25.79% and the MNL by 35.56%. The improvement is more significant when comparing with the LEACH-C protocol, which is 71.67%, 45.95%, and 52.76%, on average, for the FND, HND and MNL, respectively.

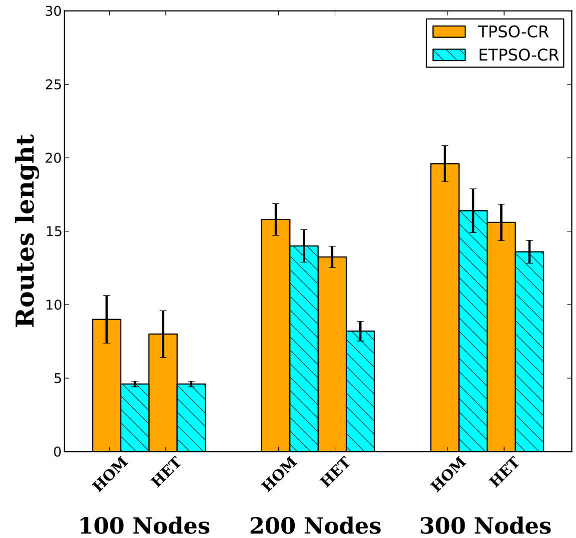

Figure 4. Example of the mean of routes' lengths in one round for homogeneous (HOM) and heterogeneous (HET) networks.

This enhancement in the network lifetime are due to the introduction of energy consumption prediction mechanism which avoids the periodic re-clustering related packet transmissions at every round. This considerably reduces the energy consumption of all nodes. Besides this reduction, another factor that helps prolonging the lifetime is the temporal/spacial balanced distribution of the CHs that are assured by allowing each node to join the nearest CH and the adaptation of rounds' durations to the residual energy of the CHs. This equilibrates energy budgets devoted for serving as CHs fairly amongst all the nodes and ensures nodes remains alive together for as long as possible.

In the obtained simulation results, the network lifetime of 200-nodes network is higher than that of 300-nodes network. This is because the network lifespan is influenced by two factors: the network density and the network traffic. Note that in our simulations we have considered different network densities (100, 200 and 300 nodes) without changing the deployment area dimensions. Increasing the density in the same deployment surface increases the number of cluster-heads (CHs). That means the distance between the CHs and their members will be reduced, which will obviously reduce the energy consumed by the member nodes to communicate with their respective CHs. On the other hand, the increase in the network density systematically increases the network traffic. Since ETPSO-CR is based on a multi-hop routing, relay nodes will be more overloaded in dense networks, which causes quick drain of the batteries.

The competition between these two factors controls the network lifetime. In 200 nodes network (a medium density), the lifetime is higher than that of 100 nodes, because the energy gain was more important than the cost in communication overhead. But for relatively high density networks (with 300 nodes), the value of MNL has decreased because the traffic has increased considerably to the point that the relay nodes have been overloaded.

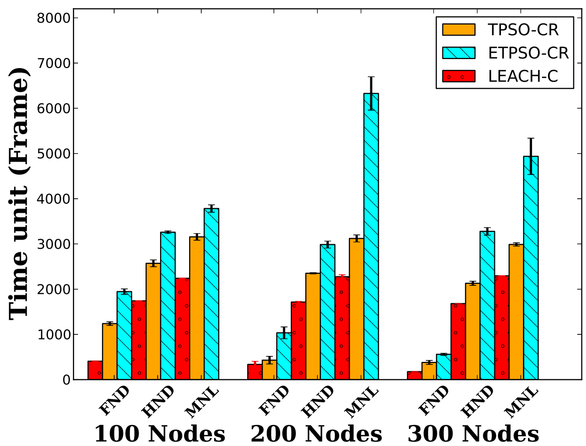

Figure 5. Network lifetime in homogeneous networks.

The number of alive nodes over time is depicted in Fig. 6, Fig. 7, and Fig. 8, for topologies of 100, 200, and 300 nodes, respectively, where the times of the first network partition (FNP) are also presented. These figures confirm that ETPSO-CR enables to always have a higher number of nodes alive than in TPSO-CR and LEACH-C. The figures demonstrate the difference increases with time and the network size, and the improvement of the FNP reaches $52,51\%$ in a network of 300 nodes as compared to the TPSO-CR protocol. Note that the FNP cannot be defined for the LEACH-C protocol since it uses direct communication from SNs to CHs, then from CH to BS (not multi-hop).

2) Total number of received data at the BS: Fig. 9 represents the number of data packets received at the BS until the last network partitioning (LNP) in TPSO-CR and ETPSO-CR, and until the LND for the LEACH-C protocol. It shows that ETPSO-CR improves this metric by approximately 22.09%, 43.06% and 31.82% for networks of 100, 200 and 300 nodes, respectively compared to TPSO-CR and 68, 76.35%, 68.23% compared to the LEACH-C protocol. This is the consequence of the reduction of the energy consumption and the increase in the network lifetime.

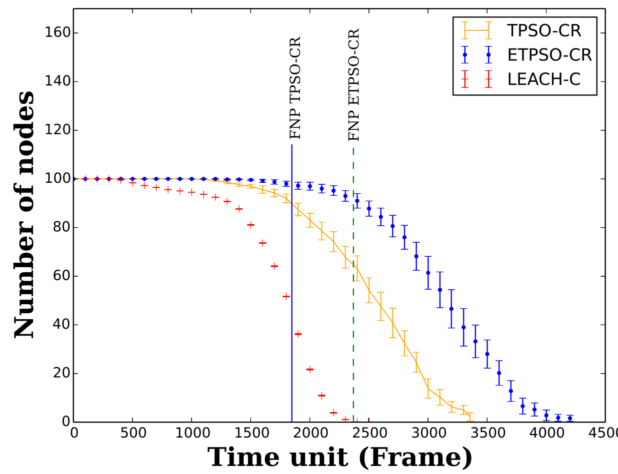

Figure 6. Alive nodes vs. time for homogeneous networks of 100 nodes.

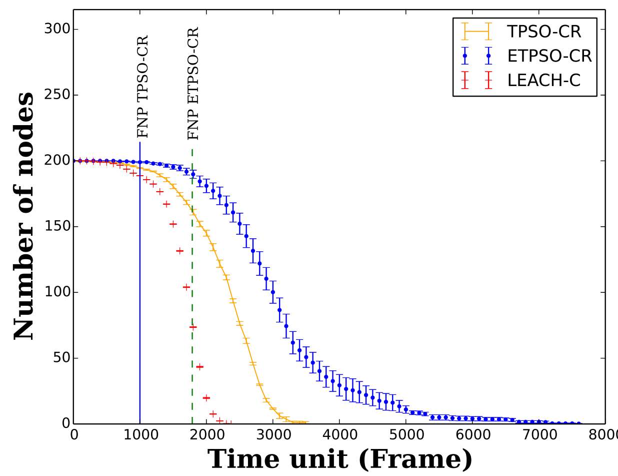

Figure 7. Alive nodes vs. time for homogeneous networks of 200 nodes.

3) Energy consumption: To justify the previously presented results, we have measured the average consumed energy throughout the network lifetime. The obtained results are shown in Fig. 10, 11 and 12 for homogeneous networks of 100, 200 and 300 nodes, respectively. It is clear how the proposed approach slow down the energy dissipation in the network over the time, which explain the enhancement of the network lifetime and the number of alive nodes, and thus the total number of received data packet.

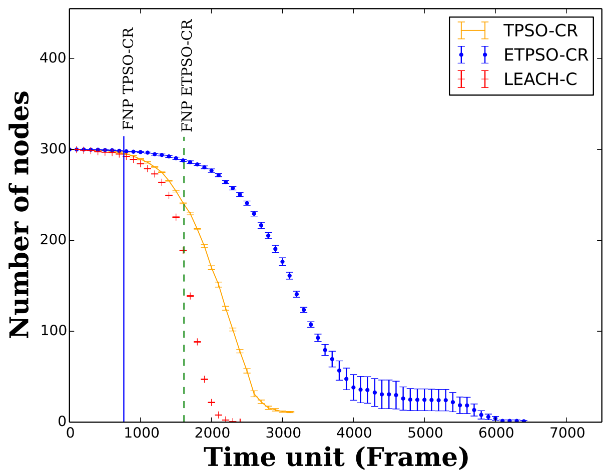

Figure 8. Alive nodes for vs. time homogeneous networks of 300 nodes.

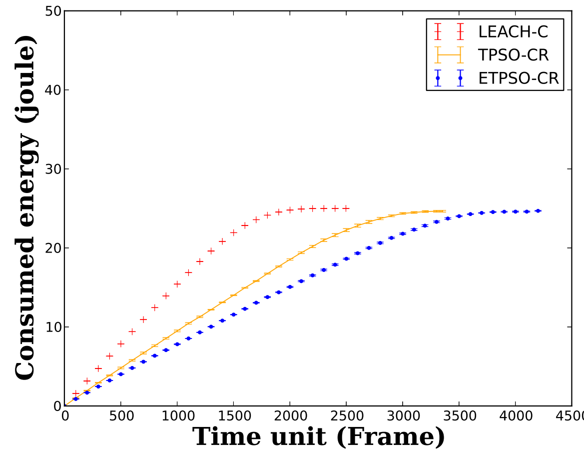

Figure 10. Energy consumption vs. time for homogeneous networks of 100 nodes.

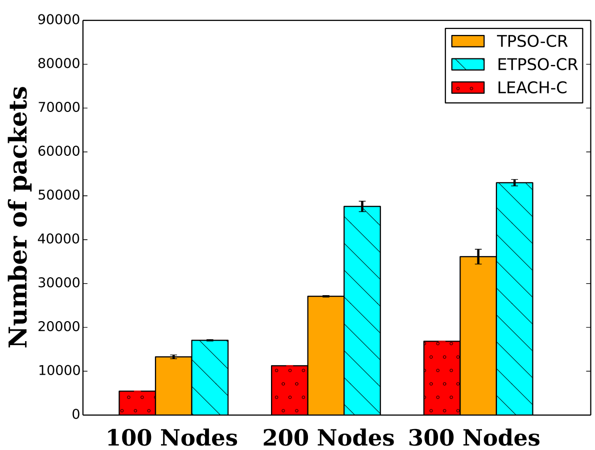

Figure 9. Total number of received data at the base station in homogeneous networks.

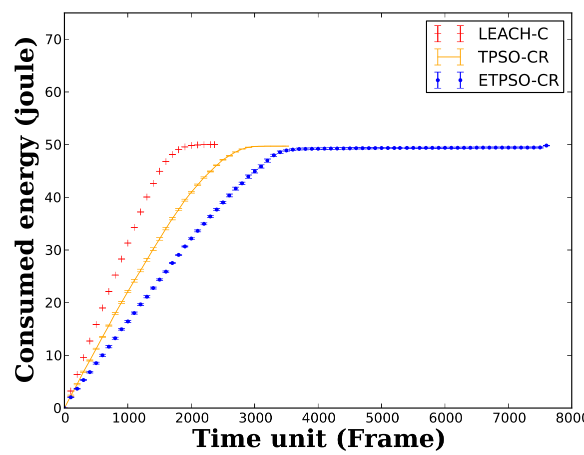

Figure 11. Energy consumption vs. time for homogeneous networks of 200 nodes.

D. Comparisons in a Heterogeneous Network

1) Network Lifetime: The same tests and comparisons presented in the previous section are repeated for networks with heterogeneous nodes, where nodes have different amounts of initial energy that are generated randomly. Fig. 13 plots the results of the network lifetime, while Fig. 14, Fig. 15, and Fig. 16 show the number of alive nodes. These figures confirm the previous results in heterogeneous network. On average, ETPSO-CR outperforms TPSO-CR by approximately 22% for the FND and the HND, 31.18% for the LNP and 20.39% for the FNP. As compared to the LEACH-C protocol, the amelioration is about 76.72%, 55.66%, 55.11% for the FND, HND, and LND, respectively.

2) Total number of received data at the BS: Fig. 17 confirms the higher number of data packets received for the ETPSO-CR protocol in heterogeneous networks, and this for all the considered node densities. Improvements are on average 11.89% for networks of 100 nodes, 45.89% for networks of 200 nodes, 29.44% for networks of 300 nodes, over the TPSO-CR protocol, and 73.32%, 80.82%, 73.20% for networks of 100, 200 and 300 nodes against the LEACH-C protocol.

3) Energy consumption: Similarly to scenarios in homogeneous networks, ETPSO-CR consumes energy more efficiently than TPSO-CR and LEACH-C even in heterogeneous networks, as shown in Fig 18, 19 and 20, respectively.

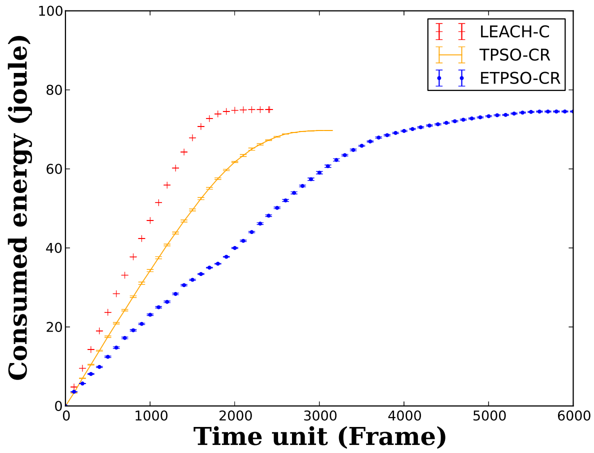

Figure 12. Energy consumption vs. time for homogeneous networks of 300 nodes.

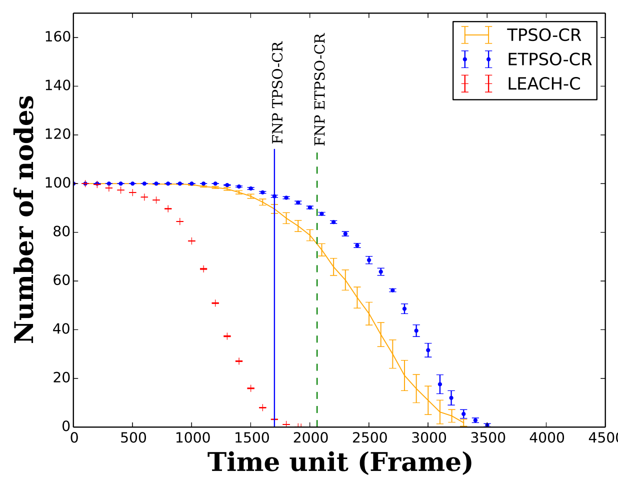

Figure 14. Alive nodes for heterogeneous networks of 100 nodes.

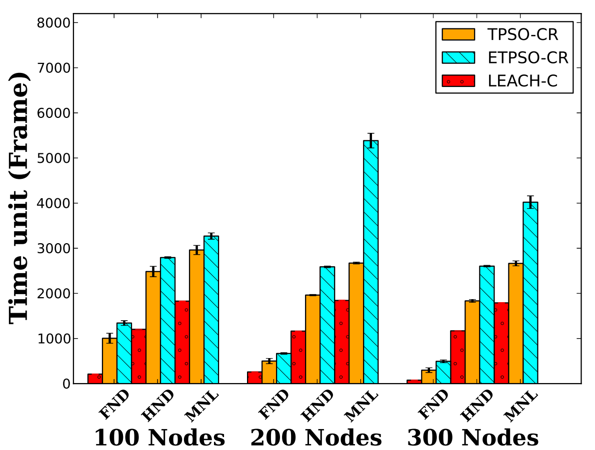

Figure 13. Network lifetime in heterogeneous networks

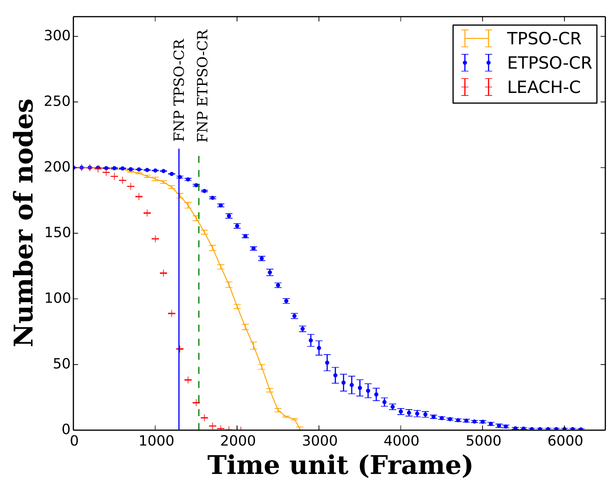

Figure 15. Alive nodes for heterogeneous networks of 200 nodes.

VI. Conclusion and Perspectives

A new clustering approach for WSN has been presented in this paper. The proposed approach features the use of three techniques for the purpose of improving the network lifetime. The first technique consists of rotating the role of CH amongst the network based on an energy prediction model, rather than periodic full-network re-clustering after exchange of energy information. This technique allows to save considerable energy that would be spent in exchanging energy information related to energy states. The second technique adapts the round-time proportionally to the CHs residual energy, which enables to save energy that would be wasted for frequent broadcasts of clustering schemes. The third one introduces some factor in the clustering objective function for electing well-distributed CHs, for the purpose of balancing the energy consumed by the CHs and minimizing the total energy dissipated by non-CH-nodes. The proposed techniques apply to any centralized clustering protocol. Without loss of generality, and for the purpose of investigating and evaluating their effectiveness, we have implemented them on the TPSO-CR protocol. Simulation results show that network lifetime, as well as the total number of received data at the BS have been clearly improved compared to the TPSO-CR and LEACH-C protocols.

Similarly to all centralized approaches based on energy prediction to reduce the re-clustering cost, the one proposed herein suffers from the fault-intolerance problem. As there

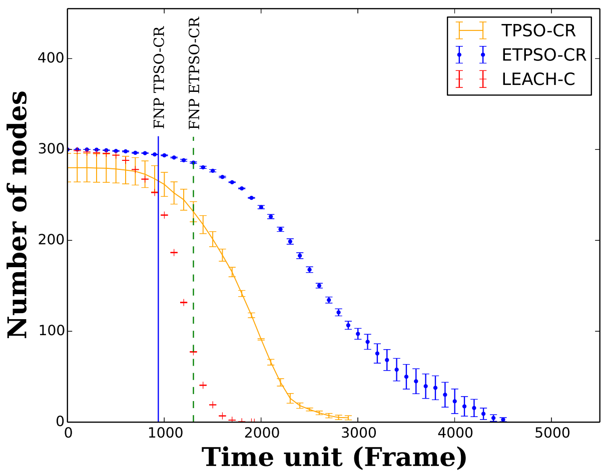

Figure 16. Alive nodes for heterogeneous networks of 300 nodes.

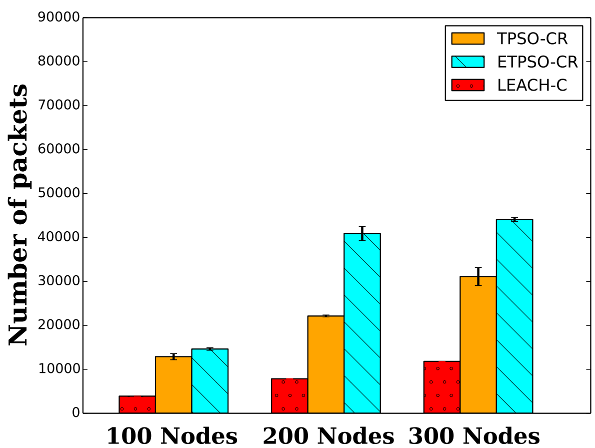

Figure 17. Total number of received data at the base station in heterogeneous networks.

is no coordination between the BS and the SNs for cluster scheme calculation, the BS may elect a failed node as CH. This problem should be considered before real deployment, and ensuring fault-tolerance to the clustering scheme is one of the perspectives to this work. As mentioned in the system model, we have considered applications relying on periodic traffic. In our future implementations, the query-driven and the event-driven traffic will be considered to cover other types of applications. The energy consumption model used in this paper (and by almost all state-of-the-art protocols as well) does not consider some important energy consumption sources, such as idle listening, overhearing, collisions, etc. Exploring a more realistic energy consumption model is also

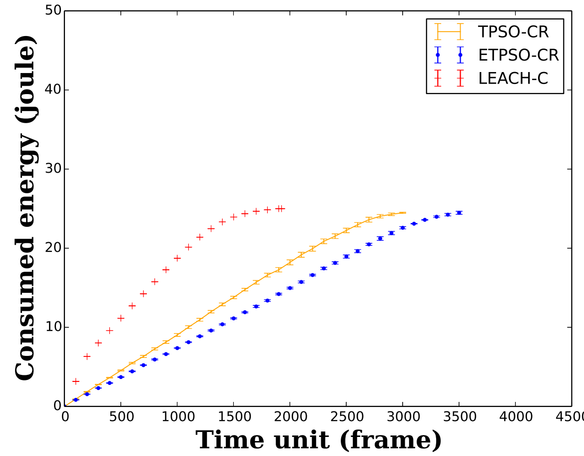

Figure 18. Energy consumption vs. time for heterogeneous networks of 100 nodes.

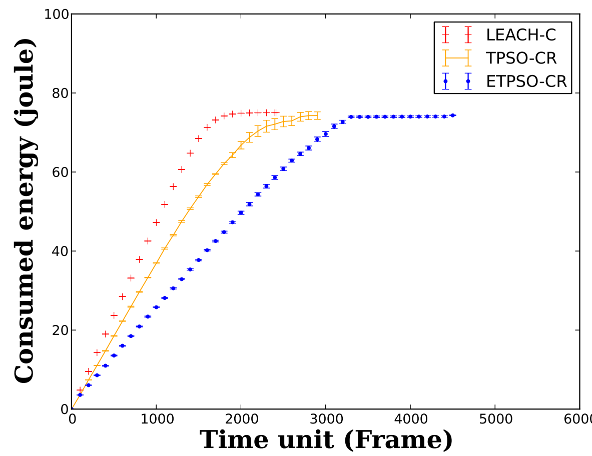

Figure 19. Energy consumption vs. time for heterogeneous networks of 100 nodes.

in our agenda.

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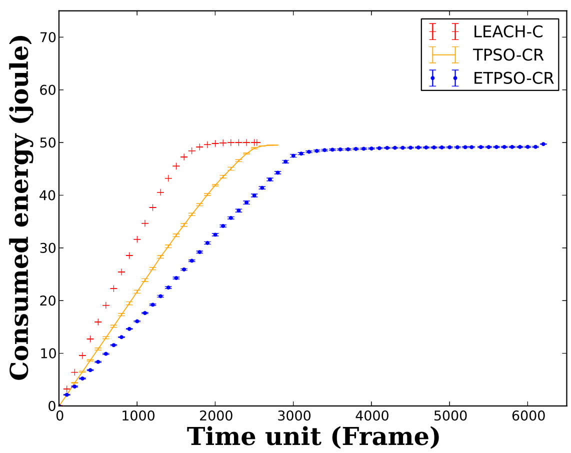

Figure 20. Energy consumption vs. time for heterogeneous networks of 100 nodes.

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