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A Hierarchical Multipath Routing Protocol in Clustered Wireless Sensor Networks

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Abstract Wireless Sensor Networks (WSNs) usually consist of many tiny sensor nodes and a Sink; despite the great variety of their applications, they are faced with many problems like limited resources, low Quality of Service such as low reliability and fault tolerance, low throughput, low scalability and insecure operational environments. It significantly degrades their overall performance. One significant solution against mentioning problems is multipath routing; but, existing multipath routing protocols have weaknesses like high overhead and resources' severe consumed, low accuracy, security vulnerabilities, low scalability and permanent usage of optimal paths. As a result, this paper proposes a hierarchical multipath routing protocol for homogeneous and clustered WSNs, called HMR-WSN. Finally, its performance is compared with the performance of HMR-LEACH routing protocol; results of algorithmic-complexity and statistical-simulation analyses show HMR-WSN is improved in terms of energy consumption, the average rate of packet delivery, throughput and accuracy. But, its performance is proportionally degraded in terms of average of route setup time, routing overhead and computational simplicity.

Keywords Wireless sensor network (WSN) · Communication protocol · Routing protocol · Multipath routing · Hierarchical clustered architecture

1 Introduction

Wireless Sensor Networks (WSNs) usually consist of many tiny sensor nodes and a Sink. Figure 1 represents an overview of WSNs [1–4].

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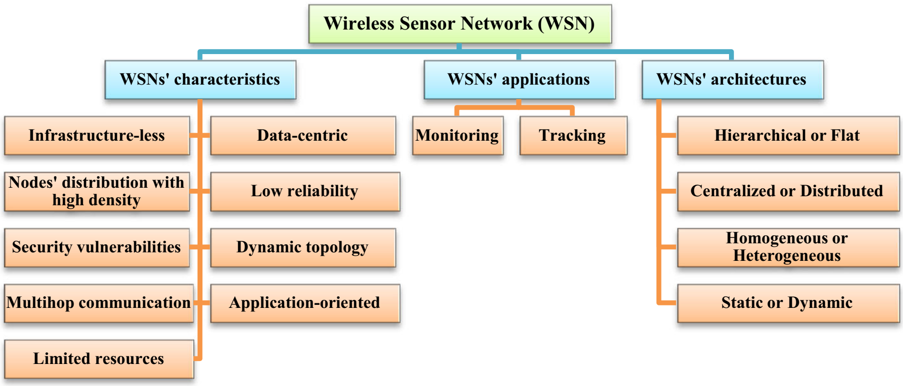

Fig. 1 Different characteristics, applications and architectures of WSNs

In the hierarchical clustered WSNs, there are other components, called Cluster-Heads (CHs); CHs gather data from their cluster's members, aggregate them and forward to the Sink. Some common problems of WSNs are their limited resources, low Quality of Service (QoS) such as low reliability and fault tolerance, low throughput, low scalability and insecure operational environments. Hierarchical multipath routing in clustered WSNs is a significant solution for solving these problems. A multipath routing protocol discovers multiple paths between source and destination nodes; it leads to congestion control, QoS improvement like increasing the reliability and fault tolerance, increasing the bandwidth and throughput, decreasing the end to end delay, balanced traffic load distribution, reducing the frequency of route discovery process, security improvement, reducing the probability of deadlock occurrence, improving the power consumption and WSNs' lifetime prolonged [2–18]. Existing multipath routing protocols have weaknesses such as imposing high overhead in WSNs and resources' severe consumed, low accuracy, security vulnerabilities, low scalability and permanent usage of optimal paths. In another direction, WSNs have constraints in using the multipath routing protocols due to resources' severe limitations, dynamic topology, high density (interference occurrence) and asymmetric and unbalanced traffic pattern. As a result, this paper proposes a hierarchical multipath routing protocol for homogenous and clustered WSNs, called HMR-WSN. The main phases of HMR-WSN are as follows:

- Multiple CHs selection in each cluster
- Elected CHs determination by every one of the cluster's members
- Balanced traffic load distribution between the elected CHs by the cluster's member
- Data transmission and routes rediscovery

Finally, the performance of HMR-WSN is compared with the performance of HMR-LEACH [23] routing protocol; results of algorithmic-complexity and statistical-simulation analyses (by NS2, TRMSim-WSN, Expert Choice and Grey Relational Analysis tools) show HMR-WSN is improved in terms of energy consumption, the average rate of packet delivery, throughput and accuracy. But, its performance is proportionally degraded in terms of average of route setup time, routing overhead and computational simplicity.

The rest of this paper is organized as follows: Sect. 2 describes the different phases of the proposed hierarchical multipath routing protocol for homogeneous and clustered WSNs (HMR-WSN), in details; Sect. 3 evaluates and analyzes the performance of HMR-WSN and comparing it with the performance of HMR-LEACH routing protocol; it briefly explains and discusses the reached results of algorithmic-complexity, simulations and statistical analyses; and finally, Sect. 4 concludes this paper by indicating the future research directions in this area.

2 HMR-WSN: A Hierarchical Multipath Routing Protocol in Clustered Wireless Sensor Networks

This section describes the different phases of the proposed hierarchical multipath routing protocol for homogeneous and clustered WSNs (HMR-WSN), in details. In HMR-WSN, time is divided by number of super-rounds; each super-round is including of a few time intervals. In each super-round, first it selects multiple Cluster-Heads (CHs) for each cluster of the clustered WSN; then, it notifies the CHs of each cluster to its members. Then, every one of the cluster's members determines its elected CHs; elected CHs can be used simultaneously, during each super-round (full-multipath routing) or they can be used separately, in each time interval; i.e. at each time interval, the cluster's member is using of one of its elected CHs for data transmission to the Sink (partial-multipath routing). After that, the cluster's member distributes its traffic load among its elected CHs, in balanced and non-uniform. Finally, each elected CH aggregates the arrived data from the cluster's members and transfers the aggregated data to the Sink. In HMR-WSN, these phases are repeated periodically for all clusters, in each super-round. In continuing the different phases of HMR-WSN is described.

2.1 Multiple CHs Selection in Each Cluster

This phase proposes an algorithm for ranking the cluster's members and selecting its multiple CHs; then, it notifies the cluster's CHs to its other members. For this purpose, in the first super-round, HMR-WSN selects the CHs of each cluster, randomly; since second super-round, the current CHs of each cluster select the new multiple CHs for the corresponding cluster; in this case, there are two approaches:

- Every one of the current CHs selects one or more new CH(s) instead of itself.
- Only one of the current CHs selects all new multiple CHs for the cluster.

The proposed algorithm for ranking the cluster's members and selecting its multiple CHs is as follows:

Step 1: Defining the ranking criteria of the cluster's members (as Table 1) and constructing the Cluster's Members Specifications Matrix as the decision matrix (D) by the current CH; it is a $(n \times m)$ matrix, as follows

$$D = \begin{bmatrix} X_{11} & \cdots & X_{1m} \\ \vdots & \ddots & \vdots \\ X_{n1} & \cdots & X_{nm} \end{bmatrix}$$

- n: number of the cluster's members (rows of the decision matrix); $i = \{1, 2, \ldots, n\}$
- m: number of the ranking criteria (columns of the decision matrix); $j = \{1, 2, \ldots, m\}$
- X_{ij}: score of the cluster's member i'th with respect to the ranking criterion j'th

Table 1 The suggested criteria for ranking the cluster's members and multiple CHs selection

No.	Criterion	Description
1	Available resources and congestion status	Available resources like Remainder Energy (RE), Empty Buffer (Buff), Available Bandwidth (BW) and Waiting Queue Length (WQL): [if: $RE < RE_{thr}$ or $BW < BW_{thr}$ or $Buff < Buff_{thr}$ or $WQL > WQL_{thr}$] $\Rightarrow$ Rank $= 0$ Congestion status $\propto \frac{WQL}{BW \times Buff}$
2	Accuracy and reliability of arriving data from the cluster's member(s)	The CH evaluates this criterion as follows: Every one of the cluster's members reports the result of its measurement (R) to the CH CH receives the reported data (R) and calculates their average (R_{avg}): $R_{avg} = \frac{\sum_{i=1}^{n} R_i}{n}$ R_i: the reported data from the cluster's member i'th n: number of the cluster's members, which reported data on this super-round CH calculates the Absolute Deviation (AD) of the reported data from every one of the cluster's members than R_{avg} and Average of Absolute Deviation (AAD), as follows: $AD = \lvert R_{avg} - R \rvert \Rightarrow AAD = \frac{\sum_{i=1}^{n} AD}{n}$ Now, it calculates the accuracy and reliability of the reported data (C_o) by the cluster's members as follows: $C_o = \text{Maximum}\left\{1 - \frac{AD}{AD_{thr}}, 0\right\}$ $\mathbf{AD_{thr}} = \alpha \times AAD$: the cluster's member with deviation equal or greater than $\mathbf{AD_{thr}}$ than the average value, its trust value is zero (Trust $= 0$) α: tolerance factor of deviation ($\alpha > 0$)
3	Distances	Average distance to other members of the cluster Distance to the gravity center of the cluster Distance to the geometric center of the cluster Distance to the Sink
4	Energy efficiency (E)	$E = \frac{E_R}{C_E}$; E_R: remainder energy; C_E: energy cost Average energy efficiency $= \frac{E_R}{\text{Average } (C_E)} = \frac{E_R}{\frac{\text{Sum of } C_E \text{ to other members of the cluster}}{\text{Number of the cluster's members}}}$ Average energy cost (C_E) to other members of the cluster
5	Percentage of participation (successful or failed transactions) in the network's processes	Participating with untrustworthy nodes Selfishness and unparticipating with trustworthy nodes Availability of the node or associated link
6	Status of data or control packets	Data or control packets' integrity Rate of old, false, forged or malicious data or control packets' injection or broadcasting them in the network Rate of data or control packets' sent, received, forwarding or delivering on the network Rate of data or control packets' dropping, loss, altering or misrouting in the network

Table 1 continued

No.	Criterion	Description
7	Stability during a super-round	It is depending on the criteria like the node's available resources, its mobility, length of super-round and route, volume of ready data, the rate of data transmission and the maximum volume of transferable data during a super-round
8	Being deadlock or density around the cluster's member(s)	Being deadlock node or failed link: it shows if the cluster's member(s) is a deadlock node or not; possible values for this criterion are: {0, 1}. If a node has no (trustworthy) forward neighbor to the Sink, it is a deadlock node Density around the node: it is equal to the number of its (trustworthy) forward neighbors which their Euclidean distance is less than its radio range or they are deployed in the radio range of the node (Degree). This parameter is normalized as: $\frac{Degree_i}{Degree_{max}}$
9	Number of times, which the cluster's member(s) previously be selected as CH (P)	Its normalized value is equal to: $\frac{P_i}{P_{max}}$
10	Waiting time (W_t)	$W_t = \frac{E_i - E_r}{E_i} \times W_{tmax}$ E_i: initial energy, E_r: remainder energy, W_{tmax}: maximum waiting time
11	Imposed delay in the network's processes	
12	Comments of the security systems like Intrusion Detection System (IDS) and firewall about the cluster's member(s)	
13	The trust level of the cluster's member(s)	
14	Strength and quality of the received signals	

Step 2: Calculating the Sum, Average ($\bar{X}$) and Standard Deviation (SD) of each ranking criterion, as follows:

$$Sum = \sum_{i=1}^{n} X_i \Rightarrow \bar{X} = \frac{Sum}{n} = \frac{\sum_{i=1}^{n} X_i}{n} \Rightarrow SD = \sqrt{\frac{\sum_{i=1}^{n} (\bar{X} - X_i)^2}{n}}$$

Step 3: Constructing the normalized decision matrix (N) by mapping its values in the range [0, 1]; it leads to remove the different measurement units and results in a scaleless decision matrix. So:

$$N = \begin{bmatrix} Y_{11} & \cdots & Y_{1m} \\ \vdots & \ddots & \vdots \\ Y_{n1} & \cdots & Y_{nm} \end{bmatrix}$$

$$Y_i = \frac{X_i - \bar{X}}{SD}$$

Step 4: Constructing the differences' matrix (C) by calculating the composite distances between the cluster's members, as follows:

$$C = \begin{bmatrix} D_{11} & \cdots & D_{1m} \\ \vdots & \ddots & \vdots \\ D_{n1} & \cdots & D_{nm} \end{bmatrix}$$

$$D_{ab} = \sqrt{\sum\nolimits_{j=1}^{m} \left(Y_{aj} - Y_{bj}\right)^2}$$

Step 5: Calculating the upper limit (D^+) and lower limit (D^-) of the composite distances for determining the homogenous members of the cluster; the cluster's members who are in the range of upper and lower limits. Other members of the cluster should be removed; due to lack of their similarity in the ranking criteria. So:

$$D^+ = D + 2SD_D$$

$$D^- = D - 2SD_D$$

$$\bar{D} = \frac{\sum_{i=1}^{n} D_i}{n} \Rightarrow SD_D = \sqrt{\frac{\sum_{i=1}^{n} (\bar{D} - D_i)^2}{n}}$$

Step 6: Determining the ideal value (D_o) of each ranking criterion in the normalized decision matrix (N); after removing the non-similar values, the ideal value of each ranking criterion is equal to its largest value; i.e.,:

$$D_o = \text{Maximum value of the ranking criterion in matrix N}$$

Step 7: Calculating the Rank (R) of every one of the cluster's members as follows:

$$C_{io} = \sqrt{\sum\nolimits_{i=1}^{n} (\text{Ideal value} - \text{standard value})^2} = \sqrt{\sum\nolimits_{i=1}^{n} (D_o - D_i)^2} \Rightarrow C_{io} = \frac{\sum_{i=1}^{n} C_{io}}{n}$$

$$SD_{Cio} = \sqrt{\frac{\sum_{i=1}^{n} \left(\overline{Cio} - C_{io}\right)2}{n}}$$

$$C_o = C_{io} + (2 \times SD_{Cio})$$

$$F_i = \frac{C_{io}}{C_o} = \frac{C_{io}}{C_{io} + (2 \times SD_{C_{io}})}, \quad 0 \leq F_i \leq 1$$

$$R_i = \frac{1}{F_i}, \; i = \{1, 2, \ldots, n\}$$

Whatever R_i be greater, those members of the cluster have higher priority to be selected as the cluster's multiple CHs. In other words, the cluster's members who their R_i is greater, they have better rank; so they are more appropriate to be selected as the cluster's multiple

CHs. Finally, it ranks the cluster's members in the descending order of their R_i values and selects the appropriate members of the cluster as its multiple CHs. The number of multiple CHs in each cluster is depending on the criteria like traffic load, the number of the cluster's members and nodes' density in the cluster, and available resources and congestion status.

2.2 Elected CHs Determination by Every One of the Cluster's Members

This phase proposes an algorithm for ranking the cluster's multiple CHs by every one of its members and determining the elected CHs, as follows:

Step 1: Defining the ranking criteria of the cluster's CHs (as Table 2) and constructing the Cluster's CHs Specifications Matrix as the decision matrix (D) by the cluster's member; it is a (n × m) matrix, as follows:

$$D = \begin{bmatrix} X_{11} & \cdots & X_{1m} \\ \vdots & \ddots & \vdots \\ X_{n1} & \cdots & X_{nm} \end{bmatrix}$$

- n: number of the cluster's multiple CHs (rows of the decision matrix); $i = \{1, 2, \ldots, n\}$
- m: number of the ranking criteria (columns of the decision matrix); $j = \{1, 2, \ldots, m\}$
- r_{ij}: score of the cluster's CH i'th with respect to the ranking criterion j'th

Step 2: Assigning the weights of the ranking criteria as follows:

- Normalizing the decision matrix (D) by one of the following methods:
  - Linear normalization: $P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}$
  - Saati normalization: for positive criteria: $P_{ij} = \frac{X_{ij}}{X_i^{max}}$, for negative criteria: $P_{ij} = \frac{X_i^{min}}{X_{ij}}$
  - Euclidean normalization: $P_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}$
- Calculating the uncertainty factor (E_j), the degree of deviation (d_j) and the weights (W_j) of the ranking criteria as follows:

Table 2 The suggested criteria for ranking the cluster's multiple CHs and elected CHs determination

No.	Criterion
1	Available resources and congestion status of the cluster's CH(s)
2	Distance to the Sink
3	Energy efficiency (E)
4	Stability during a super-round
5	Imposed delay in the network's processes
6	Comments of the security systems like Intrusion Detection System (IDS) and firewall about the cluster's CH(s)
7	The trust level of the cluster's CH(s)

$$E_j = \frac{1}{Lnn} \sum_{i=1}^{n} P_{ij} LnP_{ij},\ E_j \in [0, 1]$$

$$d_j = 1 - E_j$$

$$W_j = \frac{d_j}{\sum_{j=1}^{m} d_j}$$

Thus, the final weights of the ranking criteria are: $W = \{W_1, W_2, \ldots, W_m\}$, so that: $\sum_{j=1}^{m} W_j = 1,\ 0 \leq W_j \leq 1$. It represents the relative importance of the ranking criteria. If the decision maker has considered especial weights for the ranking criteria (λ_j), the final weights of these criteria are:

$$W_j^{'} = \frac{\lambda_j . W_j}{\sum_{j=1}^{m} \lambda_j . W_j}$$

In this case, the final weights of the ranking criteria are: $W^{'} = \{W_1^{'}, W_2^{'}, \ldots, W_m^{'}\}$, so that: $\sum_{j=1}^{m} W_j^{'} = 1,\ 0 \leq W_j^{'} \leq 1$. It represents the relative importance of the ranking criteria.

Step 3: Constructing the normalized decision matrix (N) by mapping its values in the range [0, 1]; it leads to remove the different measurement units and results in a scaleless decision matrix. For this purpose, it normalizes the decision matrix (D) by using one of the following methods:

- Linear normalization: $Y_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}$
- Saati normalization: for positive criteria: $Y_{ij} = \frac{X_{ij}}{X_i^{max}}$, for negative criteria: $Y_{ij} = \frac{X_i^{min}}{X_{ij}}$
- Euclidean normalization: $Y_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}$

$$N = \begin{bmatrix} Y_{11} & \cdots & Y_{1m} \\ \vdots & \ddots & \vdots \\ Y_{n1} & \cdots & Y_{nm} \end{bmatrix}$$

Step 4: Constructing the weighted normalized decision matrix (V) by weighting to the normalized decision matrix (N) by multiplying its columns by the weights' vector (W or $W^{'}$), as follows:

$$V = \begin{bmatrix} V_{11} & \cdots & V_{1m} \\ \vdots & \ddots & \vdots \\ V_{n1} & \cdots & V_{nm} \end{bmatrix}$$

$$V_{ij} = W_j \times Y_{ij}$$

Step 5: Determining the positive ideal solution (A*) and the negative ideal solution (A^-), as follows:

- The positive ideal solution (A*) is equal to the vector of the best values of the ranking criteria in matrix V:

$$A* = \left\{V_1^*, \ldots, V_n^*\right\},\ \text{where } V_j^* = \left\{\mathrm{Max}\left(V_{ij}\right),\ \text{if: j is a positive criterion; else: } \mathrm{Min}\left(V_{ij}\right),\ \text{if: j is a negative criterion}\right\}.$$

- The negative ideal solution (A^-) is equal to the vector of the worst values of the ranking criteria in matrix V:

$$A^- = \left\{V_1^-, \ldots, V_n^-\right\},\ \text{where } V_j^- = \left\{\mathrm{Min}\left(V_{ij}\right),\ \text{if: j is a positive criterion; else: } \mathrm{Max}\left(V_{ij}\right),\ \text{if: j is a negative criterion}\right\}.$$

Step 6: Calculating the distances between each one of the cluster's CHs and the positive and negative ideal solutions, as follows:

- Distance from the positive ideal solution: $S_i^* = \sqrt{\sum\left(V_j^* - V_{ij}\right)^2}$
- Distance from the negative ideal solution: $S_i^- = \sqrt{\sum\left(V_j^- - V_{ij}\right)^2}$

Step 7: Calculating the relative distance to the ideal solutions (C_i^*) for every one of the cluster's CHs as their rank (Rank_{CH}) by using the existing values in the weighted normalized decision matrix (V), as follows:

$$C_i^* = \mathrm{Rank}_{CH} = \frac{S_i^-}{(S_i^* + S_i^-)},\ 0 < C_i^* < 1$$

Now, ranking the cluster's multiple CHs in the descending order of their C_i^* values by the cluster's member; then, determining the elected CHs by the cluster's member which their C_i^* values are closer to 1 as its elected CHs. In other words, the cluster's CHs who their C_i^* value is greater, they are better to be selected as the elected CHs by the cluster's member. The number of elected CHs of the cluster's member is depending on the criteria like its traffic load, the number of the cluster's multiple CHs, available resources in the cluster's CHs and their congestion status.

2.3 Balanced Traffic Load Distribution Between the Elected CHs by the Cluster's Member

This phase proposes an algorithm for scoring the elected CHs of every one of the cluster's members; then, it distributes its traffic load between them, in balanced and non-uniform. Therefore, every one of the cluster's members follows these steps:

Step 1: Defining the scoring criteria of the elected CHs (as Tables 1, 2) and constructing the Elected CHs Specifications Matrix as the decision matrix (D) by the cluster's member; it is a $(n \times m)$ matrix, as follows:

$$D = \begin{bmatrix} X_{11} & \cdots & X_{1m} \\ \vdots & \ddots & \vdots \\ X_{n1} & \cdots & X_{nm} \end{bmatrix}$$

- n: number of the elected CHs of the cluster's member (rows of the decision matrix); $i = \{1, 2, \ldots, n\}$
- m: number of the scoring criteria (columns of the decision matrix); $j = \{1, 2, \ldots, m\}$
- $X_{i,j}$: score of the elected CH i'th with respect to the scoring criterion j'th

Step 2: Assigning the weights of the scoring criteria as follows:

- Normalizing the decision matrix (D) by one of the following methods:
  - Linear normalization: $P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}$
  - Saati normalization: for positive criteria: $P_{ij} = \frac{X_{ij}}{X_i^{max}}$, for negative criteria: $P_{ij} = \frac{X_i^{min}}{X_{ij}}$
  - Euclidean normalization: $P_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}$
- Calculating the uncertainty factor (E_j), the degree of deviation (d_j) and the weights (W_j) of the scoring criteria as follows:

$$E_j = \frac{1}{Lnn} \sum_{i=1}^{n} P_{ij} Ln P_{ij};\ E_j \in [0, 1]$$

$$d_j = 1 - E_j$$

$$W_j = \frac{d_j}{\sum_{j=1}^{m} d_j}$$

Thus, the final weights of the scoring criteria are: $W = \{W_1, W_2, \ldots, W_m\}$, so that: $\sum_{j=1}^{m} W_j = 1,\ 0 \leq W_j \leq 1$. It represents the relative importance of the scoring criteria. If the decision maker has considered especial weights for the scoring criteria (λ_j), the final weights of these criteria are:

$$W_j' = \frac{\lambda_j . W_j}{\sum_{j=1}^{m} \lambda_j . W_j}$$

In this case, the final weights of the scoring criteria are: $W' = \{W_1', W_2', \ldots, W_m'\}$, so that: $\sum_{j=1}^{m} W_j' = 1,\ 0 \leq W_j' \leq 1$. It represents the relative importance of the scoring criteria.
Step 3: Determining the positive ideal point (f_j^*) and the negative ideal point (f_j^-) for each one of the scoring criteria as follows:

- The positive ideal point is the best value of the scoring criterion j'th: f_j^*
- The negative ideal point is the worst value of the scoring criterion j'th: f_j^-

Step 4: Calculating the value of earning (S) and value of regret (R) for the cluster's member's elected CHs, as follows:

- S_i: relative distance of elected CH i'th than the positive ideal point:

$$S_i = \sum_{j=1}^{m} W_j \times \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)}$$

- R_i: maximum regret of elected CH i'th than farness of the positive ideal point:

$$R_i = \mathrm{Max}\left\{ W_j \times \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \right\}$$

Step 5: Calculating the score of every one of the cluster's member's elected CHs (Q), as follows:

$$Q_i = V \times \frac{(S_i - S^*)}{(S^- - S^*)} + (1 - V) \times \frac{(R_i - R^*)}{(R^- - R^*)}$$

$$S^- = \mathrm{Max}\{S_i\},\ S^* = \mathrm{Min}\{S_i\},\ R^- = \mathrm{Max}\{R_i\},\ R^* = \mathrm{Min}\{R_i\},\ V \in [0, 1];\ \text{usually: } V = 0.5$$

Now, distributing its traffic load among them according to their calculated scores; so, percentage of allocated traffic load to the every one of the cluster's member's elected CHs is equal to:

$$\frac{\text{Score } (Q_i)\text{of the elected CH i}'\text{th}}{\text{Total scores of the cluster}'\text{smember's elected CHs}} \times 100$$

2.4 Data Transmission and Routes Rediscovery

In this phase, each elected CH aggregates the arrived data from the cluster's members and transfers the aggregated data to the Sink; then, HMR-WSN is repeated periodically, in each super-round.

3 Results, Analyses and Discussions: Comparison Between Performance of HMR-WSN and HMR-LEACH Routing Protocols

This section compares the performance of HMR-WSN with the performance of HMR-LEACH [23] routing protocol. LEACH [19–23] is an abbreviation of Low Energy Adaptive Clustering Hierarchy routing protocol. It is a hierarchical, clustering-based and single-path routing protocol for WSNs. LEACH is a self-organized protocol along with dynamic categorization, which using of a random method to distribute energy consumed between all members of the cluster. In this protocol, time is divided by slots, called round; then, these steps are repeated in each round: CHs' selection, clusters formation, TDMA scheduling program creation by CHs and data transmission. HMR-LEACH [23] is an abbreviation of Hierarchical Multipath Routing-LEACH. It is based on LEACH protocol, which improves election of CH and adopts multi-hop algorithm instead of one hop to transmit data. When chooses a transmission path, HMR-LEACH protocol takes energy and distance into account and assigns a probability to each transmitting path by weight. HMR-LEACH protocol is based on the hierarchical topology. CHs transfer data to the base station by multi-hop, avoiding long-distance transmission, which makes the algorithm suitable for relatively large-scale underwater acoustic sensor network. In the process of data transmission, there is a multipath selection issue; a good selection algorithm can balance the network energy consumption and prolong the network lifetime. It is divided into two processes: multipath establishment process and path selection process. The entire network as an undirected graph $G = (V, E)$; V is the set of vertices and E is the set of edges in the graph. W (u, v) is the weight of edge (u, v), which: edge $(u, v) \in E$. The Sink is the only base station of the network. The main steps of the HMR-LEACH protocol are as follows [23]:

- First, Sink broadcasts the control package in the frequency f to determine the adjacent clusters, which refer to the cluster that directly transfer converged data to the Sink. After that, adjacent clusters broadcast in color-coded $N_i, i \in \{1, 2, \ldots, k\}$, while k is the number of adjacent clusters. If the normal broadcast frequency is not found adjacent cluster, the base station increase its broadcast frequency until the existence of adjacent clusters
- Secondly, the adjacent clusters broadcast its own color-coded information to the non-adjacent cluster in the frequency f and continue to broadcast until the broadcast coverage of the entire network. There may be some of the clusters that any color-coded cannot reach; these clusters will increase its transmission frequency until you find the existence of the color-coded.
- Third, if a cluster has received only one color-coded, it shows that the cluster has only one path leading to the base station. If receive multiple color-coded, indicating that the cluster can be multipath to transfer data to the Sink. When the color spread over, it can form a multipath to the base station. During construction of the path there will be a cluster received several the same color-coded, the solution is to record the larger weight of the path.

Simulation result indicates that HMR-LEACH outperforms the LEACH protocol and prolongs the life of the network dramatically [23].

In continuing this section discusses the reached results of algorithmic-complexity and statistical-simulation analyses. As follows tables (Tables 3, 4, 5, 6, 7, 8) and figures (Figs. 2, 3, 4) show, HMR-WSN and HMR-LEACH routing protocols are simulated and analyzed by the algorithmic-complexity and statistical techniques. Then, the performance of HMR-WSN is compared with the performance of HMR-LEACH routing protocol. Results of algorithmic-complexity and statistical-simulation analyses (by NS2, TRMSim-WSN, Expert Choice and Grey Relational Analysis tools) show HMR-WSN is improved in terms of energy consumption, the average rate of packet delivery, throughput and accuracy. But, its performance is proportionally degraded in terms of average of route setup time, routing overhead and computational simplicity.

Table 3 Algorithmic-complexity analyses of HMR-WSN and HMR-LEACH routing protocols: proposed criteria, formulas and computations

No.	Criterion	Formula	HMR-WSN	HMR-LEACH
1	Energy Consumption for data transmission: EC [24]	$E_T(K, d) = E_{elec} \times K + \varepsilon_{amp} \times K \times d^2 E_R(K) = E_{elec} \times K$	$2ek + \varepsilon + d^2 + eK' + \varepsilon K' d^4$	$3eK + \varepsilon K\ (d^2 + d^4)$
2	Average rate of Packet Loss: APL	$APL = \left(\frac{1}{DLN} + \frac{1}{BLD} + Con\right) \times \frac{1}{BW} \times \frac{1}{Buff}$	$\frac{0.2+Con_1}{BW_1 \times Buff}$	$\frac{1.2+Con_2}{BW_2 \times Buff}$
3	Average End to End Delay: AEED	$AEED = \frac{L \times (Con+P)+L}{BW \times V}$	$\frac{L \times (Con_1+P_1)+L}{BW_1 \times V}$	$\frac{L \times (Con_2+P_2)+L}{BW_2 \times V}$
4	Average Route Setup Time: ARST	The average delay in the setting up a route between source and destination nodes	$t_{Clusters' \ formation} + t_{CHs \ selection} + t_{CHs \ notification} + t_{Elected \ CHs \ determination} + t_{Balanced \ traffic \ distribution}$	$t_{CH \ selection} + t_{CH \ notification} + t_{Membership \ notification}$
5	Routing Overhead: RO	The volume of transmitting data in the route discovery process	Clusters formation + Multiple CHs selection + Elected CHs determination + $m_1 \times$ Packet $_{CH}$ + $(n-m_1) \times$ $Packet_{Membership}$	CHs selection + $m_2 \times$ Packet $_{CH}$ + $(n-m_2) \times$ $Packet_{Membership}$
6	Throughput	The volume of transmitting data per time unit or per each time interval	C × BW (bps)	BW (bps)

Table 4 Algorithmic-complexity analyses of HMR-WSN and HMR-LEACH routing protocols: assumptions and results

No.	Criterion	Considerations and assumptions	Result of Comparison
1	EC	K' < K	$EC_{HMR\text{-}WSN} < EC_{HMR\text{-}LEACH}$
2	APL	$Con_1 < Con_2$, $BW_1 > BW_2$, $\frac{Con_1}{BW_1} < \frac{Con_2}{BW_2}$	$APL_{HMR\text{-}WSN} < APL_{HMR\text{-}LEACH}$
3	AEED	$P_1 > P_2$, $BW_1 > BW_2$, $Con_1 < Con_2$, $\frac{Con_1}{BW_1} < \frac{Con_2}{BW_2}$	If: $\frac{(Con_1+P_1)}{BW_1} > \frac{(Con_2+P_2)}{BW_2} \Rightarrow$ $AEED_{HMR\text{-}WSN} > AEED_{HMR\text{-}LEACH}$ Else: $AEED_{HMR\text{-}WSN} < AEED_{HMR\text{-}LEACH}$
4	ARST	—	$ARST_{HMR\text{-}WSN} > ARST_{HMR\text{-}LEACH}$
5	RO	m_i: average number of CHs; $m_1 > m_2$	$RO_{HMR\text{-}WSN} > RO_{HMR\text{-}LEACH}$
6	Throughput	C: average number of CHs in each cluster; $C \geq 1$	$Throughput_{HMR\text{-}WSN} \gg Throughput_{HMR\text{-}LEACH}$

Table 5 Abbreviations and associated phrases in the algorithmic-complexity analyses

No.	Abbreviation	Phrase
1	$E_T(K, d)$	Consumed energy for transferring K bit data
2	$E_R(K)$	Consumed energy for receiving K bit data
3	d	Distance between source and destination
4	K	Volume of ready data (bit)
5	K'	Volume of aggregated data (bit)
6	E_{elec}	Required energy for electronic transmission; $E_{elec} = e = 50$ nj/bit
7	ε_{amp}	Signal relay when data transmission to acquiring acceptable signal to noise ratio; $\varepsilon_{amp} = \varepsilon = 100$ pj/bit/m
8	DLN	Capability of deadlock nodes and failure links detection: most attention = 10, no attention = 1
9	Con	Amount of existing congestion
10	BW	Available bandwidth
11	Buff	Size of free buffer
12	BLD	Capability of balanced load distribution: most score = 10 and lowest score = 1
13	L	Average length of each route to the Sink
14	V	Speed of transmission media (for radio waves is 3×10^8 m/s)
15	P	Complexity and volume of intermediate computations and processes
16	t_i	Delay of operation i
17	$Packet_{CH}$	Size of packet: CH notification
18	$Packet_{Membership}$	Size of packet: membership notification

Table 6 Characteristics of the simulation environment

No.	Characteristic	Value
1	Number of executions	10
2	Number of networks	20
3	Number of sensor nodes (min, max)	(500, 1000)
4	Average number of neighbor nodes	6
5	Average number of cluster's members	50
6	Percentage of relay server (CHs)	5%
7	Percentage of malicious servers (min, max)	(0, 50) %
8	Radio range	12

Table 7 Results of simulations

No.	Criterion	HMR-WSN	HMR-LEACH
1	Energy consumption for data transmission	1.69×10^{17}	1.92×10^{17}
2	Average rate of packet loss	23%	38%
3	Throughput	2.14	1.47
4	Accuracy	82.46	54.21
5	Computational complexity	9.34	6.58

Table 8 Results of simulations: normalized functional values

No.	Criterion	HMR-WSN	HMR-LEACH
1	Balanced energy consumption	0.532	0.468
2	Average rate of packet delivery	0.554	0.446
3	Throughput	0.593	0.407
4	Accuracy	0.603	0.397
5	Computational simplicity	0.413	0.587
	Overall performance	0.540	0.460

3.1 Algorithmic-Complexity Analyses

According to the above tables (Tables 3, 4, 5), this section is evaluated and analyzed the performance of HMR-WSN in terms of the algorithmic-complexity criteria and then, comparing it with the HMR-LEACH routing protocol. Results of algorithmic-complexity analyses show HMR-WSN is improved in terms of energy consumption, the average rate of packet loss and throughput. But, its performance is proportionally degraded in terms of average of route setup time and routing overhead.

3.2 Statistical-Simulation Analyses

According to the above tables (Tables 6, 7, 8) and figures (Figs. 2, 3, 4), this section is evaluated and analyzed the performance of HMR-WSN in terms of the statistical-simulation criteria and then, comparing it with the HMR-LEACH routing protocol. Results of

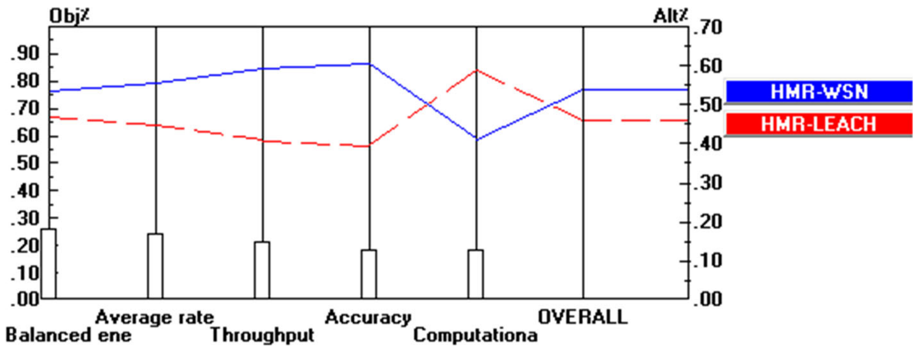

Fig. 2 Comparison between performance of HMR-WSN and HMR-LEACH routing protocols

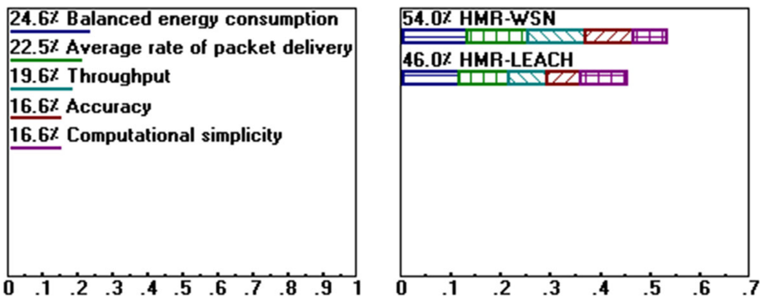

Fig. 3 Sensitivity analysis of the HMR-WSN and HMR-LEACH routing protocols' dynamicity

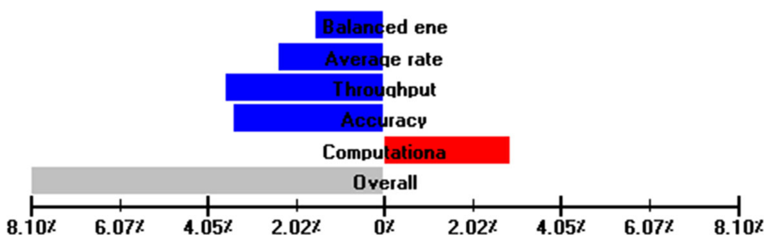

Fig. 4 Weighted head to head sensitivity analysis between HMR-WSN and HMR-LEACH routing protocols

statistical-simulation analyses (by NS2, TRMSim-WSN, Expert Choice and Grey Relational Analysis tools) show HMR-WSN is improved in terms of balanced energy consumption, the average rate of packet delivery, throughput and accuracy. But, its performance is proportionally degraded in terms of computational simplicity.

Table 9 The main characteristics of HMR-WSN: its advantages and disadvantages

No.	Properties	Description
1	Strengths	High scalability and flexibility, data-centric and location-based, and resources-aware and congestion-aware
		No need to maintain multiple paths: reducing the overhead of route maintenance and memory consumption
		Security improvement and secure data transmission: unauthorized access prevention by the traffic load distribution; also, selective forwarding and black-hole attacks reduction by using the different elected CHs for data transmission in the different time intervals
		Possibility of data aggregation: reducing the volume of transmitting data and consumed resources for data transmission
		Improving the QoS parameters like reliability and fault tolerance
		No need to use of the error notification control packet; due to the existence of backup routes (multiple CHs); so, the volume of control traffic will be reduced
		Balanced and distributed energy consumed: dynamic rotation of CHs' role among the cluster's members and balanced and non-uniform traffic load distribution between them
		Congestion control by the traffic load distribution; then, reducing the rate of data packet loss; also, it guarantees the WSN's stability
		Topology-independent and practicality
2	Weaknesses	Security weaknesses like vulnerability against Sybil attack
		Necessity of synchronization in CHs selection
		Energy and time wastage in the multiple CHs selection, elected CHs determination and balanced traffic load distribution phases; then, imposing delay in the WSN's operations
		High computational overhead and complexity

Table 10 Comparison between performance of HMR-WSN and HMR-LEACH routing protocols in terms of the algorithmic-complexity criteria

No.	Criterion	Result of Comparison
1	EC	$EC_{HMR\text{-}WSN} < EC_{HMR\text{-}LEACH}$
2	APL	$APL_{HMR\text{-}WSN} < APL_{HMR\text{-}LEACH}$
3	AEED	If: $\frac{(Con_1+P_1)}{BW_1} > \frac{(Con_2+P_2)}{BW_2} \Rightarrow AEED_{HMR\text{-}WSN} > AEED_{HMR\text{-}LEACH}$ Else: $AEED_{HMR\text{-}WSN} < AEED_{HMR\text{-}LEACH}$
4	ARST	$ARST_{HMR\text{-}WSN} > ARST_{HMR\text{-}LEACH}$
5	RO	$RO_{HMR\text{-}WSN} > RO_{HMR\text{-}LEACH}$
6	Throughput	$Throughput_{HMR\text{-}WSN} \gg Throughput_{HMR\text{-}LEACH}$

Table 11 Improvement percentage of the performance of HMR-WSN than the performance of HMR-LEACH routing protocol in terms of the statistical-simulation criteria

No.	Criterion	HMR-LEACH (%)
1	Balanced energy consumption	+12.03
2	Average rate of packet delivery	+19.49
3	Throughput	+31.37
4	Accuracy	+34.16
5	Computational simplicity	−29.64
	Overall performance	+14.81

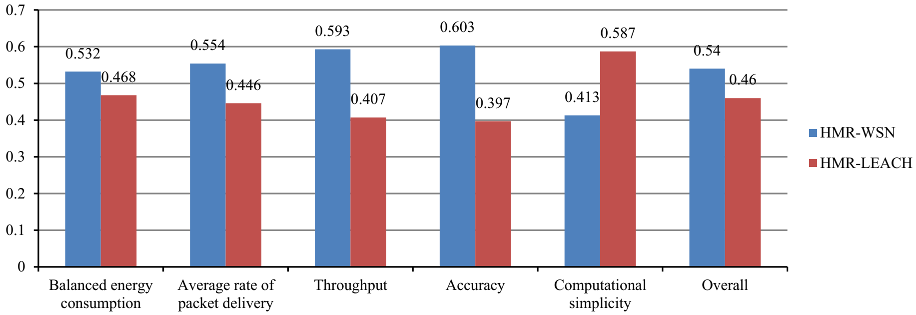

Fig. 5 Comparison between performance of HMR-WSN and HMR-LEACH routing protocols in terms of the statistical-simulation criteria

4 Conclusion and Future Directions

Nowadays, clustering and multipath routing protocols are highly interesting topics in WSNs; but, existing protocols have weaknesses like high overhead and resources' severe consumed, low accuracy, security vulnerabilities, low scalability and permanent usage of optimal paths; then, they are not appropriate for WSNs and should be improved. Therefore, this paper has proposed a hierarchical multipath routing protocol for homogeneous and clustered WSNs, called HMR-WSN. In continuing Table 9 expresses some major characteristics of HMR-WSN.

According to the follows tables (Tables 10, 11) and Fig. 5, the performance of HMR-WSN is compared with the performance of HMR-LEACH routing protocol; results of algorithmic-complexity and statistical-simulation analyses indicate HMR-WSN is improved in terms of energy consumption, the average rate of packet delivery, throughput and accuracy. But, its performance is proportionally degraded in terms of average of route setup time, routing overhead and computational simplicity.

There are several additional issues should be further studied in the future researches. Some of the most challenging proposed topics of these issues are as follows:

- Security analyses of HMR-WSN routing protocol, finding its security vulnerabilities and improving them.
- A secure and trust-based multipath routing protocol for WSNs.
- A method of balanced multiple CHs distribution in the cluster.
- Discussing the data segmentation, data aggregation and data reassembly techniques in the traffic load distribution process.

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