R-MUCH: A Clustering Routing Algorithm Using Fuzzy Logic for WSNs

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**Abstract.** An adequate usage of energy on nodes with restricted energy source is one of the major challenges in WSNs. Since data transmission is the main task that shortens node’s lifetime, it is very necessary to balance the transmission of data among the network paths. Cluster-based architecture in WSNs is one of the keys to improve energy efficiency and extend network lifetime. It reduces the number of messages transmitted towards the sink or Base Station. This is due to restricting the communication with the sink to few nodes, called Cluster Head nodes (CHs). One of the major concerns is how to choose cluster heads and route data through energy-efficient paths towards destination. In this paper, we propose R-MUCH a clustering routing algorithm. It is a multi-hop version of MUCH algorithm (Multi-Criteria Cluster Head Delegation Based on Fuzzy Logic). CHs send data in a multi-hop fashion to the sink by choosing the path that has the lowest cost in terms of energy consumption. R-MUCH chooses for each CH its next-hop. It uses fuzzy logic and relies on three factors: the distance, the node’s remaining energy and the number of times the node has served as next hop. Simulation shows that network lifetime is increased over existing approaches in the state of the art.

1. Introduction

Wireless Sensor Network (WSN) technology is described as very promising for the future [1][2]. It becomes an active research area, especially with the great progress of miniaturization technology and wireless autonomous systems. A WSN is composed of spatially distributed tiny nodes, which sense the environment and work cooperatively to deliver information in a multi-hop fashion to a sink or Base Station (denoted BS). Nodes are equipped with limited battery (≤0.5 Ah, 1.2 V) and have limited transmission range, processing and storage capabilities [3]. In many application domains, battery cannot be recharged (under-sea surveillance, tracking, disaster scenarios, etc.). Consequently, the power consumption should be reduced and carefully managed in order to keep the network alive for the longest period of time. Different components in a wireless sensor node contribute in energy consumption: the power supply, the sensing unit, the processing and transmission units. Many researches showed that data communication is the most energy consuming part, while processing consumes much less [4]. Clustering architectures [5] are widely adopted to tackle challenges related to data aggregation and routing. It groups nodes into clusters, each with cluster head. A CH is in-charge of different tasks, mainly receiving data from other nodes in the same cluster, aggregating and forwarding it [6][7]. The other nodes are Cluster Members (CM) that communicate with the sink (or
base station) through CHs. This structure is an effective way to reduce communication distance as well as the amount of data transmitted or replicated in the network [8]. On the other hand, energy depletion is faster on CHs than other nodes, since they are loaded with different duties in processing, aggregation and communication. Consequently, the selection of CHs is a critical issue in designing clustering routing protocols. In this work, we propose a distributed clustering routing algorithm that uses both single hop communication (between CH and CM), and multi-hop communication (between CHs to route data to the sink). We use fuzzy logic for: 1- Giving CMs weight and elect the convenient one for the CH mission, 2- path Cost calculation for the routing part and choosing the energy-efficient next-hop node.

The rest of the paper is organized as follows: Section 2 presents preliminaries on fuzzy logic and clustering. Section 3 discusses related works. Section 4 presents our contribution. Section 5 shows the simulation results. Section 6 concludes this paper.

2. Preliminaries

2.1. Basics of clustering

The main goal of clustering is to reduce the overall energy consumption [7]. Since CMs communicate with CHs over a shorter distance, their energy dissipation decreases. There are two types of communications: One between CMs and their CHs (called Intra-cluster) and the other is between the CH and the sink (called Inter-cluster). How to choose CHs is a great challenge. A bad selection of CHs may cause a fast energy depletion and declines the network performance. A clustering algorithm consists of two main phases: (a) The setup phase that organizes the clusters and selects the CHs; (b) the steady-state phase where member nodes in each cluster start sensing data and communicating with their CHs, which perform data collection and fusion and send the aggregated data to a sink. This process of setup and communication is repeated in each round. Here the term ‘round’ refers to the time elapsed before a network re-clustering event occurs. During cluster formation, the decision of a sensor node to become CH and join an existing cluster is typically based on different metrics. In probabilistic approaches, a random CH election is performed (as in Low Energy Adaptive Clustering Hierarchy algorithm-LEACH [9]). Other approaches use different criteria (such as the remaining energy, the distance from the sink, the centrality, the density in the network, etc.)[10]. These approaches are called attribute-based. We present an attribute-based algorithm that uses three inputs to a fuzzy system. The inputs are the node’s energy cost, its distance and the number of times it has served as CH in the previous rounds.

2.2. Fuzzy Logic System (FLS)

2.2.1. Overview. Fuzzy logic (FL) is a method of reasoning that resembles human reasoning by making decisions based on rules. It is also defined as the multi-valued logic. It differs from the boolean logic (single-valued logic) by the fact that every event can take two or more values with a degree of membership (called degree of truth) to each one of these. Let us consider the following question: “Are you sure of what you’ve heard?” In boolean logic, the answer would be either yes or no (0 or 1). However, in fuzzy logic the answer would be: “I am sure for a degree of 60 % and unsure for a degree of 40 %”. Knowledge in FL is interpreted as a collection of fuzzy rules on a collection of non-numeric values. These rules operate using a series of if-then statements [11]. In order to exemplify, the temperature is qualified using non-numeric terms such as “hot”, “warm”, etc. These terms are called fuzzy sets. However, the real value for the temperature, called the crisp value, is a numeric value (example 27°C). Each fuzzy set covers a range of numerical values. Values in [15°C, - 25°C] can be thought of as warm, [25°C, - 30°C] can be thought of as hot and so on, depending on the defined membership functions. In Figure 1, for example, 13°C can be considered 40% “COOL” and 60% “NORMAL”.

2.2.2. FLS structure. A FLS consists of three main parts (Figure 2) - A fuzzifier (using membership functions), rules evaluation (rules & inference engine), and defuzzifier. Assume an air conditioner
system is controlled by a FLS. The system adjusts the temperature of the room according to the current room temperature. The Fuzzifier block converts the given crisp input (ex: 13°C) into the appropriate fuzzy linguistic variable (ex: cold or warm). The inference is made based on a set of rules. An example of rule can be: IF (temperature is cold OR too-cold) THEN command is heat. Finally, the defuzzifier block converts the fuzzy output into the crisp output using a suitable defuzzification method.

![Figure 1. Membership Function](image1.png)

![Figure 2. Fuzzy Logic System](image2.png)

### 2.2.3. Fuzzy Logic in our work

We use fuzzy logic to determine the cost of routing from a specific CH toward the sink. We aim to decide on the convenient path for routing (i.e the path that has the lowest overall cost in terms of energy). We use Gaussian membership function (see Table 1) for fuzzification as it is common because of its smoothness and non-zero values at all point [12]. We use five fuzzy sets (denoted A): VL (Very Low), L (Low), M (Medium), H (High) and VH (Very High). For the defuzzification function, we used Center of Gravity (see Table 2). It is one of the most popular defuzzification technique used as an assessment model [13]. This method avoids the discontinuities that could appear using other defuzzification functions such as the Mean of Maxima function [14].

### Table 1. Gaussian Membership Function

| Variable  | Meaning | Gaussian Function | \( \mu_{A_k} = \exp\left(\frac{(c_k - x)^2}{2\sigma_k^2}\right) \) |
|-----------|---------|------------------|--------------------------------------------------|
| \( c_k \) | center of the \( k \)th fuzzy set \( A_k \) | | |
| \( \sigma_k \) | width of the \( k \)th fuzzy set \( A_k \) | | |

### Table 2. Center of gravity function

| Variable | Meaning |
|----------|---------|
| \( U \)  | result of defuzzification |
| \( \mu \)  | membership function after accumulation |
| \( \min \) | lower limit for defuzzification |
| \( \max \) | upper limit for defuzzification |

### 3. Related works

This section presents a list of clustering routing algorithms that are either single-hop or multi-hop. LEACH [9] and MUCH [15] are considered single-hop. Elected CHs send the aggregated data to the sink through direct communication hop. One of the main concerns in single-hop communication is that the distance between CHs and the sink could be large. Consequently, CHs located far from the sink are subjected to death earlier than the nodes located near the sink [16][17]. To overcome this, data is transmitted to the destination through large number of smaller hops. CHs send their data to intermediate CHs along the path to the sink. This multi-hop routing is considered to be more efficient [18]. Few nodes will be transmitting directly their data to the sink, while most of CHs transmit to their next-hop selected by the routing protocol. Since the transmission energy is proportional to distance squared, multi-hop routing consumes less energy than single-hop communication. LEACH [9] is based on the idea of randomized rotation of cluster-heads. It distributes the energy load equally among all the sensor nodes. In the setup phase, every node generates a random number between 0 and 1. This number is compared to a threshold \( T(n) \). If the number is less than \( T(n) \), that node will be selected as CH for that round. The threshold is as follows:
\[ T(n) = \begin{cases} \frac{p}{1-p(r \mod \frac{1}{p})} & n \in G \\ 0 & \text{otherwise} \end{cases} \] (1)

where \( p \) is the ratio of cluster-head nodes in the total number of nodes. \( r \) is the current round number. \( G \) is the set of nodes that have not been selected as CH nodes in the former \( \frac{1}{p} \) rounds. Sensors elect themselves to be CHs at a given time with a certain probability, and broadcast their status to other sensor nodes. Each node chooses the CH with the highest signal. LEACH carries out energy optimization and also reduces the amount of data transmitted. However, it has some drawbacks. It may happens that the same node is selected as CH again in other rounds. The CHs are selected randomly, so if the node with low energy is elected, it will be heavily loaded and more energy will be consumed. This results in early death of these nodes and consequently reduce the network lifetime. In FLCMN [19] (Fuzzy Logic-Based Clustering Algorithm for Multi-hop Wireless Sensor Networks), every node has its own satisfaction factor. It is calculated using fuzzy inference system that takes three inputs into consideration: node residual energy, number of neighbor nodes and the average residual energy of neighbor nodes. In every cluster the node that has the lowest factor will be CH. In this algorithm, a multi-hop transmission scheme based on Fibonacci is used. The goal is to avoid the hot spot problem between clusters and to distribute data load among the neighboring CHs. In EMHR [20], the node that has the highest remaining energy is elected as CH. Then every cluster head (say CH \( i \)) selects its Next-Hop (CH \( j \)) based on a weighting function. This function takes into consideration: the distance between the two neighboring CHs (CH \( i \) and CH \( j \)), the distance between CH \( j \) and the sink, and the remaining energy of CH \( i \).

EMHR-FL [21] (Energy-Efficient Multi-hop Hierarchical Routing Protocol using Fuzzy Logic) is an extension of EMHR[20]. Authors consider the parameters proposed in EMHR not sufficient for energy efficient routing. They highlighted the problem of load occurring on the next-hop CH. For this purpose, they introduced a new weighting parameter which is the node’s density. It reflects the number of neighboring CHs that may use this node as Next-Hop and thus consume more of its energy. Unlike EMHR, the weighting parameters are inputs to a fuzzy system instead of a static function and the output is the cost of adopting CH \( j \) as a next-hop for CH \( i \). In MUCH [15], every CM computes its weight in a cluster and sends it to its CH. The latter chooses the node that has the lowest weight to be its delegate for the next round. The weight of a CM, is computed based on three parameters: its distance to sink and to other CMs, its energy cost, and the number of times it has been chosen as CH in the previous rounds. MUCH decreases the energy dissipation during intra-cluster communication. The communication between CHs and the sink is single-hop. These nodes are subjected to early death when transmitting to far sink [18]. The integration of multi-Hop (“short” paths) communication in MUCH could be a solution to increase the nodes’ lifetime. Many metrics were suggested in the literature for the selection of energy-efficient paths. In [19],[21, 22], the selection is based on the least energy dissipation path. Authors in [17],[23], choose the path that has the lowest number of hops to sink. Authors in [19–21] give each neighboring CH a cost and the one that has the lowest cost will be the next-hop. In this work, we use three parameters to determine for each CH its next-hop that decreases energy depletion during inter-cluster communication.

4. Our Contribution

The energy dissipated on a node is directly related to the transmission distance [18]. We suppose that every CH is connected to each of its neighbouring CHs via single-hop link and has a direct path to the sink. The goal is to avoid routing to next-hop nodes that are low energy, located far from the sink or have heavy load to transmit. We assign a cost to every single path link between two CH nodes. It is the cost in energy for sending data via this link. The value ranges from zero to one. As the cost decreases, the priority for a CH to transmit via this link increases.
4.1. Setting the cost
We compute the cost of each single-hop (between CHs) using FL system (Figure 3). The system has three inputs:
- The remaining energy in the source CH denoted “ReSrc”.
- The remaining energy on the candidate next-hop node denoted “ReDst”.
- The distance between the two nodes composing the single-hop link, denoted Distance”.
- The number of times a candidate CH has been next hop before, denoted “NextHopNb”. If this number increases, the cost increases.

![Figure 3. Fuzzy system](image)

The output is the cost denoted LinkCost. A link (or hop) between two consecutive CHs has low cost when the remaining energy of the two nodes is high. It is also low when the distance between nodes is low. The relation between inputs and the cost is represented by if-then rules (Fuzzy Rules), illustrated in Table 3. It has three fuzzy values {L, M, H}. NextHopNb is expressed by five fuzzy values {VL, L, M, H, VH}.

| ReSr | ReDs | Distance | NextHopNb | Link Cost |
|------|------|----------|-----------|-----------|
| H    | H    | L        | VL        | L         |
| H    | H    | L        | M         | M         |
| H    | H    | M        | VL        | M         |
| H    | H    | H        | M         | H         |
| M    | M    | L        | VL        | L         |

**Table 3. Fuzzy Rules.**

![Table 4. Link Costs](image)

| Path | Link Cost |
|------|-----------|
| P_1  | 0.4       |
| P_2  | 0.3       |
| P_3  | 0.15      |
| P_4  | 0.05      |
| P_5  | 0.8       |
| P_6  | 0.2       |
| P_7  | 0.8       |

![Table 5. Possible paths](image)

| Path  | Total Cost |
|-------|------------|
| Direct (P_1) | 0.4 |
| via CH_2 (P_12) | >0.75 |
| from CH_1 to sink. |
| Direct (P_2) | 0.8 |
| via CH_4 (P_45) to CH_5 | 0.45+0.05=0.55 |
| via CH_6 (P_67) to CH_7 | 0.55+0.20=0.75 |

4.2. Selection of the paths for CHs
R-MUCH runs after the selection of CHs. At each round, every CH sends its remaining energy to the sink (or BS) via the old path. The sink runs the fuzzy system to get the cost on each hop between CHs.
Then it finds for every CH the best path in terms of energy efficiency. It selects the path that has the lowest total cost. To exemplify, given the topology in Figure 4, let $P_i$ be the direct hop from CH$_i$ to the sink, and $P_{ij}$ be the hop between two neighbouring CHs, where CH$_i$ is the source and CH$_j$ is the destination. Every path is composed of consecutive hops to the sink. Table 4 presents the link costs obtained after running the fuzzy system. The sink will have then the information about paths. Table 5 and Table 6 show the path costs from CH$_1$ and CH$_5$ respectively. The sink will choose the link $P_1$ because it has the lowest total cost and informs CH$_1$ that his next hop is the sink. On the other hand, for CH$_5$, the sink chooses the path $P_5P_4$ because it has the lowest total cost. The sink then informs CH$_5$ that the next hop is CH$_4$. The path selection for a specific CH at each round is described in Figure 5(a).

4.3. Description of R-MUCH

R-MUCH aims to reduce energy consumption during intra-/inter-cluster communication. In the setup phase, clusters are organized and CHs are selected using MUCH algorithm. Each CH selects the node that has the lowest weight among the cluster members, to be its delegate for the coming round. In the steady state phase, CHs adopt the path that has the lowest cost (as described in the previous section). The whole process continues until all nodes die (Figure 5(b)).

5. Simulation

In our simulation, we have a rectangular area, which consists of one static sink and several sensor nodes. We made the following assumptions: nodes are homogeneous, location-aware and energy constrained. Each sensor node has a unique identifier (ID), and the same initial energy. Each CM node attempts to transmit a q bit message at its allocated time-division multiple-access (TDMA) schedule and the received messages from CMs can be aggregated in a single message by the CH. Note that the TDMA schedule [24] makes certain that there are no data collisions during the network activities. In such a way, the TDMA schedule saves energy by allowing nodes to sleep all the time except during the node’s transmission time. As all the data collected by the sensor nodes are forwarded to a sink node, the placement of the sink has a great impact on the energy consumption and network lifetime [25–29]. Therefore, we took two scenarios.
In the first scenario, the sink is located at the center of the network. In the second scenario, the sink is located outside the network rectangular area. We used MATLAB to evaluate the performance of our algorithm. We compared our work to FLCMN[19] and EMHR-FL[21]. We refer to the following performance metrics: the nodes’ remaining energy, the number of dead nodes and the network lifetime. Two definitions are used for the network lifetime: First Node Dies (FND) and Last Node Dies (LND). FND is the time when the first node dies in the network and LND is the time when the last node dies.

5.1. Scenario 1

The network consists of 250 nodes randomly distributed over an area of 100mx100m. Simulation parameters are presented in Table 7. Figure 6 shows the remaining energy on each node in the network at round 200. We notice that the energy saving is increased using our approach compared to other algorithms. Nodes’ remaining energy in R-MUCH is higher than in FLCMN and EMHR-FL by 51.2% and 89.6% respectively. This is because in FLCMN and EMHR-FL there is no consideration of the distance from the CH to sink, and the distance to CMs. This causes the selection of far CHs possible, hence, they will be subject to die at early rounds, and CM nodes to consume too much energy.

Table 7. Simulation parameters

| Parameters                  | Value          | Parameters                  | Value          |
|-----------------------------|----------------|-----------------------------|----------------|
| Network Size                | 100m×100m      | Initial energy              | 0.5 J          |
| Number of nodes             | 250            | $E_{elec}$                  | 50 nJ/bit      |
| Location of sink            | Center         | $\epsilon_{mp}$             | 0.0013 pJ/bit/m²|
| Location of nodes           | Random         | $\epsilon_{fs}$             | 10 pJ/bit/m²   |
| Aggregation energy $E_{DA}$ | 5 nJ/bit       | Number of rounds            | 200            |

![Figure 6. Remaining energy on each node at round 200](image)

![Figure 7. Total remaining energy per round](image)
In RMUCH we avoided the selection of these CHs. Figure 7 shows the total remaining energy in the network per round until round 200. We can notice that R-MUCH gives the higher remaining energy. Figure 8 illustrates the death of nodes. We evaluated the lifetime of the network by three metrics: FND, HND (half node dies) and LND (as shown in Figure 10). We can notice that the earliest death in nodes occurs in FLCMN at round 218. However, First node dies in R-MUCH occurs at round 609. The whole network goes down in EMHR-FL at round 1138, earlier to the other algorithms. RMUCH doubles the network lifetime compared to EMHR-FL. The LND in our work was earlier than FLCMN that is because of two reasons:

- In FLCMN, authors distribute the traffic between CHs and their neighbouring CHs according to Fibonacci sequence. However, they didn’t take into consideration the lifetime of CMs while selecting CHs. There is no consideration of the distance between member nodes and the elected CH. This causes member nodes far from the CHs to die at early rounds. This is obvious in the FND in Figure 8. FND occurred at round 168 earlier than RMUCH.

- As result of the above point, during late rounds many of the cluster members far from their CHs in FLCMN were subjected to earlier death. This decreased the energy consumption load on the new selected CHs and made them last longer because of the absence of almost 80% of CM neighbours. Late death of nodes isn’t alone an indication of the network lifetime because the energy consumption could be unequally distributed between nodes. This unbalanced power consumption may cause network partition, blocking the transmissions from sensors to CH nodes [30]. To measure the energy balancing we used the standard deviation. It measures the energy variation between nodes according to the mean. The lower this value is, the closer the energy level to the mean (in energy balancing the lower the deviation is, the more is the equilibrium). Figure 11 shows the energy variation in FLCMN and R-MUCH. It indicates that R-MUCH maintains better energy balancing.
5.2. Scenario 2

In this scenario, the sink is located outside the network area. Figure 9 shows the remaining energy at each node in round 200. It shows that R-MUCH maintains higher remaining energy compared to other algorithms. 48% of the nodes in R-MUCH have higher energy level than the nodes in FLCMN. Moreover, 90% of the nodes have higher energy level than the nodes in EMHR-FL. The total remaining energy per round is presented in Figure 12. We can notice that R-MUCH shows the highest total remaining energy per round, when the sink is located outside the network area. This delays the death of nodes and increases the network lifetime.

5.3. RMUCH versus MUCH

Our simulation results show that RMUCH outperforms MUCH for multihop communication scenario where the sink is located far from the sensor nodes (Figure 13(a)). 95% of the nodes in RMUCH have higher remaining energy. However, for single-hop scenarios where the sink resides close to the nodes, a slight difference in the number of dead nodes per round exists between the two algorithms (see Figure 13(b)). The reason behind this is the energy that RMUCH consumes for finding the convenient next-hop node on the path. The next-hop could be the sink itself or a neighbour CH. However in MUCH, CHs send data directly to the sink. This explains why FND in RMUCH occurs earlier than MUCH. On the other hand, the remaining energy per node in R-MUCH is higher than MUCH. 65% of the total nodes in R-MUCH have higher remaining energy. Figure 14(a) shows the variation in terms of LND, HND and LND between RMUCH and MUCH. The network lifetime (LND-FND) shows an enhancement of 4% in RMUCH over MUCH algorithm. Figure 14(b) shows the variation in terms of LND, HND and LND when the sink is located outside the area.
RMUCH achieves 31% gain in FND over MUCH. 37% gain in HND and 12% gain in LND were achieved by RMUCH over MUCH. The reason behind this gain is due to the multihop mode in RMUCH that can ease the nodes far away from the cluster head by reducing the burden of long distance communication with the sink. Single-hop mode in MUCH needs to go over a longer distance to reach a far sink with more energy transmission.

6. Conclusion
In this paper, we proposed a new clustering routing algorithm (R-MUCH) for multi-hop communication scenarios. The algorithm uses fuzzy logic for the CHs election and routing. Our
Simulation results show that R-MUCH reduces the energy consumption in the network. It achieves a balanced energy usage and prolongs the network lifetime compared to the other presented algorithms. This achievement is due to the distribution of CH mission among the nodes and the selection of next-hop nodes on the least energy consuming path. In the future works, we aim to explore more complex fuzzy functions for routing in heterogeneous sensor network.

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