Energy Aware Fault Tolerant Re-clustering Algorithm for Wireless Sensor Networks

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***Abstract*—Since communication and data transmission present the most energy consuming task in Wireless Sensor Networks (WSNs), cluster-based routing protocols emerged as significant solutions for the energy conservation problem. In this paper, a fault tolerant based unequal clustering algorithm is proposed to extend the network lifetime of wireless sensor nodes. A threshold value is fixed to avoid the re-clustering process in some rounds leading to reduce the total number of data packets. The performance of the improved clustering algorithm is carried out with the network simulator NS3. A comparison between both unequal clustering with and without fault tolerant technique shows that avoid holding the selection of CHs in some rounds achieves better performance in terms of energy consumption and network lifetime.**

***Index Terms*—Wireless Sensor Network, fault tolerance, energy depletion, re-clustering, threshold, energy harvesting.**

I. Introduction

Generally, a Wireless Sensor Network (WSN) is composed of a big number of sensor nodes, deployed over a certain area, communicating together in order to achieve a specific application [1]. If every node is powered via a battery, recharging or changing batteries from one time to another, especially, for a large-scale network becomes impracticable. For long term applications, prolonging lifetime of wireless sensor nodes by energy efficiency is an issue that should be highly considered [2]–[4]. One aspect, which should be thereby definitively treated, is the data packets scheduling [5] and their circulation in the network by suitable routing algorithms [6].

Therefore, a cluster-based routing protocol is introduced as an energy efficient network protocol that can be used by sensor nodes to forward their sensed data to the sink and results in load balancing and network lifetime extension. A clustering algorithm, as depicted in Fig. 1, enables organizing the network into clusters where sensor nodes transmit their data over shorter distance to their corresponding cluster heads (CHs). CHs aggregate the received data packets and then send it to the sink node or to the base station (BS). However, since the CH is responsible to aggregate data packets from different nodes within the same cluster, it carries some extra load and it can die quickly. For this reason, various clustering algorithms use relay nodes with larger transmission range and higher energy source, which minimize the load of CHs by acting as an intermediate node between CHs from different hops. Despite having higher energy compared to normal nodes, relay nodes are also battery constrained. Therefore, they are prone to failure. Generally, the failure of nodes can damage the network performance and limit their services. The failure of CHs still the most harmful because when a CH fails to receive data from its cluster members, then the sensor nodes can not transmit their data to the base station [7]. Moreover, in case of a multi-hop communication, where CHs forward their data packets to other CHs from different hops, a failed CH affect the network connectivity and the network performance is deteriorated.

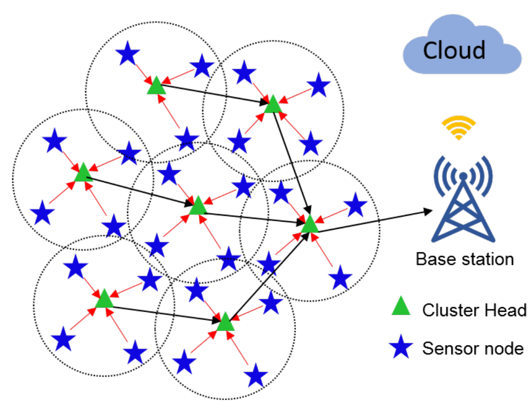

Fig. 1. A WSN-based clustering model.

Hence, the most existing cluster-based routing protocols support the fault tolerance technique by performing the re-clustering process, which consists on changing the CH at periodic intervals by fixing a threshold value. Therefore, the additional communication overheads are reduced and the total number of transmitted packets is minimized leading to an extended network lifetime. The aim of this paper is to enhance an existing unequal clustering algorithm described in [1] by implementing a fault tolerant technique. To this end, the re-clustering process is avoided in some rounds by fixing a threshold energy value.

The rest of the paper is structured as follows: Section II is dedicated to present some related works. Section III describes the proposed fault tolerant re-clustering algorithm. Section IV provides the simulation results.

II. Related works

The choice of routing algorithm is important to minimize resource usage in constrained environment. Many studies prove that hierarchical routing protocols [8], [9] are very suitable for static sensor networks, and an excellent clustering algorithm [10] is the key of research on hierarchical routing protocols. Unequal clustering-based routing algorithms, where the size of cluster is reduced from one hop to another from the BS, are introduced as energy efficient approaches. In fact, they solve the hotspot problem created by the multi-hop communication topology.

In this context, a Distributed load balancing Unequal Clustering based on Fuzzy approach (DUCF) [11] is proposed, where the size of a cluster is calculated based on different factors like distance to BS, node degree and residual energy. The smallest cluster size is assigned to CH closer to the BS because it is used a router for other distant CHs. However, the selection of CH is performed in each round. Thus, a huge amount of energy is consumed. In [12], an Improved Fuzzy Unequal Clustering algorithm (IFUC) is presented. To select the CH and to determine the radius of each cluster, the residual energy of a node, its distance to the base station and its density are used as input parameters for the fuzzy system. The clustering process is carried in each round.

Many fault tolerant clustering protocols are proposed for WSNs in which reducing energy, and enhancing the network lifetime are their common objectives. In [13], the Informer Homed Routing (IHR) algorithm is introduced as an energy aware fault tolerant method for WSN. A backup CH is used to take the role of the main CH, when this later is failed. In [14], a fuzzy logic based-energy efficient protocol (MACHFL-FT) to cluster heterogeneous nodes in WSN is introduced. In fact, it avoids the re-clustering operation in each round by fixing a threshold.

Authors in [15] proposed an unequal clustering algorithm using a partitioned circles network model. To select CHs, a fuzzy logic system used, where the node residual energy, number of neighboring nodes and centrality of node among its neighbor are involved as input variables. However, the selection of CHs is hold in each round. This main contribution of the current paper is improving the work described in [15] by avoiding the re-clustering process in some rounds to extend the network lifetime.

III. Proposed scheme

In [15], a fuzzy-based unequal clustering algorithm was proposed to reduce the network energy consumption. The network area is assumed as a circle, partitioned into a certain number of rings with a specific radius. The base station is placed in the center. All nodes have the same initial energy. Generally, this existing algorithm is divided into two main phases (Fig. 3): Cluster formation and data collection. After calculating the optimal radius of each cluster and the number of nodes in each ring, the cluster formation phase starts. In fact, each node broadcasts a discovery neighboring message within the cluster radius to create its routing table including the list of neighbors and the residual energy.

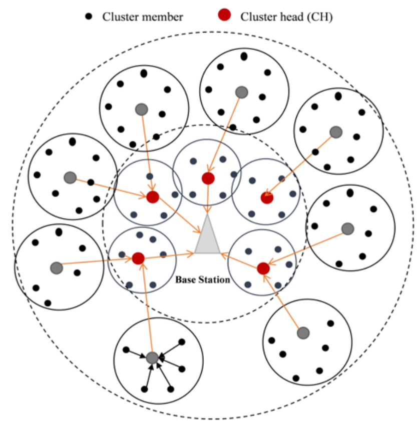

Fig. 2. Description of the network topology.

Once nodes are deployed and the network is established, each node executes a fuzzy logic algorithm to calculate its chance to be a CH. Three parameters are used as inputs for the fuzzy logic system, namely, the residual energy, density and centrality. Then, nodes within the same cluster share their chances. The node having the highest chance will select itself as a CH and will transmit an announcement message to its node members informing them with its status. Other nodes will continue sending their data to the recently nominated CH.

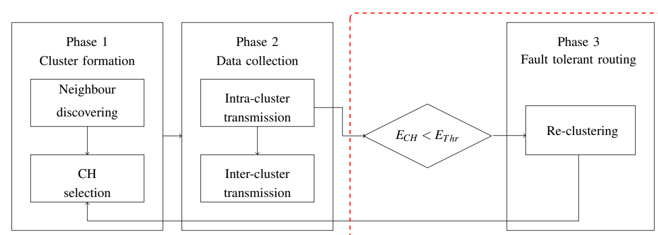

Fig. 3. Block diagram of the proposed clustering-based routing algorithm.

Then, the data collection phase starts including intra-cluster and inter-cluster data transmission steps. During the intra-cluster data transmission sub-phase, each CH maintains a TDMA [16] schedule and assigns the TDMA slots to cluster members. Then, the nodes of the same cluster exchange their data with their cluster heads in its pre-allocated time slot. As assumption, a time slot for 10 ms is used. So, each node will wake up only when its time slot starts. The energy consumed by each node should be updated and recalculated for each round.

During the inter-cluster data transmission sub-phase, every CH from ring (k) will forward the aggregated data packet directly to the BS in case of being a CH from the first ring or to another CH from ring (k-1). Since energy is the key objective of this paper, the residual energy as well as distances between CHs from successive rings have been highly recommended. To select a CH_i from the next ring as a relay node, the transmitter CH_j should calculate the ratio of residual energy of CH_i, $E_{res}(CH_i)$, and distance between CH_i and CH_j, $d_{CH_i-CH_j}$, as expressed in eq. 1.

$$ratio(E_{res}, d_{CH_i-CH_j}) = \frac{E_{res}(CH_i)}{d_{CH_i-CH_j}} \quad (1)$$

If two CHs have the same ratio value, CH_j chooses the CH with highest residual energy. After performing routes between CHs from different rings, the data packets will be exchanged between CHs until reaching base station.

From the second round, a threshold value of energy is fixed, which enables all CHs of the first round to compare their residual energy to the defined threshold (threshold = 40% in this paper). So, if a CH has higher energy level than the threshold, then, there is no need to select a new CH. Therefore, the energy needed to the re-clustering process is saved. However, when a CH has less remaining energy than the threshold, the selection a new CH is required. In fact, if the level of energy of a CH is depleted or insufficient to run the current round, not only the data sent from this node is lost but also the energy dissipated by all cluster members is consequently lost. That's why at this stage, the detection of energy depletion of CHs will take place.

Algorithm. 1 describes in details the overall working process of the proposed energy aware clustering solution.

Algorithm 1: Fault tolerant unequal clustering-based routing algorithm

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N: total number of sensor nodes in the network
E_res(i): residual energy of node i
density(i):density of node i
centrality(i):centrality of a node i
chance(i):chance of node i to be a CH
threshold: fixed threshold value
list_neig: List of neighbors for node i
Node deployment
phase 1: Cluster formation
  1) Neighboring discovery
  2) Calculate the chance of being a CH
     for i ← 1 to N do
       for j ← 1 to list_neig do
         chance(i) = fuzzy(E_res(i), density(i), centrality(i))
       end
     end
  3) Select the CH for each cluster
     for i ← 1 to N do
       send (chance(i), list_neig)
       if (chance(i) ← max(chance)) then
         node i is selected as CH
       else
         node i is selected as CH
       end
     end
     if (list_neig = ∅) then
       node i is selected as cluster member
     end
phase 2: Data collection
  1) Intra-cluster data transmission
     for i ← 1 to N do
       for j ← 1 to list_neig do
         send (data_packet (j) toCH (j))
       end
     end
  2) Inter-cluster data transmission
     for m ← 1 to list_CH_k do
       for n ← 1 to llist_CH_(k-1) do
         send (data_packet (CH_k) toCH_(k-1))
       end
     end
phase 3: Fault tolerant routing
  1) Re-clustering process
     if (E_res(CH_i) ≺ threshold) then
       Shift the position of the CH to another node within same cluster
     end
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IV. Performance evaluation

A group of sensor nodes are deployed randomly in a $100m \times 100m$ area. Fig. 4 presents the dispersion of nodes in the field and the selected CHs from the first of data collection cycle. 25 nodes are deployed in the first ring and 75 nodes are dispersed in the second ring. All detailed configuration is illustrated in Table I. Here, the low-power wireless sensor node, panStamp NRG 2.0 [17], is used.

Simulation results are carried out using the network simulator NS3. The values are expressed in term of rounds, which defines the data collection cycle. The used energy model is described in the next sub-section. To evaluate the performance of the proposed fault tolerant-based battery depletion algorithm, some parameters such as the consumed energy of nodes and the number of dead nodes in each round are considered.

TABLE I
Configuration parameters

Parameter	Value
Network size	100 m x 100 m
Number of nodes	100
Transmission range	70 m
Sleep current	1 μA
Tx current	19.2 mA
Rx current	16 mA
Data rate	38.4 kbps

A. Energy model

Based on the real state of sensor nodes in each phase [17], an accurate energy model would assure an approximate realistic prediction of network lifetime. For example, the energy consumed for a transmitter node, E_{Tx}, can be described in eq. 2:

$$E_{Tx} = V \times I_{Tx} \times \Delta t_{Tx} \quad (2)$$

Afterwards, calculating the energy consumption of a sensor node is resumed in its scheduling chronogram. The total consumed energy is the sum of all energies in different states (eq. 3).

$$E_{total} = \sum_i E_i \quad (3)$$

, where E_i presents the energy consumption for each state i.e. transmission state (Tx), reception state (Rx), sleep state, and even a switch state has been considered in order to provide a precise and realistic energy consumption. E_{total} is the total energy consumed in Joule, V presents the supply voltage

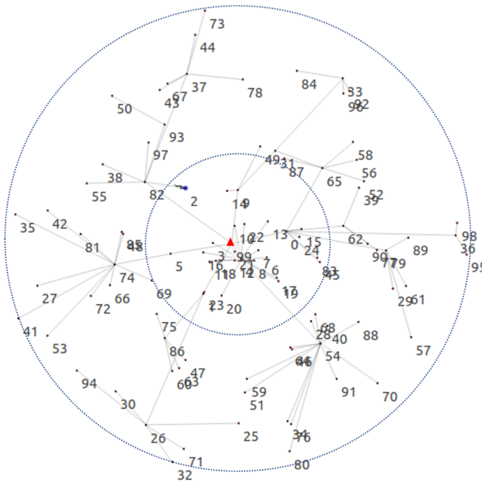

Fig. 4. Network partitioning into clusters.

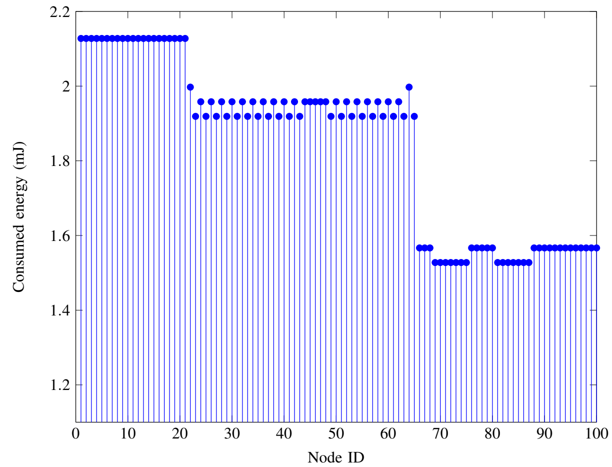

Fig. 5. Consumed energy for each node without fault tolerance.

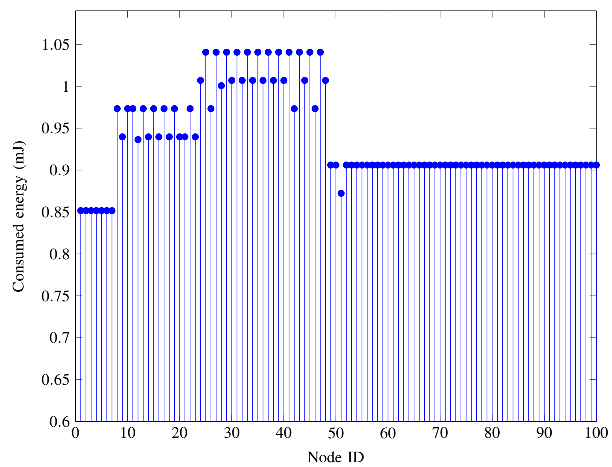

Fig. 6. Consumed energy for each node with fault tolerance.

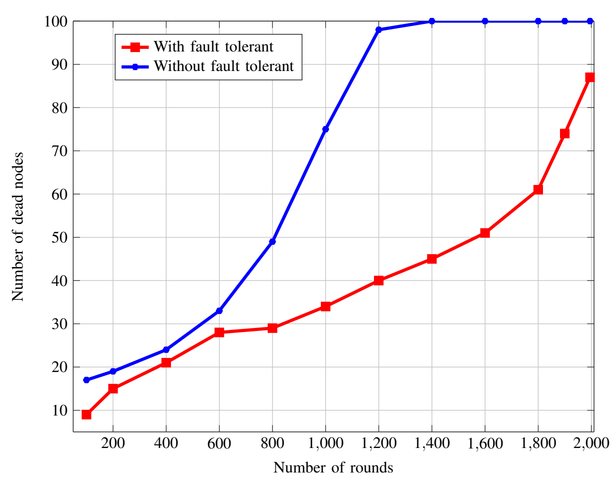

Fig. 7. Network lifetime over rounds.

in Volt. Despite of a minor decrease, the voltage will be considered as a constant in this work due to its complicated gait in terms of calculation. I is the current consumption in Ampere, Δt is the state duration in seconds. The chosen energy model is primarily based on three parameters.

Computing remaining energy in batteries requires two parameters as shown in eq. 4.

$$E_{remaining} = E_{initial} - E_{consumed} \tag{4}$$

The consumed energy of a sensor node,$E_{consumed}$, is calculated with eq. 3, while, computing initial energies ($E_{initial}$) of sensor nodes requires some details about the battery available in its datasheet [18]. With 3000 mAh of battery capacity and 1.5 Volt of its voltage, each sensor has 16200 Joule of initial energy. Each node has 32400 Joule as initial energy.

B. Simulation evaluations

The energy consumption of sensors nodes after the process of the fault tolerant clustering is evaluated. Then, the results with the existing unequal clustering [15] are compared. The first evaluated parameter is the consumed energy of the whole network. It is noticed from Fig. 5 and Fig. 6, a decrease of the energy consumption of all the deployed nodes. For example, the consumed energy of the node having the ID number one is decreased from 2.13 mJ to 0.9 mJ. Since the proposed fault tolerant clustering algorithm avoids the selection of CHs in each round by fixing a threshold value, the number of the exchanged messages is reduced and thus the total energy is saved.

Simulations, illustrated in Fig. 7, prove that the unequal clustering algorithm using fault tolerant technique outperforms the existing unequal clustering in terms of network lifetime. As seen in Fig. 7, at round 1000, all the nodes are died in the case of unequal clustering without fault tolerant, while only 40 nodes are died in the other case.

As explanation for the results illustrated in Fig. 5, Fig. 6 and Fig. 7, since the transmission and reception of packets between nodes within same cluster in the clustering process increase the total consumed energy, avoiding the re-clustering process in some rounds by using a preset threshold can save the network' total energy.

V. Conclusion

In this paper, a fault tolerant based unequal clustering algorithm is proposed to extend the network lifetime of heterogeneous nodes. Cluster heads are selected based on a fuzzy logic system by considering the node' residual energy, its density and its centrality. The proposed clustering algorithm avoids the selection of CH in each round by fixing an energy threshold value. Hence, the number of transmitted data packets between cluster members is decreased significantly and so the total consumed energy is reduced. As future work, the proposed solution will be implemented in a real hardware to evaluate more its performance.

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