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Research article

Optimal vs rotation heuristics in the role of cluster-head for routing in IoT constrained devices ☆

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ABSTRACT

Wireless Sensor Networks (WSNs) are crucial for implementing the Internet of Things (IoT) vision. A WSN can include distributed devices that can be battery powered, have a small amount of memory, have limited CPU processing capabilities and limited transmission range. WSNs are categorised into two main types that are homogeneous and heterogeneous. Homogeneous WSNs are composed of nodes that are all equal while heterogeneous ones are composed of nodes that can have different transmission rate and different initial energy. Collecting data in an energy efficient manner is one of the main goals when building wireless sensor networks since devices are battery powered and battery replacement can be difficult or impossible to be performed. Clustering protocols are one of the main approaches that have been used in order to collect data in an energy efficient way. A clustering protocol groups nodes into a set of clusters. Each cluster has a representative node that is referred to as Cluster Head (CH). This collects data from its cluster members and forwards them to an external Base Station, possibly in a multi-hop way among cluster heads. A *rotation* strategy for electing the cluster head is often used together with clustering in order to prolong the network lifetime. Rotation eliminates the overhead traffic that is needed for leader election and cluster formation since the old cluster heads directly designate new ones. In this work, we describe an Optimum Rotation Scheduling (ORS) that uses Integer Linear Programming in order to find the optimum rotation strategy. ORS assumes the WSN clusters are already formed by using some clustering protocol. A novel integer linear programming formulation is then used in order to define a cluster head rotation that produces the optimum cluster lifetime. Comparisons with existing heuristics and the provided optimum are then shown and discussed by means of extended simulations involving both homogeneous and heterogeneous WSNs.

1. Introduction

The Internet of Things (IoT) is a technological innovation that allows the interconnection of distributed devices. This interconnection enables innovative applications [2,3] such as smart cities, smart retails, smart industry and connected cars. Wireless Sensor Networks (WSNs) are an essential part of IoT systems. WSNs can be viewed as a virtual skin that senses the physical environment,

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generates the related data which are transmitted inside the IoT system. WSNs data are usually forwarded via a gateway system (also referred to as Base Station, BS) to a centralised infrastructure where are stored and analysed.

A WSN is composed of distributed nodes that have limited memory, low CPU processing capabilities and are battery powered. WSNs can be either homogeneous or heterogeneous. Homogeneous WSNs include nodes that are all equal while heterogeneous ones include nodes that can have different transmission rate and different initial energy. Collecting data in an energy efficient manner is one of the main goals when building WSNs since devices are battery powered and battery replacement can be difficult or impossible to be performed. Clustering protocols are one of the main approaches that have been used in order to collect data in an energy efficient way. A clustering protocol groups nodes into a set of clusters. Each cluster has a representative node that is referred to as Cluster Head (CH). This collects data from its cluster members and forwards them to an external BS, possibly in a multi-hop way among cluster heads. Clustering protocols usually include the following phases: (i) cluster head election and cluster formation where cluster heads are elected and each node joins a cluster head (i.e., clusters are formed); (ii) network operation phase where sensor data reach a centralised BS. Cluster head election and cluster formation phases can be repeated over the time in order to balance the energy consumed for playing the cluster head role.

Rotation strategy [4–9] for electing the cluster head is often used together with clustering in order to prolong the network lifetime. Rotation eliminates the overhead traffic that is needed for leader election and cluster formation since the old cluster heads directly designate new ones. Rotation assumes that clusters are already formed. This can be done by using static [10,11] or dynamic [4–7] approaches. More precisely, rotation can enhance the network lifetime of static clustering protocols where clusters are formed at the beginning. Rotation can be also used in dynamic clustering protocols to reduce the overhead messages that are needed for periodic CH election and cluster formation phases. An energy model [10–16] is usually used in order to determine a static rotation schedule when rotation is combined with static routing. In this context, energy models usually provide an estimate of energy consumption in average conditions such as average distance amongst member nodes or cluster heads, simplified clustering structure (e.g., virtual grids). These simplified settings can lead to rotation schedules that have poor lifetime performance when the average settings are not representative. Dynamic clustering protocols have clusters that vary over the time and rotation is usually performed by using heuristics [4,7,17].

This paper proposes a novel Optimum Rotation Scheduling (ORS). This assumes the WSN clusters have been already formed using either a static or dynamic clustering protocol. ORS assumes one-hop clustering where all cluster heads directly communicate with the BS. This is an initial and essential step that allows us to validate the effectiveness of our strategy and then possibly extend it in the future for the multi-hop case. Moreover, considering the one-hop clustering also allows a fair comparison with one of the most referenced protocols in the field, that is LEACH [18].

Our ORS is based on a novel Integer Linear Programming formulation. More precisely, ORS computes the number of times each node can play the cluster head role and the member role. This allows each node to play the CH role a certain amount of time and then delegates the next member node to play the CH. This delegation is done without the need of any addition cluster head election or cluster formation thus without the need of any overhead messages. ORS provides an optimum cluster lifetime when first node die (FND) lifetime measure is considered. FND assumes that a WSN dies when the first node (of any cluster) completely depletes its energy.

We have compared ORS with the state of art clustering protocols and we have obtained an increase of around 20% in lifetime.

1.1. Outline

The remaining of this paper is structured as follows: Section 2 describes the Network and Radio models that have been used; Section 3 described the ORS Integer Linear Programming formulation that provides an optimum rotation schedule; Section 4 presents the related literature; Section 5 outlines all heuristics our ORS is compared with; Section 6 reports and comments on extended simulations that compare ORS with various heuristics, including LEACH; finally, Section 7 provides the conclusions and describes future works.

2. Radio and network models

This section details the network and radio models that have been considered.

2.1. Radio model

In this paper, the LEACH [18] energy consumption model has been used. This is a commonly adopted model [4,7,15,19] which takes into account free space and multi path channel effects. Sensor nodes have a transceiver circuitry that consume $E_{elec} = 50$ nJ/bit. Moreover, a sensor consumes additional energy, namely the amplification energy E_a, that is subject to the distance d from the sender to the receiver. More precisely, when $d < d_0 = 75$ m a free space model is assumed and E_a becomes $E_{fs} = 10$ pJ/bit/m^2. When $d \geq d_0 = 75$ m a multi-path model is assumed and E_a is equal to $E_{mf} = 0.0013$ pJ/bit/m^4. Eq. (1) is the energy a node spends in order to send k bits at distance d. Eq. (2) defines the energy that is needed in order to receive k bits. The exponent n is 2 for the free space model and 4 for the multi-path one.

$$E_{Tx}(k,d) = k(E_{elec} + E_a d^n) \quad (1)$$

$$E_{Rx}(k) = k(E_{elec}) \quad (2)$$

2.2. Network model

Nodes are not mobile and are assumed to be uniformly distributed in a two dimensional square field. All nodes have the same aggregation and processing capabilities. Each node has a unique network identifier and can dynamically vary its transmission range depending on the distance of the receiver. The BS is not mobile and is located outside the WSN field. The BS is not battery constrained and has much more CPU processing power and memory when compared with WSN nodes.

This work uses the LEACH communication model [18] where all CHs can directly reach the BS. We use the *round* model in order to define the delivery of the data from the sensor nodes to the BS. In this model, each member node sends its reading data to its CH. Each CH gathers the readings from each member node, performs data aggregation (if any) and forwards its data to the BS. More precisely, a round starts from the collection of sensor readings from each member node and ends when all CHs have sent their aggregated data to the BS. The data traffic generated by the member nodes is often referred to as *intra-traffic* communication while the traffic generated by the CHs to BS communication is referred to as *inter-traffic* communication.

The WSN heterogeneity model is inspired by the work in [17] where sensors can have different initial energy and different sending rate. The notation $T(i)$ and E_{max_i} is used in order to denote the number of bits the member node i sends to its CH during a round and the node initial energy, respectively. In the rest of the paper, N is used to denote the set of all nodes that are inside the WSN and $1 \dots n$ denote elements in N. The notation ch is used to denote a node in N that is playing the cluster head role while M_{ch} denotes a set of member nodes that share the same cluster head ch. It is worth mentioning that M_{ch} is a subset of N that includes all member nodes that forward data to ch but M_{ch} does not include the cluster head ch itself. The notation CR is used to define a cluster i.e., all member nodes plus its cluster head.

In the rest of this section, we formally define the amount of bits that are sent during intra-traffic and inter-traffic communication. These definitions are used in order to define the energy that is spent by a node when is playing the cluster head and the member role.

$$R_{intra}(ch) = \sum_{i \in M_{ch}} T(i) \tag{3}$$

Eq. (3) defines the *intra-traffic communication* $R_{intra}(ch)$. This specifies the amount of bits that are received by the cluster head ch during a round. $T(i)$ is used to denote the transmission rate of a member node i.

$$T_{intra}(ch) = max([R_{intra}(ch) + T(ch)](1 - AR), M_{min}) \tag{4}$$

Eq. (4) specifies the *inter-traffic communication* that is generated by a cluster head ch. This is the amount of bits that a cluster head ch sends to the BS during a round where $R_{intra}(ch)$ is the intra-traffic communication that is defined in Eq. (3), $T(ch)$ the transmission rate of the cluster head ch, AR defines the aggregation rate and M_{min} defines a constant. This specifies the minimum amount of inter-traffic communication (i.e., the minimum amount of bits) a CH must send to the BS. More precisely, as soon as ch receives $R_{intra}(ch)$ bits from its members and adds its data $T(ch)$, ch performs aggregation. This results in a certain amount of bit that cannot be less then the constant M_{min}. We can notice that ch sends a minimum amount of inter-traffic M_{min} when the constant AR is set to 1 while all data received by its member nodes are forwarded without any aggregation when AR is set to 0. In our experiments M_{min} is set to 1024 and 512.

We can now define the amount of energy a cluster head ch consumes during a round by using the following equation:

$$E_{CH}(ch) = E_{Rx}(R_{intra}(ch)) + E_{Tx}(T_{intra}(ch), d_{ch,BS}) \tag{5}$$

where $E_{Rx}(R_{intra}(ch))$ is the amount of energy ch consumes for receiving the intra-traffic $R_{intra}(ch)$ bits while $E_{Tx}(T_{intra}(ch), d_{ch,BS})$ is the amount of energy ch consumes to send the inter-traffic data to the base station. The notation $d_{ch,BS}$ is used in order to denote the distance between the ch and the BS.

We can also define the energy a node i in M_{ch} consumes for playing the member role as follows:

$$E_m(i, ch) = E_{Tx}(T(i), d_{i,ch}) \tag{6}$$

E_{Tx} is defined by Eq. (1) where it is clear that the distance between the member i and its cluster head ch (i.e., $d_{i,ch}$) affects the energy consumption of the sender (in this case the member node).

3. Integer linear programming formulation

When considering clustering protocols, one usually has to face with different phases, as follows:

1. *cluster head election and cluster formation* — in the cluster election phase CHs get elected. Afterwords, in the cluster formation phase, nodes that are not cluster heads join a CH. Effectively, this phase partition the WSN into a set of clusters $\{CR_1, \dots, CR_n\}$ where each cluster CR_k has a cluster head ch_k;
2. *network operation* — in this phase, sensors collect data and, accordingly with the round model, send them to the cluster heads, which in turn deliver them to the BS;
3. *rotation* (if any) — in this phase, the cluster head changes within each cluster according to some policy. Usually, the current cluster head delegates one of its joint nodes to substitute it in the role of cluster head.

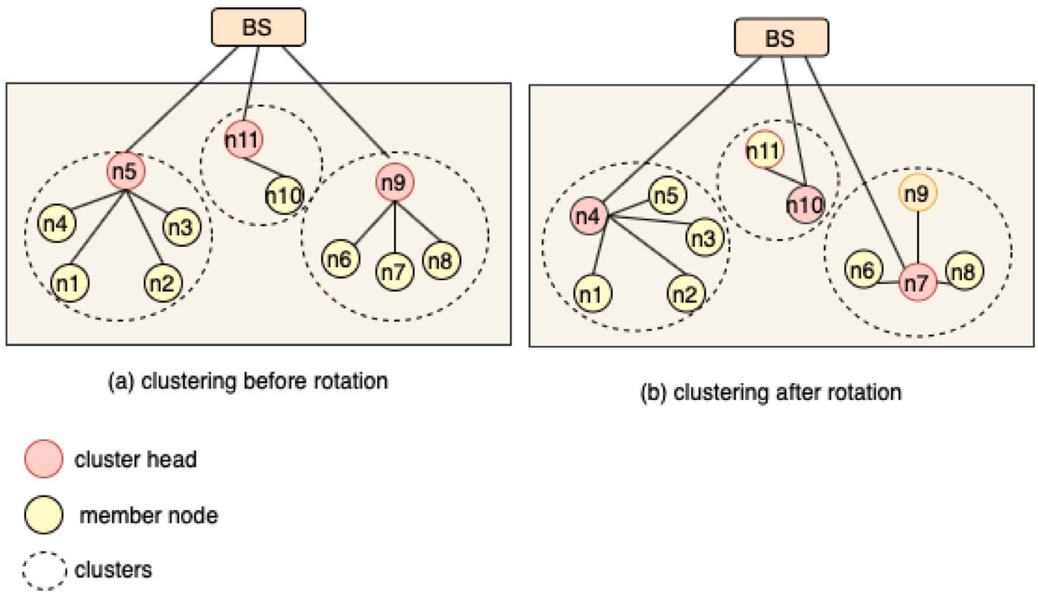

Fig. 1. One-hop clustering before and after rotation.

Various clustering protocols [7,19,20] repeat the cluster head election and cluster formation phase after each round. This allows to balancing the energy consumed in order to perform the cluster head role. Effectively, at each round t (with $t = 1, \ldots, T$) these protocols create a new partition $\{CR_{1t}, \ldots, CR_{nt}\}$ where each cluster CR_{kt} has a newly elected cluster head ch_{kt}. The WSN will die at time T when there exists a sensor that has not enough energy to play the CH or member role. When the rotation phase is used, the partition is formed only once at the beginning and does not change anymore. The current cluster head directly designates one of its members as new CH. In other words, the same partition $\{CR_1, \ldots, CR_n\}$ will be kept throughout all rounds t (with $t = 1, \ldots, T$) while each cluster CR_k at round t has a new cluster head ch_{kt} which is designated by the previous cluster head ch_{kt-1}. Rotation reduces the overhead of cluster head elections and cluster formation, and improves the first node die life time measure. In Fig. 1, it is shown a clustered WSN where rotation is applied. In particular, the figure shows a possible change occurred in the cluster heads roles, even thought clusters do not change.

Rotation can be realised by means of a mathematical model by which a predetermined schedule is evaluated according to the expected traffic. In particular, we define the Optimum Rotation Scheduling (ORS) by means of an Integer Linear Programming (ILP) formulation in order to find the optimum rotation. Our ORS can be applied as follows:

1. the initial WSN clustering is performed, that is, the partition $\{CR_1, \ldots, CR_n\}$ is calculated and a cluster head for each cluster is elected;
2. ORS is applied to each cluster CR_k in order to find the optimum scheduling, that is, for each node i in CR_k we find the number of times i needs to play the cluster head role and the member role;
3. each node i receives its schedule;
4. each cluster head performs the number of rounds planned in its schedule and then delegates one of its members as new CH.

In the following we describe the ORS formulation.

$$x_{it} = \begin{cases} 0 & \text{node } i \text{ is member node at round } t \\ 1 & \text{node } i \text{ is CH at round } t \end{cases} \tag{7}$$

Eq. (7) defines a binary variable x_{it} that is a representation of the role of node i at round t. It is 0 if i is not a cluster head at time t (i.e., i is a member node), 1 otherwise (i.e., i is cluster head at time t).

$$z_t = \begin{cases} 0 & \text{if the cluster is dead at time } t \\ 1 & \text{if the cluster is still alive at time } t \end{cases} \tag{8}$$

Eq. (8) defines a binary variable z_t that represents the activity of the cluster CR at round t. In particular, when $z_t = 0$, it means there is at least one node in CR which has not enough energy to play the member role, or that none of the nodes within CR has enough energy to play the cluster head role. In such cases, we say the cluster is dead. When $z_t = 1$, instead, we say the cluster is still alive, i.e., all the nodes have enough energy to play the member role and at least one of them can play the cluster head role.

In the following, we define our Optimum Rotation Scheduling (ORS):

$$\begin{cases} \max \sum_{t=1}^{T} z_t \\ \text{(i)} \sum_{t=1}^{\bar{t}} \left(E_{CH}(i) \cdot x_{it} + \sum_{\substack{\hat{\imath} \in CR \\ \hat{\imath} \neq i}} E_m(i,\hat{\imath}) \cdot x_{\hat{\imath}t} \right) \leq E_{max_i} + M \cdot (1 - z_t), \quad \bar{t} = 1 \dots T,\ i \in CR \\ \text{(ii)}\ z_t = \sum_{i \in CR} x_{it}, \qquad t = 1 \dots T \\ \text{(iii)}\ z_{t+1} \leq z_t, \quad t = 1 \dots T \end{cases} \tag{9}$$

The goal is to maximise the lifetime of each cluster, thus the lifetime of the whole WSN. In particular, we consider the first node die (FND) lifetime measure. FND assumes that a WSN dies when the first node (of any cluster) completely depletes its energy.

In particular, constraint (9).(i) guarantees that each sensor has not depleted all its energy. In fact, in each round $\bar{t}$, the amount of energy spent until this time by the sensors to play the cluster head role and the member role is less than the energy initially assigned to the node (i.e., E_{max_i}). The variable $x_{\hat{\imath}t}$ is 1 when the node $\hat{\imath}$ is cluster head at time t, 0 otherwise. The usage of quantity $M \times (1 - z_t)$ in the inequality is a 'trick' to ensure that the constraint (9).(i) remains true when the cluster dies (i.e., $z_t = 0$).

Constraint (9).(ii) guarantees that, at each round t, only one node plays the cluster head role whereas all other sensors within the same cluster play the member role.

Constraint (9).(iii) guarantees that once a cluster is dead, it remains as such from there on. This means that either there is at least a node without enough energy to play the member role, or all the sensors within the cluster have not enough energy to play the CH role. Since senors are battery powered, once $z(t)$ becomes zero, it cannot change its value in subsequent runs.

4. Related work

The rotation technique has been widely exploited in the literature in order to make a uniform consumption of the energy among the nodes composing a WSN and consequently to extend its lifetime, measured in terms of first node die. A discussion about various approaches faced so far is now reported.

The selection of the cluster head with a rotation strategy has been proposed in [10]. The paper assumes that the WSN is organised in concentric annuli. Nodes inside an annulus can be elected as CH in a preliminary election with high probability. As we do assume, clusters are created only once, at the beginning of the process, and then a rotation is applied until the first node dies. The rotation with respect to the CH role is accomplished after a fixed number of rounds, evaluated according to a mathematical model that takes into account the average energy consumption required to play the role of cluster head or member.

In [11], clustering is accomplished according with an Area-Partitioning strategy. Again, the WSN is statically visualised by concentric annuli. There are actually three different strategy to accomplish rotation for cluster heads. According to some precomputed threshold, the rotation is realised in a static or dynamic fashion. In fact, either it is accomplished according to a fixed scheme, or an adaptive schedule is considered when the energy consumption gets lower than the fixed threshold, hence considering the residual energy of the nodes.

In [21], heterogeneous WSNs are considered, and a clustering protocol based on the Energy-Coverage Ratio is proposed. The number of clusters is chosen according to an energy consumption model in order to minimise the energy required to cover the area of interest. Consequently, CHs are chosen so as to maximise the coverage. Reasonably, cluster heads that have consumed too much energy to play their role become members in the subsequent interaction. The membership to a cluster is realised by simply considering the cluster head that minimise the distance.

An unequal clustering strategy based on feedback mechanisms, named FMUC, has been proposed in [15]. FMUC subdivides the WSN into virtual layers according to a mathematical model. This realises a uniform distribution of the ratio between the energy consumption and the total energy initially associated with each layer. Each cluster is associated with a layer and its size is chosen according to the energy consumption ratio of each layer. The feedback mechanism is realised by the cluster heads that send to the BS the size of their clusters. Once the BS has collected all such values, these are then broadcast to all the nodes. However, such data are processed just by the cluster heads that consequently can update their competition radius in order to participate in subsequent CH elections.

In [4–7], the rotation to play the CH role is more adaptive. In particular, heuristics have been used that consider various parameters. These may include the residual energy of the nodes, the rate of transmission of a node, or the initial energy associated with a node.

The clustering algorithm HEED [19] has been improved in [4] in terms of WSN lifetime. Such an improvement has been realised by including a rotation strategy to HEED. In particular, by starting from the clustering obtained by applying HEED, a rotation mechanism has been included for the election of new cluster heads that takes into account the residual energy of the nodes.

Similarly to the above process, the clustering algorithm UHEED [22] has been improved in [7] in terms of WSN lifetime. Such an improvement has been realised by including a rotation strategy to UHEED. In particular, by starting from the clustering obtained by applying UHEED, a rotation mechanism has been included for the election of new cluster heads each time a node has completely drained its battery.

Another interesting approach for rotation has been proposed in [5]. It evaluates a threshold for rotation based on the current energy load of the cluster head. In this way, the risk for premature depletion of the energy owned by CHs is reduced. Actually, clusters are also split when no member has enough energy to play the CH role.

To a more general extent, clustering protocols usually take decisions on the bases of estimations of the energy required to accomplish the required communications. Such estimations are in turn based on values that do not represent the actual scenario. In fact, to simplify the evaluations, for instance, average distances between CHs and their members are taken into account or simplified setting like virtual grids or virtual layers are considered. Such simplifications are then reflected into the rotation strategies. In this way, overhead messages required to keep the network updated of the actual values is reduced. On the other hand, average values are not always well representative of the actual situation. This may clearly lead to reduce the lifetime of a WSN that could have benefit of the real values on which an effective rotation strategy should operate.

In this paper, we aim to solve the problem to prolong the WSN lifetime by proposing an optimum rotation strategy that does not consider average values. In fact, our approach is based on actual distances and detailed energy evaluations. Interestingly, it can be adapted to any clustering algorithm and does not require simplifications with respect to the outcome of the clustering.

5. Rotation heuristics in details

In this section, we provide some details about the rotation heuristics we compare our ORS with. These are REECHD, CER-CH, LEACH and ERHEED.

ER-HEED [4] enhances HEED [19] clustering method with the introduction of rotation. HEED includes cluster formation, cluster head election and network operation phases. During the cluster head election phase the node with the highest residual energy has more probability of becoming cluster head. Nodes become members of their closest CH. HEED generally prevents the overlapping of different clusters. Reelection takes place after five rounds in order to balance energy consumption. ER-HEED [4] enhances HEED first node die lifetime measure by replacing reelection with rotation where a cluster head selects as CH its member node with highest energy.

Low Energy Adaptive Clustering Hierarchy (LEACH) [18] is the clustering protocol that first introduced the concepts of clustering WSNs. LEACH elects the cluster heads by performing a randomised election. Reelection takes place after five rounds in order to load balance the energy consumption. The current cluster heads cannot be elected in two consecutive rounds. Each CH aggregates member node data which is forwarded directly to the BS. It is worth mentioning that LEACH do not use the node residual energy for CH election.

Rotating Energy Efficient Clustering for Heterogeneous Devices (REECHD) is a clustering protocol that generates clusters with unequal size. This is done in order to balance the intra-cluster communication for heterogeneous wireless sensor network. CH election considers the node's residual energy and its transmission rate. Eq. (10) defines the node probability of becoming CH. Parameter K is used in order to constrain CH_{prob} value between 0 and 1 (so that it defines a probability). Parameter K is set to $K = 2$. C_{prob} is a predefined initial probability (e.g., 5%). This sets the initial percentage of CHs amongst all WSN nodes. $E_{r_{CH}}$ is the residual node energy, $E_{max_{CH}}$ is the maximum energy of the node (it is equal to a fully charged battery), $T(CH)$ is the transmission rate of the node, T_{max} is the highest transmission rate of the WSN (it corresponds to the rate of the node which has the highest transmission rate in the WSN). CH_{prob} value of a node is not allowed to fall below a certain threshold P_{min} (e.g., 10^{-4}), that is selected to be inversely proportional to E_{max}.

$$CH_{prob} = max\left(\frac{C_{prob}}{K}\left(\frac{E_{r_{CH}}}{E_{max_{CH}}} + \frac{T(CH)}{T_{max}}\right), P_{min}\right) \tag{10}$$

REECHD also defines the intra-traffic rate limit (ITRL) (see Eq. (11) for a formal definition) that is used in order to limit the amount of inter-traffic inside a cluster. More precisely, each CH must accept new member nodes only when the summation of the member node transmission rate does note exceed the value ITRL. This is defined using following equation:

$$\sum_{i=1}^{|member\_set|} sending\_rate(i) < ITRL \tag{11}$$

REECHD has the following five different phases:

1. *cluster head election* where a subset of the WSN nodes become cluster heads;
2. *cluster formation* where each WSN node that is not cluster head attempts to join a CH in order to form clusters. A node joins the least cost CH which can be calculated according to a cost function that is defined by Eq. (10);
3. *CH routing tree definition* where a routing tree which involves clusters head is defined. This allows CHs to forward data to the BS. A top-down strategy is used by REECHD in order to define the routing tree;
4. *network operation* where data are delivered to the BS. REECHD performs five rounds of data delivery.
5. *rotation* where the current CH elects the next CH by considering Eq. (10) as a weight function. Rotation phase is triggered at the end of every network operation phase.

CER-CH defines a routing tree and a CH rotation that can be combined with any clustering strategy. More precisely, starting from any clustering criteria, CER-CH defines a rotation heuristic that is combined with a top-down CH routing tree definition.

$$E_{TDMA}(CH, CH_f) = E_{inter}(CH, CH_f) + E_{intra}(CH) \tag{12}$$

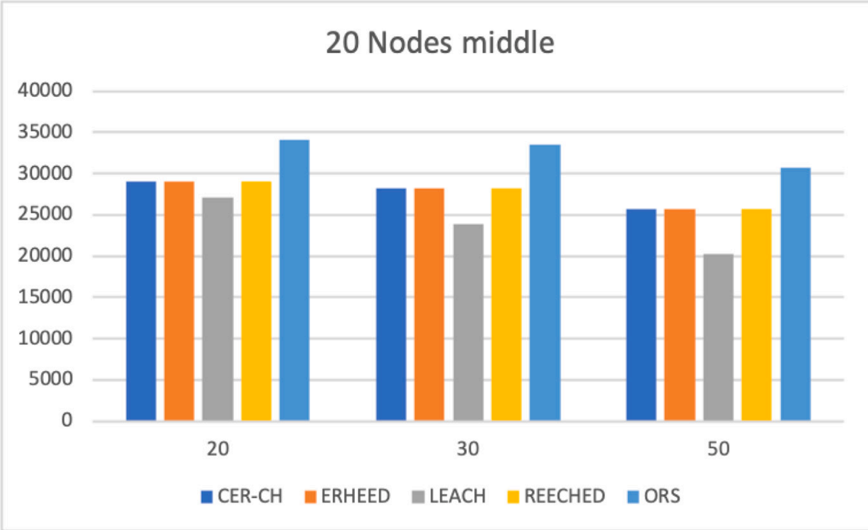

Fig. 2. On X axis: the sensor communication radius (i.e., 20, 30 and 50 m), on Y axis the WSN lifetime (i.e., the number of rounds before the first node dies). Middle cluster simulation setting with 20 sensors.

The selected cluster head should reduce the E_{TDMA} energy consumption (see Eq. (12) for details) where $E_{inter}(CH, CH_f)$ is the energy the node spends for inter-traffic communication. This regards the forwarding of data from the CH to the next hop (i.e., another CH or the BS). $E_{intra}(CH)$ is the energy the node spends for intra-traffic communication that is to receive data from its cluster members.

$$CER - CH(CH, CH_f) = \frac{E_{r_{CH}}}{E_{TDMA}(CH, CH_f)} \tag{13}$$

Eq. (13) defines the weight function used by CER-CH to perform rotation where $E_{r_{CH}}$ is the node residual energy. This estimates the number of times a node can play the cluster head role.

6. Comparison and discussion

We consider 20 nodes that are uniformly distributed inside a cluster. We remind that for our simulations we are considering just the sensors inside a single cluster. Hence, 20 nodes represent a reasonable size as the CH must take care of collecting and processing all the data from its members. The diameter of a cluster is considered of different sizes among the set {20, 30, 50} metres. Our simulation uses the following three main settings:

- **Cluster far apart** where the cluster centre is located at coordinate (0, 0), the base station is located at (50, 175);
- **Cluster Middle** where the cluster centre is located at coordinate (50, 50), the base station is located at (50, 175);
- **Cluster close to BS** where the cluster centre is located at coordinate (50, 100), the base station is located at (50, 175);

In the homogeneous case all nodes have the same initial energy (i.e., 4 joule) and have the same transmission rate (i.e., 1024 bits per message). In the heterogeneous WSN case the initial energy of a node is randomly chosen within the interval $[1, 4]$ joules and the message size falls within the interval $[500, 3000]$ bits. This message size is drawn in the first setup phase and then is kept constant throughout the entire WSN simulation. Nodes have the same processing and aggregation capability. More precisely, a CH aggregates all received messages into a single one of 1024 bits. Nodes have a unique IDs and can transmit at various power levels which depend on the distance of the receiver.

6.1. Homogeneous WSNs simulations

An important parameter to be considered for our experiments is the maximum communication radius of a sensor. However, by empirical observations, we concluded that such a parameter is not relevant for the results obtained within one cluster, as long as the chosen radius guarantees connectivity within the cluster. To this respect, we report in Fig. 2 the lifetime of all heuristics and the optimum for a Middle setting cluster that is composed of 20 sensors. We have chosen a max transmission range (for intra-cluster communication) of 20, 30 or 50 m. We can observe that the maximum communication radius does not affect much the trend obtained for each of the five applied algorithms. The cluster far apart and cluster close to BS settings are not shown since they have the same trend of the cluster Middle setting. It is worth mentioning that the lifetime value increases as the cluster is closer to the BS.

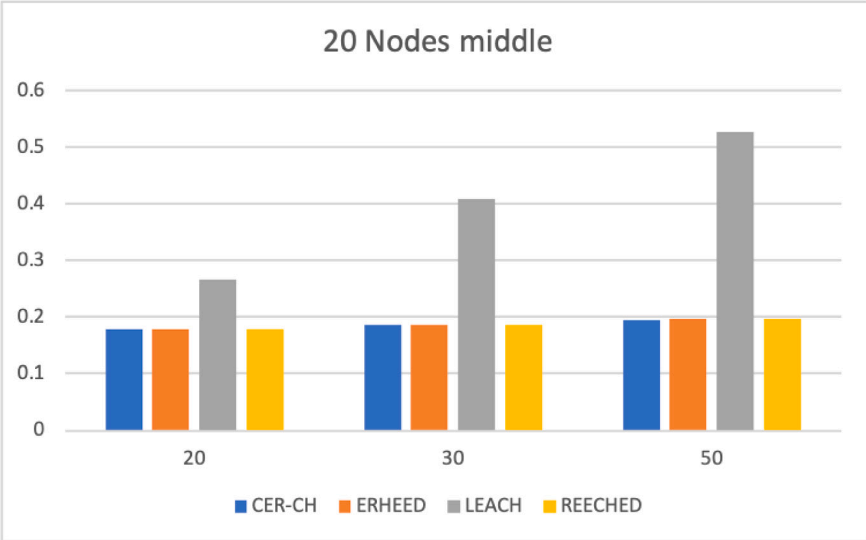

Fig. 3. On X axis: the sensor communication radius (i.e., 20, 30 and 50 m), on Y axis: loss in percentage of the heuristics w.r.t. ORS. Middle cluster simulation setting with 20 sensors.

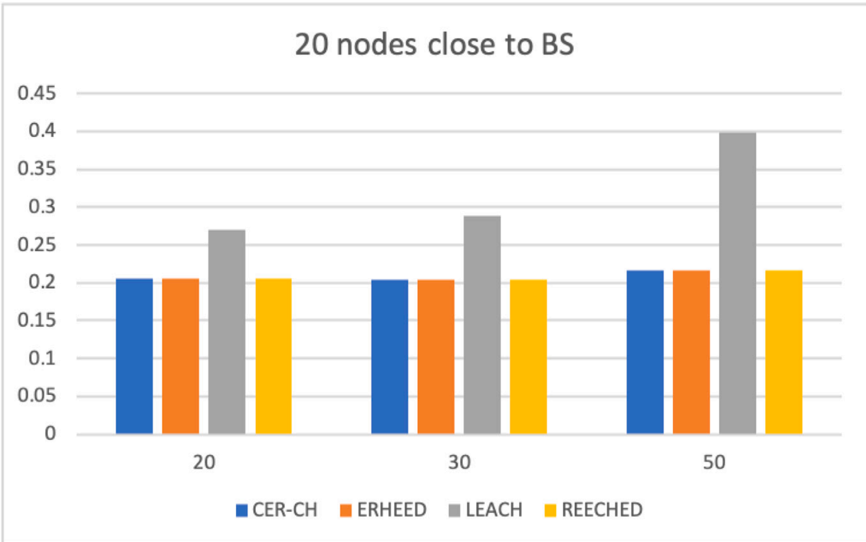

Fig. 4. On X axis: the sensor communication radius (i.e., 20, 30 and 50 m), on Y axis: loss in percentage of the heuristics w.r.t. ORS. Cluster close to BS setting with 20 sensors.

Fig. 3 shows the loss in percentage of the heuristics with respect to the optimal rotation. For instance, when the cluster radius is 50, ERHEED, CER-CH and REECHED lose around 20% while LEACH more than 50%. ERHEED, CER-CH and REECHED lose most of the energy as consequence of overhead messages. These are needed in order to perform the rotation protocol. Another portion of energy is lost as consequence of the rotation heuristic itself. More precisely, all heuristics choose the next cluster head by considering a specific set of parameters and not the whole factors affecting energy consumption. For instance, ERHEED only looks at the residual energy while CER-CH at the ratio between consumed energy as CH and residual energy. This suggests the requirement for a new heuristic that considers further parameters such as relative distances of the sensors to the CH, their consumption as member nodes and so on. As we are going to see, this observation is exacerbated when WSNs are heterogeneous in terms of rate and max energy. When LEACH is considered, its random selection leads to a worse performance since the aforementioned parameters are completely neglected. Similar considerations can be provided for the cases where the cluster is close to the BS and far apart.

Fig. 4 shows the loss in percentage of the heuristics w.r.t. ORS when the cluster is close to BS. We can observe that for CER-CH, ERHEED and REECHED have a slightly worse performance as the cluster is closer to the BS. In fact, the contribution of the

Table 1
Average, Maximum and Minimum loss in percentage of the heuristics w.r.t. ORS in the case of 20 Nodes cluster in the Middle and radius 30.

	CER-CH	ERHEED	LEACH	REECHED
AVG	0.186	0.186	0.408	0.186
MAX	0.188	0.188	0.495	0.188
MIN	0.182	0.182	0.341	0.182

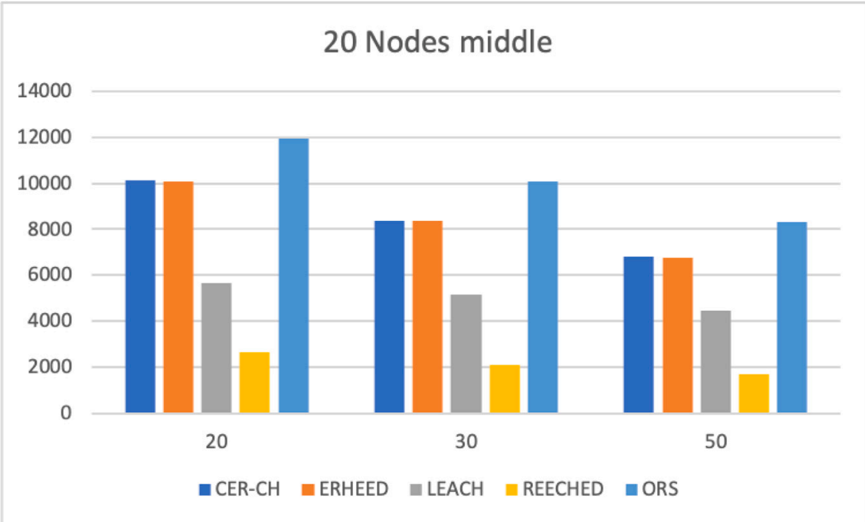

Fig. 5. On X axis: the sensor communication radius (i.e., 20, 30 and 50 m), on Y axis the WSN lifetime (i.e., the number of rounds before the first node dies). Middle cluster simulation setting with 20 sensors.

transmission to the BS becomes closer to the consumption inside the cluster, hence, making such a contribution less relevant. This energy consumption also makes CH to BS communication similar for all nodes which slightly improves LEACH performance.

Another interesting observation can be deduced by looking at Table 1. This reports the average, minimum and maximum loss in percentage of the heuristics w.r.t. ORS in the case of 20 nodes cluster in the middle setting and radius 30. It is evident that the behaviour of the heuristics is rather stable across the tested networks. Therefore the variance is almost zero. Intuitively, this is consequence of the homogeneous settings where nodes have equal initial energy and rate.

6.2. Heterogeneous WSNs simulations

More interesting is the heterogeneous case, where sensors may start their work with different energy levels and different transmission rates.

Fig. 5 the lifetime of all heuristics and the optimum for a Middle setting cluster that is composed of 20 sensors. We have chosen a max transmission range (for intra-cluster communication) of 20, 30 or 50 m. Of course, the more the range of heterogeneity, the less the chance for LEACH to guarantee the network persistence. In fact, by choosing at random the cluster-head may result in selecting the sensor with less charging available. However, the worst performance is provided by REECHED. In fact, the strength of this algorithm is mainly focused on building clusters with variable size rather than on rotation. Since in our simulations we are considering a single cluster with fixed size, the advantages of REECHED are somehow obscured. This is evident in comparison with the simulation that are shown in the previous section for the homogeneous case since in that case all clusters would have the same size. ERHEED and CER-CH have the best performance since they are conceived for equal-sized clustering and their rotation strategies have been proved to be effective. Their performance is very close to the optimal one similarly to the homogeneous case. The cases where the cluster is close to the BS and far apart can be neglected since the trend is exactly the same as the middle case.

Fig. 6 shows the loss in percentage of the heuristics with respect to the optimal rotation. For instance, when the cluster radius is 50, ERHEED and CER-CH lose around 23% while LEACH and REECHED more than 90% and 700%, respectively. For this reason in Fig. 7 we focus on the trend of ERHEED and CER-CH only in order to better appreciate their performance. Similarly to the homogeneous case, ERHEED and CER-CH lose most of the energy as consequence of overhead messages although slightly more energy is lost by the heuristic strategy. We can also notice a slightly higher impact on the performance as the size of the cluster increases. This highlights the relevance of the strategy applied by the heuristics. Similar considerations can be provided for the cases where the cluster is close to the BS or far apart.

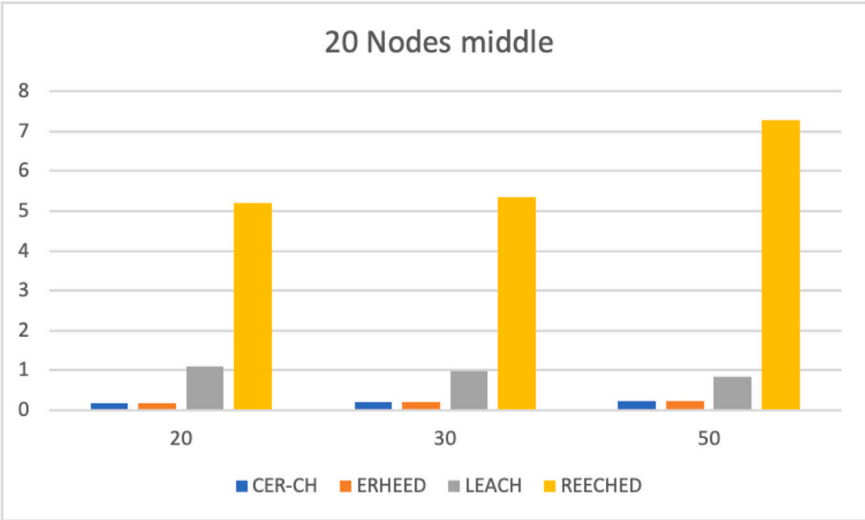

Fig. 6. On X axis: the sensor communication radius (i.e., 20, 30 and 50 m), on Y axis: loss in percentage of the heuristics w.r.t. ORS. Middle cluster simulation setting with 20 sensors.

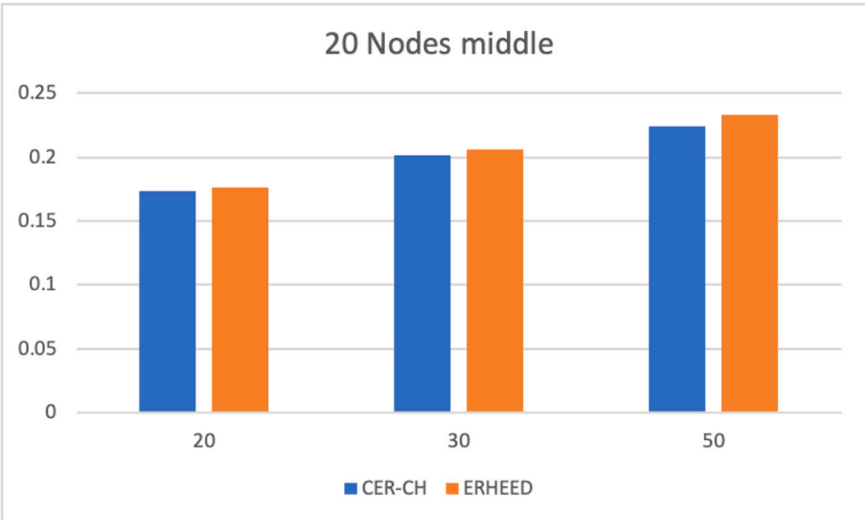

Fig. 7. On X axis: the sensor communication radius (i.e., 20, 30 and 50 m), on Y axis: loss in percentage of the heuristics w.r.t. ORS. Cluster close to BS simulation setting with 20 sensors.

Table 2 shows the average, minimum and maximum loss in percentage of the heuristics w.r.t. ORS in the case of 20 nodes in the middle cluster setting and radius 30 m. The behaviour of the heuristics vary a lot across the tested networks. Therefore the variance becomes more relevant and higher w.r.t. the homogeneous case. This confirms the intuition that heterogeneous settings can heavily affect the heuristics performance. For instance a node that has low energy and high rate will be not selected as cluster head by the heuristics when a node with very high energy is left. This high-rate low-energy node generates lots of intra-traffic thus quickly depleting the node energy. This confirms once again the requirements for new heuristics that takes into account such occurrences (i.e., the member node traffic). This can be rather complicated since requires to consider the energy consumed as CH and as node member. In particular, the consumption as node member depends on a CH that is unknown.

7. Conclusions and future work

The paper proposes a novel Integer Linear Programming formulation in order to devise an Optimum Rotation Scheduling (ORS) for clustered WSNs. We assumes the network has been already clustered by using some static or dynamic clustering protocols. Our ORS allows the definition of an optimal cluster rotation schedule. More precisely, ORS calculates for each node the number of times

Table 2
Average, Maximum and Minimum loss in percentage of the heuristics w.r.t. ORS in the case of 20 Nodes cluster in the Middle and radius 30.

	CER-CH	ERHEED	LEACH	REECHED
AVG	0.202	0.206	0.988	5.341
MAX	0.279	0.289	1.379	11.841
MIN	0.124	0.127	0.638	0.750

required to play the CH role. After that time, the node performing the cluster head role can delegate a new CH without the need of any re-election. This saves overhead messages. ORS optimises the rotation by considering the first node die lifetime measure. It produces a rotation schedule that results in the optimum cluster lifetime. Extensive simulations have been provided in order to compare existing heuristics with the optimum values. In particular, the homogeneous and heterogeneous cases have been considered. In both settings, it turns out that in order to improve on the performances of the existing heuristics, one should somehow include in the strategy the energy consumption required by a node when it is a member of a cluster and not only when it is the CH. Moreover, the resolution of our integer linear programming formulation is rather efficient since our optimal algorithm works within single clusters (i.e., the number of nodes is limited).

As future work we plan to extend our model to the multi-hop case.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Leonardo Mostarda reports financial support was provided by Italian Ministry of University and Research (MUR)m, Next Generation U (PNRR) fundings.

Data availability

No data was used for the research described in the article

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