IMPERIAL COLLEGE LONDON

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DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2004

MSc and EEE/ISE PART IV: M.Eng. and ACGI

FUZZY SYSTEMS

~~Thursday, 20 May 9:30 am~~

~~Time allowed: 0:15 hours~~

This course is assessed by coursework, plus a short oral exam. Details follow

~~**There are ZERO questions on this paper.**~~

~~**Answer ZERO questions.**~~

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : P. De Wilde
Second Marker(s) : E.H. Mamdani

Ξ4 75
Jsc 4.25
C 2.4

Fuzzy Systems Exam Coursework 2003-2004 Deadline April 26th 2004 at 10.00 am *

Download the research paper *Designing Power-Aware Self-Reconfiguring Topology for Mobile Wireless Personal Area Networks Using Fuzzy Logic*, Qilian Liang, IEEE Transactions on Systems, Man, and Cybernetics, Part C, Vol. 33, No. 3, p. 390–394, August 2003 via the library's electronic journals access.

This paper uses fuzzy clustering and fuzzy associative memory to select the master/controller in a wireless personal area network. The aim of this coursework is to evaluate whether the fuzzy associative memory can be replaced by a non-fuzzy heuristic. Read section I. Do not look up any references. You do not have to understand the low-energy adaptive clustering hierarchy (LEACH) algorithm. Read section II A. How would you modify the cost function (1) if the signal has to pass through different types of media (1/20)?

Section II B explains the fuzzy c-means clustering algorithm. The book by Ross that is used as part of the course text also explains this algorithm. Why does the column sum of $\mathbf{V}_{cn}$ has to be equal to 1, but not the row sum (1/20)? The word prototype here means just a vector, it has nothing to see with learning. The solutions of the minimization procedure (5) are called stationary points, implying that the function J does not change at these points. There is no stochastic process here. For the inner product induced norm in Theorem 1, you can just assume Euclidean distance. The minus sign in (7) means subtraction of sets. Equations (8) and (9) show different results for the elements u_{ik} depending on the set I_k. In equation (9), read $\tilde{I}_k$ instead of $\tilde{i}_k$. The result (10) holds for both (8) and (9). The matrix norm can be the sum of the squares of the elements in the matrix.

Familiarize yourself with fuzzy c-means using the Matlab function `fcm` from the fuzzy toolbox. Check from a simple example (for example 3 points) that `fcm` does the same as the method described in section II B. Then try

*Post it in the appropriate locked box in the undergraduate office, level 6.

1/12/2003

more points. Would it be possible to use Matlab `fcm` in a real-time communication application (1/20)?

Section II C describes the selection of the master/controller from among the nodes (the paper uses the term "election" rather than selection). Give an example of the operations $\star$ and $\mathcal{T}_{i=1}^{p}$ in equation (11) (1/20). The set G^l is called a consequent because it comes after THEN in the IF-THEN rule. Is equation (12) the same as the center of gravity (centroid)? Section II B 2) explains the criterium for a node to become master/controller of a cluster. Make sure you understand (13), table I and figure 4 well. You should be able to understand how figure 5 is obtained.

The main part of your coursework consists of two tasks. First, determine whether you can replace the master/controller selection procedure by a heuristic that does not use membership functions. The heuristic can be a formula or a procedure (algorithm). Using simulations, you have to convince me either that the heuristic is a good approximation, or that it is not possible to find a good approximation (5/20). You can use constructs from the Matlab fuzzy toolbox if you want, but you need to be able to describe what you have programmed without reference to Matlab. This first task does not include the use of fuzzy clustering.

Secondly, implement master/controller selection using your best heuristic. Do this using the Matlab `fcm` function. Explain your algorithm without listing code (2/20). What I want to see is how well your procedure works, for different densities of nodes. Figure 5 in the paper, for example, is not very informative. Decide for yourself how many nodes to use. Choosing a large number of nodes is not necessarily better to verify hypotheses. Go beyond a mere description of your simulations, try to be as general as they allow you to be (4/20).

Read sections III and IV as well. The exam is not based on them, but they will help you to better understand the problem. Use `fcm` together with `initfcm` and your CID number to make your simulations different from those of your friends. Use the CID number on your college security card, multiplied by a power of 10 of your own choice, but such that the significant digits used make your simulations verifiably different from those of your friends. I should be able to verify the difference from your report, not by inspecting your code.

The Challenge. If you want to get top marks, you have to do this challenge. However, you will get better marks for a good report without the challenge than for a mediocre report with the challenge solved.

A random graph consists of vertices (nodes) and edges (links). Two nodes are connected by an edge with probability $p \in [0, 1]$. If you had to select a master/controller in a random graph, how would you do that? (You do not have to actually do it, just explain). You need to describe how you do the clustering (2/5), and how you select the master (1/5). Use formulas as well as words. How would you define a fuzzy partition of a random graph (2/5)? A lot has been published on random graphs, but the solution to this challenge will be new.

You could organize your work as follows.

day 1 Read the paper, looking up anything you don't understand in your lecture notes. Plan what you are going to program. Do not contact the author of the paper, he has been asked to ignore your emails.

day 2 Answer the questions that can be answered without programming. Do the programming, and debug your program.

day 3 Run the simulations, and collect the results in a form that you can present in your report. Simulations can be in any programming language, on any machine. The use of Matlab will simplify your work, but make sure that you have control over the parameters that you want to vary.

day 4 Write the report. It should be maximum six pages (single sided) a4, in a font not smaller than 10 point. You will not get marks for anything exceeding six pages, even if it is appendices. Font size in tables and figures should be at least 10 point, or the tables and figures will not be marked. Describe the problem, and how you have solved it. Describe your simulations, but do not give programme listings. Do not give references to the literature. Make sure you do and answer everything that is asked for in the coursework. Do not bind the report, but staple the pages together. Mention your name, and for what degree (e.g. MEng Elec. Eng., MEng ISE, MSc) you are studying.

day 5 Check the consistency and quality of your work. Make last minute changes if necessary. If you feel confident and have the time, tackle the challenge. Resist the temptation to spend more than five 8-hour days of intensive effort on your coursework. You will not be compensated for it in marks. Just as an exam paper requires a concentrated effort over a few hours, this coursework requires a concentrated effort over a few days.

Do not forget to attend on the "exam" day, to be advertised in your exam schedule. Bring a copy of your report with you, and your college security card. I will ask you one or two questions based on what you have written in your report, to make sure that you have written it yourself. No preparation is necessary. Good luck.

Dr. P. De Wilde

Designing Power Aware Self-Reconfiguring Topology for Mobile Wireless Personal Area Networks Using Fuzzy Logic

Qilian Liang

Abstract—In mobile wireless personal area networks (WPAN), the position of each node changes over time. A network protocol that is able to dynamically update its links in order to maintain strong connectivity is said to be "self-reconfiguring." In this paper, we propose a mobile wireless personal area networks (WPAN) design method with self-reconfiguring protocol for power efficiency. The WPAN is self-organized to clusters using an unsupervised clustering method, fuzzy c-means. A fuzzy logic system is applied to master/controller election for each cluster. A self-reconfiguring topology is proposed to manage the mobility and recursively update the network topology. We also modify the mobility management scheme with hysteresis to overcome the *ping-pong* effect. Simulation results show that our scheme performs much better than the existing algorithm.

Index Terms—Fuzzy logic, personal area network, power aware, topology.

I. Introduction

The IEEE 802 Working Group has developed a set of standards for short range wireless communications commonly referred as wireless personal networks (WPAN) [15]. To address the need for low-power low-cost wireless personal area networks, the IEEE New Standards Committee officially sanctioned a new task group in December 2000 to begin the development of low-rate WPAN (LR-WPAN) standard, called 802.15.4. The goal of Task Group 4, as defined in the Project Authorization Request [11], is to provide a standard having ultra-low complexity, cost, and power for low-data-rate wireless connectivity among inexpensive fixed, portable, and moving devices. Generally an LR-WPAN network is organized as a star or peer to peer topology depending on the application. A network topology may considerably affect the overall power consumption of the system. Thus, it is important to design a topology for self-organizing WPAN to reduce the power consumption. Conserving battery power is very significant because battery life is not expected to increase significantly in the coming years. In additions, for mobile WPAN, the position of each node changes over time, the protocol must be able to dynamically update its links in order to maintain strong connectivity. A network protocol that achieves this is said to be "self-reconfiguring" [13]. In this paper, we propose a power aware self-reconfiguring topology for mobile WPAN.

In [13], Rodoplu and Meng developed a general mathematical theory for designing a minimum power topology within one cluster for a stationary network. Their approach only considers the immediate locality of a node. McDonald and Znati [8] proposed an (α, t) cluster to help minimize the far-reaching effects of topological changes while balancing the need to support more optimal routing. In [20], Wu *et al.* combined the concept of power control and with busy-tone-based protocols to further increase channel utilization. Similar to [20], a power control loop was proposed in [1] to control the transmitting and receiving power level in ad-hoc wireless network. In [21], a location aided power aware routing protocol was proposed. In [6], a power-efficient gathering in sensor information systems (PEGASIS) method is proposed, but no mobility of sensor nodes is assumed, which is not true for mobile ad hoc networks. Singh *et al.* [16] proposed power-aware routing and discussed different metrics in power-aware routing; Li *et al.* [5] extended their work and proposed an online power aware routing in wireless ad-hoc networks. In [14], a power aware virtual base stations (PA-VBS) protocol was proposed, which elect a mobile node from a set of nominees to act as a base station. In [18], a new power aware routing protocol was proposed to evenly distribute the power consumption rate of each node and minimize the the overall transmission power for each connection request simultaneously. In [4], a low-energy adaptive clustering hierarchy (LEACH) scheme was proposed in [4]. In this paper, we propose a power aware self-reconfiguring topology for mobile WPAN.

The rest of the paper is organized as follows. In Section II, we propose a power aware topology for WPAN. In Section III we propose a self-reconfiguring topology for mobile WPAN, and this scheme is modified with hysteresis to overcome the *ping-pong* effect. In Section IV, we compare our algorithm against the LEACH algorithm proposed in [4]. Conclusions are presented in Section V.

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II. Power Aware Topology for WPAN

A. Power Consumption Model and Cost Function

Three models are often used for wireless communications: path loss, large-scale variations, and small-scale variations [12]. Similar to [13], we concentrate only on path loss that has distance dependence which is well modeled by $1/d^p$, where d denotes the distance between the transmitter and receiver antennas, and the exponent p is determined by the field measurements for the particular system at hand [12], for example, $p = 2$ for free space, $p = 1.6$–1.8 for in building line-of-sight, and $p = 4$–6 for obstructed in building. Suppose there are c clusters in the WPAN, and m_i nodes in the ith cluster, we use the following cost function to minimize the power consumption

$$J \triangleq \sum_{i=1}^{c} \sum_{k=1}^{m_i} (d_{ik})^p \tag{1}$$

where p (path-loss exponent) is a constant for a fixed environment, and

$$d_{ik} = \|\mathbf{x}_k - \mathbf{v}_i\| \tag{2}$$

where $\|\cdot\|$ is the Euclidean distance between one node ($\mathbf{x}_k$) and its cluster center ($\mathbf{v}_i$), where $\mathbf{x}_k$ and $\mathbf{v}_i$ can be 2-D or 3-D geography information. We partition the network to clusters via minimizing the total power consumption using an unsupervised clustering—Fuzzy c-Means (FCM).

B. Network Partition Using an Unsupervised Clustering—Fuzzy c-Means

FCM clustering is a data clustering technique where each data point belongs to a cluster to a degree specified by a membership grade. This technique was originally introduced by Bezdek [2] as an improvement on earlier clustering methods. Here we apply FCM clustering to WPAN partition. Our objective is to partition n nodes to c clusters which will consume minimum power.

Definition 1 (Fuzzy c-Partition for WPAN): Let $\mathbf{X} = x_1, x_2, \ldots, x_n$ be n nodes, $\mathbf{V}_{cn}$ be the set of real $c \times n$ matrices, where $2 \le c < n$. The Fuzzy c-partition space for $\mathbf{X}$ is the set

$$M_{fc} = U \in V_{cn} | u_{ik} \in [0, 1] \quad \forall\, i, k \tag{3}$$

where

$$\sum_{i=1}^{c} u_{ik} = 1 \quad \forall\, k$$

and

$$0 < \sum_{k=1}^{n} u_{ik} < n \quad \forall i.$$

The row i of matrix $U \in M_{fc}$ contains values of the ith membership function, u_i, in the fuzzy c-partition U of $\mathbf{X}$.

Definition 2 (Fuzzy c-Means Functionals): We modify (1) to

$$J(\mathbf{U}, \mathbf{v}) = \sum_{i=1}^{c} \sum_{k=1}^{n} (u_{ik})^2 (d_{ik})^p \tag{4}$$

where $\mathbf{U} \in M_{fc}$ is a fuzzy c-partition of X; $\mathbf{v} = (\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_c)$ where $\mathbf{v}_i$ is the cluster center of prototype u_i, $1 \leq i \leq c$; and, u_{ik} is the membership of $\mathbf{x}_k$ in fuzzy cluster u_i. $J(\mathbf{U}, \mathbf{v})$ represents the distance from any given data point to a cluster weighted by that point's membership grade.

The solutions of

$$\min_{\mathbf{U} \in M_{fc}, \mathbf{v}} J(\mathbf{U}, \mathbf{v}) \tag{5}$$

are least-squared error stationary points of J. The fuzzy clustering algorithm is obtained using the necessary conditions for solutions of (5) as summarized in the following:

Theorem 1 [2]: Assume $\|\cdot\|$ to be an inner product induced norm: let $\mathbf{X}$ have at least $c < n$ distinct points, and define the sets ($\forall K$)

$$I_k = \{i | 1 \leq i \leq c; d_{ik} = \|\mathbf{x}_k - \mathbf{v}_i\| = 0\} \tag{6}$$

$$\tilde{I}_k = \{1, 2, \ldots, c\} - I_k \tag{7}$$

Then $(\mathbf{U}, \mathbf{v})$ is globally minimal for J only if (ϕ denotes an empty set)

$$I_k = \phi \Rightarrow u_{ik} = \frac{1}{\left[\sum_{j=1}^{c} \left(\frac{d_{ik}}{d_{jk}}\right)^p\right]} \tag{8}$$

or

$$I_k \neq \phi \Rightarrow u_{ik} = 0 \quad \forall i \in \tilde{I}_k \text{ and } \sum_{i \in I_k} u_{ik} = 1 \tag{9}$$

and

$$\mathbf{v}_i = \frac{\sum_{k=1}^{n} (u_{ik})^2 \mathbf{x}_k}{\sum_{k=1}^{n} (u_{ik})^2} \quad \forall i. \tag{10}$$

The following iterative method is used to minimize $J(\mathbf{U}, \mathbf{v})$:

1) Initialize $\mathbf{U}^{(0)} \in M_{fc}$ (e.g., choose its elements randomly from the values between 0 and 1). Then at step $l (l = 1, 2, \ldots)$:
2) Calculate the c fuzzy cluster centers $\mathbf{v}_i^{(l)}$ using (10) and $\mathbf{U}^{(l)}$
3) Update $\mathbf{U}^{(l)}$ using (8) or (9).
4) Compare $\mathbf{U}^{(l)}$ to $\mathbf{U}^{(l-1)}$ using a convenient matrix norm, i.e., if $|\mathbf{U}^{(l)} - \mathbf{U}^{(l-1)}| \leq \varepsilon_l$ stop; otherwise, return to step 2.
5) Each node has c membership degrees with respect to the c clusters. Determine which cluster this node belongs to based on the maximum membership. By this means, every node is classified to one cluster and the network is partitioned to c clusters.

As an example, we applied FCM to organize 200 nodes to six clusters, as illustrated in Fig. 1.

C. Master/Controller Election Using Fuzzy Logic Systems

A master/controller in a WPAN receives data from nodes in its cluster and performs data aggregation, and transmits data to the gateway. So a master/controller is much more energy-intensive than a regular node, and it's desirable that a master/controller is located in the centroid (center) of a cluster so that all the other nodes can communicates with it with less energy consumption.

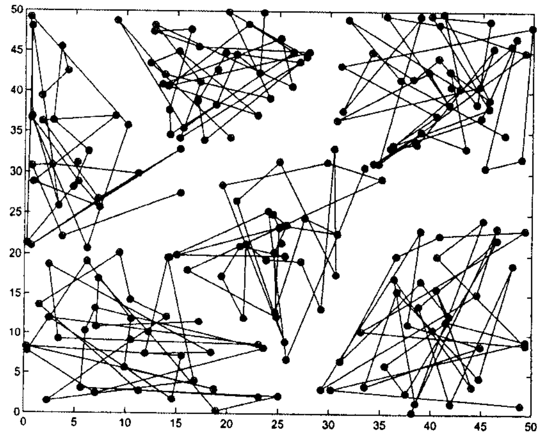


Fig. 1. Example: 200 nodes are partitioned to 6 clusters using FCM. The connection lines only denote that the nodes are in one cluster, not routing paths.

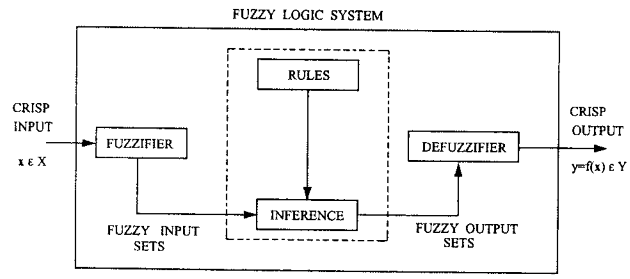


Fig. 2. Structure of a fuzzy logic system.

The master/controller for each cluster can be elected based on the centroid of each cluster v_i $(i = 1, 2, \ldots, c)$, and the remaining power of each node. An ideal master/controller should be very close to the cluster centroid and has very high remaining battery capacity. But generally both conditions are not satisfied at the same time. To compromise this, we apply a fuzzy logic system to master/controller election.

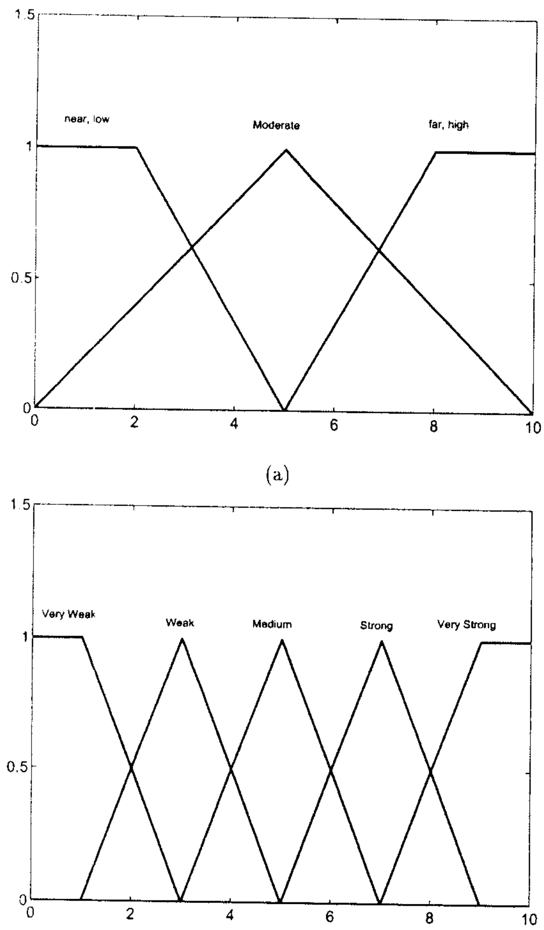
1) Overview of Fuzzy Logic Systems: Fig. 2 shows the structure of a fuzzy logic system (FLS) [9]. When an input is applied to a FLS, the inference engine computes the output set corresponding to each rule. The defuzzifer then computes a crisp output from these rule output sets. Consider a p-input 1-output FLS, using singleton fuzzification, *center-of-sets* defuzzification [10] and "IF–THEN" rules of the form

$$R^l\text{: IF } x_1 \text{ is } F_1^l \text{ and } x_2 \text{ is } F_2^l \text{ and } \cdots \text{ and } x_p \text{ is } F_p^l \text{ THEN } y \text{ is } G^l$$

Assuming singleton fuzzification, when an input $\mathbf{x}' = \{x_1', \ldots, x_p'\}$ is applied, the degree of firing corresponding to the lth rule is computed as

$$\mu_{F_1^l}(x_1') \star \mu_{F_2^l}(x_2') \star \cdots \star \mu_{F_p^l}(x_p') = \mathcal{T}_{i=1}^{p} \mu_{F_i^l}(x_i') \tag{11}$$

where $\star$ and $\mathcal{T}$ both indicate the chosen t-norm. There are many kinds of defuzzifiers. In this paper, we focus, for illustrative purposes, on the center-of-sets defuzzifier [10]. It computes a crisp output for the FLS by first computing the centroid, c_{G^l}, of every consequent set G^l, and, then computing a weighted average of these centroids. The weight



(a)

(b)

Fig. 3. MFs used to represent the linguistic labels. (a) MFs for antecedents, and (b) MFs for consequent.

corresponding to the lth rule consequent centroid is the degree of firing associated with the lth rule, $T_{i=1}^{p}\mu_{F_i^l}(x_i')$, so that

$$y_{cos}(\mathbf{x}') = \frac{\sum_{l=1}^{M} c_{G^l} T_{i=1}^{p} \mu_{F_i^l}(x_i')}{\sum_{l=1}^{M} T_{i=1}^{p} \mu_{F_i^l}(x_i')} \tag{12}$$

where M is the number of rules in the FLS. In this paper, we design a FLS for master/controller election initiation.

2) Master/Controller Election: The master/controller is elected based on two descriptors: *distance of a node to the cluster centroid*, and *its remaining battery capacity*. The linguistic variables used to represent the distance of a node to the cluster centroid were divided into three levels: *near*, *moderate*, and *far*; and those to represent its remaining battery capacity were divided into three levels: *low*, *moderate*, and *high*. The consequent—the possibility that this node will be elected as a clusterhead—was divided into five levels, *very strong*, *strong*, *medium*, *weak*, *very weak*. We used trapezoidal membership functions (MFs) to represent *near*, *low*, *far*, *high*, *very strong*, and *very weak*; and triangle MFs to represent *moderate*, *strong*, *medium*, and *weak*. We show these MFs in Fig. 3(a) and (b).

TABLE I
RULES FOR MASTER/CONTROLLER ELECTION. ANTECEDENT 1 IS *DISTANCE OF A NODE TO THE CLUSTER CENTROID*, ANTECEDENT 2 IS *ITS REMAINING BATTERY CAPACITY*, AND CONSEQUENT IS *THE POSSIBILITY THAT THIS NODE WILL BE ELECTED AS A MASTER/CONTROLLER*

Rule #	Antecedent 1	Antecedent 2	Consequent
1	near	low	medium
2	near	moderate	strong
3	near	high	very strong
4	moderate	low	weak
5	moderate	moderate	medium
6	moderate	high	strong
7	far	low	very weak
8	far	moderate	weak
9	far	high	medium

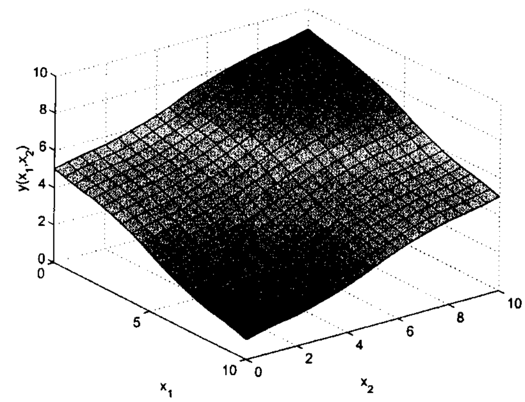


Fig. 4. Master/controller election decision surface.

Based on the fact that a master/controller should be very close to the cluster centroid and should have very high remaining battery capacity, we design a fuzzy logic system using rules such as:

R^l: IF *distance of a node to the cluster centroid* (x_1) is F_l^1, and *its remaining battery capacity* (x_2) is F_l^2, THEN the possibility that this node will be elected as a master/controller (y) is G^l.

where $l = 1, \ldots, 9$. We summarize all the rules in Table I.

For every input (x_1, x_2), the output is computed using

$$y(x_1, x_2) = \frac{\sum_{l=1}^{9} \mu_{F_l^1}(x_1)\mu_{F_l^2}(x_2) c_{avg}^l}{\sum_{l=1}^{9} \mu_{F_l^1}(x_1)\mu_{F_l^2}(x_2)}. \tag{13}$$

By repeating these calculations for $\forall\, x_i \in [0, 10]$, we obtain a hypersurface $y(x_1, x_2)$, as plotted in Fig. 4.

As an example, we randomly generate 80 nodes (a cluster) within a square with 10 meters on each side. Each node has random battery capacity in [0, 10]. The distances of each node to the cluster centroid are normalized to [0, 10] scale. Each node is characterized by the two descriptors. We apply (13) to compute the election possibility for each node, and pick the node having the highest election possibility as the master/controller, as illustrated in Fig. 5. We also plotted the node having the maximum battery capacity and the node having the nearest distance to the cluster centroid in Fig. 5. In contrast, a randomized rotation of the clusterhead was proposed in LEACH [4], which can't per-

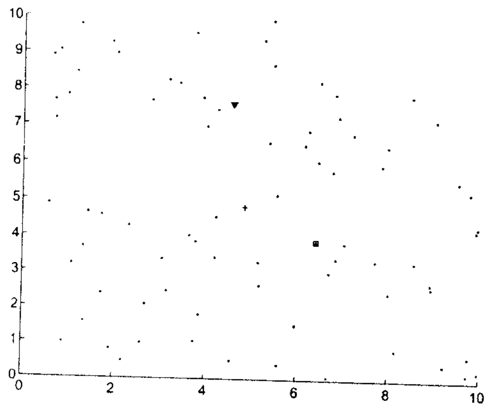


Fig. 5. One example for master/controller election. The elected master/controller (distance: 2.5473, battery capacity: 9.4265) is denoted using "square" □, the node with the maximum battery capacity (distance: 4.1533, battery capacity: 9.9136) is denoted using "triangle (down)" ∇, and the node with the nearest distance (distance: 0.1792, battery capacity: 1.4917) to the centroid is denoted using +.

form well if several high battery level nodes are very close to each other because the clusterheads were elected first, then the cluster members will self-organize themselves based on its distance to the clusterhead.

We assume that hybrid TDMA and FDMA are used, i.e., different clusters work in different frequency band (FDMA), and nodes are coordinated using TDMA in each cluster. The master/controller can set up a TDMA schedule and transmits this schedule to the nodes in its cluster. We assume perfect synchronization in this paper, so no collision will happen and the nodes which are not in transmission can stay in sleeping mode (the energy consumption is trivial).

III. Self-Reconfiguring Topology for Mobile WPAN—Mobility Management

A. Mobility Management Scheme

A network protocol that can update its links to maintain strong connectivity with the mobile nodes is said to be "self-reconfiguring." There exist different mobility patterns in a mobile WPAN:

1) nodes are moving in different directions with different speeds;
2) some nodes die out while others are mobile;
3) new nodes join in while others are mobile;
4) some nodes die out and some new nodes join in while other nodes are mobile.

In case 1, the total number of nodes does not change; and in cases 2–4, the number of nodes may change. Without loss of generality, we assume that the number of nodes and their locations may change from time to time. We dynamically and recursively update the partition of clusters based on the assumption that the number of clusters is constant. This approach is possible because our approach is an iterative optimization method. We summarize the procedures for updating the connectivity among nodes.

1) Collect the of status of each node including its geography information and its remaining battery capacity.
2) For every new node, randomly choose its membership degree to each cluster $\mathbf{u}^i$ and $\sum_{i=1}^{c} u^i = 1$. If a node dies out or leaves the network, delete its membership.
3) Update the total number of nodes n. Keep the existing c cluster centers $\mathbf{v}_i^{(l)}$ as the initial values for the next iteration.
4) Calculate the c fuzzy cluster centers $\mathbf{v}_i^{(l)}$ using (10) and $\mathbf{U}^{(l)}$.
5) Update $\mathbf{U}^{(l)}$ using (8) or (9).

G	PUI	UW	Payload	G
10	24	3	433	10

Fig. 6. Burst format used in this paper.

6) Compare $\mathbf{U}^{(l)}$ to $\mathbf{U}^{(l-1)}$ using a convenient matrix norm, i.e., if $\|\mathbf{U}^{(l)} - \mathbf{U}^{(l-1)}\| \le \varepsilon_L$ stop; otherwise, return to step 4.
7) Each node has c membership degrees with respect to the c clusters. Determine which cluster this node belongs to based on the maximum membership. By this means, every node is classified to one cluster and the network is partitioned to c clusters.
8) Elect the master/controller for each cluster based on the scheme presented in Section II-C.
9) Setup the star topology based on the partitioned clusters and elected master/controller for each cluster.

The above procedure can be used by a network periodically for every short period of time since every node is mobile and its remaining battery capacity is time-varying.

B. Mobility Management With Hysteresis

In the network partition update (because of the mobility), a node will be switched to another cluster if the membership degree to its current cluster is less than the membership degree to another cluster. Similarly, a master/controller will be switched if the election possibility for the current master/controller is lower than one node in its cluster because of mobility and remaining battery capacity. Both schemes will have *ping-pong effect*, the repeated switch between two clusters caused by the rapid mobility.

Motivated by the handoff scheme in celluar networks [22], we modify the mobility management scheme with hysteresis, which allows a new master/controller to be elected only if the election possibility of a new master/controller candidate is sufficiently higher by a hysteresis margin. Similarly, the network partition with hysteresis will allow a node to switch to another cluster only if the membership degree to another cluster is higher enough by a hysteresis margin than the membership degree to the current cluster. This modification can prevent the *ping-pong effect*.

IV. Simulations

In our experiments, we used a 100-node WPAN where nodes are randomly distributed between $(x = 0, y = 0)$ and $(x = 500\ \mathrm{m}, y = 500\ \mathrm{m})$; each node has random battery level between J to $3J$ and an unlimited amount of data to communicate; and each node is mobile with different velocity from 0 to 1 m/s. Assume that a node will reverse its moving direction if it reaches the border.

In Fig. 6, we summarize the burst format we used. There are 480 QPSK symbols per burst, ten guard symbols at the beginning and end of the burst; 24 public user information (PUI) symbols; three symbols unique word (UW) for training. and 433 symbols for payload. The random bits generator generates a binary data stream with equally likely zeros and ones, which are for the payload bits (866 bits). The burst builder can insert some header and control bits, and makes a complete burst with 960 bits, and then 960 bits are modulated to 480 QPSK symbols. It takes 5 ms to transmit such a burst, so the symbol rate is 96 ks/s, and the information (payload) bit rate is 173.2 kb/s. The channel bandwidth is set to 125 KHz.

We used the same model as in [4] for the radio hardware energy dissipation where the transmitter dissipates energy to run the radio electonics and the power amplifier, and the receiver dissipates energy to

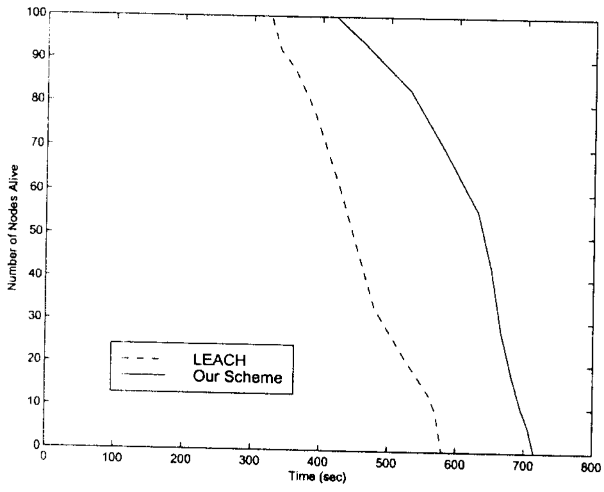


Fig. 7. Number of nodes alive versus time for our scheme and LEACH.

run the radio electronics. We chose the path-loss exponent $p = 2$. To transmit an l-symbol message a distance d, the radio expends:

$$E_{Tx}(l, d) = E_{Tx-\mathrm{elec}}(l) + E_{Tx-\mathrm{amp}}(l, d) = lE_{\mathrm{elec}} + l\epsilon d^2 \quad (14)$$

and to receive this message, the radio expends

$$E_{Rx}(l) = E_{Rx-\mathrm{elec}}(l) = lE_{\mathrm{elec}}. \quad (15)$$

The electronics energy, E_{elec}, as described in [4], depends on factors such as coding, modulation, pulse-shaping and matched filtering; and the amplifier energy, ϵd^2 depends on the distance to the receiver and the acceptable bit error rate. In this paper, we chose: $E_{\mathrm{elec}} = 50$ nJ/sym, $\epsilon = 10$ pJ/sym/m^2. Same as [4], [19], the energy for data aggregation is set as $E_{DA} = 5$ nJ/sym/signal.

We applied our designing methodology to this senario. Initially, we partition the 100 nodes to four clusters (as validated in [4]) using FCM, and then elect the master/controller for each cluster using the scheme described in Section II-C. Each node communicates directly with its master/controller. In every 10 s, the topology is updated based on the iteration procedure proposed in Section III. The hysteresis margin was set to 0.5 (in 0 to 10 scale) for switching in master/controller election, and the hysteresis margin for a node to change to another cluster was set to 0.05.

Energy is consumed whenever a node transmits or receives data or performs data aggregation. When a node uses up its energy, it dies out. Since the initial node locations and battery capacities were random, we ran Monte-Carlo simulations for 100 times. We compared our algorithm against the LEACH scheme proposed in [4], as plotted in Fig. 7. From this figure, we see that our scheme performs much better than the LEACH scheme. The possible reasons are as follows:

1) Our master/controller election scheme considers the distance to the gateway, as well as the remaining battery capacity.
2) FCM is a soft clustering algorithm, and it is realized via minimizing a cost function.
3) Hysteresis threshold can help to avoid abrupt changes in master/controller election and cluster membership of nodes.

V. Conclusions

In this paper, we propose a mobile wireless personal area networks (WPAN) design method with power aware self-reconfiguring topology. The WPAN is self-organized to clusters using an unsupervised clustering method, fuzzy c-means. A fuzzy logic system is applied to master/controller election for each cluster. A self-reconfiguring topology is proposed to manage the mobility and recursively update the network topology. We also modify the mobility management scheme with hysteresis to overcome the *ping-pong* effect. Simulation results show that our scheme performs much better than the LEACH scheme.

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