www.ietdl.org

Published in IET Communications
Received on 14th July 2010
doi: 10.1049/iet-com.2010.0638

In Special Issue on Distributed Intelligence and
Data Fusion for Sensor Systems

ISSN 1751-8628

Multiple mobile agents' itinerary planning in wireless sensor networks: survey and evaluation

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Abstract: Over the last decade, mobile agent (MA) systems for surveillance applications in wireless sensor networks (WSNs) has gained much attention. However, a conventional MA-based WSN may have the issues of energy efficiency and task duration as the scale of the network is increased. In order to overcome the drawbacks of using a single MA, dispatching two or more MAs for data collection simultaneously is a promising alternative in a WSN. The authors first discuss the itinerary planning issues for multiple MAs: deciding the number of MAs to be dispatched, grouping of source nodes for each MA, routing of each MA for its assigned source nodes. The authors then survey the existing algorithms for these issues, and evaluate their performance by OPNET.

1 Introduction

In conventional wireless sensor networks (WSNs) (e.g. [1]), sensors perform the data fusion and deliver the data to a sink node. Mobile agent (MA)-based WSNs (e.g. [2–4]) provide an alternative approach of data fusion and delivery. That is, an application-specific MA, which is a special software containing executable codes to be run in sensor nodes [5], is dispatched to the surveillance area. The MA traverses the area of interest to extract, collect and fuse sensory data from source nodes, and then carry the result back to the sink. This approach may result in a significant improvement on the network efficiency, such as information fusion, load balancing, contention/interference avoidance in WSNs.

The MA deployment in WSNs may typically have the following design issues [6], such as the overall system architecture, MA itinerary planning and middleware system design. Among these issues, itinerary planning determines the order of source nodes (with sensory data) to be visited by an MA, which has a significant impact on the system performance. Thus, how to find out an optimal itinerary for the MA to visit the source nodes of interest is critical. In some sense, the itinerary problem is also closely related to vehicle routing problem (VRP) [7], where the objective of VRP is also to find a set of delivery routes for target customers, satisfying given constraints while minimising total cost. Obviously, finding an optimal itinerary for an MA is NP-hard [8]; thus, heuristic algorithms have been proposed.

MA-related research has become more interesting after Chen *et al.* [9] presented the potential benefit of using multiple MAs, such as the scalability to deal with large-scale WSNs and the optimisation of task load by partitioning area among the MAs. Compared to the single MA itinerary planning (SIP) problem, dispatching multiple MAs require the system to consider three key elements: (i) the quantity of MAs, (ii) grouping of source nodes for each MA, and (iii) itinerary planning of each MA. These elements are correlated to each other; thus, the computational complexity of the solution is dramatically increased. Let us call these problems collectively a multiple MA itinerary planning (MIP) problem.

There are a few existing studies for the MIP problem. The work in [9] first illustrates the potential advantages of using multiple MAs and proposes an iterative solution. That is, the MIP algorithm is deemed as the iterative version of an SIP solution. The MIP problem can be divided into four parts: (i) selection of a visiting central location (VCL) for each MA; (ii) determination of the set of source nodes of each MA; (iii) determination of the source visiting sequence; and (iv) the iterative framework.

In this paper, we survey the prior algorithms for the above issues and compare their performance by extensive simulations in OPNET. The contribution of this work includes two aspects: (i) this is the first survey work on MIP solutions. It provides an overview of the state of the art in this area; (ii) the simulation experiments compare the related work comprehensively.

The remainder of the paper is organised as follows. Section 2 introduces the design framework of multiple MA-based WSNs, and the itinerary planning issues are listed in Section 4. The state of the art of MIP solutions is discussed in Section 5.

Performance evaluation of the representative schemes is carried out by simulation in Section 6. Section 7 points out plenty of open issues and Section 8 concludes this paper.

2 Multiple MAs-based WSNs

The multiple MAs-based WSN is an evolution version of the single MA-based WSN. Instead of dispatching a single MA to the network, it enables two or more MAs to execute the task simultaneously. These multiple MAs work in a cooperative pattern. The whole data fusion application is then fragmented and completed by each MA, respectively.

Fig. 1 compares the data fusion patterns among conventional, single MA-based and multiple MAs-based WSNs. In conventional WSNs, the raw data sensed by the sensors, denoted by light rectangles, are transmitted from sensors to the sink directly as shown in Fig. 1*a*. In contrast, the single MA-based WSN dispatches one MA (denoted by the dark rectangle) to retrieve the information sensed by travelling around all source sensors in sequence, as shown in Fig. 1*b*. The novel solution of using MA provides advanced features, including application flexibility [10], raw data pre-processing, stability and fault-tolerance. In addition, it eliminates the multiple flows between the source nodes and the sink, which will reduce the potential contentions and interferences in the WSN.

However, these benefits from MA are only applicable to small-scale networks. Once the network size grows, number of source nodes will be increased, and the distribution of source nodes will become more complicated. This leads to three critical issues.

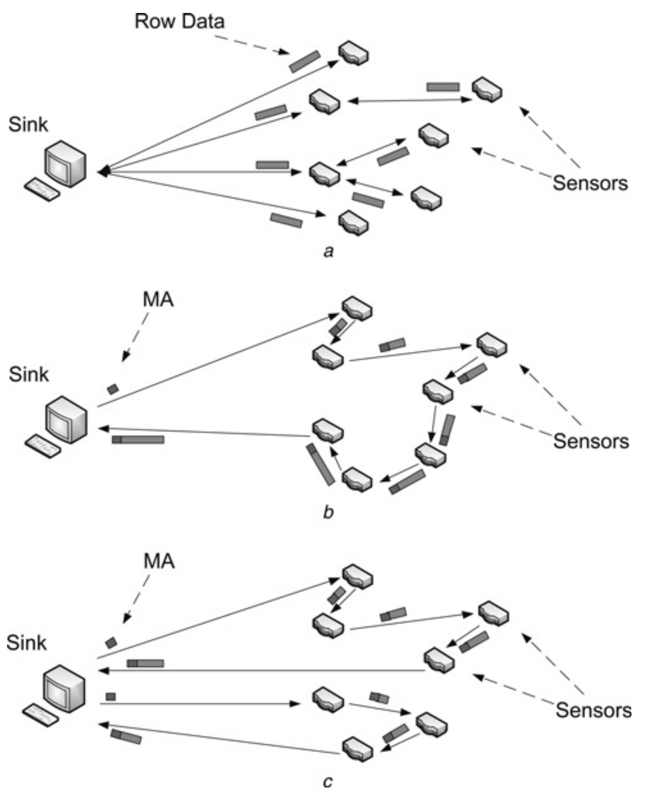

Fig. 1 *Comparison of data fusion patterns in the WSN*

a Conventional
b Single MA
c Multiple MAs

1. *Delay scalability:* A single MA roams in a network for data collection. The round-trip time of visiting all of the given source nodes in sequence within a large-scale WSN will become quite long.
2. *Potential route inefficiency:* Often, the source nodes may be distributed in a clustered manner [11]. A single MA has to migrate from one cluster to another, carrying the data that it retrieved previously. The ever-increasing size of MA packet will consume substantially more energy if the clusters are far away from each other.
3. *Traffic load balancing:* In the perspective of the whole network, it is better to distribute the traffic load across the network. However, sensor nodes in the agent itinerary will deplete their energy faster than others. Note that the MA packet size will be increased as it collects more and more data from the sensor sources.

Consequently, a multiple MA-based system is induced to overcome all these drawbacks [9]. The main idea of a multiple MA-based system is to share the data fusion task load with several MAs. Fig. 1*c* gives an example solution with two MAs. Seven sensor nodes are divided into two groups, nodes within each of which are visited by a particular MA dispatched from the sink. The performance of this approach can exceed that of a single MA system if the nodes are well grouped and itineraries are well designed. However, a multiple MA-based system reintroduces more transmission traffic in the network, bringing negative effects to the system performance. Therefore a multiple MA system should find out the optimal balance on the trade-off on the performance and efficiency.

In order to design the MA-based WSNs with high efficiency, we categorise four important design issues as follows:

1. *Architecture:* The multiple MA system motivates the research society to redevelop the MA-based WSNs from the architecture aspect. Since multiple MAs coexist in the network and the content of MAs are potentially relevant, there are arising interests in the efficient merging of tasks of MAs, especially for the cases in which the surveillance region is far away from the sink. The maintenance of the synchronised working pattern for multiple MAs is still an open issue.
2. *Itinerary planning:* The itinerary planning for multiple MAs will significantly affect the efficiency of the system. SIP problem has been proven to be NP-complete, and so the MIP is more complicated. The detail of itinerary issues will be presented in Section 4.
3. *Middleware design:* In order to make the MA accomplished with an existing sensor network system, middleware design is commonly adopted. Researchers should design middleware for MA deployment over resource-rich wireline networks to provide rich functions for a wide variety of tasks. However, the severe hardware and energy limitations in WSNs will lead to many technical challenges in designing a practical MA middleware for WSNs [6].
4. *Hardware design:* Hardware design is one of the most critical challenges for multiple MAs system. As required by the simultaneous cooperation of MAs, the hardware should support the concurrent transmitting of multiple packets. Multiple interfaces design may provide sufficient capacity to the requirement; however, it is an expansive way from the industrial perspective.

doi: 10.1049/iet-com.2010.0638

3 Theoretical research regarding MIP

From a theoretical perspective, the itinerary problem is closely related to the VRP [7]. VRP is a combinatorial optimisation and integer programming problem, which seeks optimal routes to serve a number of target customers with a fleet of vehicles, satisfying specific requirements or constraints while consuming minimal total cost. The MAs in MIP problems perform similar role of the vehicles in VRP, whereas the source nodes are representing the target costumers. The side constraints of VRP include time limitation, cost requirements or even in-journey pick-up requirements, and similar to MIP, the VRP has been also identified as an NP-hard problem, which pushed researchers to dedicate to find heuristic solutions. Moreover, the MIP problem, as well as VRP, can be generalised as one type of the travelling salesman problems (TSP), which have already attracted many research efforts. Effective adoption of TSP (or VRP) algorithms will facilitate and accelerate MIP research; for example, several MIP solutions [12–15] are based on the algorithms for minimal spanning tree (MST) problem, which has been deeply discussed in TSP. However, the MIP is much more complicated than TSP or VRP, regarding the special environment of wireless links, unique energy-consuming models, limited transmission range per hop and the increasing content load that MAs are carrying.

In order to mathematically format the MIP problems, we define a WSN, $S = \{s_0, s_1, \ldots, s_{n-1}\}$, by a complete graph $G = (V, E)$, consisting of a set of n vertices, $|V| = n$, where each vertex $i \in [0,1, \ldots, n-1]$ in V corresponds to a sensor node s_i, $i \in [0, \ldots, n-1]$, and each edge l_{pq} in E corresponds to a wireless link between sensor s_p and sensor s_q. Note that the sensor s_0 corresponds to the sink node, which sends out MAs and receives MAs. Also there are m source nodes in the WSN, included in a specific subset, denoted by S', where $S' \subset S$.

In order to represent the transmission cost of wireless link, each edge l_{pq} is assigned with a link cost c_{pq}, $p,q \in [0,1, \ldots, n-1]$, which can be a function of the power loss of the signal transmission over the wireless link l_{pq} or other metrics depending on the design of the algorithms. Given the cost matrix $\boldsymbol{C} = \{c_{pq} \| l_{pq} \in E\}$, the MIP problems ask for a set of k near-optimal itineraries, $I = \{I_0, I_1, \ldots, I_{k-1}\}$, so that the sum of the costs of all the itineraries in I is minimised. Note that any itinerary should be a subset of S, including a sequence of sensor nodes, which contiguously connect together like a chain ring by wireless links, originated from and terminated at the sink s_0. Also all source nodes in S' should be covered by I, while any two itineraries should share no common source node to avoid interference. Therefore within one task interval of MAs, the total cost over all itineraries can be calculated as

$$c_{\text{total}} = \sum_{i=1}^{k} \sum_{j=0}^{|I_i|} \left[\left(\sum_{r=0}^{j} d_{ir} + L \right) c_{pq} \right], \quad p, q \in [0, 1, \ldots, n-1]$$

where $|I_i|$ means the number of visited nodes in the itinerary I_i of the ith MA, d_{ir} is the amount of data that the ith MA can collect from the rth visited source node in the itinerary I_i, L is the initial size of an MA, or say, the length of the core programming codes, and c_{pq} is the cost of utilising the link l_{pq} traversed by the ith MA on its jth hop in the itinerary I_i, where the node s_p should be the jth visited node and s_q should be the $(j+1)$th visited node. Note that when $r = 0$ or $r = 0$, the zeroth node means the sink s_0, and the zero hop means the link from sink s_0 to the first node, whereas the last hop of the itinerary is the link from the last node to the sink.

Depending on the specific purpose of any variation of MIP, the constraints and target objective will be slightly changed. From related literatures, it is already proved that the MIP problem is NP-hard [7, 8], and so researchers are carrying out various heuristic near-optimal solutions, which we will categorise and discuss in following sections.

4 Itinerary planning issues for multiple MAs

Among the design issues for multiple MAs in WSNs, itinerary planning is the most challenging topic, which we decompose into three elements, quantity of MAs, grouping of source nodes and itinerary for each MA.

4.1 Quantity of MAs

The original idea of multiple MAs came from the inefficient itinerary of the scenario with single MA, where all source nodes should be visited by the only MA in sequence. The long itinerary distance and the increasing packet length of MA induce longer task duration and redundant energy consumption. Multiple MAs are consequently induced to solve the problem by splitting the source nodes by groups and assigning one corresponding MA for each group. However, more involved MAs will produce more wireless transmission flows in the network. These co-existing flows will possibly introduce more collisions and unbalanced energy consumption issues, thus, reduce the benefits from MA system. Therefore the quantity of MAs is a trade-off factor in the solutions of MIP problems.

4.2 Grouping of source nodes

The purpose of utilising multiple MAs is to reduce the unnecessary route in single-MA case and maximise the aggregation ratio during the migration of the MA. The source nodes in the network should be grouped and assigned to their corresponding MAs optimally. The source nodes in the same group should be intrinsic related, for example, geographically close to each other. In addition, since the task duration for a multiple MA system is measured by the longest individual end-to-end delay among all MAs, there should be a balance on the number of MAs and the number of source nodes in different groups to achieve an optimised task duration.

4.3 Itinerary for each MA

After deciding the number of MAs with its corresponding group of source nodes, the route for each MA should be determined. Although the system can treat each route as an independent itinerary planning problem, there is still a little difference. The overlap of the MA routes should be avoided, or there will be collision and interferences among the wireless transmission flows.

5 State of the art of the solutions to MIP

There are a few of work focusing on the MIP problem. In this section, we survey four representative approaches to depict the state of art on the MIP topic. In contrast to SIP approaches, MIP solutions have to set up some groups for source nodes, which will be visited by corresponding MAs. Throughout this paper, we call this procedure as source grouping. In addition, in order to distinguish from the whole itinerary planning, we denote MA routing as the process of determining an itinerary for one particular MA to visit the designated group of source nodes.

5.1 Centre location-based multiple MA itinerary planning

Chen *et al.* [9] first proposes a centre location-based MIP solution (CL-MIP). The main idea of CL-MIP is to deem the MIP solution as an iterative version of an SIP, which consists of four steps:

1. *Selection of VCL for an MA:* CL-MIP assumes that the source nodes with higher geographical relevance should be in the same group. Consequently, the agent's VCL should be selected at the centre of an area with a high source node density. In CL-MIP, the calculation of VCL is based on a gravity algorithm, which imitates the gravity accumulation in natural world.
2. *Source grouping:* After selecting the VCL, the next step is to specify the visiting area, typically a circle/oval centred at the VCL with an assigned radius. All the source nodes in the group will be included in the visiting list of the corresponding MA.
3. *MA routing:* Within one group of source nodes, the itinerary of the MA is planned the same as the SIP problem, whereby existing SIP solutions can be applied, such as local-closest-first (LCF), global-closest-first (GCF) [16], genetic approach [17], mobile agent-based directed diffusion [18], itinerary-energy-minimum-for-first-source-selection (IEMF) algorithm and the itinerary-energy-minimum-algorithm [8] and so on. In CL-MIP solution, IEMF is adopted because of its higher efficiency and lower computational complexity.
4. *SIP iteration:* If there are uncovered source nodes, the next VCL will be calculated based on the remaining set of source nodes. The previous process will repeat until all of the source nodes have been assigned to an MA.

The contributions of CL-MIP includes that: it first proposes a four-step generic framework for solving the MIP problem, which reutilises the existing SIP solutions; the proposed gravity algorithm precisely describes the density centre of the groups of source nodes, which is the basis of source grouping. However, there are still unsolved issues as follows:

- The determination of the sets of source nodes is only based on geographical information. The load balancing among MAs is not considered.
- The efficiency of source grouping by a circle is questionable. Circle-shaped source grouping is not a generic solution considering those scenarios with irregularly distributed nodes. In addition, the radius of the source nodes grouping will also strongly effect the performance of CL-MIP, although its optimal value is still not measured or analysed explicitly.
- The work merely transforms an MIP problem to a repetition of SIP problems by a four-step framework. This greedy approach may lead to a substantially sub-optimal MIP solution.

5.2 Direction-based multiple MA itinerary planning

The proposal in [19] induces an alternative perspective on the step of source grouping, the angle gap-based MIP (AG-MIP). The main idea of AG-MIP is based on the criteria that most of the information-relevant source nodes are located in the same direction from the view of the sink. Therefore the source grouping method is direction oriented. The proposed scheme connects the sink and all source nodes with beelines, and the angle gaps $\Delta\theta$ between the beelines become a critical factor to describe the relevant degree among the source nodes. There is a VCL, which is determined by the two nodes with minimal angle gap. AG-MIP does not utilise shape of circle for source grouping. Instead, the nodes within a particular angle gap threshold θ around one central location should be included in the same group. This approach may result in some isolated source nodes that are located near the group. They will finally be considered as a special group after several iterations. Note that AG-MIP enables all the source nodes in a particular direction as a single group.

The most significant contribution of AG-MIP is to provide a novel vision on source nodes grouping. Another benefit of AG-MIP is that by using the angle gap to split the whole network into non-overlap sectors, the contention and interferences among different MA flows will be potentially reduced. However, the AG-MIP is still constrained within the four-step framework proposed in CL-MIP. The same as CL-MIP, the angle-oriented grouping method is an optimisation to specific applications, which cannot be counted as a generic solution. Furthermore, how to find out an optimal angle gap threshold θ is still an open issue.

5.3 Tree-based multiple MAs itinerary planning

The proposal in [12] models the MIP problems as a totally connected graph (TCG). In the TCG, vertices are the sensor nodes in the network, and the weight of an edge is derived from the estimated hops between the two end nodes of the edge. The authors calculate an MST with the TCG, and suggest that all source nodes in a particular subtree in the MST should be considered as a group.

Furthermore, the authors introduce a balancing factor α while calculating the weights in the TCG, to effect the forming of a balanced minimum spanning tree (BST). The balancing factor achieves flexible control on the trade-off between energy cost and task duration. By adjusting α, the quality-of-service (QoS) requirements in the term of delay can be satisfied for a large range of applications while trying to reduce the energy cost to a minimal level. This approach algorithm is called BST-based MIP (BST-MIP). The main contribution of BST-MIP is that it analyses the critical impact of the geographic positions of source nodes on the source grouping, and then evaluates the MST approach. The source nodes grouping algorithm in BST-MIP becomes more generic, which can be applied to a variety of sensor nodes deployments. However, the same as CL-MIP and AG-MIP, this scheme did not change the four-step framework proposed in CL-MIP.

There are some other tree-based methods for solving MIP problems, including NOID [13], CBID [14] and TBID [15]. NOID proposes a heuristic algorithm to suggest an appropriate number of MAs that minimises the overall data fusion cost, and to construct near-optimal itineraries by adopting the constrained minimum spanning tree problem. In NOID, the geographical distant is considered as the main

IET Commun., 2011, Vol. 5, Iss. 12, pp. 1769–1776
doi: 10.1049/iet-com.2010.0638

factor for the cost weight between two source nodes, which is different from hop-account-oriented BST-MIP. In order to effectively include the nodes that are far away from the centre, NOID uses a trade-off function for balancing. From the formatted tree, by migration and connection operations, near-optimal itineraries are planned. NOID outperforms LCF and GCF, but it suffers from low working speed and high computational complexity.

CBID applies a tree structure with branches for planning the itineraries. While deriving the tree structure, CBID follows a greedy approach to always include the node, which will make the total cost minimal. Furthermore, one MA will be cloned as two slave MAs at certain branch joint to visit individual tree branches for collecting data until the leaf nodes. Finally, slave MAs will go reversely and forward collected data to the MA at the joint then to the sink. CBID performs much better with respect to metrics of itinerary length and response time. However, CBID faces to scalability problem: as the size of the WSN increases, more branches will be created, which will degrade the performance significantly because of the interference. Also, the reversed trips of slave MAs consume unnecessary cost (for about one more time), which should be improved in future designs.

Another tree-based heuristic method, TBID, consists of two procedures: partitioning the whole WSN coverage around the sink into concentric zones, and building the MA itineraries from inner zones to outer ones. TBID also utilises greedy-like approach to always select the nearest node to form the binary tree. TBID generates low itineraries for MAs, but it has similar shortages as CBID, that is, the doubly consumed energy in the reverse routes, and the interference among the huge amount of branches. Furthermore, all tree-based schemes lack dynamical recovery for transmission failures, which will be one critical open issue for future research.

5.4 Genetic algorithm-based multiple MAs itinerary planning

The genetic algorithm-based multi-agent itinerary planning (GA-MIP) algorithm is proposed in [20]. The authors substantiate the proposed GA approach by encoding how many MAs are dispatched and which sensors are covered by individual MAs. The main features of this work can be summarised as follows:

- GA-MIP first proposes a novel two-level coding method for GA to solve MIP problem. The coding represents the source grouping and MA routing solution within a unique gene.
- In each evolutional iteration, the crossover and mutation operators are always the essential elements. GA-MIP provides a set of novel crossover and mutation operators according to the two-level coding.
- Fitness function, sometimes called select operator, sets up a criterion for selecting the better genes to survive. It is the most critical issue in GA design, which controls the direction of convergence. GA-MIP constructs a performance-aware fitness functionthat can derive a near-optimal solution for the MIP problem.
- The GA-MIP scheme considers MIP as a single problem instead of the four-step approach in previous three schemes.

Although extensive simulations have been carried out to show the better performance of GA-MIP in terms of the delay and energy consumption, the higher computational complexity of GA-MIP makes the implementation of GA-MIP still questionable. Also the fitness function on energy estimation in the paper is not the most optimal one, which still requires future investigation.

6 Simulation and performance evaluation

6.1 Simulation

In order to compare the performance of the SIP and MIP solutions, we carry out simulations in OPNET 'Note 1: OPNET, http://www.opnet.com/'. All of the four types of MIP solutions we mentioned above are implemented, and LCF, one of the typical SIP algorithms, is also realised in the simulation platform for comparison.

Following the most popular network model in MA research, the nodes are uniformly deployed within a 1000 m × 500 m field, where the sink node is located at the centre and multiple source nodes are randomly distributed around. The sink has infinite power supplement and high computational capacity, while every sensor node equips a battery with capacitance of 5 J. We set the energy consumption in sending, receiving and idle status to 0.66, 0.395 and 0.034 W, respectively.

In order to verify the scalability of the algorithms, we set the total number of sensor nodes to 800. And during the simulation, the number of source nodes is varied from 10 to 40 by the step of 5. All source nodes are randomly deployed based on the recalculation of the seeds. For each scenario with specified number of source nodes, extensive simulations are performed with different random seeds.

The parameters for MA system are shown in Table 1. For AG-MIP, the threshold angle gap θ is set to $\pi/6$, whereas for BST-MIP, the α value is set to 0.6. The parameters of GA-MIP are listed in Table 2.

6.2 Performance evaluation

We depict the results collected from the simulation and evaluate the efficiency of the five schemes, with respect to the metrics of energy cost, task duration and their product.

Table 1 Simulation parameters for a mobile agent system

raw data size	2048 bits
MA code size	1024 bits
MA accessing delay	10 ms
data processing rate	50 Mbps
raw data reduction ratio	0.8
aggregation ratio	0.9
network size	1000 × 500
radio transmission range	60 m
number of sensor nodes	800
MAC layer standard	802.11 b

Table 2 Simulation parameters for GA-MIP

GA iterations (I)	450
GA original population (P)	400
ordering crossover ratio	0.8
ordering mutation ratio	0.5
grouping mutation ratio	0.4
population expanding factor α	1

We calculate the energy cost for the migration of all MAs in the network as the energy efficiency, which accumulates the energy consumption of all activities for all MAs to obtain the sensory data from all the target sources, including transmitting, receiving, retransmissions, overhearing and so on, within one task cycle.

Fig. 2 illustrates the impact of the quantity of source nodes on energy cost. It is obvious that all of the five schemes consume more energy when the number of source nodes in the network increased. As the only SIP solution, the energy cost for LCF grows from 0.2 to 0.54 J per task when the number of source nodes increases. For the MIP solutions, GA-MIP and BST-MIP consume a bit more than LCF, whereas CL-MIP and AG-MIP are shown to be more energy efficient. Note that the value for AG-MIP stays the lowest among the five algorithms. In contrast, GA-MIP becomes the worst solution when the source node's quantity is set above 30.

The task duration is another critical criterion to evaluate the MA system, especially for some time-expensive applications (i.e. object location and tracking). It represents the round-trip time for one particular task. For the case of the SIP algorithm, it is equivalent to the average end-to-end reported delay, which is the average delay from the time when an MA is dispatched by the sink to the time when it returns to the sink. In the case of the MIP algorithm, since multiple agents work in parallel, there must be one agent that returns to the sink at the last. Then, the task duration of the MIP algorithm is equal to the maximum delay among of the task durations of all MAs.

Fig. 3 shows the task duration comparison among LCF and the four MIP schemes. Apparently, LCF approach takes the longest task duration because the single MA has to visit all source nodes distributed in the network. The value of end-to-end delay for LCF grows from 0.3 to 1.2 s along with the increasing number of source nodes. In contrast, the task durations for four MIP solutions are relatively shorter. Especially, the GA-MIP outperforms all other schemes; its the task duration stays below 0.2 s in most cases.

For the purpose of assessing algorithms in a bi-dimensional way, the energy–delay product (EDP) is defined for representing the overall performance from the aspects of both the energy efficiency and the task duration, calculated by EDP = energy × delay. For time-sensitive applications in WSNs, EDP gives us a unified view: the smaller this value is, the better the unified performance will be.

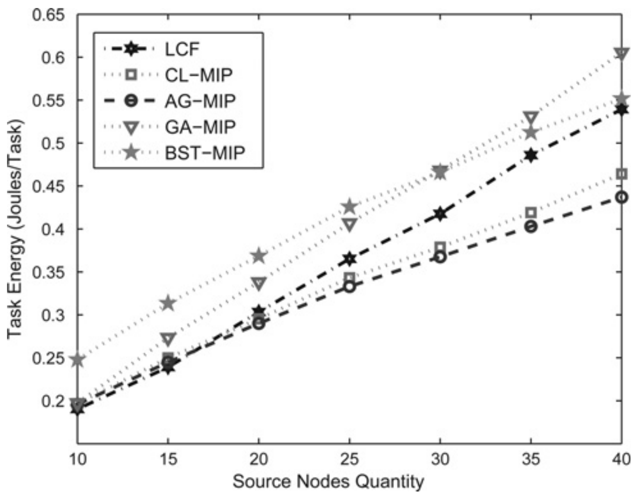

Fig. 2 *Impact of source nodes quantity on energy cost*

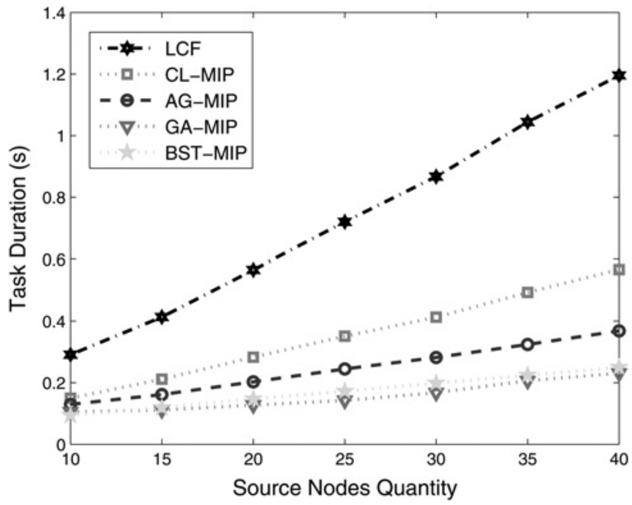

Fig. 3 *Impact of source nodes quantity on task duration*

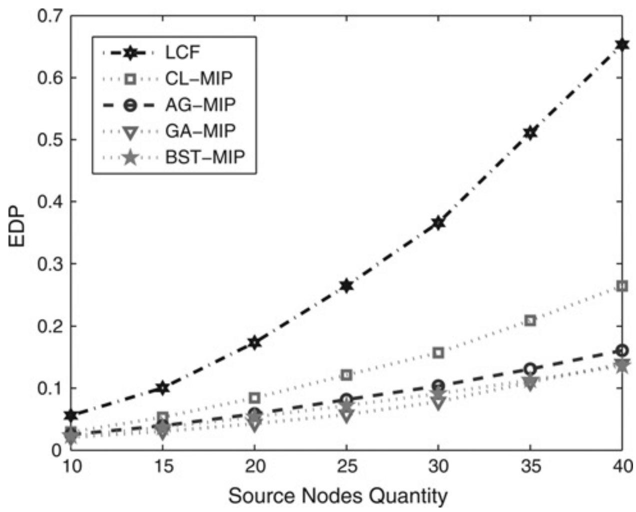

Fig. 4 *Impact of source nodes quantity on EDP*

Fig. 4 evaluates the overall performance of LCF and the four MIP schemes from the aspect of EDP. Owing to LCF's poor performance in task duration, it has the largest EDP value, which indicates its poorest overall capability among all algorithms. AG-MIP, BST-MIP and GA-MIP have comparable EDP values, which exceed that of CL-MIP. From the whole view, GA-MIP can be considered as the best scheme. However, it is observed that for the simulation case with 40 source nodes, the EDP value of GA-MIP is slightly larger than that of BST-MIP. This phenomenon can be explained by the incomplete convergency of GA evolution, which is limited by the iteration times and original populations in our simulation because of the computational complexity.

7 Open issues and research directions

Until now, most of the work on MA-based WSNs target the MIP near-optimal solutions, which mainly focus on the algorithms of source grouping and MA routing [8, 9, 12–19]. Particularly, researchers have designed four kinds of algorithms (centre location-based, directional angle-based, MST-based and GA-based algorithms) to efficiently solve the MIP problems, and to offer satisfying performance. However, the proposals still have some drawbacks, which

doi: 10.1049/iet-com.2010.0638

should be further improved in the future, for example, finding the optimal angle threshold for directional angle-based schemes [19], optimising the trade-off between number of MAs and length of the itineraries in tree-structured schemes [12–15], reducing the computational complexity of GA-MIP [20] and so on.

Furthermore, considering the various constraints of the WSN environment and QoS requirements, research work on multiple MAs-based WSNs still has a long way to go. We herein list and discuss several potential research issues as follows:

- *Delay-QoS-oriented MIP:* Supposing the source nodes have real-time data for the sink with specified time deadlines [21], MIP solutions will have to consider the itinerary cost conjunctively with the delay QoS, which current schemes consider little. In such a condition, an MA sometime needs to visit source nodes on time to meet the deadlines, even consuming higher itinerary costs. So there should be effective algorithm to balance the itinerary cost and time requirements optimally. Also, the delay synchronisation among MAs will be quite challenging.
- *Joint of MAs in MIP:* Current MIP solutions utilise multiple independent MAs for collecting data with distinct itineraries, sharing no common parts. As pointed in [14, 22], in many practical cases, it will be more efficient to effectively merge itineraries of two MAs, or to split one MA into two MAs with different itineraries, at certain proper locations. Overcoming such a problem will bring higher efficiency of multiple MAs-based WSNs, as well as higher complexity of the itinerary planning algorithms. Although CBID [14] and TBID [15] propose algorithms to split the itinerary tree into branches, but it still desires more improvement on the scalability and reliability, as well as the efficient merging of itineraries.
- *Environment dynamics:* Practically, wireless transmission in WSNs faces to frequent failures because of the network dynamics, such as link disconnections and node congestions. However, most present MIP solutions pre-define itineraries for MAs, considering little about how to overcome node failures. Future designs of multiple MAs-based WSNs should improve the reliability and failure tolerance, so that when some source nodes fail to route MAs, itinerary backup or recovery mechanisms need to be applied.
- *MIP with mobility:* In mobile WSNs, where sensors keep changing positions by time, such as deep-sea WSNs [23] and vehicle WSNs [24], solving MIP problems becomes more challenging. Researchers have to first generalise accurate mobility models of mobile sensors, then apply flexible source grouping methods and efficient itinerary planning algorithms based on the prediction of positions of nodes, to guarantee the reachability [25]. Multi-path [26] and multi-cast [27] mechanisms can be good candidates, and learning ideas from delay-tolerant network technology [27, 28] can also be another possible way.
- *Online itinerary planning:* A new topic has become more interesting in MA research, which is the way to carry out online itinerary planning of the MAs when they are roaming within the WSN. Definitely, this will further improve the flexibility and reliability of the itineraries of MAs, but it requires high computational complexity and more complicated algorithms, which could be much challenging.

8 Conclusion

The multiple MAs approach enhances the capacity of WSNs. It provides a flexible control on the trade-off between energy consumption and task duration for a desired overall performance. In this paper, we study the features of multiple MAs WSNs and discuss the open issues in this field from four aspects, including system architecture, itinerary planning, middleware design and hardware design. Furthermore, we explicitly survey four types of existing MIP proposals and evaluate the performance with extensive simulations. The evaluation results have shown the different features and performances of the four schemes, and our discussion on the open issues illustrates a future vision for the researchers.

9 Acknowledgments

This research was partly funded by the National Science Council of the R.O.C. under grants NSC 98-2219-E-197-001 and NSC 98-2219-E-197-002. It was also supported in part by the NAP of Korea Research Council of Fundamental Science & Technology, and the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency)(NIPA-2010-(C1090-1011-0004)). The ICT at Seoul National University provides research facilities for this study.

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doi: 10.1049/iet-com.2010.0638