Heuristic Algorithm and Cooperative Relay for Energy Efficient Data Collection with a UAV and WSN

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***Abstract* – This work [1] presents a heuristic algorithm for optimizing the average total energy consumed by the ground-based nodes in data collection applications with an unmanned aerial vehicle (UAV). For each cluster of nodes, the UAV is assumed to fly over at least one of them to collect data. In advance of each flight only the positions of the nodes are known to the UAV. After flying into communication range of any of the nodes in a cluster, it receives information about the remaining energy of each node. This knowledge is then used by the UAV to find which node to fly to. Essential criteria include the average energy consumption, flight distance for visiting the network, and the life-time of the network. In order to show the robustness of the algorithm, we compare the results to the following two cases: when the UAV is always flying to node closest to the cluster center or to least energy node of each cluster, respectively. Moreover, cooperative data relay is also applied in a compatible IEEE 802.11 hierarchal network for the nodes and the UAV. The simulation results show noticeable benefits of this cooperative data relay used in data collection, particularly with respect to the energy consumption and the longevity of the whole network of nodes.**

Index Terms – CSMA/CA 802.11, data relay, cooperative communication, unmanned aerial vehicle, path planning.

I. INTRODUCTION AND RELATED WORK

Recently UAS (unmanned aerial system) technology has become popular in various fields, with both civilian and military applications. The popularity of UAVs (unmanned aerial vehicles) is because of its low operation cost and safety enhancement for humans when compared to the conventional manned aircrafts. For instance, UAV could be very useful in wildfire management, observing support [1], agricultural monitoring, and border surveillance, environmental and meteorological monitoring [2], as well as for search and rescue missions [3]. In these scenarios, the UAV usually visits the area of interest to collect data from deployed nodes on the ground or on the sea surface. These nodes are not necessarily only deployed onshore or in nearby areas, but are also complexly implemented in remote areas where communication facilities are not available. For instance, in order to monitor the environmental status at a remote area, many nodes are to be deployed in the area. They record the surrounding information and wait for the availability of a mobile sink node. The UAV could be a very useful and flexible data collector [4], [5], and can easily repeat its flight for more data collection. In such applications, the UAV would be in charge of communicating with and collecting data from each node. The data measurements from nodes would be transmitted to a base station or a data center for analysis. In order to keep the whole network operating for a longer time, it is essential to minimize the average energy consumed by each node or maximize the energy of low energy nodes for its data transmission to the UAV. This energy could be affected by the UAV flight path or its waypoints. In addition, cooperative or non-cooperative communication between any pair of nodes might be another factor influencing the lifetime of the network. In the cooperative communication case, each node could become a relay node for its neighboring nodes. Otherwise, each node can only communicate directly with the UAV.

In flat ad hoc networks, there has been a lot of research on energy efficient algorithms in data transfer from all nodes to a static or a mobile sink node. Most of the papers have proposed an efficient routing scheme or a cooperative MAC for data relaying among the nodes in order to minimize the total energy consumption and maximize the network lifetime [6]-[8]. Other research has focused on finding the optimal path for the mobile sink node under the constraints of node energy consumption. For a hierarchical network, which includes ground-based nodes, and one or several UAVs, the data collection has also drawn much attention [9]-[11]. There has been a recent research on maximizing data collection using UAVs by applying network coding techniques, but only communication constraints are majorly concerned [12]. In many other studies, data collection has been properly optimized with an assumption that the UAV flight is programmed in advance. In our prior study, given the node position is known, the optimal path of UAV could be found under the constraints that the communication between the UAV and nodes must always remain [13]. The paper could be further developed by adding node's energy consumption to existing constraints. However, this optimization (based on mixed integer linear programming-MILP) would be less practical when the network has a large number of nodes or the node's energy is unknown. This is due to the computational complexity of running the optimization problem, and it would neither be suitable for online nor even offline optimization. In the former case, the UAV may need to loiter and wait for the result of the optimization, which decides the next motions. In the latter case, the UAV would need to have all the information in advance of the flight. Since we in this paper examine the case of many nodes on ground and their energy is assumed to be unknown, we will use an optimization algorithm that can be solved during the UAV's flight. The contribution of this paper is providing the best representative node in each cluster of nodes given that their energy consumption is minimized, and thereby the network lifetime is maximized. Theoretically, it would be best if the UAV could fly over each node such that the best channel condition

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between the node and the UAV could be obtained. However, the number of waypoints will increase linearly with the network size. This would significantly increase the flight time. In this paper, for simplicity, we assume that the UAV flies over one node per cluster; although this constraint could be relaxed. The following cases are to be evaluated and compared: 1) when the UAV flies to node closest to the center of the cluster; 2) when the UAV flies to least energy node in each cluster, and 3) when the UAV flies to the node that minimizes the energy consumed by the cluster.

The energy consumption for data transmission by nodes could be further optimized if a cooperative data relay scheme is applied. In this case, the total energy for relaying and forwarding is minimized. The optimization algorithm applied is a modified Bellman-Ford algorithm; and the base for data relaying relied on a cooperative relay MAC protocol, which is compatible with IEEE 802.11 standard. This scheme could be adopted from our prior study in [14]. In this case, there are not only UAV but also nodes on the ground. A feasible communication protocol is to combine both random access and reserved access in the system. Random access is used when UAV try to communicate with any node of a cluster at the beginning and reserved access could be used when UAV already received information from the cluster and its nodes. Further information on the system description, simulation and evaluation, as well as analysis and conclusion are given in details in the next sections.

II. DATA COLLECTION WITH A UAV

A. Data collection without relaying between nodes

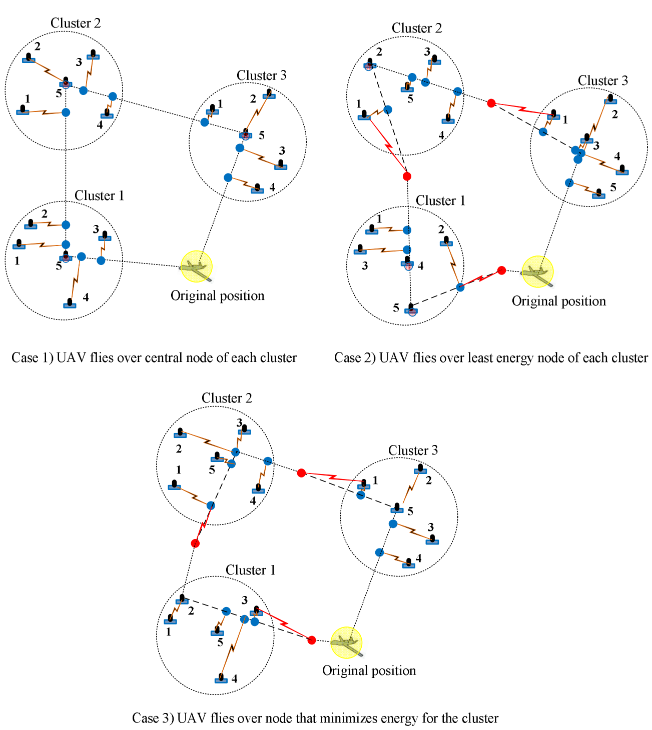

Fig. 1. Data collection by the UAV in three cases

In this system, many nodes are randomly distributed on the area of interest. The nodes are gathered together in some isolated clusters. Each node has at least one wireless interface for data communication (i.e. IEEE 802.11). The UAV is also equipped with at least one similar wireless interface such as for a node. The UAV plays the role of the data collector and visits all the clusters to receive data from the nodes belonging to the clusters.

In the case of no data relaying between any pair of nodes, each node needs to send its data directly to the UAV when the communication condition is at its best. This is achieved when the UAV has the shortest distance and LOS with the node; hence, energy for node's transmission is saved (Fig. 1). In this figure, red circles show the moment when UAV first communicates with a node of one cluster; and blue circles indicate the moments that data are transmitted to the UAV by respective nodes.

In this figure, it shows three basic cases of how to create waypoints for the UAV, when the target is to fly over one node for each cluster. In case 1, the UAV flies to node that is closest to the central position of all nodes in each cluster. The central position could be averagely calculated from all the nodes' coordinates. The UAV flight could be easily defined because the positions of the nodes are known in advance. And the flight path is constituted by the edges, which connect all the selected nodes, and with its original position (Fig. 1).

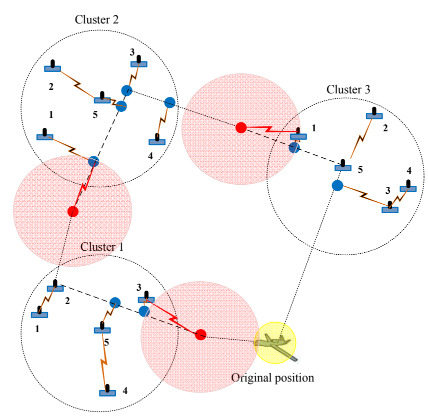

Fig. 2. Data collection with node's cooperation

It is assumed that the UAV flies at a constant altitude, so for simplicity of the figures, the projections of the UAV and its flight path are presented on the ground together with the nodes. In this figure, the small blue circles show the moments (times) where the distance between a node and the UAV is minimal. In case no.1 the UAV's flight path is predefined, and is not affected by the energy level of the nodes. In case no.2, the least remaining energy node of each cluster would be selected as the waypoint of the UAV to visit. This selection will start when the UAV is able to communicate with the closest node in that cluster. This could be done by a broadcasting message sent by the UAV, and it then listens to the feedbacks from the node. Through this information, the remaining energy of all the nodes in the cluster could be known by the UAV; hence, the least energy node could be decided. After that, the UAV starts to change its flight route which aims to the selected node. Before the position of the least energy node is known, the UAV simply flies to the central node of cluster no.1. After reaching the selected node of this cluster (node 2), the UAV changes its route which then points to the central node of the next cluster (cluster no.2). Similar to the processes in cluster no.1, during flying to the central node of cluster no.2, it also repeats broadcasting messages to this cluster and gets actual information from nodes there. The process is repeated for all the clusters in the network, before the UAV return back to its original position. For case no. 3, the process is quite similar to case no. 2. However, in this case, the selected node is the one which minimizes the total energy consumption by all the nodes in the cluster it is going to visit.

B. Data collection with cooperative relaying between nodes

In this system, data relaying between any pair of nodes is used if the transmitting node finds it beneficial (from an energy conserving point of view) to relay data to a relay node rather than direct transmission to the UAV. For example, in Fig. 2, node 4 in cluster no.1 does not transmit its data directly to the UAV, but relays data to node 5. This relay node will then forward this data to the UAV when it flies pass at its closest proximity (Fig. 2). This case happens only when the total energy used for transmitting data to node 5 and then for forwarding data to the UAV (by node 5) is less than the energy for transmitting the same data directly to the UAV (by node 4). The relaying processes are explained in details in Section C.

C. Cooperative data relay in 802.11 network with UAV

1) Multirate of 802.11 network with UAV

In the IEEE 802.11 standard, the packets may be transmitted at different rates, which are closely related to the channel condition such as signal-to-noise ratio (*SNR*) and the bandwidth (*B*). Assuming that there is only one active node transmitting data at a given time and no significant external interference source, the instantaneous signal-to-noise ratio SNR_{ij} between two nodes *i* and *j* in a LOS channel is [16]:

$$SNR_{ij} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^\alpha N} \quad (1)$$

where $N = kTBN_f$, is the noise, with k=1.38e^{-23} J/K being the Boltzmann constant, T=300K is the ambient temperature, B is the bandwidth, N_f is the noise factor at receiver node, P_t is transmission power at the transmitting node, and G_t and G_r are the gains at the transmitting and receiving nodes, respectively. In order to maximize efficiency of initial phase when UAV was searching for any node in a cluster, omni-directional antennas are used. Furthermore, λ is the wavelength ($\lambda = c/f$, where c=3E+5 km/s and f is the carrier frequency), d is the distance between the two nodes, and α is the exponential path loss factor. Following our prior study in air-ground communication, α could be applied with a value of 2.25 for communication between air and ground [17]. Usually an exponential path loss factor of three or four is applied for signal propagation between any pair of nodes on the ground. Using Equation (1) with standard conditions of operation for IEEE 802.11g, the feasible transmission rates vary from 54Mbps to 1Mbps depending on the following conditions: type of communication (between two nodes or between a node and the UAV), and their separation distance. Assuming that the channel fading is unchanged during packet transmission and the distance between any pair of nodes as well as between each node and the UAV is known at the moment of transmission, the respective transmission rates could be accordingly determined.

2) Metrics for data relay

By assuming that the distance between any pair of nodes located in the communication range of both transmitter and receiver is known, the respective transmission rate on the path between them can be calculated. Also, the UAV can calculate the relative distance with any node on the ground after it receives the information from the nearest node of their cluster. Therefore, the according energy usage is known, and we have $E_{ij} = P_{ij}^t t_{ij}$. By applying a standard transmitting power P_0^t, the energy consumption on the path between nodes *i* and *j* is:

$$E_{ij} = P_0^t t_{ij} = L P_0^t / R_{ij}.$$

where Rij is the data bit rate between the two nodes *i* and *j*; L is the length of the common packet that each node would send to the UAV. The algorithm used to select the optimal route for data packet is a modified Bellman-Ford algorithm.

3) Modified Bellman-Ford algorithm

This algorithm is used to solve the problem of finding the optimal relay route for data from a node to the UAV. The reason for using the modified version is to have the possibility of limiting the number of relay nodes used while still finding the optimal path in terms of energy. For a complete description of the Bellman-Ford algorithm, the reader is referred to [18]. Here, all nodes in the clusters and the UAV are modeled as a weighted directed graph. The weight associated with an edge representing the energy consumption used for data transmission on the channel between two respective nodes is, $W_{ij} = L P_0^t / R_{ij}$.

III. PERFORMANCE EVALUATION

A. Parameters

In this paper we survey the data transmission bit rates measured in the IEEE 802.11g standard. At these ranges, it would be suitable enough to apply for at least the sample applications with the UAVs as mentioned in Section I as well as for many other scenarios. The antennas gain in this system is assumed to be 1 dBi for both transmitting and receiving ones (Table 1). Regarding the transmission rates in Table 2, they are obtained from the relation between the rate and operating distance applied in the IEEE 802.11g standards [19]. These standard rates are the results of applying an exponential path loss of three and a specific value for signal-to-noise ratio [20]. For a communication channel between a node and the UAV, an exponential path loss of 2.25 could be applied, so a conversion in operating distance is needed. With the same value of SNR, the corresponding rates and new operating distances are shown in Table 2. The value of d_{max} represents the maximal communication distance at which the transmitter applies a standard transmitting power and the receiver still acquires acceptable receiving signal strength, i.e. not smaller than the receiving sensitivity.

In this evaluation, three clusters of nodes are examined. Each cluster is assumed to have a number of nodes and this number is the same for all clusters. Also, all nodes in a cluster can communicate with each other within its communication range. After each iteration of data collection, the status of each node is properly changed and it becomes unknown by the UAV in the next iteration.

TABLE 1. SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Frequency	2.4 GHz	UAV's waypoints	Case no.1,2,3 & with relay
Bandwidth	20 MHz		
P_0^t	0.2 W	# clusters	3
G_{et}, G_r	1 dBi	# nodes/cluster	10, 50, 100
Initial node energy	0.1 J	UAV height	150 m
UAV avg. speed	25±3 m/s	Packet size (L)	500 bytes
Rec. sensitivity	-94 dBm	Sensing radius (by UAV)	290 meters
Communication range	100 m		
UAV initial pos.	[0, 0]	Clusters central	[200 200] [1000 3000] [3000 1000]
# observed interactions	7000		

TABLE 2. DATA BIT RATEs FOR 802.11g STANDARD
(*With path loss exponents of 2.25 and 3.0, BER≤10⁻⁵*)

Rate (Mbps)	Distance (m)	Rate (Mbps)	Distance (m)
Ex. path loss α =2.25 (between a node and the UAV)			
54	54	12	204
48	69	9	219
36	114	6	261
24	146	2	328
18	189	1	d_{max1}
Ex. path loss α =3 (between a pair of nodes)			
54	20	12	54
48	24	9	57
36	35	6	65
24	42	2	77
18	51	1	d_{max2}

B. Results

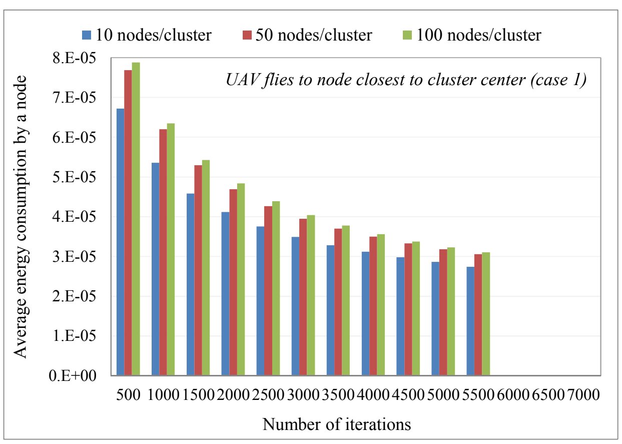

Fig. 3. Average energy consumption in case no.1

The following major criteria are to be evaluated throughout all the cases described above. They include the average energy consumed by each node and lifetime of the total network. For the first factor, the lower value it has, the less number of the active nodes remains. This is because the smaller number of nodes, the less possibility of spending much energy due to the separated nodes. So the average energy consumed by all the nodes in the cluster is small. When there is only one node in the cluster, the energy consumption would be minimal, and it becomes zero if there is no working node in the cluster. The second factor could be evaluated by examining the percentage of nodes that have died in the network due to battery drain. The higher value it has, the fewer number of active nodes remains in the network. If this value reaches 100%, it means all the nodes in the network are dead, and there is no active node to transmit data, and consequently the average energy becomes zero. The tour length of the UAV could be also evaluated but it has not been taken into account of route (flight path) optimization in this paper.

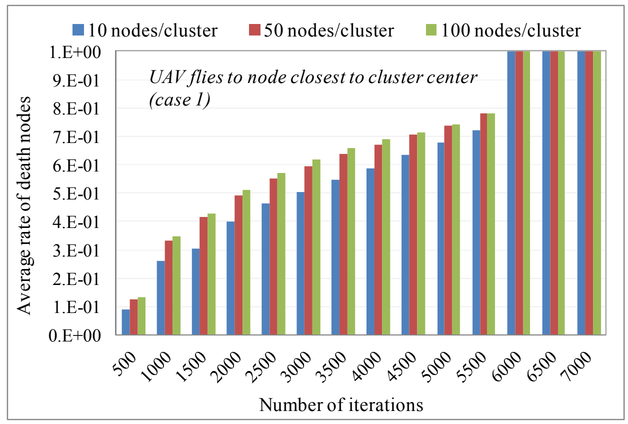

Fig. 4. Average rate of dead nodes in case no.1

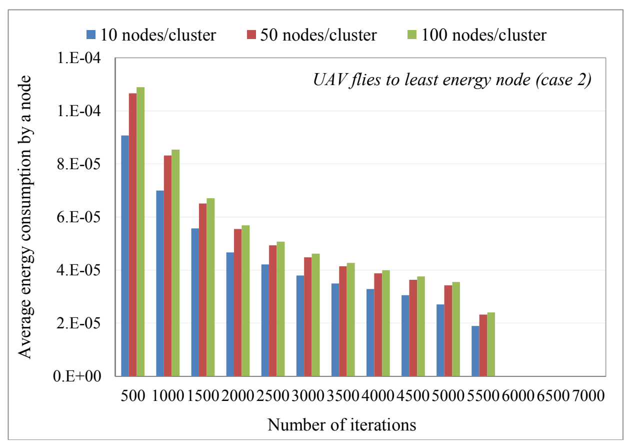

Fig. 5. Average energy consumption in case no.2

Figure 3-4 shows the results of those two metrics in case no.1 (*UAV flies over the central node*), Figs. 5-6 shows case no.2 (*UAV flies over the least energy node*), and Figs. 7-8 shows case no.3 (*UAV flies over the node with minimal total energy*). In these figures, the horizontal axis represents the number of iterations, which means the number of UAV's flight repetition. From results in Figs. 3-8, there is a common trend that the more iterations of data collection, the lesser average energy consumption, and the higher rate of dead nodes in the network. To explain the first observation, it is noticed that in initial phase there are many nodes in each cluster but this number would decrease with an increasing number of iterations. Consequently, the number of active nodes is reduced; therefore, the nodes positions might not be as separated as they were at the initial phase and the average energy is decreased. For the second observation, it is quite logical to have a higher percentage of dead nodes after many of iterations because of their energy drain. The results also show that in case no. 3 where the UAV flies over the node with minimal total energy consumption, system obtains the best results. This is shown by the least energy consumption and the lowest percentage of the dead nodes in comparison with results in the previous two cases.

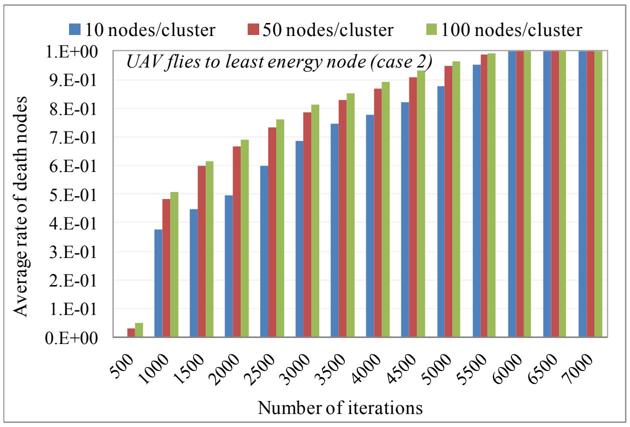

Fig. 6. Average rate of dead nodes in case no.2

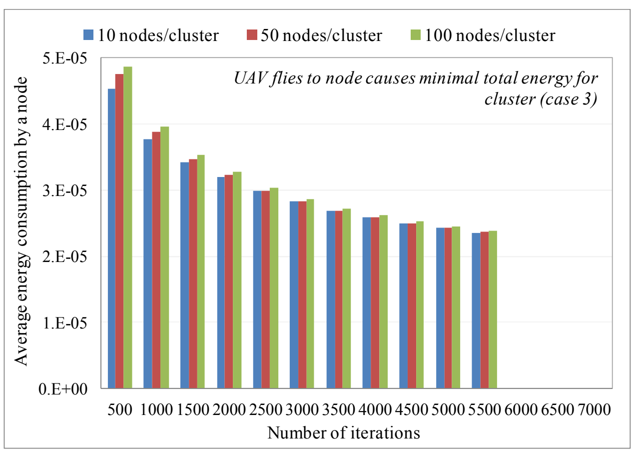

Fig. 7. Average energy consumption in case no.3

In the case data relaying scheme is adopted, a modified Bellman-Ford algorithm would be applied for cooperative data relay optimization. Figures 9-10 shows a noticeable benefit in terms of low energy consumption and extended longevity for whole network. More specifically, after the iterations of 6000, the network is usually totally down in all those three cases (cases no.1-3), but it shows that still 40% of the nodes are active and working if optimization and data relaying is applied. It also shows that the denser the network nodes the lower energy consumption and the longer network availability could be obtained. This could be the result of better possibilities in finding a relay node for more efficient energy usage. For more visible data, Fig. 11 reviews all the four cases (three cases without data relaying at no.1-3, and the case with data relaying) of simulations in terms of average energy consumption at the specific condition of 10 nodes per cluster.

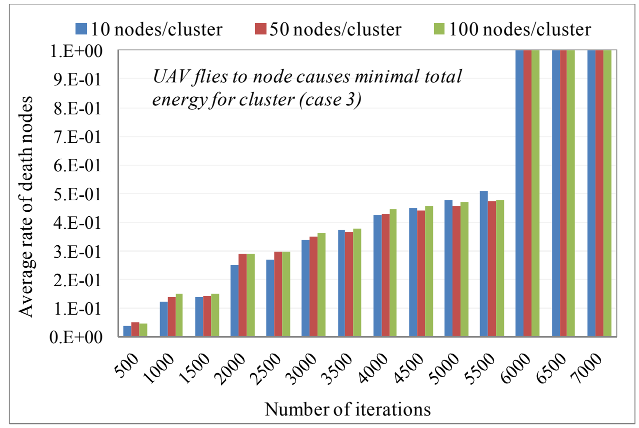

Fig. 8. Average rate of dead nodes in case no.3

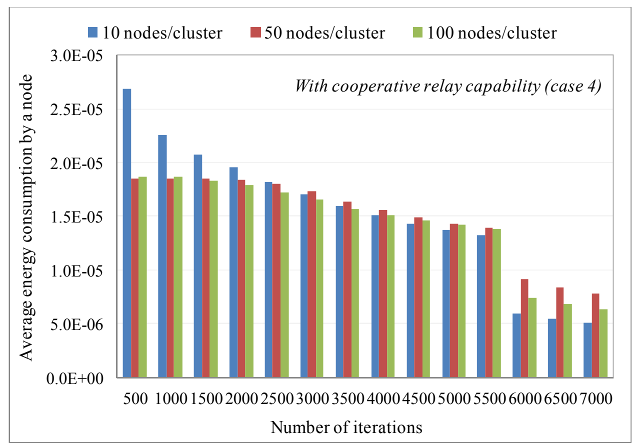

Fig. 9. Average energy consumption in the case with relay

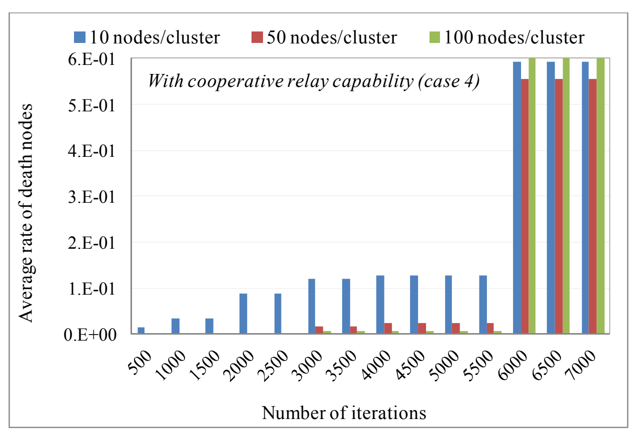

Fig. 10. Average rate of dead nodes in the case with relay

The tour length of the UAV in the four cases is presented in Fig. 12 when applying the same conditions with the results shown in Fig. 11. Until a value of 2500 iterations, while there are still many active nodes in all cases, tour length in case of with data relaying is a bit smaller than that in other three cases. However, it is not always the smallest value, for instance from 3000 iterations, the tour length in case of flying over the minimal energy consumption node by the UAV is usually larger than its value in the case of flying over central nodes of clusters. In this paper, tour length is not our main interest; hence, it may still remain a compromise for the tour length of the UAV while we save most the energy consumption of the nodes and whole network.

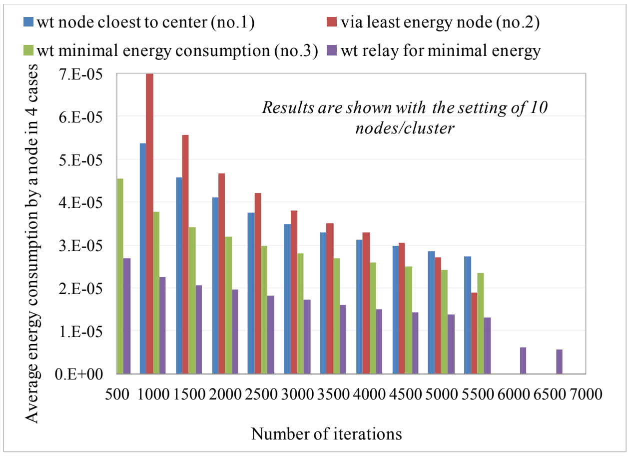

Fig. 11 Benefits of applying data relay in terms of energy

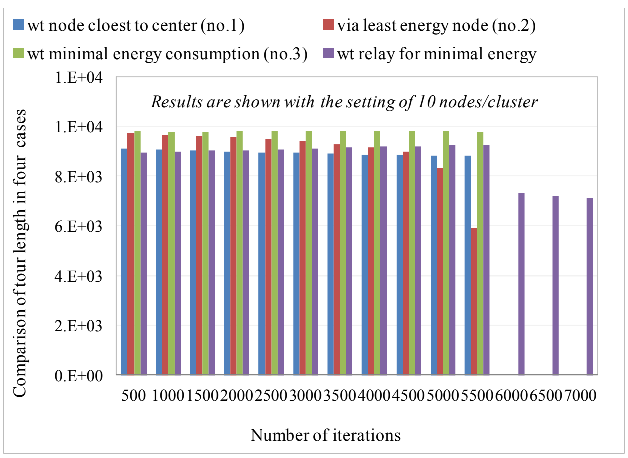

Fig. 12 Average tour length in the four cases

IV. CONCLUSION

The combination of the cooperative data relay and the optimization scheme that selects the least energy node consumption for the cluster's node has shown its significant benefits in terms of minimizing the energy consumption and maximizing the network lifetime. In most of the cases, this combination can reduce energy consumption as well as the percentage of dead nodes in the network to a half. This heuristic scheme could be easily applied to a network with limited information on the nodes. Furthermore, this scheme could easily be modified to adapt with the case that there are more than one node required to be visited by the UAV for each cluster; however, the computational complexity would be increased. The system performance would be optimized in a more refined way if additional criteria such as average transmission bit rate, system bit-error-rate, and UAV's tour length are added into the objective function. Regarding to multiple access schemes between nodes and the UAV, with exact information about the moment the UAV would visit each node, a combination of TDMA and CSMA/CA methods could be more efficient with low contention and system complexity.

REFERENCES

[1] E. W. Frew and T. X. Brown, "Networking issues for small unmmaned aircraft systems," *J. of Int. and Robotic Sys.*, vol. 54, pp. 21-37, 2008.

[2] J. J. Ruz, O. Arevalo, G. Pajares, and J. M. de la Cruz, "UAV trajectory planning for static and dynamic environments," InTech, 2009, pp. 581-600.

[3] SWARMIX Project. [Online]. Available: http://www.swarmix.org/index.php?show=home

[4] J.A. Cobano, J.R. Martinez-de Dios., R. Conde, J.M. Sanchez-Matamoros, Anibal Ollero, "Data Retreiving from Heterogeneous Wireless Sensor Network Nodes Using UAVs," J. Intell Robot Syst, pp. 133-151, 2010.

[5] Izhak R., Runhe Z., "Placement of UAVs as Communication Relays Aiding Mobile Ad Hoc Wireless Networks," in Proc. IEEE Military Communications Conference (MILCOM'07), Orlando, FL, Oct. 2007.

[6] Chi M., Yuanyuan Y. "A Battery-Aware Scheme for Routing in Wireless Ad Hoc Networks," IEEE Trans. On Vehicular Technology, vol. 60, no. 8, pp. 3919 - 3932, 2011.

[7] Oliveira, H.A.B.F. "A Novel Greedy Forward Algorithm for Routing Data toward a High Speed Sink in Wireless Sensor Networks," in Pro. ICCCN, Aug. 2010

[8] M. Lucchi, A. Giorgetti, M.Z. Win, and M. Chiani "Using a UAV to collect data from low-power wireless sensors," in Proc. XIX Congresso Nazionale AIDAA, Vol. 86, pp. 141-150, Forli, Italy, Sep. 2007.

[9] Shuai G., Hongke Z., Tianfei S. and Ying W., "Network Lifetime and Throughput Maximization in Wireless Sensor Networks With a Path-constrained Mobile Sink," in Proc. 2010 International Conference on Communications and Mobile Computing

[10] Andrea G., Matteo L., Marco C., and Moe Z. W. "Throughput per Pass for Data Aggregation from a Wireless Sensor Network via a UAV," IEEE Trans. On Aerospace and Electronics System, vol. 47, no. 4, pp. 2610-2626, Oct. 2011.

[11] Tzung-Cheng C., Tzung-Shi C., and Ping-Wen W. "On Data Collection Using Mobile Robot in Wireless Sensor Networks," IEEE Trans. On Sys., Man, and Cybernertics- Part A: System and Humans, vol. 41, no. 6, Nov. 2011.

[12] P. B. Sujit, Daniel E. Lucani, and Joao B. Sousa "Bridging Cooperative Sensing and Route Planning of Autonomous Vehicles," IEEE J. Sel. Areas in Commun., vol. 30, no. 5, pp. 912-922, Jun. 2012

[13] E. I. Grøtli, T. A. Johansen, "Path planning for UAVs under communication constraints using SPLAT! and MILP," J. of Intelligent and Robotic System, vol. 65, 2012..

[14] D. T. Ho, E. I. Grøtli, S. Shimamoto, T. A. Johansen, Optimal Relay Path Selection and Cooperative Communication Protocol for a Swarm of UAVs, The 3rd International Workshop on Wireless Networking & Control for Unmanned Autonomous Vehicles: Architectures, Protocols and Applications (GC'12 Workshop - Wi-UAV), Dec. 2012.

[15] R. Jafari, A. Encarnacao, A. Zahoory, F. Dabiri, H. Noshadi, and M. Sarrafzadeh, "Wireless sensor networks for health monitoring," Proc. Mobile and Ubiquitous Systems: Networking and Services , pp. 479-481, Jul. 2005.

[16] A. Goldsmith, "Wireless communications," Cambridge university press.

[17] D.T Ho, J. Park, S. Shimamoto, J. Kitaori "Performance evaluation of multi hop relay network for oceanic air traffic control communication," *IEICE Trans. on Commun.* vol. E94-B, no. 1, pp. 86-96, Jan. 2011.

[18] O. Burdakov, P. Doherty, K. Holmberg, P.-M. Olsson, "Optimal placement of UV-based communication relay nodes", Journal of Global Optimization, vol. 48, no. 4, pp. 511-531, 2010.

[19] The 802.11g standard. [Online]. Available: http://standards.ieee.org/getieee802/download/802.11g-2003.pdf

[20] The 802.11a/g OFDM PHY. [Online]. Available: http://www.comlab.hut.fi/opetus/333/2004slides/topic15.pdf