Evolutionary Based Type-2 Fuzzy Routing Protocol for Clustered Wireless Sensor

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ABSTRACT:
Power management is an important issue in wireless sensor network as the sensor nodes are battery-operated devices. For energy efficient data transmission, many routing protocols have been proposed. To achieve energy efficiency in wireless sensor networks, Clustering is an effective approach. In clustering routing protocol, Cluster heads are selected among all nodes within the wireless sensor network and clusters are formed by assigning each node to the nearest cluster. Energy efficiency, network lifetime and uncertainties are the main drawbacks in clustering routing protocols. In this paper, a new clustering routing protocol named T2FLSBA is introduced to select optimal cluster heads. The proposed protocol is based on type-2 fuzzy logic system. To achieve the best performance based on the application, its parameters are tuned based on bat algorithm. The three important factors - residual energy, the density of neighbour sensor nodes and the distance to sink are taken into consideration as inputs of T2FLSBA protocol to compute the probability of a node to be a candidate cluster head. The simulation results show that the proposed routing protocol outperforms the existing clustering routing protocols in terms of prolonging the network lifetime and energy consumption of sensor nodes.

Keywords: Wireless Sensor Network, Type-2 Fuzzy Logic System, Bat Algorithm, Energy Efficiency.

1. INTRODUCTION

Wireless sensor networks are commonly used in all fields of sciences and industries such as area monitoring, machine health monitoring, natural disaster prevention, Air pollution monitoring and etc. A wireless sensor network generally consists of a large number of sensor nodes. The sensor node is equipped with the sensing devices, microprocessor, wireless transmitter and battery. The power supply component in the nodes is very important since the network lifetime depends on energy consumption of the nodes within the network. Therefore, innovative techniques that prolong network lifetime are required.

Nowadays, there are many routing protocol for power management in wireless sensor networks. Clustering routing protocols are one of them that have a suitable performance in these networks[1,2]. In clustering routing protocol, each cluster is formed by a number of adjacent sensor nodes, consists of a Cluster Head (CH) and many cluster members, and data gathered by the sensor nodes is transmitted to the sink through the CHs. Clearly, clustering routing protocols have a variety of advantages, such as scalability, less load, less energy consumption and more robustness. First suggested clustering routing protocol is Lowe Energy Adaptive Clustering Hierarchy (LEACH) protocol. The goal of LEACH is to prolong the lifetime of network by balancing the energy consumption of the sensor nodes[3].

In LEACH protocol, each sensor node uses a stochastic algorithm at each round to decide whether it will become a cluster head in this
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A drawback of LEACH protocol is that the selection of cluster heads is completely stochastic, and the number of cluster heads is constant in all rounds. In order to improve LEACH algorithm, a coverage-preserving energy-based clustering algorithm (CEC) is proposed in [4]. Also, in [5,6] two optimization algorithms are proposed to prolong lifetime of a single-cluster network. A cluster-based architecture is proposed for tracking a mobile target in wireless sensor network to prolong network lifetime in [7]. Based on average energy of wireless sensor network, the cluster-heads are selected by a probability based on the ratio between residual energy of each sensor and the average energy of the network in [8] and was shown the proposed method achieved longer lifetime than current clustering protocols in heterogeneous environments. Also, a clustering algorithm is proposed in [9] based on the high correlation among the overlapped field of views for the wireless multimedia sensor networks. Authors in [10] proposed a power-efficient gathering in sensor information systems to prolong network lifetime of wireless sensor network. In the proposed method, each node communicates only with a close neighbour and takes turns transmitting to the base station. In [11], a novel scheme is proposed for extending network lifetime via joint power allocation and optimal cluster head selection in wireless sensor network by strict constraints on outage probability at the destination.

In last decade, some protocols are proposed based on fuzzy logic system to handle uncertainties in wireless sensor networks. In [12,13], two cluster head selection protocols are proposed based on type-1 fuzzy logic system. Type-2 Fuzzy Logic System (T2FLS) generalize type-1 so that more uncertainty can be handled. T2FLS was introduced by Zadeh[14]. Recently, T2FLS is utilized for clustering routing protocol design in wireless sensor network to prolong network lifetime[15,16].

Clearly, using a T2FLS for CHs selection in the clustering routing protocol will be good as well since a T2FLS can handle not only the rule uncertainties, but also the uncertainties result from measurements or inputs. In this paper, a T2FLSBA protocol has been proposed to select cluster heads in wireless sensor networks. Residual energy, density of neighbour sensor nodes and the distance to sink are taken into consideration as inputs of proposed T2FLSBA to compute the probability of a sensor node to be a candidate CH in each round. The proposed protocol prolong network lifetime and balance the network load effectively. Also, to achieve the best performance based on the application, T2FLSBA parameters are tuned based on bat algorithm.

The rest of the paper is organized as follows: Section 2 briefly reviews some hierarchical clustering routing protocols in wireless sensor network. In section 3, dynamic model of wireless sensor network is introduced. In section 4, the T2FLSBA protocol is proposed as an effective solution to the problem. The optimization procedure of T2FLSBA protocol using bat algorithm is described in section 5. Also, section 6 presents simulation results and comparison with other LEACH-based routing protocols. Finally, section 7 provides summary of the paper.

2. Related works

In last years, various clustering routing protocols are proposed to effectively select CHs in wireless sensor networks, and many of them are based on LEACH protocol. In this section, some clustering routing protocols are discussed that are related to proposed algorithm.

LEACH is a hierarchical protocol in which most nodes transmit to CHs, and the CHs aggregate the data from other sensor nodes and forward it to the sink. Each node uses a stochastic algorithm at each round to determine whether it will become a cluster head in this round. LEACH assumes that each node has a radio powerful enough to directly reach the base station or the nearest cluster head, but that using this radio at full power all the time would waste energy. In set-up phase of each round, each node generate a random number between 0 and 1, if random number is smaller than
threshold value, \( T(n) \), as (1), the node become CH in the round. In (1), \( P \) is the desired percentage of cluster heads, \( r \) is the number of current round and \( G \) is set of sensor nodes that can be selected as CH in current round. In LEACH, sensor nodes that have been CHs cannot become cluster heads again for \( 1/P \) rounds. Other ordinary nodes select the closest CH to determine their cluster in setup phase. In the steady-phase of current round, The CH use Time Division Multiple Access (TDMA) to communicate with the nodes in its cluster.

\[
T(n) = \begin{cases} 
\frac{P}{1 - P \left( \left\lfloor \frac{n}{\sum_{i=1}^{P} \left\lfloor \frac{i}{p} \right\rfloor} \right\rfloor \right)} & \text{if } n \in G \\
0 & \text{otherwise}
\end{cases}
\]

In order to improve the performance of LEACH, a new Power-Efficient Gathering in Sensor Information Systems (PEGASIS) is proposed in [17]. In this work, all sensor nodes are connected in a chain and communication only with the nearest neighbor. A chain-cluster routing protocol (ECR) is proposed in [18]. ECR achieved lower energy consumption than that of LEACH or PEGASIS. In LEACH protocol, residual energy of sensor nodes is not taken into account for CH selection. An extension of LEACH has been introduced, LEACH-EP, that an energy factor is also taken into account[19]. In [20], the paper investigated a distributed LEACH-based CH selection algorithm called LEACH with Distance-based Threshold.

As mention before, fuzzy logic systems are utilized in order to prolong network lifetime in wireless sensor network. In [13], to select cluster heads in each round, a centralized fuzzy logic system is used. In this algorithm, energy level, centrality and concentration are considered as fuzzy logic system inputs. Another improved LEACH protocol using fuzzy logic is proposed in [21]. In [12], a distributed fuzzy-based protocol is proposed. So, sink does not need to collect the information of all nodes. By utilizing randomized periodical rotation together with fuzzy logic, a fuzzy energy-aware unequal clustering algorithm is developed in [22]. Also, a clustering protocol based on a type-2 fuzzy logic and ant colony optimization is proposed in [23]. Also in [24], to prolong network lifetime, a multi-objective fuzzy clustering algorithm is developed.

3. System Model

Consider a wireless sensor network that the sensors are organized into clusters, where one sensor performing as the cluster head in each cluster. All non-cluster head sensors transmit their data to the cluster head in each cluster, and cluster heads transmit gathered data to base station.

3.1 Power consumption model

In order to calculate energy consumption(1) the first order radio communication model [1] is utilized. To transmit an \( l \) bit data packet from the transmitter node to the receiver node with a distance \( d \) between them, the energy consumption for the transmitter node and receiver node can be calculated as (2) and (3) respectively. In (2) and (3), \( E_{elec} \) is the energy dissipation of per bit for transmitter and receiver, \( E_{amp} \) is amplifier energy in free space, \( E_{mp} \) is amplifier energy multipath environment and \( d_0 \) is threshold distance. The distance \( d_0 \) is defined as \( d_0 = \left( \frac{E_{elec}}{E_{mp}} \right)^{1/2} \). Also, \( E_{elec} \) depends on such electronic factors as digital coding, modulation, filtering, and spreading of the signal.

\[
E_{TX}(l, d) = \begin{cases} 
{l \cdot E_{elec} + l \cdot E_{amp} \cdot d^2} & \text{if } d \leq d_0 \\
{1 \cdot E_{elec} + l \cdot E_{amp} \cdot d^2} & \text{if } d > d_0
\end{cases}
\]

4. The proposed clustering based routing protocol

In this paper, a new clustering routing protocol named T2FLSBA is introduced to select optimal cluster heads. The proposed protocol is based on type-2 fuzzy logic system. The three important factors- residual energy as (4), the distance to sink as (5), and the density of neighbor sensor nodes as (6) are taken into consideration as inputs of T2FLSBA to compute the probability of a node to be a candidate cluster head.
where \( N \) is number of alive sensor nodes in the network. \( F \) is desired percentage of nodes to be CHs that is computed as (7) and (8). \( E(n) \) is residual energy of sensor node \( n \). \( d(n, sink) \) is distance from sensor node \( n \) to the sink. In (8), \( M \) is the maximum length of the side of square region, \( d_{sink} \) is the distance between nodes and the sink. Finally, the threshold value of each node can be calculated as (9). In (9), \( COFLS \) is crisp output value of tepe-2 fuzzy logic system.

\[
P = \frac{K}{N} \\
K = \sqrt{\frac{N}{2\pi}} \frac{E_{\text{ avg}}}{d_{\text{sink}}} M \\
T_{\text{2FLSBA}}(u_i) = \begin{cases} 
\text{COFLS} & \text{if } E(n) \geq \frac{1}{N} \sum_{n=1}^{N} E \\
0 & \text{otherwise} 
\end{cases} (9)
\]

A complete fuzzy logic system consists of three main components: Fuzzifier via membership functions, an inference and Defuzzifier via membership functions to create the crisp outputs[25].

**4.1 Fuzzifier**

The fuzzifier maps a numeric vector \( \mathbf{x} = (x_1, x_2, \ldots, x_d) \) into type-2 fuzzy set as \( \tilde{A}_X \).

In this paper, to simplify the calculation, singleton fuzzifier is used. \( \tilde{A}_X \) is a type-2 fuzzy singleton if \( u_{\tilde{A}_X} = 1/1 \) for \( x = x' \) and \( u_{\tilde{A}_X} = 0/1 \) otherwise. As mention before, three important factors- residual energy, the density of neighbour sensor nodes and the distance to sink are taken into consideration as inputs ofT2FLSBA to compute the probability of a sensor node to be a candidate cluster head. For convenience, the domains of inputs are all taken to be the unit interval [0,1] as (10). In (10), \( u_i(n) \) is \( i \)-th input variable for the node \( n \). \( \tilde{u}_i = \min(u_i) \) and \( \max(u_i) \) are the maximum and minimum value of the \( i \)-th input variable among the network. Three membership functions are used for each input. Figure 1, Figure 2 and Figure 3 show the three inputs and their membership functions. Clearly, all secondary membership functions (MFs) are taken to be interval sets. In fuzzy logic system, the output variable is the probability of the sensor node becoming the candidate CH. In this paper, MFs of output variable are shown in Figure 4. As shown in Figure 4, MFs of output variable are divided into seven levels: Very Weak (VW), Weak (W), Little Weak (LW), Medium (M), Little Strong (LS), Strong (S), and VeryStrong (LS).
As mentioned before, three fuzzy membership functions are considered for each input in the proposed fuzzy logic system. So, the number of fuzzy if-then rules is 27. The schematic of a type-2 fuzzy logic system is shown in Figure 5. By denoting three input variables as \( u^1 \), \( u^2 \) and \( u^3 \) and output variable as \( y \), the basic form of the \( l \)-th rule can be described as (11).

\[
\text{Rule } R_l: \text{IF } u^1_l \text{ is } A^{1^l}_l \text{ and IF } u^2_l \text{ is } A^{2^l}_l \text{ and IF } u^3_l \text{ is } A^{3^l}_l \text{ THEN } y \text{ is } B^l
\]

In (11), \( R_l (l = 1, 2, 3) \) are the type-2 antecedent fuzzy sets and \( B^l \) are the type-2 consequent fuzzy sets. Finally, the rules are shown in Table 1.

**Figure 2**: membership functions of second input variable (Distance)

**Figure 3**: membership functions of third input variable (Density)

**Figure 4**: membership functions of output variable (Probability)

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**Table 1: T2FLS Rules**

<table>
<thead>
<tr>
<th>Rule No.</th>
<th>( u^1 )</th>
<th>( u^2 )</th>
<th>( u^3 )</th>
<th>Output variable Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Near</td>
<td>Low</td>
<td>VW</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Near</td>
<td>Medium</td>
<td>VW</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>Near</td>
<td>High</td>
<td>W</td>
</tr>
</tbody>
</table>

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4.3 Output Processing

In this paper, the center of sets type-reducer is utilized. The type-reducer generates a type-1 fuzzy set output, which is then converted in a numeric output through running the defuzzifier. The weight associated with the \( l \)-th centroid is the degree of firing corresponding to \( l \)-th rule, \( \mathbf{[\tilde{\mu}^l(x), \tilde{\nu}^l(x)]} \), in which \( \tilde{\mu}^l(x) \) and \( \tilde{\nu}^l(x) \) are computed by lower membership function and upper membership functions of antecedent type-2 fuzzy sets \( \tilde{\mu}^l \). Therefore, \( \tilde{\mu}^l(x) \) and \( \tilde{\nu}^l(x) \) can be written as (12)and (13)respectively.

\[
\tilde{\mu}^l(x) = \mu_{\tilde{E}}(x_1) \mu_{\tilde{E}}(x_2) \mu_{\tilde{E}}(x_3)
\]

(12)

\[
\tilde{\nu}^l(x) = \nu_{\tilde{E}}(x_1) \nu_{\tilde{E}}(x_2) \nu_{\tilde{E}}(x_3)
\]

(13)

The output of center of sets is as (14).Clearly, this interval set, \( \tilde{\nu}_{con}(x) \), is determined by its two end points that are \( y_m \)and \( y_p \).

\[
y_{con}(x) = [y_m, y_p] = \int_{-\infty}^{y_m} \frac{1}{\sum_{l=1}^{2^d} \sum_{k=1}^{2^d} \tilde{\mu}^l(x)} dx \int_{y_m}^{y_p} \frac{1}{\sum_{l=1}^{2^d} \sum_{k=1}^{2^d} \tilde{\nu}^l(x)} dx \int_{y_p}^{\infty} \frac{1}{\sum_{l=1}^{2^d} \sum_{k=1}^{2^d} \tilde{\mu}^l(x)} dx
\]

(14)

In (14), \( [y_m^t, y_p^t] (t = 1, \ldots, 2^d) \) corresponds to the centroid of type-2 interval consequence set \( \tilde{E}^t \). Clearly, equation reveals the uncertainty at the output of type-2 fuzzy logic system due to rule uncertainties.

4.4 Defuzzifier
From the type-reducer, an interval set $Y_{ecs}(x)$ is obtained to defuzzify it the average of $y_n$ and $y_p$ is used, so the defuzzified output of an interval singleton T2FLS is as follow:

$$y(x) = \frac{y_n + y_p}{2}$$  \hspace{1cm} (15)

5. T2FLSBA optimization procedure

In this paper a new clustering routing protocol is proposed to select cluster heads in each round. The proposed protocol uses some concepts from the sensor nodes details such as: residual energy, the density of neighbour sensor nodes and the distance to sink. In previous section, a T2FLS is proposed to select cluster heads. As shown in Figure 1 to Figure 3, T2FLC have three parameters for input membership functions and $\mathfrak{R}$ parameters for output membership functions. Changing in these parameters leads to have many different operations of proposed algorithm. So, each parameter must be optimized in range of [0,1].

In this paper Bat Algorithm (BA) is utilized to optimize T2FLC parameters. BA [26] is a population-based swarm intelligence algorithm with good global exploration ability among the search space. In this paper, termination of the pre-specified number of iterations is considered as the stopping criterion for optimization phase.

5.1. Fitness function

The fitness function must be defined based on the application specifications. In this paper, the multi-objective fitness function and its constraints are considered as (16). In (16), three objective terms, the first node dies (FND), the half nodes die (HND), and the last node dies (LND) are utilized. Also, $w_1$ to $w_3$ are three constant weights to adjust the relative importance of the three objective terms within the proposed cost function.

$$\text{fitness function} = w_1 \text{FND} + w_2 \text{HND} + w_3 \text{LND}$$

Subject to:

\begin{align*}
0 & \leq M_i \leq 1 \\
0 & \leq T_i \leq 1 \\
0 & \leq L_i \leq 1 \\
0 & \leq G_i \leq 1 \\
\end{align*}  \hspace{1cm} (16)

5.2 Bat Algorithm

BA is a metaheuristic approach that is based on echolocation behaviour of bats. Initial population is generated randomly for $n$ number of bats with $d$ dimensions. To generate the initial population, following equation is used.

$$x_{ij} = x_{\text{min}} + K(x_{\text{max}} - x_{\text{min}})(i - 1, 2, ..., n) \leq x_{ij} \leq x_{\text{max}}$$  \hspace{1cm} (17)

In (17), $K$ is a random number between 0 and 1, $x_{\text{min}}$ is lower boundary for $j$-th parameter and $x_{\text{max}}$ is upper boundary for $j$-th parameter.

5.3 Population updating

Step size to generate new solution in BA is defined by the frequency. The pulse frequency is an arbitrary value for each population. Range of each pulse frequency is between upper and lower boundaries. In other words, Frequency controls the pace and range of movement and update bat position and velocity. The pulse frequency is updated as (18).

In (18), $f_{\text{min}}$ is lower frequency boundary, $f_{\text{max}}$ is upper frequency boundary and $r$ is a random number between 0 and 1. The position and velocity of bat are updated as (19) and (20) respectively.

In and, $x_i \in \mathbb{R}^d$ is position of $i$-th bat in $k$-th iteration, $v_i \in \mathbb{R}^d$ is velocity of $i$-th bat in $k$-th iteration and $x^* \in \mathbb{R}^d$ is the global best solutions in the population.
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\[ f_t = f_{base} + (f_{base} - f_{min}) \alpha \]
\[ v_t^n - v_t^{n-1} + (x_t^{n-1} - x_o^n) f_t \]
\[ x_t^n = x_t^{n-1} + v_t^n \]

To increase exploration, a solution is selected among the best solution and Radom walk is applied. Thus a new candidate solution is generated as (21).
\[ x_{new} = x_{best} + aR \]

where \( R \) is average Loudness of all the Bats and \( a \) is a random number between 0 and 1. In BA Loudness and pulse emission rate must be adjusted as iterations proceed. The loudness and pulse emission rate are updated as (22) and (23) for each bat.
\[ A_{t+1} = aA_t \]
\[ r_{t+1} = r_t[1 - e^{-r^2}] \]

6. Simulation Results

In this section, the performance of T2FLSBA against the LEACH protocol [7], the energy-aware LEACH-EP protocol [17], and the distance-aware LEACH-DT protocol [18] in terms of the total number of data packets received in sink from start of operation, FND, HND and LND are evaluated. The parameter of the network model is shown in Table 2. To illustrate the performance of the proposed protocol, different scenarios are considered. Simulations are performed using Matlab software. Based on network lifetime and application specifications, the fitness function parameters must be set. In this section, the fitness function parameters are \( w_1 = 0.8, w_2 = 0.2 \) and \( w_3 = 0 \). Clearly, the parameters of T2FLSBA protocol must be optimized in first round to prolong network lifetime. Therefore, BA algorithm is utilized to optimized T2FLSBA parameters in each scenario.

Table 2: network parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial energy of nodes</td>
<td>6.5 J</td>
</tr>
<tr>
<td>( E_{elec} )</td>
<td>50 nJ/bit</td>
</tr>
<tr>
<td>( E_{pr} )</td>
<td>10 pJ/bit/m^2</td>
</tr>
<tr>
<td>( E_{rep} )</td>
<td>0.0013 pJ/bit/m^2</td>
</tr>
<tr>
<td>Data Aggregation Energy</td>
<td>5 nJ/bite</td>
</tr>
<tr>
<td>Control packet size</td>
<td>200</td>
</tr>
<tr>
<td>Data packet size</td>
<td>6400 bit</td>
</tr>
</tbody>
</table>

6.1 Scenario I

In the first scenario, the sink is located at the center (100 m, 100 m) of the wireless sensor network. Also, the network dimensions are fixed with 100 m×100 m. Simulation results are shown in Figure 6. In Figure 6, the total number of alive sensor nodes versus rounds is shown. Clearly, the proposed protocol is more suitable than the other protocols, because node deaths begin later and residual energy variance of sensor nodes is reduced. Additionally, quantitative results are shown in Table 3. Clearly, the T2FLSBA protocol outperforms other protocols.
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Figure 6. Number of alive sensor nodes versus rounds in scenario I

Table 3: network parameters in Scenario I

<table>
<thead>
<tr>
<th>Protocol</th>
<th>FND (round)</th>
<th>HND (round)</th>
<th>LND(round)</th>
<th>Total data packets received</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2FLSBA</td>
<td>1535</td>
<td>1563</td>
<td>1649</td>
<td>153900</td>
</tr>
<tr>
<td>LEACH</td>
<td>319</td>
<td>1145</td>
<td>2322</td>
<td>113600</td>
</tr>
<tr>
<td>LEACH-EP</td>
<td>589</td>
<td>1191</td>
<td>1762</td>
<td>118200</td>
</tr>
<tr>
<td>LEACH-DT</td>
<td>683</td>
<td>1233</td>
<td>1800</td>
<td>121100</td>
</tr>
</tbody>
</table>

6.2 Scenario II

In the second scenario, the sink is located at (300 m, 50 m) of the wireless sensor network. Also, the network dimensions are fixed with 100 m x 100 m. Simulation results are shown in Figure 7. As Scenario I, the proposed protocol is more suitable than the other protocols. Finally, quantitative results are shown in Table 4.

Figure 7. Number of alive sensor nodes versus rounds in scenario II

Table 4: network parameters in Scenario II

<table>
<thead>
<tr>
<th>Protocol</th>
<th>FND (round)</th>
<th>HND (round)</th>
<th>LND(round)</th>
<th>Total data packets received</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2FLSBA</td>
<td>150</td>
<td>166</td>
<td>180</td>
<td>16520</td>
</tr>
<tr>
<td>LEACH</td>
<td>18</td>
<td>109</td>
<td>176</td>
<td>10610</td>
</tr>
<tr>
<td>LEACH-EP</td>
<td>42</td>
<td>128</td>
<td>174</td>
<td>12340</td>
</tr>
<tr>
<td>LEACH-DT</td>
<td>132</td>
<td>153</td>
<td>165</td>
<td>15030</td>
</tr>
</tbody>
</table>

6. CONCLUSION

In this paper, a new clustering routing protocol has been proposed to prolong network lifetime in wireless sensor network. The proposed protocol is based on type-2 fuzzy logic system. Three important factors- residual energy, the density of neighbour sensor nodes and the distance to sink are taken into consideration as inputs of T2FLSBA to compute the probability of each sensor node to be a candidate cluster head in the current round. In order to improve performance of proposed algorithm, type-2 fuzzy logic system parameters are optimized. Tuning these parameters is an import issue to achieve the best

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performance. To illustrate the performance of the proposed protocol, different scenarios are considered. Based on simulation results, the T2FLSBA protocol outperforms LEACH, LEACH-EP and LEACH-DT protocols.

REFERENCES


