www.ietdl.org

Published in IET Wireless Sensor Systems
Received on 21st September 2012
Revised on 25th December 2012
Accepted on 4th January 2013
doi: 10.1049/iet-wss.2012.0117

ISSN 2043-6386

Routing protocol based on genetic algorithm for energy harvesting-wireless sensor networks

Yin Wu, Wenbo Liu

College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, People's Republic of China

E-mail: bonnywu2005@yahoo.com.cn

Abstract: Traditional routing protocols are no longer suitable for the energy harvesting-wireless sensor networks (EH-WSN), which is powered by the energy harvested from environment instead of batteries. Rather than minimising the energy consumption and maximising the network lifetime, the main challenge in EH-WSN is to maximise its working performance under energy harvesting constraints. In this study, the authors propose a centralised power efficient routing algorithm energy harvesting genetic-based unequal clustering-optimal adaptive performance routing algorithm (EHGUC-OAPR) which contains two parts: (i) energy harvesting genetic-based unequal clustering algorithm EHGUC and (ii) optimal adaptive performance routing algorithm (OAPR). First, the base station (BS) uses EHGUC algorithm to form clusters of unequal size and select associated cluster heads, in which the clusters closer to the BS have smaller size. Then, the BS adopts OAPR algorithm to construct an optimal routing among each cluster heads. The numerical results show that EHGUC-OAPR is not only well applied to EH-WSN, but also has a great improvement in network energy balance and data delivery ratio.

1 Introduction

Traditional wireless sensor network is always powered by batteries for easy to use. However, because of the limited battery capacity, maximising network lifetime become the most important challenge being studied in wireless sensor network. Routing protocol research is one of the main approaches of extending network life because generally the transmission power is the major component of wireless sensor node's power dissipation.

A new class of wireless sensor network that harvest energy from the environment (solar, wind, vibration etc.) is emerging because of its intrinsic capability of self-sustainable [1–3]. When the power dissipation is less than the power harvested in a specific working cycle, the energy harvesting-wireless sensor networks (EH-WSN) would never break down expect for hardware failure. So the objective of routing optimisation in EH-WSN no longer be extending network lifetime, but be maximising the workload that can be autonomously sustained by it under given environment power constraints.

Recently several dedicated approaches have been proposed [4, 5]. That is, nodes with higher energy harvesting rates (e.g. nodes that are exposed to more sunlight) are more preferable for relaying packets to the base station than those with lower rates. Zhi *et al*. [6] have designed an opportunistic routing protocol (EHOR) for EH-WSN, which uses a regioning approach to group nodes and takes residual energy of node and distance from sender into consideration. In [7, 8], a solar cell energy model is incorporated into geographic routing to improve network performance. Another solution is proposed by Bogliolo *et al.* [9] and further extended in [10], the main idea is to model the network as a flow network and obtain the solution by solving the maxflow problem to maximise throughput. As in all these achievements, wireless nodes have to process some communications and computations on a certain level in the routing forming stage, which is sensitive to the node itself [11]. So a centralised algorithm running in the base station (BS) by building the correlation of power consumption, energy harvesting and packet transmitting reliability would do a great favour to the wireless nodes, which makes them more economical in data acquisition and transmission.

Genetic algorithm (GA) and evolution algorithms have been greatly researched and applied in the routing protocol of wireless sensor networks (WSN) [12–15], the focus is mainly concentrated on the design of fitness function to optimise network performance. Among all the research, genetic optimization-based clustering protocol has gained some attention [16, 17], this approach has the advantages of reducing energy dissipation and enhancing system lifetime effectively, as well as enhancing resource allocation and bandwidth reusability.

In this paper, we present a novel energy harvesting-based clustering algorithm EHGUC-OAPR which consists of energy harvesting genetic-based unequal clustering algorithm EHGUC and optimal adaptive performance routing algorithm OAPR. It organises EH-WSN via unequal clustering and multihop routing. EHGUC selects an optimal group of nodes with high weighted sum (energy harvesting rate, distance between nodes etc.) as the cluster heads and divides all nodes in the network into different size clusters. This algorithm cannot only maximise the revenues gained by routing packets successfully through the network, but also optimise the energy management of the network by making the clusters closer to the BS having smaller size. Thus the cluster heads of these clusters will consume lower energy during the intra-cluster data processing, and can preserve more energy for the inter-cluster relay traffic. OAPR algorithm is an adaptive inter-cluster multihop routing algorithm which aims to maximise the network performance, particularly it chooses next hop by taking energy sustainability of nodes into consideration to reduce possibility of fast dying and to improve reliability of packet transmission.

The rest of this paper is organised as follows: in Section 2, we formulate the problem of energy aware routing with energy harvesting, and present our network and energy model. In Section 3, we present our algorithm and briefly discuss its implications. In Section 4, we provide the results and discussion. Finally, Section 5 concludes the paper.

2 System model and problem formulation

Cluster-based routing algorithms can be classified into two categories, namely: centralised and distributed. A centralised clustering algorithm uses global knowledge of the network to determine the cluster and consequently is able of making better clusters than distributed one. The reason is centralised systems have complete control on the number of cluster heads and their position, thus electing cluster heads where they are needed.

2.1 Network model

We consider a multihop EH-WSN composed of energy harvesting sensor nodes and one single base station (sink nodes with unlimited power supply and network connectivity). Data are sampled by sensor nodes and routed to BS; each sensor node could also act as routers for other nodes, and each can be either cluster head or ordinary node; data fusion is used here to reduce the total data message sent; and the node transmission power is adjustable, namely nodes could adjust its transmission power according to the distance.

The EH-WSN can be represented as a directed graph $G = (V, E)$. The vertices $v \in V$ represent the nodes (i.e. the sensor nodes and the base station). An edge $\langle u, v\rangle \in E$ represents a wireless link between the two nodes $u, v \in V$, which allows them to exchange packets.

2.2 Radio model

Our approach uses the radio model proposed in [18] with the same radio constants. We consider that the energy consumed for transmitting information within the cluster is proportional to d^2, where d is the distance between nodes. However, for a long range transmission such as from a cluster head to the base station, the energy consumed is proportional to d^4. To achieve an acceptable signal-to-noise ratio (SNR), the energy consumption of the transmitter is given by

$$\begin{aligned} E_{TX}(k, d) &= E_{\text{elec}}K + E_{fs}kd^2 \\ E_{TX}(k, d) &= E_{\text{elec}}K + E_{mp}kd^4 \end{aligned} \tag{1}$$

Where k is the number bit of the message and d is the distance. E_{elec} (nJ/bit) is the energy dissipated per bit to run the transmitter or the receiver circuit, and E_{fs} (pJ/(bit m^{-2})), E_{mp} (pJ/(bit m^{-2})) is the energy dissipated per bit to run the transmit amplifier depending on the distance between the transmitter and receiver. The energy consumption of the receiver is given by

$$E_{RX}(k) = E_{\text{elec}}K \tag{2}$$

The constants used in the radio model are as follows [19]: $E_{\text{elec}} = 50$ nJ/bit, $E_{fs} = 10$ pJ/(bit m^{-2}), $E_{mp} = 0.0013$ pJ/(bit m^{-4}). The data fusion model used in our simulations assumes that the overall information collected by a cluster of n nodes, where each node collects k bits of data, can be compressed to k bits regardless of the number of nodes in that cluster. In our simulations, the energy cost for data aggregation is set as $E_{\text{D}} = 5$ nJ/bit.

2.3 Energy model

We assume that all wireless sensor nodes are equipped with energy harvesting devices, for example, solar panels. The available environmental energy may vary temporally at a single node. At the same time, there may be spatial variations of the harvested energy for different nodes. So in this paper, we assume that each node n has an individual harvesting power rate $P_{\text{EH},n} > 0$. The harvested energy is stored in a storage device (e.g. a battery) and we denote the stored energy $E_{\text{S},n}$. The maximum battery capacity is define as $E_{\text{M},n}$. We assume the BS has an unlimited power source.

Since radio communication is the main energy consumer in most sensor networks, we assume (without loss of generality) that data sensing and packet creation consumes negligible energy. Thus the energy model of EH-WSN at node n is

$$\begin{aligned} P_n(\tau) = {} & \min\big(P_n(\tau-1) + P_{\text{EH},n}(\tau-1), E_{\text{M},n}\big) \\ & - I\big(a_n(j)\big)\big(E_{TX} + E_{RX}\big) \end{aligned} \tag{3}$$

Where we consider a discrete time system in each sensor node. At the end of each time slot τ, $P_n(\tau)$ is the residual energy at node n. At the beginning of time slot τ, node n receives the energy replenishment accumulated in the previous time slot, represented by $P_{\text{EH},n}(\tau - 1)$. In all times, the maximum energy at node n is not allowed to exceed $E_{\text{M},n}$, $I(\cdot)$ is the indicator function and $a_n(j)$ is the event that node n receives and transmits packets.

Every node should keep $P_n(\tau) > 0$, otherwise it will close down until it has harvested enough energy to startup again. So we should design the routing protocol properly to avoid nodes closing down. Keeping energy sustainability and maximising workload just are two corresponding counter constraints.

If we take $R(j)$ as the revenue gained by routing jth packet to BS through the sensor network, thus our goal is to maximise the total revenue over a finite time horizon $[0, t]$

$$G_t := \sum_{j:j\leq T} R(j)I(a(j)) \tag{4}$$

Where $a(j)$ is the event that jth packet is received and transmitted, and T is the total number of packets to be transferred in the time interval $[0; t]$. As for the revenue, if we take $R(j) = 1$, then G_t should be exactly the total throughput in the time interval; else if we take $R(j)$ as a function of number of hops between source node and BS, then G_t could be the energy dissipation of the routing protocol. In this paper, we take G_t as energy balance and packet delivery ratio, in which energy balance avoids closing down of nodes and packet delivery ratio represents reliable transmission.

3 EHGUC-OAPR algorithm

The operation of EHGUC-OAPR algorithm is based on a centralised control mode which is implemented at the BS. It runs in rounds: each round begins with a set-up phase when the clusters are organised and the multihop routing for inter-cluster communication is found, followed by a steady-state phase when the sensor nodes perform periodical data gathering for a predefined time. During the set-up phase, nodes send information about location, energy level and energy harvesting rate to BS. BS uses EHGUC algorithm to divide all nodes into some specified clusters of unequal size and associated cluster head is selected (Fig. 1), then OAPR algorithm is adopted to build an energy efficient multihop routing protocol among all cluster heads as well as maximise the revenue. At the end of the set-up phase, BS broadcasts a message that contains the information about the clusters and the multihop routing. According to this message, every node confirms its role and each cluster head knows its next hop. Thus the system is able to go into the steady state phase. Notice that EHGUC-OAPR algorithm executes cluster head election and routing discovery only in the first round, whereas in other rounds operates cluster adjustment and routing update instead.

3.1 Set-up phase

At the first stage, initialisation of the EH-WSN is made when sensor nodes are deployed to the area. In set-up phase, information about the distances between all nodes and energy status are gathered. To obtain the values of distances, nodes send advertisement messages to the network. Each node receives these advertisement messages from other nodes at various signal strengths, and then calculates distances using (5). In the equation, d_{ij} is the distance between node i and node j, f is the communication frequency, c is the speed of light, P^{r} is the received signal strength and P^{s} is the sender signal strength

$$d_{ij} = s\left(P^{\mathrm{r}}\right)^{-1/2}, \quad \text{where} \quad s = c\left(P^{\mathrm{s}}\right)^{1/2}/4\pi f \qquad (5)$$

In our routing protocol, an advantage is that these distance values are obtained by using signal strengths (5) without GPS hardware which would cause a high extra cost. When all nodes complete obtaining the distances between its neighbours, it will send the information to BS with the residual energy and energy harvesting rate together.

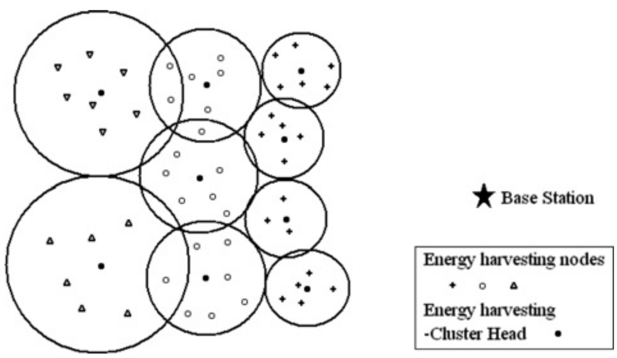

Fig. 1 *Network structure diagram of EHGUC-OAPR*

3.2 EHGUC algorithm

The proposed EHGUC routing algorithm is enhanced by using GA to create optimal clusters under a given environment energy constraints. The EHGUC result identifies the suitable cluster heads for the EH-WSN. All sensor nodes are represented as bits of a chromosome. A population consists of several chromosomes and the best chromosome is used to generate the next population. Based on the survival fitness, the population transforms into the future generation. Every sensor node has its own identification (ID) number, but in a chromosome the cluster member node should be coded as its cluster head's ID. A network of m nodes is represented by a chromosome of m numbers. We design the fitness function with the objective of not only minimising the energy consumption and maximising the network revenue, but also producing clusters with uneven size to balance the energy consumption among the cluster heads.

Firstly, based on the energy information of every node, the BS computes the average energy sustainability of all nodes

$$ST(n) = \frac{E_{\mathrm{M},n}}{\left(P_{\mathrm{EH},n} + \sigma\right)\log \mu}\left(\mu^{\lambda(n)} - 1\right) \quad \text{where} \quad \lambda(n) = \frac{E_{\mathrm{M},n} - E_{\mathrm{S},n}}{E_{\mathrm{M},n}} \qquad (6)$$

σ and μ are the appropriately chosen constants. To ensure that only nodes with sufficient energy sustainability are selected as cluster heads, the nodes with $ST(n)$ below the average are eligible to be cluster head candidates for this round. Next,

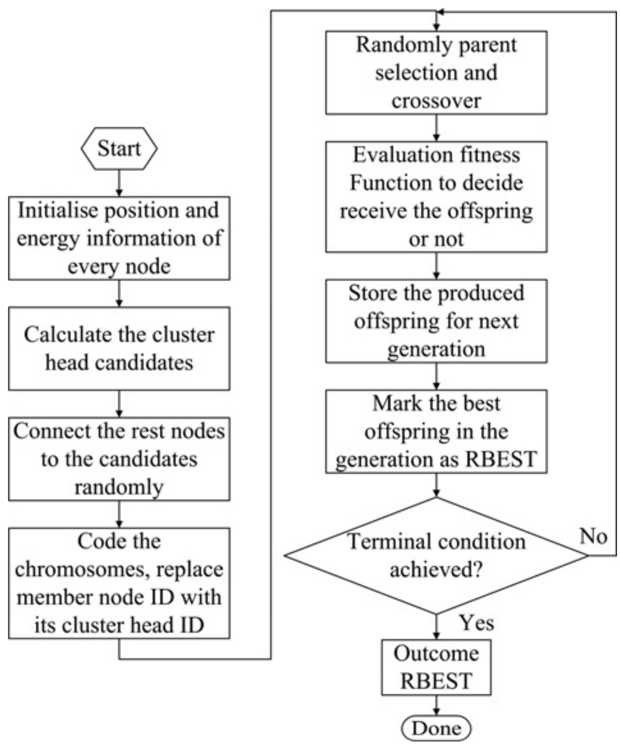

Fig. 2 *Flowchart of EHGUC algorithm for cluster setup phase*

IET Wirel. Sens. Syst., 2013, Vol. 3, Iss. 2, pp. 112–118
doi: 10.1049/iet-wss.2012.0117

the BS runs the GA algorithm to determine the best cluster heads that can minimise the fitness function, as defined by

$$F = Af_1(Cl_p) + Bf_2(Cl_p) + Cf_3(Cl_p) + Df_4(Cl_p) \quad (7)$$

$$f_1(Cl_p) = \sum_{j=1}^{\beta}\left[\left(\sum_{i=1}^{\alpha_j} d_{ijhj}\right) + d_{hj\mathrm{bs}}\right] \quad (8)$$

$$f_2(Cl_p) = \sum_{j=1}^{\beta}\left[\sum_{i=1}^{\alpha_j} ST(ij)/ST(hj)\right]/k \quad (9)$$

$$f_3(Cl_p) = \sum_{j=1}^{\beta}[d_{hj\mathrm{bs}}]/\beta \sum_{j=1}^{\beta}\sum_{i=1}^{\alpha_j} d_{ij\mathrm{bs}} \quad (10)$$

$$f_4(Cl_p) = 1/\sum_{j=1}^{\beta}\left(\sum_{i=1}^{\alpha_j} E_{TX}\left(1, d_{ijhj}\right) + \alpha_j E_{RX}(1)\right) \quad (11)$$

Where f_1 is the sum of Euclidean distances of cluster member to its cluster head and cluster heads to the BS, Cl_p is a chromosome in the current round, α_l ($l = 1, \ldots, \beta$) is the number of cluster members, β is the number of clusters in the EH-WSN, d_{ijhj} is the Euclidean distance from node i in cluster j to its cluster head, $d_{hj\mathrm{bs}}$ is the Euclidean distance from jth cluster head to the BS. Function f_2 is the ratio of the average energy sustainability of cluster members with its cluster head. Function f_3 is the ratio of the average Euclidean distance of the cluster heads to the BS with the sum of Euclidean distance of all the sensor nodes to the BS. Function f_4 is the inverse of transmission energy in intra-clusters, on the side inter-cluster transmission energy will be discussed in next section. The constants A, B, C, D are predefined constants used to weight the contribution of each of the sub objectives and $A + B + C + D = 1$. The fitness function defined above has the objective of simultaneously minimising the intra-cluster distance between nodes and their cluster heads, as quantified by f_1; and of maximising the cluster head's energy sustainability in its cluster as quantified by f_2; and of producing clusters with unequal size as quantified by f_3; and also of optimising the energy dissipation in the clusters as quantified by f_4. According to the fitness function, a small value of f_1, f_2 suggests compact clusters with the optimum set of nodes that have sufficient energy to perform the cluster head tasks. A small value of f_3 means that the size of the clusters located closer to the BS is smaller. A small value of f_4 shows that the formed clusters are more energy efficient. Fig. 2 shows the flowchart of EHGUC algorithm applied during the clusters setup phase.

3.3 OAPR algorithm

After clustering, BS use OAPR algorithm to construct an inter-cluster routing among all cluster heads in EH-WSN, we hope to minimise the total energy dissipation and maximise the network revenue based on each head node's energy harvesting condition.

Based on the above computation, energy conditions of every cluster heads and Euclidean distance between them have achieved. So a head node i chooses its next hop j by using the greedy algorithm, Node j should has the least value of the cost function among all the cluster heads (include cluster head i) located between node i and the BS.

Table 1 Network and parameters

Parameter	Value	Parameter	Value
network coverage	(0, 0)–(500, 500)	A, B, C, D	0.2, 0.5, 0.2, 0.1
base station location	(250, 700)	x, y, z	0.5, 0.3, 0.2
σ, μ	0.1, 5	population size	30
data packet size, bit	4000	crossover probability	0.6
information packet size, bit	200	number of generations	100

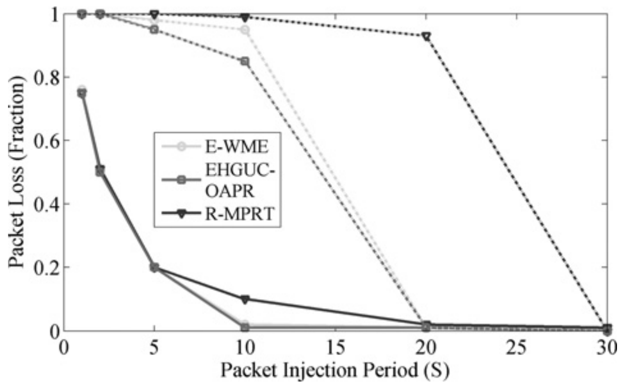

Fig. 3 *Average packet loss (solid lines) and worst case (dashed lines) packet loss of the three routing algorithms*

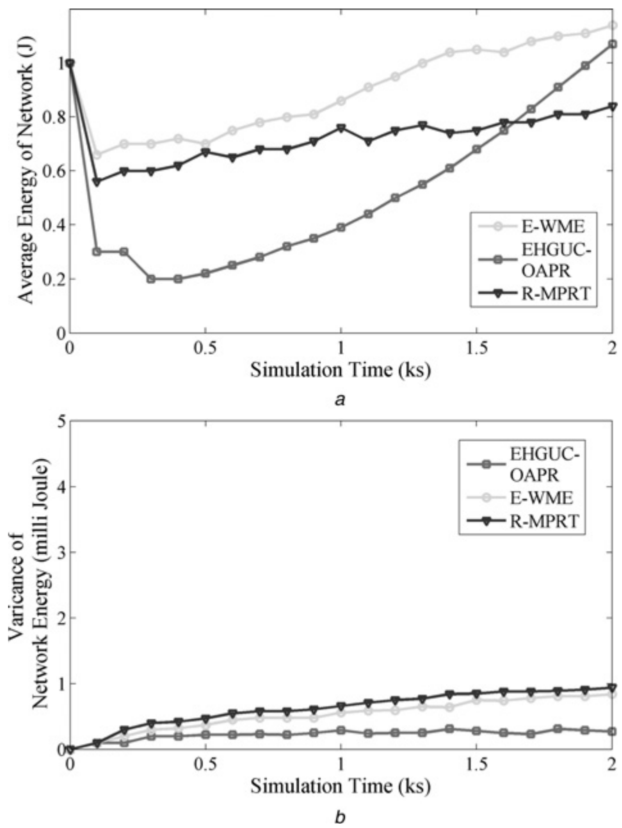

Fig. 4 *Energy balance comparison of three algorithms*

a Average energy of EH-WSN over simulation time
b Variance of network energy over simulation time

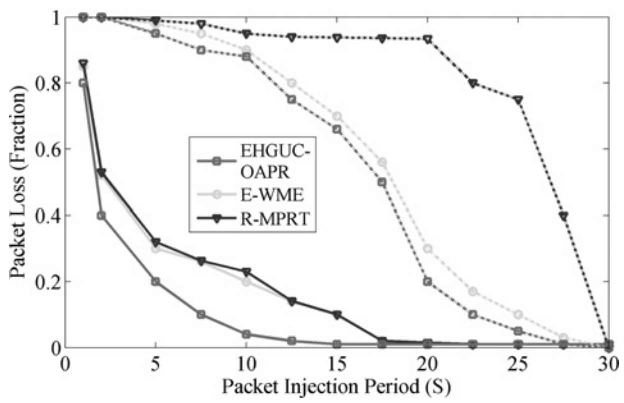

Fig. 5 *Average packet loss (solid lines) and worst case (dashed lines) packet loss of the three routing algorithms under non-uniform energy harvesting rate*

The cost function is defined as

$$\cos t(i, j) = x\,(d_{ij} + d_{j\text{bs}}) + yST(j) + zST(k) \qquad (12)$$

Where d_{ij} is the distance from i to j, $d_{j\text{bs}}$ is the distance from j to BS and k is the next hop node of j. That is, we take the next two hop nodes' energy sustainability into consideration, this can avoid choosing the next hop node which has neighbors of weak energy sustainability. Of course x, y, z are coefficients denoting the significance of each factor and $x + y + z = 1$. So in this way we can get an optimal adaptive inter-cluster routing with high reliability.

3.4 Cluster adjustment and routing update

As soon as the EHGUC-OAPR algorithm has run its course, BS should broadcast a inform message to all the nodes in EH-WSN which contains the work role of each node. Then cluster nodes would communicate with their cluster head in one hop routing by TDMA, whereas cluster heads would use CDMA to transmit messages in multihop routing to BS. At the end of predefined running time of this round, cluster adjustment and routing update should be activated for the EHGUC-OAPR algorithm in BS only elects cluster head and finds routing in the first round. Thus every cluster head collect its member nodes' present energy sustainability information, and elect the nodes with least value (include head itself) to be next cluster head directly. New cluster head should copy information about its cluster members and neighbour cluster head from the former, and then the inter-cluster and intra-cluster routing can be updated. At last if the average energy sustainability of a cluster changes drastically (below one half of before), it must send a message to BS to restart the EHGUC-OAPR algorithm immediately.

4 Simulation and analysis

We now describe the results from our simulations. To evaluate the performance of the proposed routing protocol EHGUC-OAPR, we use OMNET++ to simulate our protocol, E-WME proposed in [5], and R-MPRT proposed in [10] and compares their performance. We ran the simulations for 200 energy harvesting nodes randomly deployed in a 500 m × 500 m network area, and BS is 200 m away from the EH-WSN. Some other parameters are shown in Table 1.

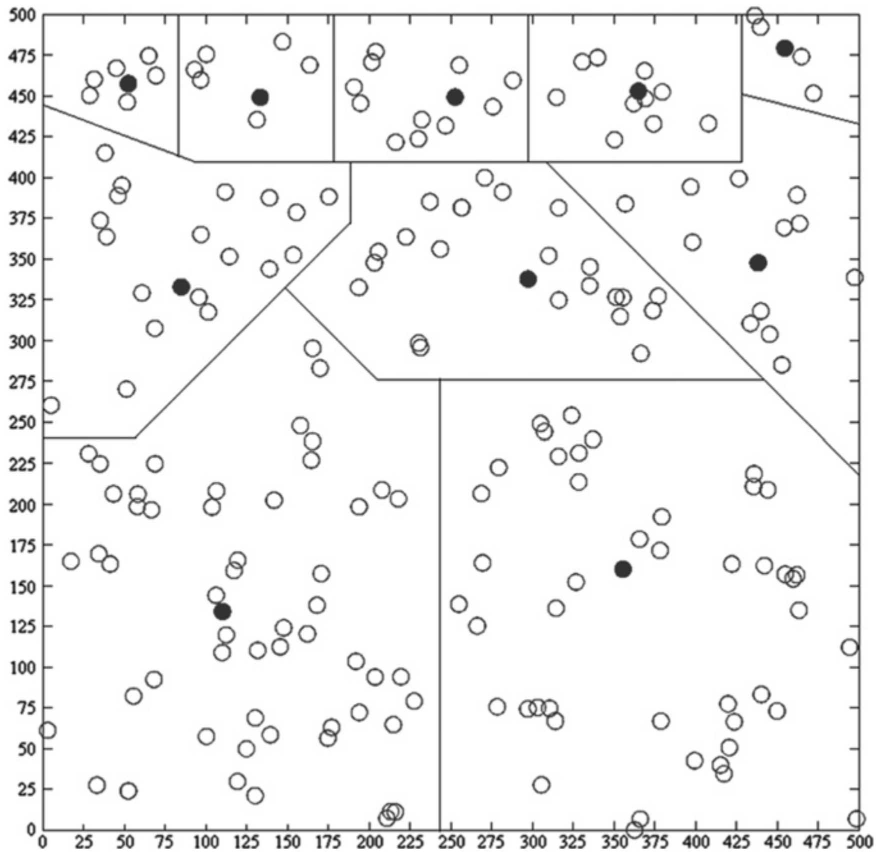

Fig. 6 *Example of EHGUC-OAPR routing EH-WSN*

doi: 10.1049/iet-wss.2012.0117

The battery capacity is 100 J, however the initial energy is set to 1 J. This enables the nodes to process the first few setup packets, yet requires the node to harvest the energy for processing further data collection packets. Here we simulate with a perfect MAC protocol, an ideal channel characteristic for simplicity.

First we evaluate metrics: average packet loss and worst case packet loss, which represent the total number of lost packets divided by the total number of generated packets by all nodes and the highest number of lost packets originating from a single node divided by total number of packets generated by the node. Having a high worst case packet loss ratio means that there are single nodes in the network whose data rarely arrive at the base station, that is, nodes are disabled or its neighbours are lack of energy. Fig. 3 illustrates the average packet losses and worst case packet loss for a uniform energy harvesting scenario in which all nodes have the harvesting power rate $P_{\mathrm{EH},n} = 1$ mW.

In general, the packet losses increase while packet injection periods (The network workload) become shorter. The average packet losses of the E-WME and EHGUC-OAPR algorithms are very similar, R-MPRT performs slightly worse. However, the result in worst packet losses shows very different, and our EHGUC-OAPR performs best for it updates cluster heads periodically.

Next we evaluate metrics: mean value and variance of all nodes' energy in EH-WSN. We collect the residual energy of every node at one time and then compute its mean value and variance. Having a high mean value and a low variance represents the EH-WSN has a strong energy balance. Fig. 4 illustrates the mean value and variance of network energy for a uniform energy harvesting scenario in which all nodes have the harvesting power rate $P_{\mathrm{EH},n} = 1$ mW.

As can be seen from the figure, EHGUC-OAPR algorithm consumes more energy than other two routings in the starting setup time, for it requires the nodes to measure their distances from each other and detect energy harvesting rates due to lack of GPS. However after this slightly complicated operation, EHGUC-OAPR makes network running more powerful than E-WME and R-MPRT because it effectively balance the energy consumption for data transmission between the clusters close to the BS and the clusters far away from the BS.

So far all simulations above have been performed under the assumption that all nodes are exposed to the same environmental source, and thus have the same harvesting power rate $P_{\mathrm{EH},n}$. To investigate the influence of an unbalanced spatial distribution of environmental energy, we studied a scenario as follows: The harvesting power rates $P_{\mathrm{EH},n}$ are normally distributed. The mean value is equal to the constant harvesting rate $P_{\mathrm{EH},n} = 1$ mW.

Fig. 5 shows the packet losses of this non-uniform energy harvesting setting, we found that EHGUC-OAPR algorithm still outperforms the other two protocols, for it could update the inter-cluster heads and intra-cluster members periodically according to the environment energy.

Finally, we show an example of EHGUC-OAPR-based EH-WSN in Fig. 6, BS is located in (250, 700). In which the solid dots are cluster heads at that moment and obviously that the cluster region closer to the BS is smaller than that is farther.

5 Conclusions

In this paper, we propose a novel routing protocol based on GA for EH-WSN. We use a centralised approach in which the BS runs a genetic-based clustering algorithm and an inter-cluster routing algorithm with intensive memory and CPU requirements, whereas additional cluster adjustment and routing update with a small footprint running on the nodes. Extensive results indicate that EHGUC-OAPR can effectively balance the energy consumption of the entire network and efficiently improve the data delivery ratio. We have also shown that it outperforms the existing routing protocols E-WME and R-MPRT, even under non-uniform energy harvesting situation. In addition the algorithm is easy to implement in reality as it just requires local short-term energy harvesting information.

6 Acknowledgments

This work was supported by the National Nature Science Foundation of China (no. 51005121). The authors also gratefully acknowledge the helpful comments and suggestions of the reviewers, which have improved the presentation.

7 References

1 Alippi, C., Galperti, C.: 'An adaptive system for optimal solar energy harvesting in wireless sensor network nodes', *IEEE Trans. Circuits Syst. I, Regul. Pap.*, 2008, **55**, (6), pp. 1742–1750

2 Shen, X., Bo, C., Zhang, J., Tang, S., Mao, X., Dai, G.: 'EFCon: energy flow control for sustainable wireless sensor networks'. *Ad Hoc Netw.*, 2011, pp. 1–11

3 Ongaro, F., Saggini, S.: 'Li-ion battery-supercapacitor hybrid storage system for a long lifetime, photovoltaic based wireless sensor network', *IEEE Trans. Power Electron.*, 2012, **27**, (9), pp. 3944–3952.

4 Noh, D.G., Kim, J., Lee, J., Lee, D.G., Kwon, H., Shin, H.S.: 'Priority-based routing for solar-powered wireless sensor networks'. Proc. Int. Symp. Wireless Pervasive Computing, 2007, pp. 53–58

5 Lin, L., Shroff, N.B., Srikant, R.: 'Asymptotically optimal energy-aware routing for multihop wireless networks with renewable energy sources', *IEEE/ACM Trans. Netw.*, 2007, **15**, (5), pp. 1–12

6 Zhi, A.E., Tan, H.P., Seah, W.K.G.: 'Opportunistic routing in wireless sensor networks powered by ambient energy harvesting', *Comput. Netw.*, 2010, **54**, (17), pp. 2943–2966

7 Chu, H.C., Siao, W.T., Wu, W.T., Huang, S.C.: 'Design and implementation an energy-aware routing mechanism for solar wireless sensor networks'. Proc. IEEE Int. Conf. High Performance Computing and Communications, 2011, pp. 881–886

8 Tutuncuoglu, K., Yener, A.: 'Optimum transmission policies for battery limited energy harvesting nodes', *IEEE Trans. Wirel. Commun.*, 2012, **11**, (3), pp. 1180–1189

9 Bogliolo, A., Lattanzi, E., Acquaviva, A.: 'Energetic sustainability of environmentally powered wireless sensor networks'. Proc. Third ACM Int. Workshop Performance evaluation of Wireless Ad Hoc, Sensor and Ubiquitous Networks, 2006, pp. 149–152

10 Lattanzi, E., Regini, E., Acquaviva, A., Bogliolo, A.: 'Energetic sustainability of routing algorithms for energy-harvesting wireless sensor networks', *Comput. Commun.*, 2007, **30**, (14–15), pp. 2976–2986

11 Hasenfratz, D., Meier, A., Moser, C., Chen, J.J., Thiele, L.: 'Analysis, comparison, and optimization of routing protocols for energy harvesting wireless sensor networks'. Proc. IEEE Int. Conf. Sensor Networks, Ubiquitous, and Trustworthy Computing, 2010, pp. 19–26

12 Chakraborty, A., Mitra, S.K., Naskar, M.K.: 'A Genetic algorithm inspired routing protocol for wireless sensor networks', *Int. J. Comput. Intell. Theory Pracitce*, 2011, **6**, (1), pp. 1–10

13 Zungeru, A.M., Ang, L.M., Seng, K.P.: 'Classical and swarm intelligence based routing protocols for wireless sensor networks: a survey and comparison', *J. Netw. Comput. Appl.*, 2012, **35**, (5), pp. 1508–1536

14 Saleem, M., Ullah, I., Farooq, M.: 'BeeSensor: an energy-efficient and scalable routing protocol for wireless sensor networks', *Inf. Sci.*, 2012, **200**, pp. 38–56

15 Saleem, M., Khayam, S.A., Farooq, M.: 'A formal performance modeling framework for bio-inspired ad-hoc routing protocols'. Proc. ACM Conf. Genetic and Evolutionary Computation, 2008, pp. 103–110

16 Huruiala, P.C., Andreea, U., Laura, G.: 'Hierarchical routing protocol based on evolutionary algorithms for wireless sensor networks'. Proc. Int. Conf. Roedunet, 2010, pp. 387–392

17 Hussain, S., Matin, A.W., Islam, O.: 'Genetic algorithm for energy efficient clusters in wireless sensor networks'. Proc. Fourth Int. Conf. Information Technology, 2007, pp. 147–154

18 Heinzelman, W.B., Chandrakasan, A.P., Balakrishnan, H.: 'Energy-efficient communication protocol for wireless microsensor networks'. Proc. Int. Conf. Hawaii System Sciences, 2000, **1**, (8), pp. 3005–3014

19 Latiff, N.M.A., Tsimenidis, C.C., Sharif, B.S.: 'Energy-aware clustering for wireless sensor networks using particle swarm optimization'. Proc. IEEE Int. Symp. Personal, Indoor and Mobile Radio Communications, 2007, pp. 1–5

IET Wirel. Sens. Syst., 2013, Vol. 3, Iss. 2, pp. 112–118
doi: 10.1049/iet-wss.2012.0117