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Energy Harvesting Aware Routing Protocol for Wireless Sensor Network

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***Abstract*—This paper considers energy efficiency of routing protocols in wireless sensor networks. Many routing protocols for sensor network have been proposed, some of them tried to cope with the ad-hoc nature while some others focus on improving the energy efficiency. We propose an Energy Harvesting Aware Ad hoc On-Demand Distance Vector Routing Protocol (AODV-EHA) that not only inherits the advantage of existing AODV on dealing with WSN's ad hoc nature, but also make use of the energy harvesting capability of the sensor nodes in the network, which is very meaningful to the data transmission in nominated environmental and military applications. Simulations results show the energy cost of data packet delivery along the route determined by proposed routing protocol has advantages over other existing competitors.**

I. INTRODUCTION

Ad hoc network is defined as a self-configuring network without infrastructure that made of mobile devices [1], and Wireless Sensor Networks (WSN) is an subset of ad hoc network in which the "devices" are sensor nodes that are wirelessly interconnected. The number of nodes within a WSN may varies from a few to hundreds of thousands, each of them could be with the following functions: sensing, data relaying and data exchanging (even with another network outside the WSN) [2].

WSN applications such as chemical leakage detection and enemy detection are operated in severe environment (and this paper is focus on this kind of application) have some common features, two of them are quite distinct: The first one is that nodes are usually deployed without careful pre-planning, which means network topology is lack of prior awareness. Moreover network topology may be changed by exterior force as time goes by.

The eventual purpose is to transmit the useful information from any node to the desired destination, usually this could not be completed by direct transmission and the data packet may travel through one or more intermediate nodes before reaching the destination. Thus to determine the best path in between, namely, the routing process becomes an important issues in WSNs. Routing protocols in general sense has been well studied and a series of routing protocols have been proposed [1, 3]. Traditional routing options for WSNs includes data centric approach (e.g. Directed Diffusion), reactive approach (e.g. DSR), etc. Especially, an on-demand approach (also could be considered as reactive approach), which so called Ad hoc On-Demand Distance Vector (AODV) routing is another worth discussing candidate with advantage in coping with the Ad hoc nature of some WSNs as AODV do not require global knowledge of the network topology.

Another interesting feature is that in this kind of applications the nodes are often unreachable after deployment, as a result replacement of energy source (usually battery) is difficult or even impossible. To tackle this issue, some efforts on improving the energy efficiency of routing protocol itself have been made, such as the routing method described in [4] develop a way to minimize energy consumed for routing data packets, but the shortage is that location information is required.

Another solution is to introduce external energy source, thus the concept of renewable energy can be taken into account, and this kind of energy can be harvested from the surrounding environment in various forms. A typical energy harvesting system consists of tree components: Energy source, harvesting architecture and the load, where energy source is the source of energy that could be collected from (e.g. solar, wind, thermal, etc.), harvesting architecture implies the mechanisms that how the energy is harvested and transformed to electricity, and load represents the consumption of harvested energy [5]. The sunlight, or so called solar energy (solar cell is a common application) is the easiest way to get energy from and can supply a power of approximately $15mW/cm^2$ [6, 7]. Basically, solar energy is not controllable and varies over time, but since the length of daylight on any specific date could be estimated accurately (even some cell phone application could do this job well), its statistical property could be analyzed; another choice for free energy source is wind (Anemometer is an example application) and could generate as much as 1200 mWh of energy each day [8]; there are some other alternative energy sources which are related to the motion of human-being.

Among aforementioned potential candidates, wind power is not suitable for WSNs as the size of wind driven generator is too bulky to be mounted on a wireless sensor node. Motion power is also off the table since the WSN applications we are talking about are deployed in severe environment in which human activities are rare (means very limited energy source or even does not exist). The solar power is quite considerable because not only the sunlight is easy to access, but also the solar panel could be made small enough to be mounted on the wireless sensor nodes.

Since the factor “energy harvesting” is injected, the existing routing strategy in WSNs could be revised. Some energy harvesting aware routing algorithms, e.g. Distributed Energy Harvesting Aware Routing Algorithm (DEHAR) [9], in which a new concept ”energy distance” is defined and taken into consideration when determining the route. To be more specific, the spacial distance between any certain sender node and its receiver node is transformed to a weighted distance which is so called the ‘energy distance‘ (the ‘weight‘ here is related to the current energy status of the sender). And the aim of DEHAR is to figure out the route with minimum total energy distance rather than spacial distance in general sense.

The limitation of all the above-mentioned attempts is that they just solely try to cope with either of the two features. Therefore we propose the Energy Harvesting Aware AODV routing protocol (AODV-EHA) that not only inherits the advantage of existing AODV on dealing with WSN’s ad hoc nature, but also make use of the energy harvesting capability of the sensor nodes in the network.

The rest of this paper is organized as follows: Section II summarizes background knowledge and theoretical analysis of AODV-EHA and its competitors. In Section III, provides simulation results that illustrating the advantage of the proposed routing protocol. The conclusion and further issues are in Section IV.

II. COMPARISON OF AODV-EHA AND ITS COMPETITORS

A. *Overview of the Original AODV Routing Protocol*

As stated in [10], the network that adopts AODV is silent until a connection is requested. After that the sender node (or source node) that needs a connection broadcasts a Route Request (or RREQ for short) for connection. Other nodes in the network forward this message, and record the node that they heard it from, creating a temporary routes back to the sender node. When a node receives such a message and already has a route to the desired receiver node (or destination), it sends a Route Reply (RREP) backwards through a temporary route to the requesting node. The sender node then adopt the route with least hops through other nodes.

Eventually, the original AODV attempts to figure out the route with least communication hops from any source node to the destination node. In other words, suppose the total number of possible routes in between is N and along any ith route (i is an integer and $1 \leq i \leq N$) there are j_i nodes, if the kth route is the optimal one determined by AODV, then it satisfies j_k=min$[j_1, j_2, ..., j_N]$

B. *Overview of the DEHAR*

As mentioned in Chapter I, the basic idea of DEHAR is to introduce a new concept, ”energy distance”: the energy distance between a certain sender node and its receiver node can be considered as a weighted spatial distance in between that is related to the current energy status (how much energy could be harvested from ambient) of the sender. Assume along any ith route, the total energy distance is D_i is defined as

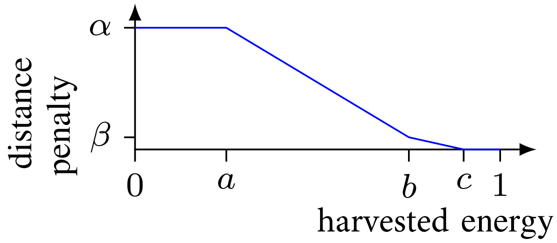

Fig. 1. Relation between energy availability and distance penalty

$$D_i = D_{i1} + D_{i2} + ... + D_{ij_i} \tag{1}$$

Suppose m is an integer and $1 \leq m \leq (j_i - 1)$, thus D_{im} is the energy distance from node m to $m+1$ and $D_{im} = d_{im} + f(\alpha_{im})$, where d_{im} is the spacial distance between node m and $m+1$ on the ith route, α_{im} is the energy could be harvested and used for data transmission at mth node that is defined over $[0, 1]$ (normalized with respect to the energy required for transmission). And the function $f(\alpha_{im})$ can be considered as “distance penalty” (more harvested energy refers to less distance penalty and vice-versa) defined as follows

$$f(\alpha_{im}) = \begin{cases} 0 & , \quad 1 \geq \alpha_{im} > c \\ u\frac{\alpha_{im}-c}{b-c} & , \quad c \geq \alpha_{im} > b \\ (u-v)\frac{\alpha_{im}-b}{a-b} + v & , \quad b \geq \alpha_{im} \geq a \\ u & , \quad a > \alpha_{im} \geq 0 \end{cases} \tag{2}$$

where a, b and c are different thresholds of energy could be harvested for data transmission. As already defined in [9], c determines the upper bound for sensitivity, a is the lower bound for energy availability and b describes the point of change between different sensitivities of variations in energy availability. v and u are the penalty amplitude and maximum penalty, respectively. The author also provide a chart showing an example of relation between energy availability and distance penalty in Fig. 1: (in this example $a = 0.25$, $b = 0.75$, $c = 0.9$, $\alpha = 50$, $\beta = 5$)

The optimal route (denoted by the kth route) determined by DEHAR satisfies that $D_k = min[D_1, D_2, ..., D_N]$. Note that after all the spacial distance are encoded to “energy distance”, DEHAR calculates the shortest energy distance by using existing method such as Directed Diffusion.

C. *An new AODV based routing approach: AODV-EHA*

As described in Chapter I, the AODV-EHA utilizes the advantages of original AODV together with the promising energy harvesting simultaneously: not only be adapted to the every changing network topology (the entire network do not need to be known by the routing algorithm in advance), but also achieve energy efficiency for a longer network lifetime. All these features are achieved by making full use of the existing mechanism of AODV without extra complexity and routing overhead.

Unlike the original AODV described in Chapter II-A, the proposed AODV-EHA intends to find out the route with least transmission cost rather than least hop count. The practical operation of AODV-EHA is similar to original AODV, changes are in the formation of the corresponding messages: Route Requests (RREQs), Route Replies (RREPs), etc.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |R|A|    Reserved     |Prefix Sz|   Hop Count   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Destination IP address                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Originator IP address                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Lifetime                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Fig. 2. RREQ Message Format in Original AODV

The RREQ format of the original AODV is shown in Figure 2 [10].

In AODV-EHA, the field “hop count is replaced with “energy count. “Energy count here implies the prediction of average transmission cost to successfully deliver a data packet from the Originator node to the node handling the request. The predictions are stated in eq. 3 - 7 of this section later.

Same process will apply to RREP message as well in AODV-EHA, the field “hop count is replaced with “energy count. But the “energy count here denotes the prediction of average transmission cost to successfully deliver a data packet from the Originator node to the Destination node.

Since original AODV routing protocol sends these messages (RREQ, RREP, etc.) in the route discovery process, thus there is no additional routing overhead in AODV-EHA.

In the rest of this chapter, the analysis on energy consumption of AODV-EHA is presented.

On any chosen ith route, the expected total transmission cost E_i in terms of energy can be calculated as

$$E_i = E_{i1} + E_{i2} + ... + E_{ij_i} \tag{3}$$

where E_{im} denotes the estimation of transmission cost from the mth node on this route to its next hop $(1 \leq m \leq j_i - 1)$. Transmission cost depends on successful delivery of a packet possibly after a number of reattempts. To be more specific, transmission cost has the form

$$E_{im} = K_{im} \left(P_{im} + P_c + P_r \right) t \tag{4}$$

where K_{im} is the predicted average number of retries after a packet is successfully transmitted from node m to its next hop node $m+1$, P_{im} is the minimum required radio transmission power level at node m to successfully deliver a data packet to the next hop; P_c is the processing power at node m (consumed by circuits of the node for the preparation of radio transmission, e.g. coding and modulation); P_r is the receiving power at next hop $m+1$ (consumed for receiving data, e.g. demodulation and decoding); and T is the transmission time needed for delivering a packet.

Some of the nodes are assumed to be capable of harvesting energy from the surrounding environment. The harvested energy is considered as free and accounted in E_{im} as

$$E_{im} = K_{im}[P_{im} + P_c + P_r - \alpha_{im}R)]t \tag{5}$$

where R is the maximum output power of the photo-voltaic power generator, and $\alpha_{im} = 0$ if node m is without energy harvesting or α_{im} is an random number defined over $[0, 1]$ if node m has energy harvesting. As addressed in Chapter I, for the nominated applications, solar cells are more suitable to be mounted on sensor nodes considering the size (e.g. wind driven generator is too bulky) or energy source accessibility (e.g. motion power is hard to access since nodes operate in severe environment where human activity is rare).

For these nodes, $\alpha_{im} = R^{'}/R$ where $R^{'}$ is the active power level of the photo-voltaic power generator. For a photo-voltaic power generator [11], its active power is assumed to follow a $\beta-$distribution given by the following probability density function:

$$F(R^{'}) = \frac{\Gamma(p+q)}{\Gamma(p)\Gamma(q)} \left(\frac{R^{'}}{R} \right)^{p-1} \left(1 - \frac{R^{'}}{R} \right)^{q-1} \tag{6}$$

where p and q are the shape parameters of the distribution, Γ is the Gamma function. Beta distributions are fit to the past recorded of sunlight data using the algorithm that minimizes the KS statistic [12], and its shape parameters p and q depends on the specific geographic location where sunlight data are recorded. This assumption is also based on the past recorded sunlight data and statistical correlation analysis of solar radiance and consumer load.

From [13], in order to successfully transmit a packet from node m to its next hop node $m+1$, the expected average number of retries K_{im} can be calculated as

$$K_{im} = \frac{1}{1 - e_{im}} \tag{7}$$

where e_{im} is the probability of the packet not been delivered (or outage probability) from node m to node $m+1$ on any attempt. Based on the previous work in [14], e_{im} can be expressed as an function in P_{im}.

Eventually the optimal route (denoted by the kth route) determined by proposed AODV-EHA satisfies that $E_k =$ min $[E_1, E_2, ..., E_N]$.

D. Comparison of Different Routing Protocols

In this part, we will compare the performance of the AODV-EHA routing protocol described above with that of other routing protocols (e.g. original AODV and DEHAR) in terms of transmission cost in general sense (numerical analysis is in Chapter III). The choice of the optimal candidate is determined in accordance with the following proposition:

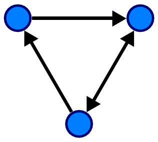

Fig. 3. An Simple Example of Directed Graph

Proposition 1. *If the very purpose is to find a route with least transmission cost in terms of energy between specified source and destination nodes , thus the route determined by AODV-EHA is the optimal under this criterion [15].*

Proof. Any specific network topology could be considered as a directed graph (an simple example is shown in Figure 3) with non-negative edge weights, the vertexes represent different nodes in the network, the edge weights represent "average transmission cost (in terms of energy consumption) after a packet is successfully delivered" between pairs of nodes that could communicate with each other. According to Chapter II-C and the above definition of edge weights we know that the if AODV-EHA is adopted, it is to find the "shortest path" in the graph, and this "shortest path" is a path with minimum weights from source vertex to destination vertex. By contrast, if original AODV or DEHAR is adopted, the edge weights refer to 1 hop or weighted spatial distance in between the node pair that is related to the current energy status of the sender vertex (node), respectively.

The AODV-EHA process could be denoted by $\delta(s,d)$, where s is the source vertex (source node), d is the destination vertex (destination node), and $\delta(s,d)$ is given by:

$$\delta(s,d) = min\{w(p) : p \text{ is one of the many possible paths from } s \text{ to } d \tag{8}$$

where $w(p)$ is the total weight of path p.

To be more specific, a path p is defined as:

$$p = v_1(\text{or } s) - > v_2 - > ... - > v_k(\text{or } d) \tag{9}$$

where $v_1, v_2, ..., v_k$ are all the vertexes (nodes) included on this path. Especially, v_1 is identical to source vertex s, and v_k can be considered as the destination vertex d. Thus the total path weight $w(p)$ could be calculated as

$$w(p) = \sum_{i=1}^{k-1} w(v_i, v_{i+1}) \tag{10}$$

where $w(v_i, v_{i+1})$ is the weight of edge $v_i - > v_{i+1}$.

Similar to the proof method used for proving correctness of Dijkstra algorithm [15], we can prove that $\delta(s,d) \leq w(p)$, thus the path (or route) determined by $\delta(s,d)$ (or AODV-EHA) is with the minimum path weight (or total transmission cost in terms of energy) compare to all the other possible paths (including the path determined by original AODV or DEHAR). Theorem is proved.

□

TABLE I
SIMULATION SETUP

Parameters	Descriptions
Simulation Area	500 m × 500 m
Node Radio Range	250 m
Traffic Type	CBR
Packet Size	127 bytes
Data Rate	20 kbps
Threshold β	10
Processing Power Level P_c	10^{-4} W
Receiving Power Level P_r	5×10^{-5} W
Outage Requirement e^*_{im}	10^{-4}

III. PERFORMANCE EVALUATION

In this section, the performance of original AODV, AODV-EHA and the DEHAR are analyzed under MATLAB platform. The word "performance" here implies:

- Average transmission cost between any two arbitrary nodes with in the network after a data packet is successfully delivered
- Average hop count of the route (may be determined by any routing protocol) where the data packet traveled through between those two arbitrary nodes.

Then the performance of these 3 routing approaches are compared and the relationship between them is revealed.

A. Simulation Setup

The size of simulation area is 500 m × 500 m, the communication range of each node is 250 m. We choose IEEE 802.15.4 to define the physical and data-link layer, which is suitable for low data rate but very long battery life application[16]. According to specification mentioned in [16], in all our simulations the traffic type is CBR with a data rate of 20 Kbps and the size of each packet is 127 bytes . Other parameters could be find in Table I.

B. Simulation Results

The simulations using Monte-Carlo approach are performed, two typical simulation scenarios are considered:

Scenario 1: Stationary destination node.

This scenario can be considered as the application of environment surveillance, the engineer just stay at a fixed observation point in the region where the WSN is deployed, and collects data from the nodes. The nodes number varies from 10 to 90.

Figure 4 compares the average end-to-end transmission cost of original AODV, DEHAR and AODV-EHA, after a data packet is successfully delivered.

Figure 5-6 show the average end-to end route length (hops) of the original AODV, DEHAR and AODV-EHA.

From Figure 4 , we can conclude that as the number of nodes increase, both the average transmission cost of AODV-EHA and DEHAR decrease gradually, and AODV-EHA overcomes DEHAR in any case in terms of energy saving. On the other hand, the same records of original AODV

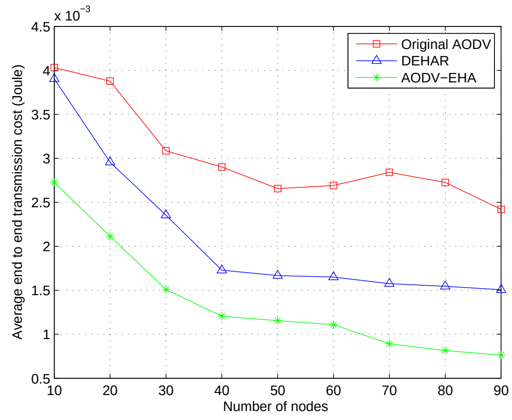

Fig. 4. Average Transmission Cost versus the Number of Nodes

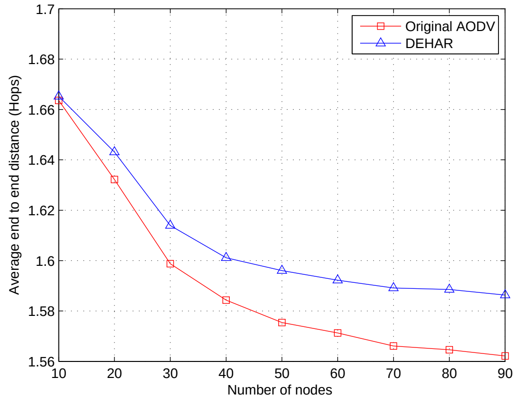

Fig. 5. Average Route Length (Hop Count) versus the Number of Nodes

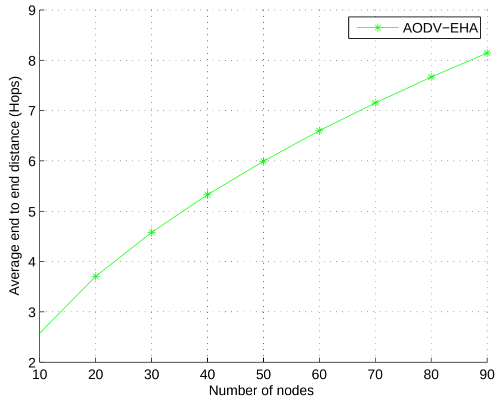

Fig. 6. Average Route Length (Hop Count) versus the Number of Nodes

fluctuates along with the nodes number increases, and showing an unapparent descending tendency, but is always with more cost compare to that of DEHAR and AODV-EHA in all instances.

But on the contrary, under AODV-EHA, the route length is increasingly high as the nodes number in the area goes up, while that of original AODV and DEHAR are slightly reduced, as can be seen from Figure 5-6. Longer route length may lead to longer end-to-end delay, but normally it should not be a problem in this scenario, e.g. meteorological observation frequency is normally at minute level [17].

Scenario 2: Destination node with mobility

This scenario can be considered as the application of enemy detection on battle field, engineer (or data collecting device) could be assigned to any position in the area where WSN is deployed, not tied a fixed place as we do in scenario 1. In the same way as in scenario 1, Monte-Carlo approach is adopted and the only difference is the position of data collecting point is random instead of stationary. The nodes number varies from 10 to 90.

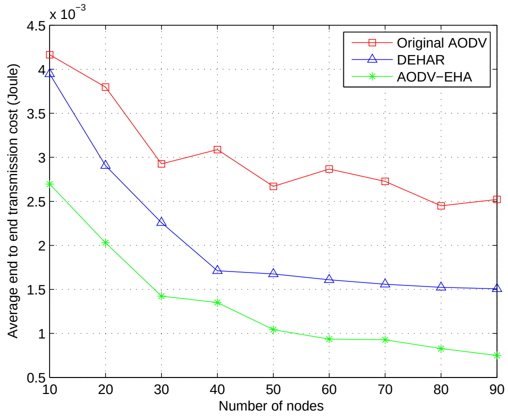

Fig. 7. Average Transmission Cost versus the Number of Nodes

Figure 7 compares the average end-to-end transmission cost of original AODV, AODV-EHA and the DEHAR, after a data packet is successfully delivered.

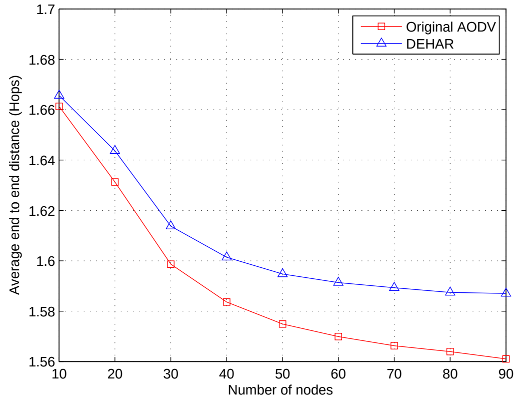

Fig. 8. Average Route Length (Hop Count) versus the Number of Nodes

Figure 8-9 show the average end-to end route length (hops) of the original AODV, DEHAR, and AODV-EHA.

From Figure 7, we can conclude that as the number of nodes increase, the average transmission cost of AODV-EHA

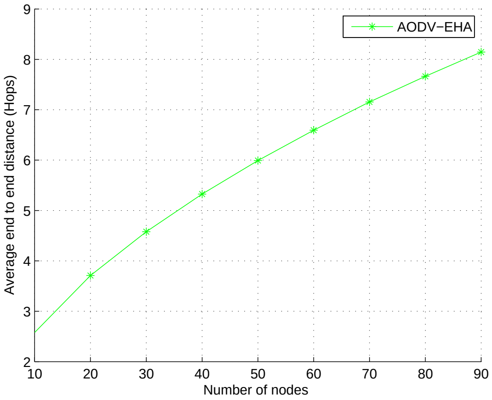

Fig. 9. Average Route Length (Hop Count) versus the Number of Nodes

and DEHAR decrease gradually, and AODV-EHA overcomes DEHAR in any case in terms of energy saving. On the other hand, the same records of original AODV fluctuates along with the nodes number increases, and showing an unapparent descending tendency, but is always with more cost compare to that of DEHAR and AODV-EHA in all instances.

But on the contrary, under AODV-EHA, the route length is increasingly high as the nodes number in the area goes up, as can be seen in Figure 9. Longer route length may lead to longer end-to-end delay, which could be a negative affect to time sensitive applications such as the one in this scenario. Thus before make the decision, the exact delay-tolerance level, energy consumption requirement, nodes distribution density, etc., for practical situation should be carefully evaluated, and see which routing protocol shall be the best trade-off between those factors concerning.

IV. CONCLUSIONS

In this paper, we introduce the AODV-EHA routing protocol for the nominated environmental, military, or commercial WSN applications. In these applications, nodes are usually deployed without careful pre-planning and are not static after initial deployment. Meanwhile nodes are energy sensitive since they usually work in severe environment and battery replacement are usually not possible. AODV-EHA not only inherits the advantage of existing AODV on dealing with WSN's ad hoc nature, but also makes use of the energy harvesting capability of the sensor nodes in the network. Consequently, AODV-EHA achieved both energy efficiency and capability of handling network topology change. By using simulations, we evaluate the performance of original AODV, AODV-EHA and the DEHAR are analyzed under MATLAB platform. Although AODV-EHA is usually with the largest routing path length, it has the smallest transmission overhead along the determined route.

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