

Performance evaluation of two fuzzy-based cluster head selection systems for wireless sensor networks

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Abstract. Sensor networks supported by recent technological advances in low power wireless communications along with silicon integration of various functionalities are emerging as a critically important computer class that enable novel and low cost applications. There are many fundamental problems that sensor networks research will have to address in order to ensure a reasonable degree of cost and system quality. Cluster formation and cluster head selection are important problems in sensor network applications and can drastically affect the network's communication energy dissipation. However, selecting of the cluster head is not easy in different environments which may have different characteristics. In this paper, in order to deal with this problem, we propose two fuzzy-based systems for cluster head selection in sensor networks. We call these systems: FCHS System1 and FCHS System2. We evaluate the proposed systems by simulations and have shown that FCHS System2 make a good selection of the cluster head compared with FCHS System1 and another previous system.

1. Introduction

Recent developments in technologies such as wireless communication and microelectronics have enabled Wireless Sensor Network (WSN) applications to be deployed for many applications such as battlefield surveillance and environment monitoring. An important aspect of such networks is that the nodes are unattended, resource-constrained, their energy cannot be replenished and network topology is unknown. The resource-constrained limitations make it essential for these sensor nodes to conserve energy to increase life-time of the sensor network [1–3,15,16].

Recently, there are lot of research efforts towards the optimization of standard communication paradigms for such networks. In fact, the traditional Wireless Network (WN) design has never paid attention to constraints such as the limited or scarce energy of nodes and their computational power.

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Also, in WSN paths can change over time, because of time-varying characteristics of links, local contention level and nodes reliability. These problems are important especially in a multi-hop scenario, where nodes accomplish also at the routing of other nodes' packets [3,22].

There are many fundamental problems that sensor networks research will have to address in order to ensure a reasonable degree of cost and system quality. Some of these problems include sensor node clustering, Cluster Head (CH) selection and energy dissipation. There are many research works that deal with these challenges [4,9–13,17–19].

The cluster based algorithms could be used for partitioning the sensor nodes into subgroups for task subdivision or energy management. Cluster formation is one of most important problems in sensor network applications and can drastically affect the network's communication energy dissipation. Clustering is performed by assigning each sensor node to a specific CH. All communication to (from) each sensor node is carried out through its corresponding CH node. Obviously one would like to have each sensor to communicate with the closest CH node to conserve its energy, however CH nodes can usually handle a specific number of communication channels. Therefore, there is a maximum number of sensors that each CH node can handle. This does not allow each sensor to communicate to its closest CH node, because the CH node might have already reached its service capacity. CHs can fuse data from sensors to minimize the amount of data to be sent to the sink. When network size increases, clusters can also be organized hierarchically.

In the conventional cluster architecture, clusters are formed statically at the time of network deployment. The attributes of each cluster, such as the size of a cluster, the area it covers, and the members it possesses, are static. In spite of its simplicity, the static cluster architecture suffers from several drawbacks. The fixed membership is not robust from the perspective of fault tolerance. If a CH dies of power depletion, all the sensors in the cluster render useless. Also, fixed membership prevents sensor nodes in different clusters from sharing information and collaborating on data processing. Dynamic cluster architectures, on the other hand, offer several desirable features. Formation of a cluster is triggered by certain events of interest.

In this work, we deal with the CH selection. A method for CH selection is as follows. When a sensor with sufficient battery and computational power detects (with a high Signal-to-Noise Ratio: SNR) signals of interest, it volunteers to act as a CH. This is a simple method, because no explicit leader (CH) election is required and, hence, no excessive message exchanges are incurred. However, selecting of the CH in this way is not easy in different environments which may have different characteristics such as error rate, SNR, throughput and so on.

The heuristic approaches based on Fuzzy Logic (FL) and Genetic Algorithms (GA) can prove to be efficient for traffic control in wireless networks [6–8,14].

In this paper, in order to deal with this problem, we propose two fuzzy-based systems for cluster head selection in sensor networks. We call these systems: FCHS System1 and FCHS System2. We evaluate the proposed systems by simulations and have shown that FCHS System2 make a good selection of the cluster head compared with FCHS System1 and another previous system.

The paper is organized as follows. In Section 2, we discuss the related work. In Section 3, we introduce the proposed systems design. In Section 4, we present the simulation results. Conclusions are given in Section 5.

2. Related work

In this section, we review related work in clustering algorithms. Several clustering methods such as weighted clustering [11], hierarchal clustering [9] and dynamic clustering [12] algorithms have been

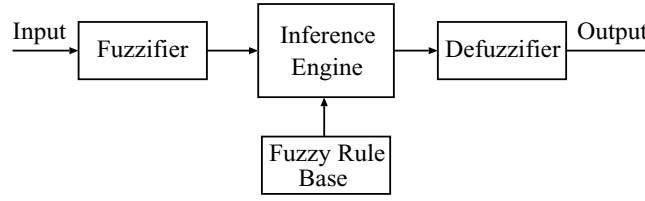


Fig. 1. FLC structure.

proposed to organize nodes as a cluster. Most algorithms elect leaders based on certain weights or iteratively optimize a cost function or use heuristic to generate minimum number of clusters. The Distributed Clustering Algorithm (DCA) [10] assumes quasi-stationary nodes with real-valued weights. The Weighted Clustering Algorithm [11] elects a node based on the number of neighbors, transmission power and so on. The Max-Min d-Clustering Algorithm [4] generates d-hop clusters with a run time of $O(d)$ rounds. This algorithm does not minimize the communicating complexity of sending information to the information center.

The hierarchal clustering scheme [9] uses spanning tree-based approach to produce cluster with certain properties. However, energy efficiency is not addressed in this work. In [13], the authors have proposed an emergent algorithm that iteratively tries to achieve high packing efficiency, however negotiation among nodes to be CH and join cluster based on degree and proximity leads to high amount of communication overhead, thus wastage energy.

LEACH [17,18] uses two-layered architecture for data dissemination. In this scheme, sensors periodically elect themselves as CHs with some probability and broadcast an invitation message for nearby nodes to join the cluster. The nodes that do not intend to be CHs join the cluster based on the proximity of CH, thus minimizing the communicating cost. However, LEACH and PEGASIS [19] require the apriory knowledge of the network topology.

In [20], the authors propose a self-configuring protocol for Wireless Personal Area Networks (WPAN) using an unsupervised clustering method. A fuzzy logic system is used to select the master/controller for each cluster. In our previous work [5], we had shown by simulation results that the selection surface of our system was better than the system in [20].

3. Proposed systems

In this section, we present the design of Fuzzy-based CH Selection (FCHS) systems.

3.1. FLC structure

The Fuzzy Logic Controller (FLC) basic elements are shown in Fig. 1. They are the fuzzifier, inference engine, Fuzzy Rule Base (FRB) and defuzzifier. As shown in Fig. 2, as membership functions we use triangular and trapezoidal membership functions because they are suitable for real-time operation [21]. They are shown in Fig. 2 and are given as:

$$f(x; x_0, a_0, a_1) = \begin{cases} \frac{x-x_0}{a_0} + 1 & \text{for } x_0 - a_0 < x \leq x_0 \\ \frac{x_0-x}{a_1} + 1 & \text{for } x_0 < x \leq x_0 + a_1 \\ 0 & \text{otherwise} \end{cases}$$

Table 1
FRB1

Rule	DS	SP	NT	PCHS
1	NR	LO	LI	LS
2	NR	LO	MU	MD
3	NR	LO	HE	LW
4	NR	ME	LI	S
5	NR	ME	MU	LS
6	NR	ME	HE	MD
7	NR	HG	LI	VS
8	NR	HG	MU	S
9	NR	HG	HE	LS
10	MO	LO	LI	MD
11	MO	LO	MU	LW
12	MO	LO	HE	W
13	MO	ME	LI	LS
14	MO	ME	MU	MD
15	MO	ME	HE	LW
16	MO	HG	LI	S
17	MO	HG	MU	LS
18	MO	HG	HE	MD
19	FA	LO	LI	LW
20	FA	LO	MU	W
21	FA	LO	HE	VW
22	FA	ME	LI	MD
23	FA	ME	MU	LW
24	FA	ME	HE	W
25	FA	HG	LI	LS
26	FA	HG	MU	MD
27	FA	HG	HE	LW

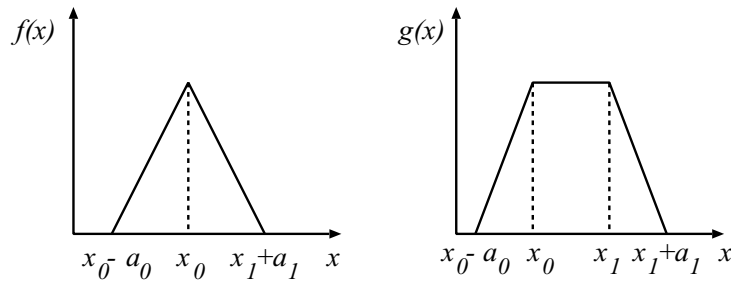


Fig. 2. Triangular and trapezoidal membership functions.

$$g(x; x_0, x_1, a_0, a_1) = \begin{cases} \frac{x-x_0}{a_0} + 1 & \text{for } x_0 - a_0 < x \leq x_0 \\ 1 & \text{for } x_0 < x \leq x_1 \\ \frac{x_1-x}{a_1} + 1 & \text{for } x_1 < x \leq x_1 + a_1 \\ 0 & \text{otherwise} \end{cases}$$

where x_0 in $f(\cdot)$ is the center of triangular function; $x_0(x_1)$ in $g(\cdot)$ is the left (right) edge of trapezoidal function; and $a_0(a_1)$ is the left (right) width of the triangular or trapezoidal function.

3.2. Design of FCHS system1

In FCHS System1, the input linguistic parameters are:

- Distance of Cluster Centroid (DS);
- Remaining Battery Power of Sensor (SP);
- Network Traffic (NT).

The term sets for each input linguistic parameter are defined respectively as:

$$\begin{aligned} T(DS) &= \{Near (NR), Moderate (MO), Far (FA)\}; \\ T(SP) &= \{Low (LO), Moderate (ME), High (HG)\}; \\ T(NT) &= \{Light (LI), Moderate (MU), Heavy (HE)\}. \end{aligned}$$

The membership functions for input parameters of FLC1 are defined as follows:

$$\begin{aligned} \mu_{NR}(DS) &= g(DS; NR_0, NR_1, NR_{w0}, NR_{w1}); \\ \mu_{MO}(DS) &= f(DS; MO_0, MO_{w0}, MO_{w1}); \\ \mu_{FA}(DS) &= g(DS; FA_0, FA_1, FA_{w0}, FA_{w1}); \\ \mu_{LO}(SP) &= g(SP; LO_0, LO_1, LO_{w0}, LO_{w1}); \\ \mu_{ME}(SP) &= g(SP; ME_0, ME_1, ME_{w0}, ME_{w1}); \\ \mu_{HG}(SP) &= g(SP; HG_0, HG_1, HG_{w0}, HG_{w1}); \\ \mu_{LI}(NT) &= g(NT; LI_0, LI_1, LI_{w0}, LI_{w1}); \\ \mu_{MU}(NT) &= f(NT; MU_0, MU_{w0}, MU_{w1}); \\ \mu_{HE}(NT) &= g(NT; HE_0, HE_1, HE_{w0}, HE_{w1}). \end{aligned}$$

The small letters $w0$ and $w1$ mean left width and right width, respectively.

The output linguistic parameter is the Possibility of CH Selection. We write for short as *PCHS*. We define the term set of *PCHS* as: $\{Very Weak (VW), Weak (W), Little Weak (LW), Medium (MD), Little Strong (LS), Strong (S), Very Strong (VS)\}$.

The membership functions for the output parameter *PCHS* are defined as follows:

$$\begin{aligned} \mu_{VW}(PCHS) &= g(PCHS; VW_0, VW_1, VW_{w0}, VW_{w1}); \\ \mu_W(PCHS) &= f(PCHS; W_0, W_{w0}, W_{w1}); \\ \mu_{LW}(PCHS) &= f(PCHS; LW_0, LW_{w0}, LW_{w1}); \\ \mu_{MD}(PCHS) &= f(PCHS; MD_0, MD_{w0}, MD_{w1}); \\ \mu_{LS}(PCHS) &= f(PCHS; LS_0, LS_{w0}, LS_{w1}); \\ \mu_S(PCHS) &= f(PCHS; S_0, S_{w0}, S_{w1}); \\ \mu_{VS}(PCHS) &= g(PCHS; VS_0, VS_1, VS_{w0}, VS_{w1}). \end{aligned}$$

The fuzzy membership functions for input parameters are shown in Fig. 3. The FRB is shown in Table 2 and forms a fuzzy set of dimensions $|T(DS)| \times |T(SP)| \times |T(NT)|$, where $|T(x)|$ is the number of terms on $T(x)$. The FRB1 has 27 rules. The control rules have the following form: IF “conditions” THEN “control action”.

Table 2
FRB2

Rule	RPS	D3N	DCC	PCHS
1	Lo	Fw	Nr	VW
2	Lo	Fw	Mo	W
3	Lo	Fw	Fr	W
4	Lo	Me	Nr	W
5	Lo	Me	Mo	W
6	Lo	Me	Fr	W
7	Lo	Mn	Nr	VW
8	Lo	Mn	Mo	VW
9	Lo	Mn	Fr	VW
10	Mi	Fw	Nr	W
11	Mi	Fw	Mo	LW
12	Mi	Fw	Fr	MD
13	Mi	Me	Nr	LW
14	Mi	Me	Mo	MD
15	Mi	Me	Fr	LS
16	Mi	Mn	Nr	MD
17	Mi	Mn	Mo	LS
18	Mi	Mn	Fr	S
19	Hg	Fw	Nr	LW
20	Hg	Fw	Mo	MD
21	Hg	Fw	Fr	LS
22	Hg	Me	Nr	MD
23	Hg	Me	Mo	LS
24	Hg	Me	Fr	S
25	Hg	Mn	Nr	LS
26	Hg	Mn	Mo	S
27	Hg	Mn	Fr	VS

3.3. Design of FCHS system2

We found that the number of the neighbor nodes is very important for the selection of the CH. To explain this effect let us consider a small network model with 14 nodes as shown in Fig. 4. In this figure, the node number 1 has 6 neighbor nodes, for this reason is selected as a CH. After that, 2 other sets of nodes remain, but node 2 has more neighbor nodes than nodes 3 and 7, thus node 2 is selected as CH. Finally, if we see 2 other remained nodes (node 3 and node 7), they have the same neighbor nodes that are not included in other clusters. In this case, the node with higher ID number is selected as CH. For this reason, node 7 is selected as CH and the procedure of CH selection is finished as shown in Fig. 5.

By considering the number of neighbor nodes as a fuzzy input parameter, we propose 3 input linguistic parameters for FCHS System2:

- Remaining Battery Power of Sensor (RPS);
- Degree of Number of Neighbor Nodes (D3N);
- Distance from Cluster Centroid (DCC).

The term sets for each input linguistic parameters are defined respectively as:

$$T(RPS) = \{Low(Lo), Middle(Mi), High(Hg)\};$$

$$T(D3N) = \{Few(Fw), Medium(Me), Many(Mn)\};$$

$$T(DCC) = \{Near(Nr), Moderate(Mo), Far(Fr)\}.$$

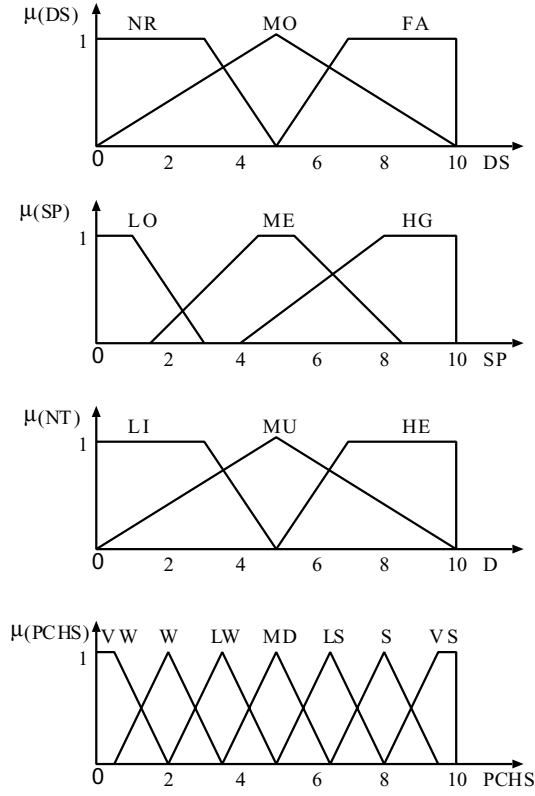


Fig. 3. Membership functions for FCHS system1.

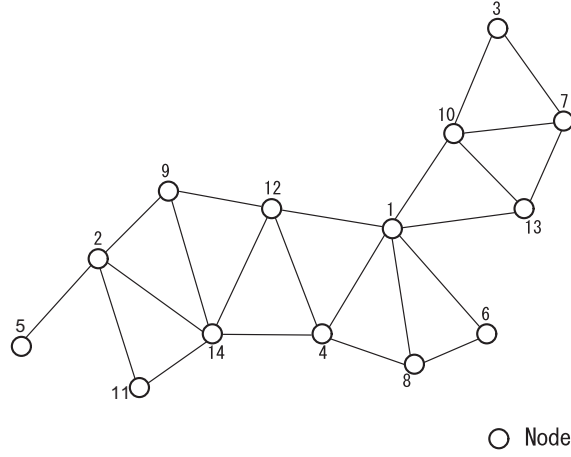


Fig. 4. A network model with 14 nodes.

The membership functions for input linguistic parameters of FLC are defined as follows:

$$\mu_{Lo}(RPS) = g(RPS; Lo_0, Lo_1, Lo_{w0}, Lo_{w1});$$

$$\mu_{Mi}(RPS) = f(RPS; Mi_0, Mi_{w0}, Mi_{w1});$$

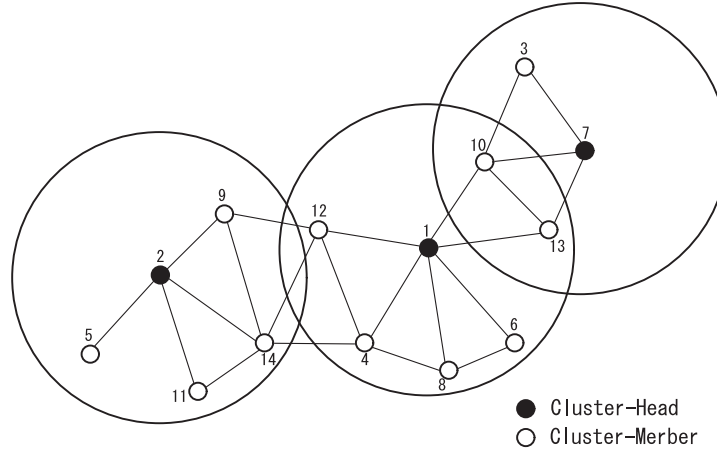


Fig. 5. CH selection process.

$$\mu_{Hg}(RPS) = g(RPS; Hg_0, Hg_1, Hg_{w0}, Hg_{w1});$$

$$\mu_{Fw}(D3N) = g(D3N; Fw_0, Fw_1, Fw_{w0}, Fw_{w1});$$

$$\mu_{Me}(D3N) = f(D3N; Me_0, Me_{w0}, Me_{w1});$$

$$\mu_{Mn}(D3N) = g(D3N; Mn_0, Mn_1, Mn_{w0}, Mn_{w1});$$

$$\mu_{Nr}(DCC) = g(DCC; Nr_0, Nr_1, Nr_{w0}, Nr_{w1});$$

$$\mu_{Mo}(DCC) = f(DCC; Mo_0, Mo_{w0}, Mo_{w1});$$

$$\mu_{Fr}(DCC) = g(DCC; Fr_0, Fr_1, Fr_{w0}, Fr_{w1}).$$

The output linguistic parameter is the *PCHS* and we define the term set the same as FCHS System1: {Very Weak (VW), Weak (W), Little Weak (LW), Medium (MD), Little Strong (LS), Strong (S), Very Strong (VS)}.

The membership functions for the output linguistic parameter *PCHS* are:

$$\mu_{VW}(PCHS) = g(PCHS; VW_0, VW_1, VW_{w0}, VW_{w1});$$

$$\mu_W(PCHS) = f(PCHS; W_0, W_{w0}, W_{w1});$$

$$\mu_{LW}(PCHS) = f(PCHS; LW_0, LW_{w0}, LW_{w1});$$

$$\mu_{MD}(PCHS) = f(PCHS; MD_0, MD_{w0}, MD_{w1});$$

$$\mu_{LS}(PCHS) = f(PCHS; LS_0, LS_{w0}, LS_{w1});$$

$$\mu_S(PCHS) = f(PCHS; S_0, S_{w0}, S_{w1});$$

$$\mu_{VS}(PCHS) = g(PCHS; VS_0, VS_1, VS_{w0}, VS_{w1}).$$

The fuzzy membership functions for input parameters are shown in Fig. 6. The FRB2 has 27 rules.

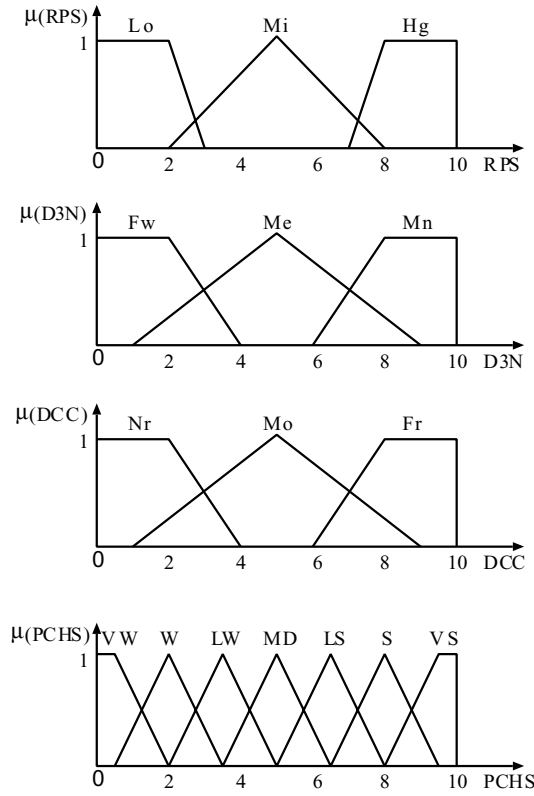


Fig. 6. Membership functions for FCHS system1.

4. Simulation results

In this section, we present the simulation results. We evaluate by computer simulations the performance of the previous system, FCHS System1 and FCHS System2.

In Fig. 7 is shown the performance evaluation of the previous system [20]. The graph in 3 dimensions shows the relation between the possibility of a sensor to be selected as a CH versus the distance and the remained sensor power. With the increase of the remained sensor power and the decrease of the distance between the sensor and sink, the possibility of a sensor to be selected as CH is increased. However, the graph surface is increased almost proportionally with the change of both parameters.

The performance evaluation of FCHS System1 is shown in Figs 8, 9 and 10. In Fig. 8 is shown the relation between the possibility of a sensor to be selected as a CH versus the distance and the remained sensor power. This is the same relation with the previous system. With the increase of the remained sensor power and the decrease of the distance between the sensor and the sink, the possibility of a sensor to be selected as CH is increased. However, the surface control of FCHS System1 is better than previous system, which results in a better CH selection and increase of the network lifetime. In Fig. 9 is shown the relation between the possibility a sensor to be selected as a CH versus the network traffic and the remained sensor power. The behavior of FCHS System1 for these parameters is almost the same with the performance in Fig. 8.

In Fig. 10 is shown the relation between the possibility of a sensor to be selected as a CH versus the distance and the network traffic situation. With the increase of the network traffic and the increase of

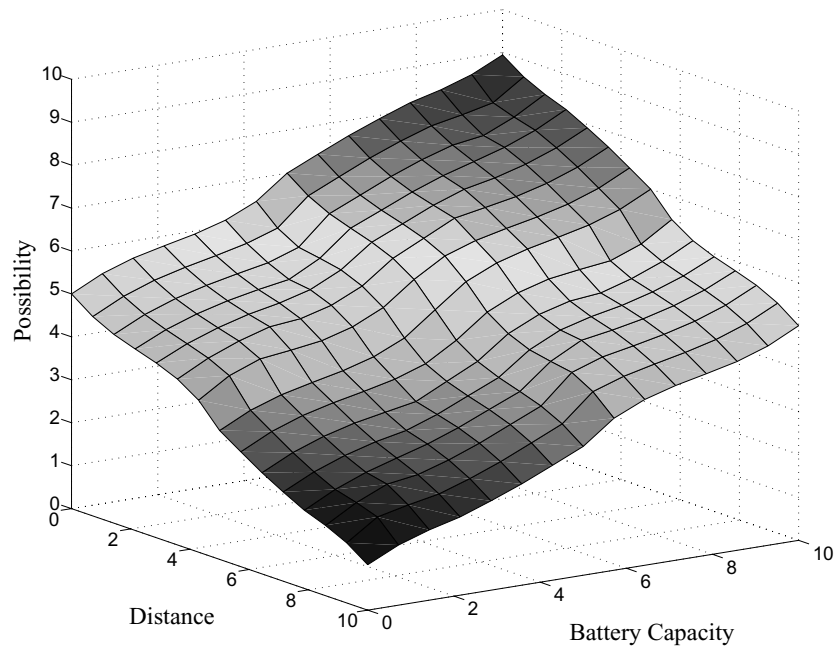


Fig. 7. Previous system simulation results.

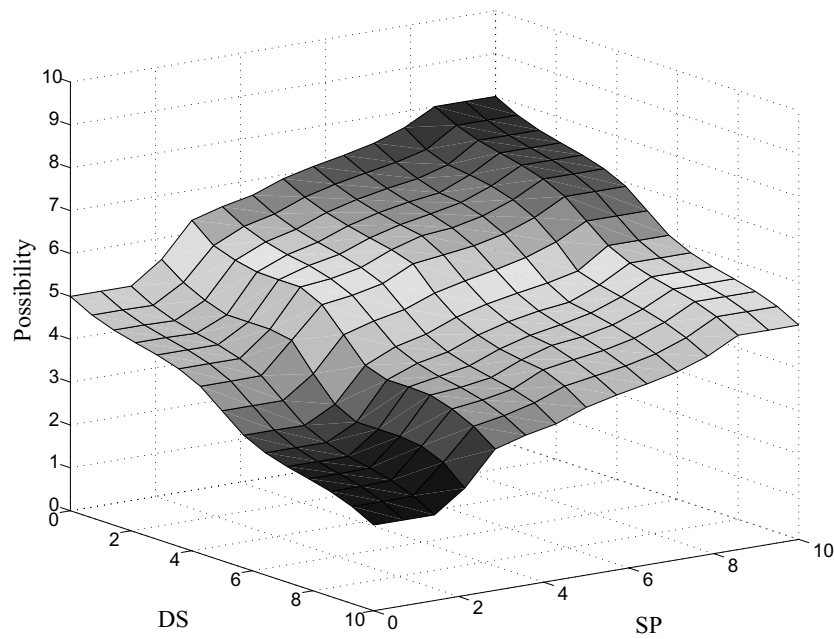


Fig. 8. FCHS System1 results (case 1).

the distance between the sensor and sink, the possibility of a sensor to be selected as CH is decreased. Different from the results in Figs 8 and 9, we see that the shape of the surface is changed proportionally with the changes of parameters. This shows, the remained battery power of a sensor is more important

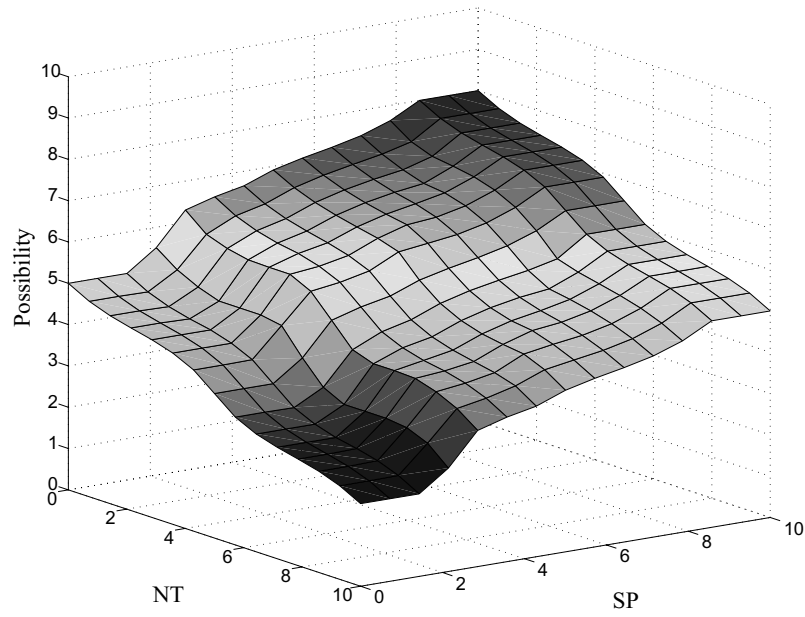


Fig. 9. FCHS System1 results (case 2).

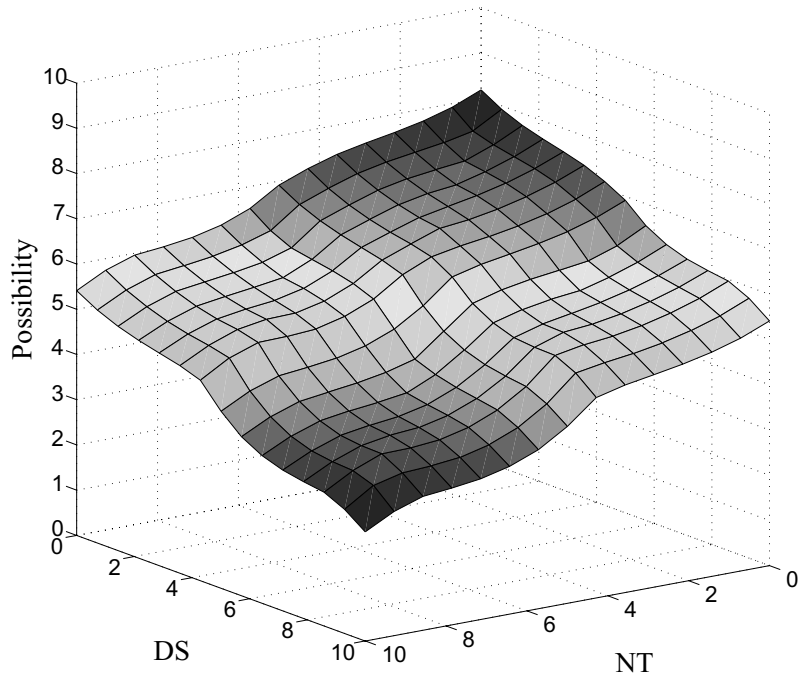


Fig. 10. FCHS System1 results (case 3).

for the selection of a CH than the traffic conditions.

We show the performance of FCHS System2 in Figs 11, 12 and 13. In Fig. 11 is shown the same relation with previous system and FCHS System1. The CH selection surface of proposed system is

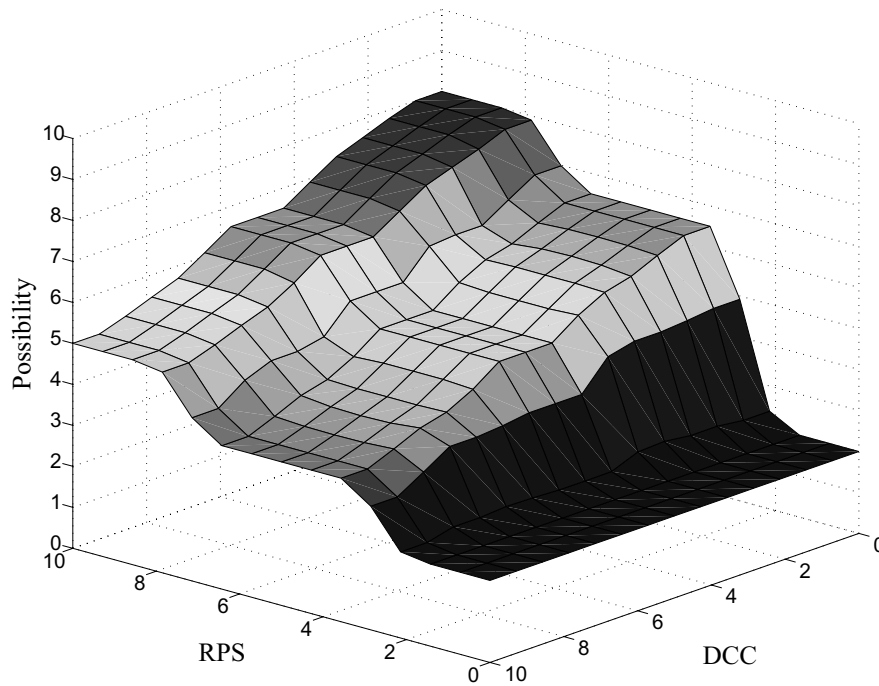


Fig. 11. FCHS System2 results (case 1).

better than the other systems. We clearly distinguish 3 zones. When, the RPS is less than 2 units the probability of a node to be selected as CH is very small. A middle zone (more than 2 units but less than 8 units), where the CH selection possibility increases slowly with increase of the RPS and decrease of DCC. A third zone (more than 8 units), where the possibility of a node to be CH is high. In this way, the proposed system can control better the RPS, which results in the increase of the network lifetime.

In Fig. 12 is shown the relation between the possibility of a sensor to be selected as a CH versus the D3N and RPS. Also, here we see 3 zones. When the RPS is low and the number of neighbor nodes (D3N) is high, the possibility that a node to be selected as CH is low. When the RPS is middle and the D3N increases, the possibility that a node to be selected as CH is increased. When the RPS is high and the D3N is high, the possibility that a node to be selected as CH is high.

In Fig. 13, we show the relation between possibility of a sensor to be selected as a CH versus the D3N and DCC. With the increase of D3N and the decrease of DCC, the possibility of a sensor to be selected as CH is increased. Different from the results in Figs 11 and 12, we see that the shape of the surface is changed proportionally with the changes of parameters. This shows that the RPS and 3DN parameters are more important for the selection of a CH than the DCC.

In Fig. 14, we show the comparison performance of the previous system, FCHS System1 and FCHS System2. When, the remaining battery power is more than 6 units, the previous system and FCHS System1 have almost the same behavior. When, the remaining battery power is between 2 and 6 units, FCHS System1 has better behavior than the previous system. However, when the remaining battery power is less than 1 unit, the probability of CH selection of FCHS System 1 is higher than the previous system. The performance of FCHS System 2 is better than the previous system and FCHS System1. When the remaining battery power is less than 2 units, the probability of the sensor to be selected as CH in FCHS System2 is very small. When the remaining battery power is between 3 and 7 units, the

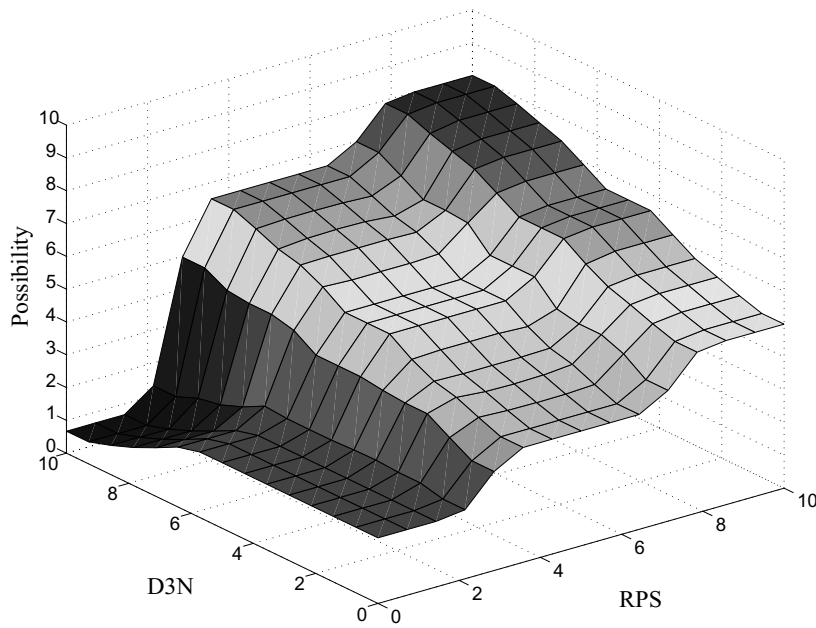


Fig. 12. FCHS System2 results (case 2).

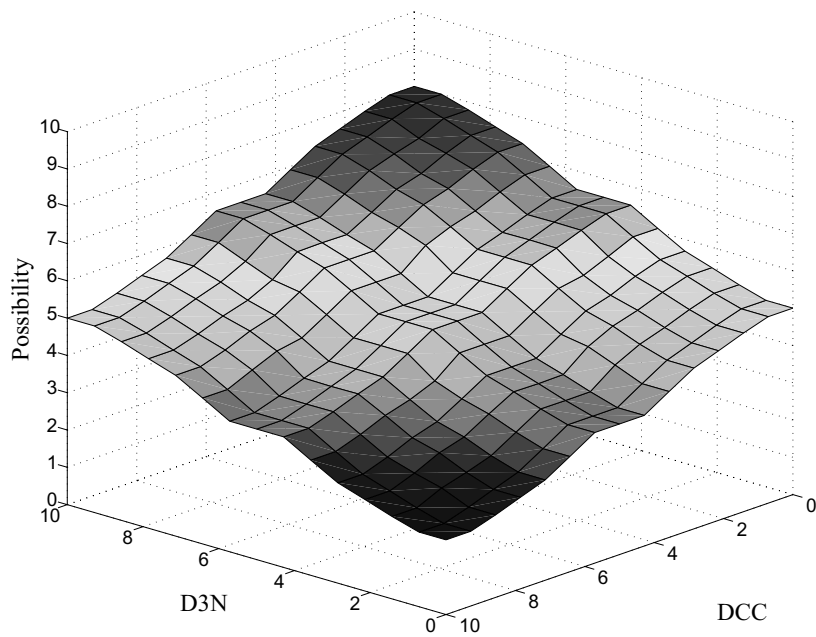


Fig. 13. FCHS System2 results (case 3).

possibility of CH selection is almost the same. For remaining battery power is more than 7 units, FCHS System2 has almost the same behavior with other systems. In this way, FCHS System2 can control better the energy of the sensor and thus increase the overall network lifetime.

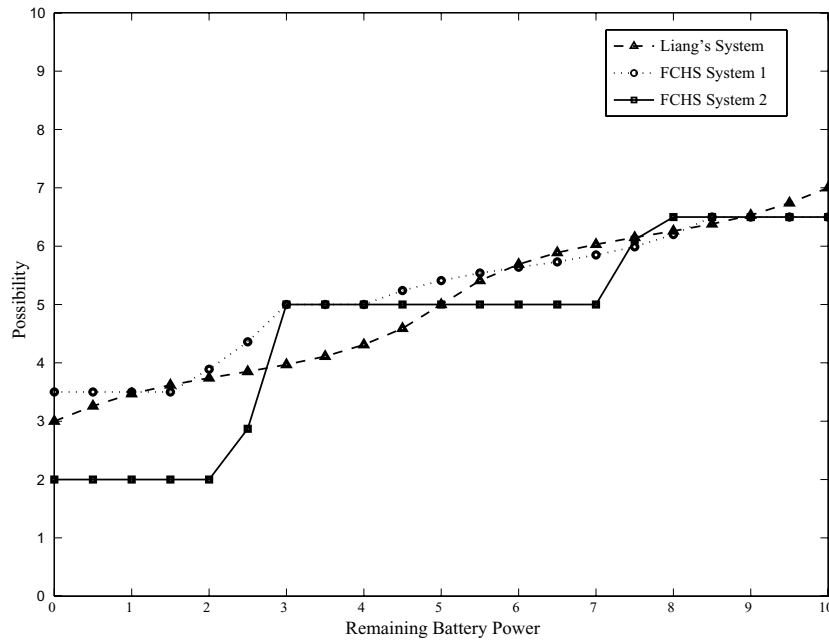


Fig. 14. Comparison between different systems.

5. Conclusions

The power conservation in WSN is a very important issue. Conserving power prolongs the lifetime of a node and also the lifetime of the whole network. Clustering is one of the energy-efficient techniques for extending the lifetime of a sensor network. Clustering techniques organize the nodes into clusters where some nodes work as CHs and collect the data from other nodes in the clusters. However, CH selection is very difficult when many parameters are used for making the decision.

In this paper, we proposed two CH selection systems based on FL. We evaluated their performance by computer simulations. The FCHS System2 shows better performance than the previous system and FCHS System1. We found that, the remained energy of the sensor and the number of neighbor nodes are more important parameters for CH selection than the distance of the node from the sink.

We are working now to implement the proposed system in NS-2 simulator in order to compare the performance with other non fuzzy-based approaches such as LEACH. In the future, we want to extend our work for large-scale WSNs.

Acknowledgment

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