



## Distributed Energy-Adaptive Routing for Wireless Sensor Networks

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**Abstract—** Most routing algorithms for sensor networks focus on finding energy efficient paths to prolong the lifetime of sensor networks. As a result, the power of sensors on efficient paths depletes quickly, and consequently sensor networks become incapable of monitoring events from some parts of their target areas. In many sensor network applications, the events that must be tracked occur at random locations and have non-deterministic generation patterns. Therefore, ideally, routing algorithms should consider not only energy efficiency, but also the amount of energy remaining in each sensor, thus avoiding non-functioning sensors due to early power depletion. This paper introduces a new metric, Energy Cost, devised to consider a balance of sensors' remaining energies, as well as energy efficiency. This metric gives rise to the design of the Distributed Energy Adaptive Routing (DEAR) algorithm devised to balance the data traffic of sensor networks in a decentralized manner and consequently prolong the lifetime of the networks. DEAR is scalable in the number of sensors and also robust to the variations in the dynamics of event generation. We demonstrate the effectiveness of the proposed algorithm by comparing three existing routing algorithms: Direct Communication Approach, Minimum Transmission Energy, and Self-Organized Routing and find that energy balance should be considered to extend lifetime of sensor network and increase robustness of sensor network for diverse event generation patterns.

**Keywords:** PA, DEAR, EC

### I. INTRODUCTION

A fundamental objective of sensor networks is to report events of a predetermined nature or transmit sensed data to sink nodes or the base station for further analysis [1-3]. To achieve this objective, a proper routing algorithm that determines the paths of the data flow should be present. While considering this basic requirement, the design of the routing algorithm should also incorporate the following factors:

- Due to sensors' limited power, the routing algorithm should have a design to allow finding

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paths consuming the least amount of power to prolong the lifetime of the sensor network.

- However, inevitably, most energy efficient routing algorithms route significant traffic via some sensors, which are close to the base station or on energy efficient paths and thereby, drain their power quickly. As a result, the sensor networks become unable to detect events from regions whose sensors are nonfunctioning. Thus, in sensor networks, apart from energy efficiency, the distribution of the data traffic over the whole network (as opposed to over heavily used routes) is an important factor towards extending its lifetime.

- Although most existing routing algorithms assume that events are generated uniformly at each sensor, events could occur randomly [4], uniformly [5] over the target area, or repeatedly [6] at a specific part of the target area. Event patterns can change from one type to another over time. Therefore, the routing algorithm should be sufficiently robust for diverse event generation functions. Addressing this problem by planned routing utilizes the energy uniformly over the entire sensor network.

- A sensor network can consist of a large number of nodes for which a central control architecture does not apply. Therefore, the routing algorithm should adopt a local decision making scheme.

Although the literature includes several routing algorithms, such as direct communication approach, hierarchical routing

methods [7, 8], self-organized routing algorithm [5], and other routing algorithms [9], little evidence exists for the effectiveness and efficiency of these algorithms with respect to the considerations mentioned earlier.

The primary idea of this research is that sensor networks can respond properly to events that have uncertainty in their position and generation rates and maximize the period when they function fully through energy balancing. In Fig.1, a sensor network has three sensors and the sensors send their messages to the base station sequentially and repeatedly. Each sensor has 9 units of an initial energy and the numbers above arrows indicate the amounts of energy required to the corresponding transmissions. If all sensors use only energy efficient paths, sensor 1 becomes depleted after each sensor transmits its message to the base station three times (Fig.1 (a)). This sensor network cannot respond properly to upcoming events after a period of time during which sensors become inactive from energy depletion, because the events have

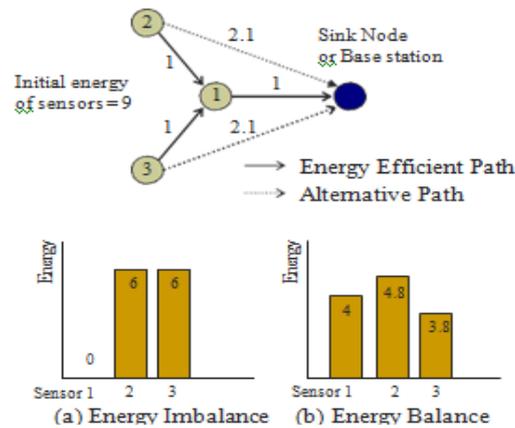


Fig. 1. Distributions of residual energies of sensors after 3 rounds: Imbalance and balance.

uncertainties in their positions and generation rates. However, an energy-balanced sensor network with alternative paths remains event-ready after a similar period because all sensors remain active (Fig.1 (b)). To capture the advantages of energy balance, this study proposes a new heuristic metric, called Energy Cost (EC), to establish energy sufficiency as well as efficiency. Since the EC is transmission energy cost relative to available energy, its value is low when required energy for transmission is low and available energy is high. Using this characteristic of this metric, a localized routing algorithm, the Distributed Energy Adaptive Routing (DEAR), is proposed to accomplish energy balance of sensor networks in an energy efficient manner.

The organization of the rest of the paper is as follows. In Section II, we present the details of the considered sensor network. After describing the details of the maximum energy-welfare routing algorithms in Section III, in Section IV we present extensive simulation results, and conclude in Section V.

## II. SENSOR NETWORK MODEL

With  $n$  homogenous sensors randomly and uniformly distributed over a target area, all sensed data must be sent to the base station. Each sensor has limited battery power. Sensors can control their respective transmission power for minimal consumption to transmit to a destination [7, 8] and they have discrete adjustable transmission power levels [10-13]. This ability is necessary to allow the routing algorithm to maximize sensor networks' operational times. Therefore, sensors can send data to either a neighbor or the base station directly, according to their routing policies [5, 7, 8]. The details of the problem are:

### A. Energy Consumption Model

Each sensor uses a fixed transmission power for communicating with its neighboring sensors while each sensor transmits data to the base station. The neighboring distance is defined as the maximal reachable distance with the fixed transmission power for neighboring sensors. For a

given sensor the sensors within its neighboring distance are its "neighboring sensors" or "neighbors". Also, each node can be aware of the current energy level of its neighbors or energy required to transmit from its neighboring nodes to the base station by anticipating and/or eavesdropping data from the neighbors.

Generally, sensors consume energy when they sense, receive and transmit data. However, the amount of energy algorithm and only a small difference exists between the power consumption for idle and receiving modes[14]. Therefore, in this work, we consider only the energy consumed while transmitting messages. According to the radio model [8], energy consumption ( $E$ ) for transmitting data is proportional to the transmission distance as well as the square of the amount of data. By normalization of the amount of sensed data, the energy consumption model is simplified to  $E=d^2$ , where  $E$  and  $d$  are the required energy and the transmission distance respectively [5].

### B. The Lifetime of a Sensor Network

We validate the effectiveness of the proposed DEAR routing algorithm using a sensor network's *lifetime* as the performance measure. The definition of sensor network lifetime is the time until the first node or a portion of nodes

become incapable, due to energy depletion, of sending data to its neighbors [5, 7, 9, 13]. The portion (number of depleted nodes) can vary depending on the context of the sensor networks. In this paper, the lifetime of a sensor network is the number of rounds until the first (L<sub>1</sub>), 10% (L<sub>10</sub>), or 20% (L<sub>20</sub>) of node(s) expend all their energy [9, 13]. We say that L<sub>1</sub> denotes the *full functioning period* of the sensor network.

### C. Event Generation Functions

For evaluation purposes, many previous studies of routing algorithms assumed that all sensors have uniform data or event generation rates [5, 7, 8]. In infrastructure monitoring applications, each sensor performs a sensing task for every fixed time and has a homogeneous event generation function or the same event generation rate. However, in many sensor network applications, this assumption becomes unrealistic. In a monitoring the migration of a herd of animals, the animals might move along a path in the target area repeatedly [6]. In the case of forest fire detection, events occur rarely and randomly over the target area [4]. Furthermore, some event generation functions can be a combination of uniform, random, and repeated types. Therefore, one must consider several event types for the evaluation of routing algorithms.

## III. DISTRIBUTED ENERGY ADAPTIVE ROUTING (DEAR)

The proposed routing algorithm uses a path with energy sufficiency as well as energy efficiency to pursue energy balance for the sensor network. Energy sufficiency depends upon the available energy, and energy efficiency depends upon the required energy. By using a composite of both quantities, a good path that achieves energy balance can be found. Only one of them, by itself cannot indicate the goodness of a path because of the dual objectives of not depleting the energy reserves of popular paths and of sending messages through energy efficient paths to ensure the total energy needed to route the messages are kept to a minimum.

The definition of the composite measure, *Energy Cost*( $EC_{ij}$ ) for a transmission from node  $i$  to  $j$  is:

$$EC_{ij} = \frac{\text{Required energy from node } i \text{ to } j}{\text{Available energy at node } i} \quad (1)$$

The *Total Energy Cost* ( $TEC_{ik}$ ) of a path  $k$  at sensor  $i$  is the composite quantity that indicates the goodness of a path. This measure is simply the sum of the energy costs in the path:

$$TEC_{ik} = \sum_{ij \in k} EC_{ij} \quad (2)$$

When a sensor, or node, needs to send data to the base station, the node checks its routing table and chooses a node among its neighboring nodes based on the energy cost. In evaluating the neighbors, the node computes the energy costs as if the neighbors will send the data directly to the base station. However, the best candidate may not send data directly to the base station if an indirect path with less energy cost exists. If the best candidate node is the node itself, it sends data to the base station and completes the routing process for the data. Otherwise, it forwards the data to the best candidate among its neighboring nodes and that node then repeats the same routing process. This process continues until a node selects itself as the best candidate and sends directly to the base station. This localized decision-making process results in a monotonic decrease of energy cost over time because the best candidate can have an indirect path that is better than direct transmission. Each sensor makes its decision with the assumption that one of its neighboring nodes sends data to the base station directly. Sensors do not care if the receiving node sends data to the base station or passes data to one of its neighboring nodes. This characteristic makes the proposed algorithm different from that proposed by Dijkstra [15] and the Distance vector algorithm [16], which consider the best path from the next node. Through this local decision making process, a sensor network can achieve energy balance and

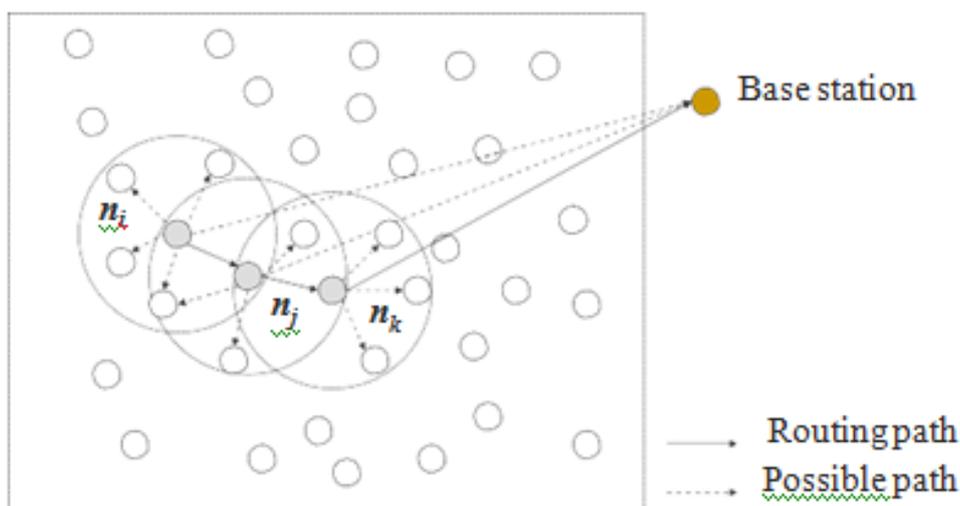


Fig. 2. An example routing path:  $n_i$  sends to  $n_j$ ,  $n_j$  to  $n_k$ , then  $n_k$  sends to the base station directly.

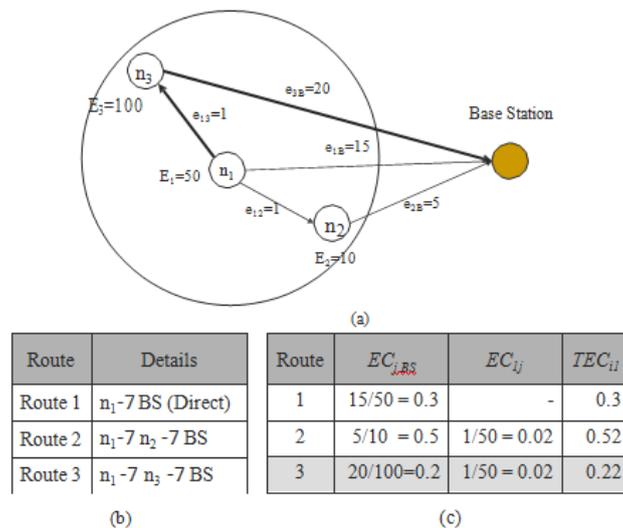


Fig. 3. An example scenario: (a) node  $n1$  needs to send data to base station and two nodes locate within its neighboring distance; (b) three alternative routes for transmission are available; (c)  $n3$  is the best candidate with the least total energy cost.

prolong the lifetime of the sensor network. We show an example of the running of the DEAR algorithm, and then discuss the details and the characteristics of the proposed algorithm.

#### A. Example

In Fig.2, node  $n1$  has three alternative routes to the base station, which are two indirect routes via neighboring nodes and one direct route.  $E_i$ ;  $e_{ij}$  represents the currently available energy of node  $i$  and the required energy for transmission from node  $i$  to  $j$ , respectively. The node  $n1$  calculates TEC value for each alternative route as in Fig. 2(c). The second column shows the energy cost for direct transmission to the base station from an alternative node, and the third column for the transmission to a neighboring node. The energy cost to each neighbor is the same because the transmission power for neighbors is fixed. By totaling these two columns, the total energy cost for each route is shown in the last column. The computational results indicate that route 3 is the least energy-expensive one with  $TEC_3=0.22$ . However, this cost can further decrease if the node  $n3$  has more cost-effective routes than direct transmission. Node  $n1$  chooses  $n3$  as the best candidate and sends data to  $n3$ . At this moment, the node adds its available energy, after transmission and destination, to the data so that all of its neighbors can update their EC tables accordingly. A node needs only the information of its neighbors for the routing decision and this updating process guarantees it since every node has the same transmission power for its neighbors. After receiving this data from node  $n1$ , node  $n3$  starts a routing process again. This routing process continues until the base station receives the data.

#### B. Steps in the DEAR algorithm

Each sensor keeps a small EC table. The EC table contains a node id, the minimum transmission power to the base station, and the available energy for each neighboring node. The steps of the algorithm are:

1) *Initialize EC table:* During the setup period, each sensor, first, finds its minimum transmission power to the base station. Then, each sensor broadcasts a setup message to neighboring nodes using a pre-set transmission power. This setup message includes sensor identification (id) and the minimum power required to transmit a message from the sensor to the base station. Every node receiving this broadcast message registers the transmitting node as one of its neighbors. This setup message includes the required energy to the base station and the node's available energy. After the setup period, all sensors initialize their EC tables.

2) *Update EC table:* A sensor updates its EC table in two cases. First, the change of a sensor's energy level should be reflected in the EC tables of its neighbors. When a sensor transmits data, all of its neighbors can receive this data. Piggybacked on the data is the information about the sending sensor's current battery level. Thus, all sensors always know the current battery levels of their neighbors. As a result, whenever a sensor's battery level changes, all EC tables including the corresponding sensor information are updated. Second, the sensor updates its EC table when network topology changes. When a new sensor joins the network or when a sensor leaves the network due to failure or depletion of energy of the existing sensors, the EC tables of all its neighbors are updated.

*Decentralized routing decision:* Based on their EC table, all nodes make a local routing decision. A node  $i$  determines the best candidate node  $J$  among its neighboring nodes ( $N_i$ ) and itself as in (5) where  $EC_{ii}=0$ .

$$J = \underset{j \in N_i \cup \{i\}}{\text{Arg min}} \{ EC_{i,j} + EC_{jB} \} \quad (3)$$

Equation (3) above implies that node  $i$  selects  $J$  as the best candidate without considering whether  $J$  sends data directly to the base station or not. If node  $i$ , itself, is selected as the best node, it sends the data to the base station and the routing process is finished. Otherwise, the data routes to  $J$  and node  $J$  performs the same process. This process continues until the data is sent to the base station. Fig. 3 shows how the DEAR algorithm operates over a sensor

network. For a given data,  $n_i$  chooses  $n_j$  among several possible routes. After the data passes to  $n_j$ , energy level of  $n_i$  changes and the EC table of  $n_j$  also changes.  $n_j$  performs the same process sequentially. In the figure,  $n_k$  sends data to the base station directly because  $n_k$ , itself, has the minimum energy cost compared to other indirect routes.

#### IV. EXPERIMENTAL RESULTS

In this section, we provide several experimental results to validate the effectiveness of the DEAR algorithm. The comparison of the algorithm is with three other algorithms discussed in [5, 8]: Direct Communication (DC), Minimum

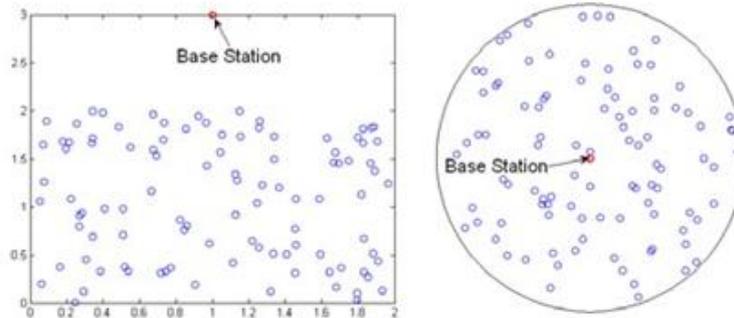


Fig. 4. The configurations of the experimental sensor networks:  $100m \times 100m$  square and  $100m$ -radius sensor networks.

Transmission Energy (MTE), and Self-Organized Routing (SOR). In DC, every sensor simply transmits data directly to the base station without considering any energy-efficient indirect path. MTE and SOR consider indirect routing to save sensor power but make routing decisions based on energy efficiency only. We coded the four routing algorithms in C programming language while solving the mathematical model using a LP solver (LINDO [17]). Two different shapes of sensor networks are used (see Fig. 4). Previous research has used these two shapes with adjusting scales [5, 7]. The first example is a sensor network with 100 nodes randomly uniformly deployed in a  $100m \times 100m$  square area with the base station located at (50, 150). The other example has 100 sensors randomly deployed in a  $100m$ -radius with the base station at (0, 0). In the square and circle sensor networks one sensor has an assigned initial battery level of 250,000 and 100,000, respectively. The initial energy levels are established by determining the amount of energy needed for the farthest node to transmit data to the base station 100 times with DC [5]. Because the sensor networks are randomly generated, 100 repeated experiments for each condition provides an average for the results.

##### A. Lifetime of Sensor Network

This experimentation evaluates the performance of the DEAR algorithm with 20m neighboring distance of the square sensor network. Fig. 5(a) plots the number of active sensors against the number of rounds for each algorithm. We call it a round that every sensor sends its data to the base station once. This graph shows that DEAR-20m has better

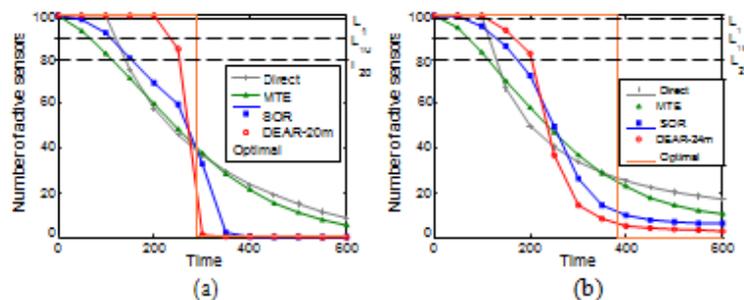


Fig. 5. Performance results: (a) and (b) plot the number of active sensors against the number of rounds and the lifetime for each algorithm with the square and the circle sensor network respectively.

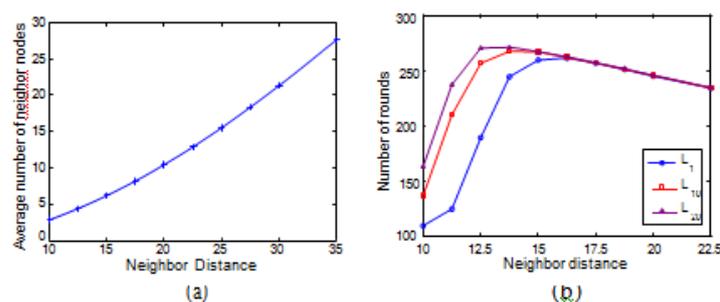


Fig. 6. (a) Number of neighbor nodes against neighboring distance (b) Number of rounds against neighboring distance for the square sensor network.

performance than DC, MTE, and SOR algorithms until 50(%) of nodes die. Also noticeable is that the DEAR algorithm has similar patterns to the Optimal. Sensors in DC, MTE, and SOR algorithms depleted their energies gradually with time.

However, in the DEAR algorithm, the majority of sensors is alive up to 200 rounds and deplete simultaneously, thus indicating good energy balancing throughout the network. Similarly, Fig. 5(b) provides the performance result for the four routing algorithms with the 100m radius sensor network. Although the superiority of performance is reduced, still, DEAR shows better performance than the other three algorithms until 40(%) of nodes drain. Also Fig. 5(a) and (b) show the lifetimes of the sensor networks (L1, L10, L20) according to the definitions in the Section 2. DEAR-20m is dominantly better than the three other routing algorithms for all various lifetime definitions, with 2.5, 2, and 1.7 times for DC, 20, 5, and 2.5 times for MTE, and 10, 2, and 1.5 times for SOR.

**B. The optimal neighbor distance for DEAR**

Fig. 6 shows the effects of neighbor distance on the lifetime of the square sensor network. The results show that the performance of the DEAR algorithm depends on neighbor distance or, equivalently, the number of neighbor nodes. Fig. 6(a) shows that the increase in neighbor distances results in an increase in the number of neighbor nodes. However, Fig. 6(b) shows that such an increase not lead to a monotonic increase of the lifetime. This phenomenon is due to the following two reasons; (1) the increased distance requires more transmission power between neighbors and (2) sensors have to expend the same transmission power for its neighboring nodes regardless of the actual distances to neighboring nodes. In this experiment, the best neighboring distance for the DEAR algorithm is 22m, 17m, and 16m (ranging between 8-12 neighbors) for L1, L10, and L20.

**C. Different Event Generation Functions**

To identify the effect of different event generation types on the lifetime of a sensor network, performed simulations use uniform, random, and repeat event generation functions. In the case of the random distribution, 25% of sensors have events randomly occurring in each round. While, for the repeat events, the assumption is that sensors from (0, 0) to (50, 50) observe repeated events.

51) TABLE I  
52) LIFETIME (L1, L10, L20) FOR DIRECT, MTE, SOR, AND DEAR WITH  
53) UNIFORM, RANDOM, AND REPEAT EVENTS

		Uniform	Random	Repeat
Direct	L <sub>1</sub>	105.28	492.72	107.75
	L <sub>10</sub>	123.38	618.1	145.76
	L <sub>20</sub>	142.34	717.15	193.34
MTE	L <sub>1</sub>	14.39	74.62	30.04
	L <sub>10</sub>	67.1	337.38	223.67
	L <sub>20</sub>	115.45	581.05	415.58
SOR	L <sub>1</sub>	28.69	111.33	154.05
	L <sub>10</sub>	145.94	562.88	316.91
	L <sub>20</sub>	109.86	771.38	418.22
DEAR-20m	L <sub>1</sub>	259.2	1012.72	685.58
	L <sub>10</sub>	266.45	1239.9	970.32
	L <sub>20</sub>	266.61	1346.73	1020.62

Table I gives the results of the lifetime of sensor networks

(L1, L10, L20) for DC, MTE, SOR, and DEAR algorithms with three different event generation types. As shown in Table1, DEAR shows a dominant performance compared with DC, MTE and SOR over the time. Especially, in the case of L1, DEAR gives approximately two to eight times better performance than the others.

Fig. 7 shows how well DEAR achieves the energy balance of sensors over the network. As discussed in [8], in DC (Fig. 7(a)), MTE (Fig. 7 (b)) and SOR(Fig. 7(c)) schemes, sensors far away and close to the base station depleted their energies about round 150. While, in DEAR, all sensors remain live and even have sufficient energy for responding to upcoming events (Fig. 7 (d)). Also notable is that DC, MTE, and SOR missed some events during the first 150 rounds. However, DEAR guaranteed that all data was transmitted to the base station for the same period.

Fig. 8 shows the routing paths for four algorithms with repeated events in the regions from (0,0) to (50,50). In the

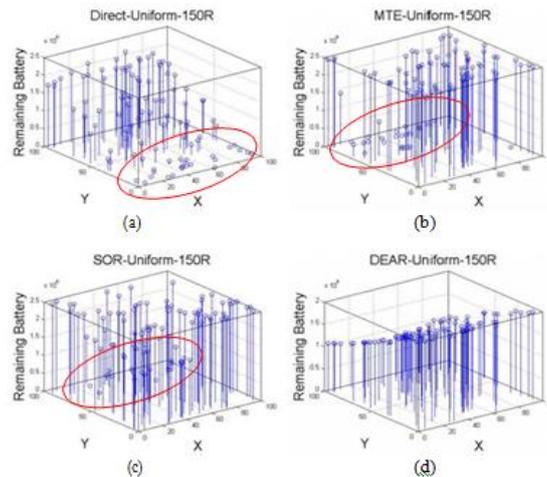


Fig. 7. Remaining energy distributions of sensors with uniform events for DC, MTE, SOR, and DEAR after 150 Rounds.

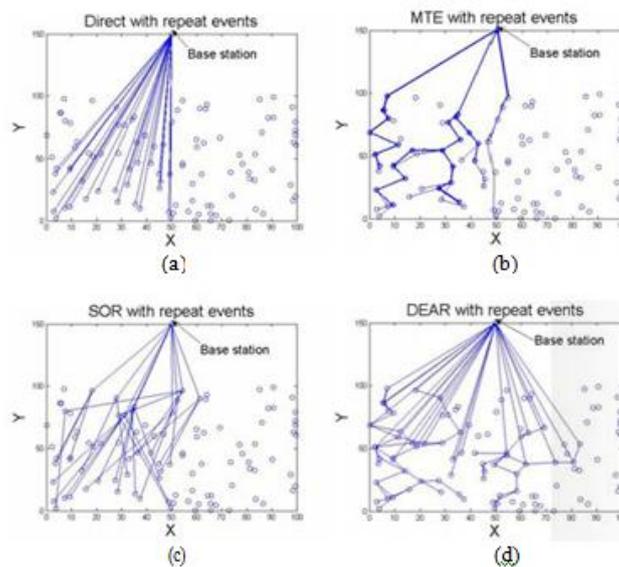


Fig. 8. Routing paths by DC, MTE, SOR, and DEAR with repeat events on the region from (0,0) to (50,50).

case of DC, MTE, and SOR, data traffic concentrates in specific sensors which have location in the region or on the efficient path. On the other hand, DEAR tries to disperse energy usage over the whole network to achieve energy balance. As a result, DEAR can keep all sensors operating for as long as possible.

## V. CONCLUSION AND FUTURE WORK

Sensor networks should be able to achieve energy balance as well as energy efficiency to prolong their lifetimes and prepare for the uncertainties of event generation. Most energy aware routing algorithms are only concerned about energy efficiency. This paper presents a heuristic criterion, called Energy Cost, to consider energy balance and efficiency simultaneously. Using this metric, we have designed and implemented the Distributed Energy Adaptive Routing (DEAR) algorithm.

The designed algorithm demonstrates its superiority to Direct Communication (DC), Minimum Transmission Energy (MTE), and Self Organized Routing (SOR) with a lifetime metric, generally accepted for evaluation of routing algorithms. Additionally, from the experimental results, the conclusion is that DEAR is robust for several event generation functions. In summary, the proposed algorithm has several desirable properties. First, it is simple and localized, supporting scalability. Second, the algorithm maintains energy efficiency for networks while keeping an energy balance. Third, the algorithm is robust to diverse event generation patterns.

The lifetime of sensor networks is one of the most popular measurements to evaluate routing algorithms. Although this work defines the lifetime of sensor network as  $L_1$ ,  $L_{10}$ ,  $L_{20}$ , the definition of lifetime can vary according to the objective and nature of sensor network. Therefore, one can investigate these of more delicate measurements which could be generally accepted. Currently, three types of event generation functions were used for the evaluation measure of the routing algorithm. Future work will involve development of more diverse and detailed event generation functions. In the future, we will also investigate the case where a sensor may move from one neighborhood to another and design algorithms and systems that can handle such movement.

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