A Novel Scheme for WSAN Sink Mobility Based on Clustering and Set Packing Techniques

Hidehisa Nakayama, *Member, IEEE*, Zubair Md. Fadlullah, *Student Member, IEEE*, Nirwan Ansari, *Fellow, IEEE*, and Nei Kato, *Senior Member, IEEE*

***Abstract*—Advances in technologies such as micro electro mechanical systems (MEMS) have empowered more efficient and smaller digital devices, which can be deployed in WSNs (wireless sensor networks) to gather useful information pertaining to a particular environment. In order to control effectively the physical system in a WSN, actuators may be employed to integrate such environmental information into the automation control system. Indeed, sophisticated entities deployed in wireless sensor and actuator networks (WSANs) act as functional robots. The approach of using the mobile sink, as an example of the actuator to control the movement of a sink, has been adopted by researchers in the past to achieve high efficiency in terms of gathering data from the sensors. This is due to the fact that in general, the sensors alone are unable to control the sink and need to send or relay a smaller amount of packet data. Although a number of methods exist in literature to utilize mobile sinks as actuators, most of these techniques are unable to guarantee data gathering from all of the sensors. As a consequence, more research effort is needed to improve the efficiency as well as fairness of data gathering. In WSANs, sinks and sensor entities should be actively controllable by the administrator. Therefore, we must consider an efficient way to access all nodes in the target networks. In this paper, we propose a novel method, based on the set packing algorithm and traveling salesman problem, to accomplish this goal. The effectiveness of our envisioned method is demonstrated through extensive computer-simulations.**

***Index Terms*—Clustering, mobile sink, set packing techniques, wireless sensor and actuator network (WSAN).**

I. INTRODUCTION

TECHNOLOGICAL advances have enabled production of small and efficient devices. Today, we are enjoying the benefits of these technologies in personal digital assistants (PDAs), cell phones, and many kinds of home appliances. Ubiquitous computing [1], in which many computational devices deployed all over the field can communicate with one another, is considered to be the next computing paradigm. In this context, we may consider WSNs as the killer application of ubiquitous computing. Furthermore, wireless sensors and actuator networks (WSANs) are emerging as a new generation of sensor networks. WSANs are expected to have a huge potential for growth due to their ability to serve as the backbone of control applications.

A WSN or WSAN possesses many application-oriented features. In general, similar to the case of a WSN, which consists of a population of sensor nodes with limited battery life, a WSAN is composed of sensors and actuators with limited computational resources. Since these sensors or actuators are small in size, they are often referred to as "smart dust" [2], [3]. Over the years, various types of these programmable entities have been developed by companies such as Crossbow [4] and Sun Microsystems [5].

The most popular application of a WSN is measuring and monitoring the conditions of a particular environment. In such an application, many sensor nodes are deployed either manually or automatically, and the deployed sensors are able to sense data such as temperature, humidity, pressure, and so forth. These collected data are then sent to the users, depending on the nature of the user-applications. For instance, in one application scenario, the sensor nodes may send data selectively. In a different scenario, the sensors may transmit data whenever they are available. On the other hand, in a WSAN, the users are able to control some actuators for a specific system. These actuators are able to perform a wide range of activities based upon the measured and monitored data gathered by the sensors, e.g., manipulating robots for watering plants, opening the windows of a room to regulate ventilation, closing the gas knobs to mitigate fire-hazards during an earthquake, and so forth.

Over the years, tremendous effort has been dedicated toward standardization of WSNs/WSANs. A prime example of such a standardization is Zigbee [6]. Basically, ZigBee is targeted at facilitating radio-frequency (RF) applications (e.g., sensors), which have limited battery power, and may not be frequently replaced in usual cases. Therefore, the objective of WSNs/WSANs is to prolong the battery life of each node and thus, to increase the lifetime of the overall network. For instance, TinyOS [7], which is the most prevalent operating system adopted in the sensors, is lightweight and tailored for interfaces and components of commonly used small hosts. In concert with the advances of individual hosts, tremendous progress has been made for data gathering from the hosts/sensors. Sensors scattered in a field can autonomously form a network to send data to various destinations. However, this requires more functionalities, and hence affects the lifetime of hosts. On the other hand, using mobile sinks for data gathering

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H. Nakayama is with the Department of Electronics and Intelligent Systems, Tohoku Institute of Technology, Sendai 982-8577, Japan.

Z. M. Fadlullah and N. Kato are with the Graduate School of Information Sciences, Tohoku University, Sendai 980-8579, Japan.

N. Ansari is with the Advanced Networking Laboratory, Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102 USA.

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is gaining more attention. For instance, the users can control mobile sinks for a purpose-designed system (e.g., a WSAN) as mentioned earlier. Thus, our efforts have been aimed at establishing a more effective data gathering scheme for mobile sinks as compared to the conventional schemes.

In this paper, we propose a novel mobility scheme to guarantee data gathering from all nodes fairly and efficiently in order to control all the nodes in a WSAN. The remainder of this paper is organized as follows. In Section II, we review related research works including KAT mobility [8] and discuss the shortcomings of conventional mobility schemes. In Section III, we present our proposed algorithm for effective data gathering at mobile sinks in WSAN environments. In Section IV, we provide and discuss the simulation results. Finally, concluding remarks are presented in Section V.

II. Related Works

The routing approaches to facilitate communication among the sink and sensor nodes (along with actuators) are extended from WSN to WSAN topologies in the work carried out by Shah *et al.* [9]. In this work, sensor nodes perform the task of sensing and actuator nodes take appropriate actions based upon the sensed phenomena in the field. In order to ensure energy-efficient and reliable communication, this work focuses on formulating a Real-time Coordination and Routing (RCR) framework for WSANs. The work attempts at coordinating sensors and actuators to provide delay-constrained energy-aware routing. To this end, clusters are formed and only cluster heads are used to coordinate with sink and/or actuators for saving the precious energy resources. This scheme uses a centralized real-time coordination amongst sensors and actuators when a fixed sink is present. On the other hand, in the absence of a sink, it adopts a distributed coordination among the deployed sensors and actuators. The cluster heads compute the best possible path to deliver the packets to the actuators within the given delay bound as efficiently as possible. However, this work does not consider mobility of the sink so that the sink would have been able to roam within the target WSAN topology to gather sensed data in a more efficient way.

The sink mobility approaches in WSNs, including prominent research works such as LEACH [10] and PEGASIS [11], may be readily applicable to WSAN topologies. Many variants, e.g., M-LEACH [12] and LEACH-C [13] techniques have also evolved over the years in order to deal with the sink mobility in WSN environments. In these schemes, sinks are static and sensor nodes form flat or tree-like networks based on various sensor network protocols. Since the positions of the deployed sensor nodes are not expected to change once they are dispersed in the sensing fields and the communication range does not alter also, there is always the concern about the isolated nodes, which may not be reached by other sensor nodes. These methods adopt the static sink, which attempts to gather data from other sensor nodes scattered over the target WSN/WSAN topology. A fixed sink, however, increases the probability of more sensor nodes to be isolated. A fixed sink requires a number of sensor nodes to forward the information from a source node located at a significant distance away from the sink. In order to collect data

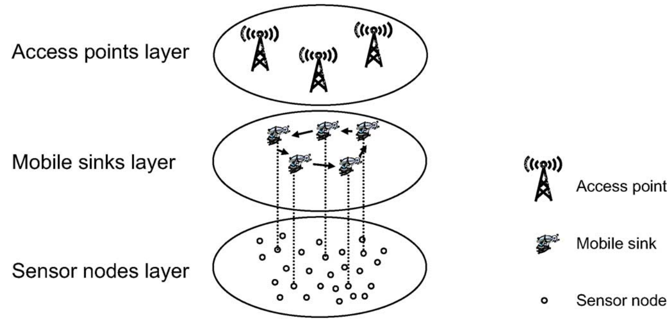

Fig. 1. Concept of the three-tier architecture.

from isolated sensor nodes and achieve higher efficiency, mobile sink schemes were introduced. In these schemes, the sink nodes roam around the sensing area and gather data from the sensors at various locations where they visit. One distinctive feature of these mobile sink schemes is their ability to reduce the amount of relayed information. MULEs [14] and TTDD [15] are two notable research works that demonstrated the effectiveness of mobile sink approaches in WSNs. MULEs [14] is one of the earliest schemes to adopt the mobile sink and divide the WSNs into a three-tier structure as shown in Fig. 1. In MULEs, two simple mobility schemes are employed, namely deterministic [Fig. 2(a)] and random mobility [16] [Fig. 2(b)] approaches. These two mobility schemes produce different trajectories of the mobile sink in the target WSN/WSAN topology. While the former mobility scheme is simple, it lacks efficiency and fairness. On the other hand, the data collecting intervals of random mobility are not stable. In other words, for certain sensors, the data gathering delay may be significantly high. In order to overcome these shortcomings, an enhanced mobility scheme, referred to as KAT mobility [8], was also introduced to facilitate efficient data gathering [Fig. 2(c)] in WSN environments. KAT mobility [8] is derived by combining the essence of clustering and the Traveling Salesman Problem (TSP). Fig. 2(c) demonstrates that a mobile sink traces in a pre-determined order by traversing the center of every cluster, which is determined by the clustering algorithm. KAT mobility achieves higher efficiency in contrast with its conventional counterparts. However, KAT mobility is not without its shortcoming, which consists in its inability to guarantee data gathering from all the sensors. Therefore, there is room for further improvement in terms of efficiency and fairness. Indeed, contemporary mobility schemes (including KAT mobility) require a number of diverse parameters. Each of these parameters needs to be adjusted appropriately in order to achieve a high level of efficiency. For instance, in KAT mobility, while the number of clusters (i.e., the grouping of the wireless sensor nodes) in the target WSN/WSAN has a great impact on efficiency, it is a rather difficult issue to determine the optimal clusters. In addition, conventional mobility schemes do not guarantee data gathering from all of the sensor nodes deployed in the target WSAN topology. These problems are further illustrated in Fig. 3(a) and (b). In Fig. 3(a), three clusters are generated in which "cross" marks indicate the centroids of the respective clusters. Ideally, when the sink moves to these centroids, all the nodes belonging to the respective centroids are

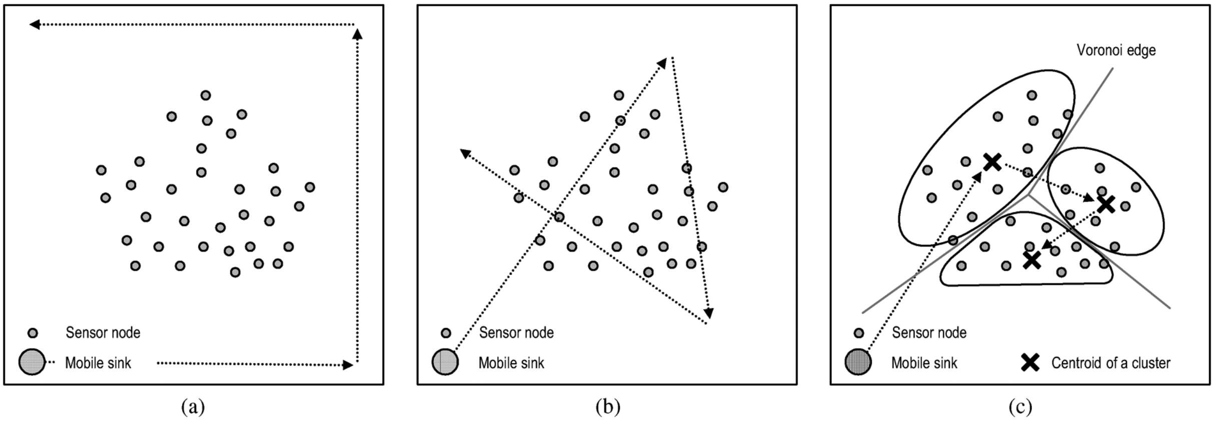

Fig. 2. Mobility Schemes. (a) Deterministic mobility. (b) Random mobility. (c) KAT mobility.

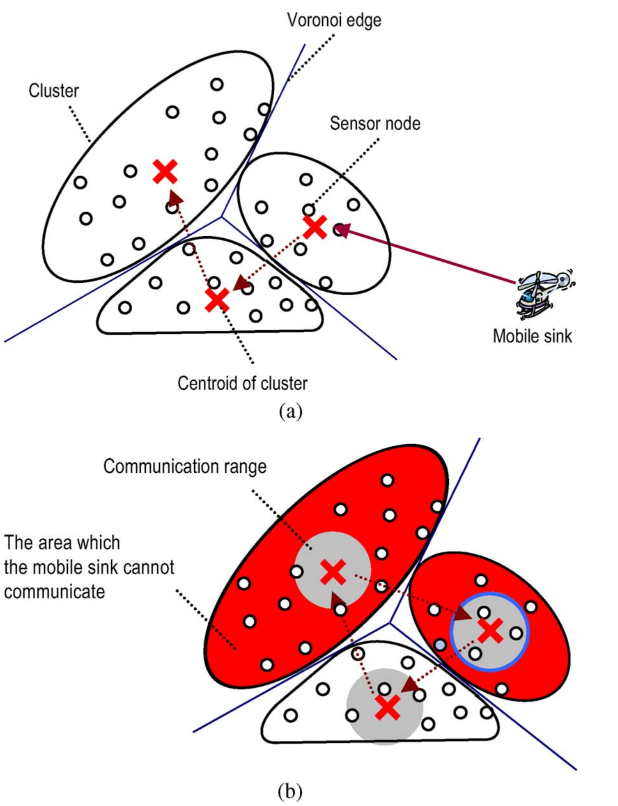

Fig. 3. KAT mobility on WSAN. (a) Overview of KAT mobility. (b) The drawback of KAT mobility.

able to communicate with the sink. However, the communication range and the cluster size influence the data gathering mechanism substantially. As a consequence, some nodes may not be reached by the mobile sink. As an example scenario depicted in Fig. 3(b), only nodes within the small circles are reachable by the sink. Nevertheless, this type of guarantee is required in certain applications, because users may demand to acquire as much detailed information as possible from all the nodes.

III. Envisioned Sink Mobility Scheme: Set Packing Algorithm and TSP (SPAT)

In order to deal with the afore-mentioned issue, we envision a novel mobility scheme that we refer to as Set Packing Algorithm [17] and TSP (SPAT) mobility throughout this paper. The design considerations of our envisioned SPAT scheme guarantees the complete data gathering from all of the sensor nodes over the sensing field in the target WSAN. In addition, SPAT ensures fairness in terms of data gathering frequency. This idea is derived from one of our earlier mobility methods called Set Covering Algorithm and TSP (SCAT) [18], which aims at achieving the same objective, but lacks fairness due to inability of the set covering algorithm to guarantee coverage of all sensor nodes without overlapping clusters.

The reason why the proposed SPAT method adopts the set packing algorithm is basically similar to that of adopting the set covering algorithm. The set packing problem is also a NP-hard one. However, it is capable of reducing duplicated data gathering. In contrast with the set covering algorithm, the output of the set packing algorithm does not produce duplicated sensor nodes. As a consequence, theoretically speaking, the set packing algorithm does not produce duplicated data. Instead, though some sensor nodes may be beyond the communication range of the mobile sink, the SPAT algorithm is designed to accommodate for few additional clusters for those nodes. This is considered to be a trade-off in order to avoid generating a large number of replicated nodes in the clusters.

In the remainder of the section, the functionality of the envisioned SPAT algorithm is delineated. Before delving into detail, we first introduce the maximum set packing algorithm and explain why we intend to employ this technique in our proposed sink mobility scheme.

A. Maximum Set Packing Algorithm Tailored for SPAT

Given a finite set S and a list of subsets of S, one may be able to formulate the k-set packing problem, which is deterministic and NP-complete [17]. The k-set packing problem is to determine whether there are k disjoint subsets in the list, i.e., k subsets in the list that are pairwise disjoint. The maximum set packing problem [19], which is NP-hard, is the maximized/optimized version of the k-set packing problem. The maximum set packing problem attempts to find the maximum number of pairwise disjoint sets in the list. In the k-set cover problem, the greedy algorithm approaches the H_k-approximation algorithm, where $H_k = \sum_{i=1}^{k}(1/i)$ is the k-th harmonic number, such that the solution obtained by the greedy algorithm is no more or

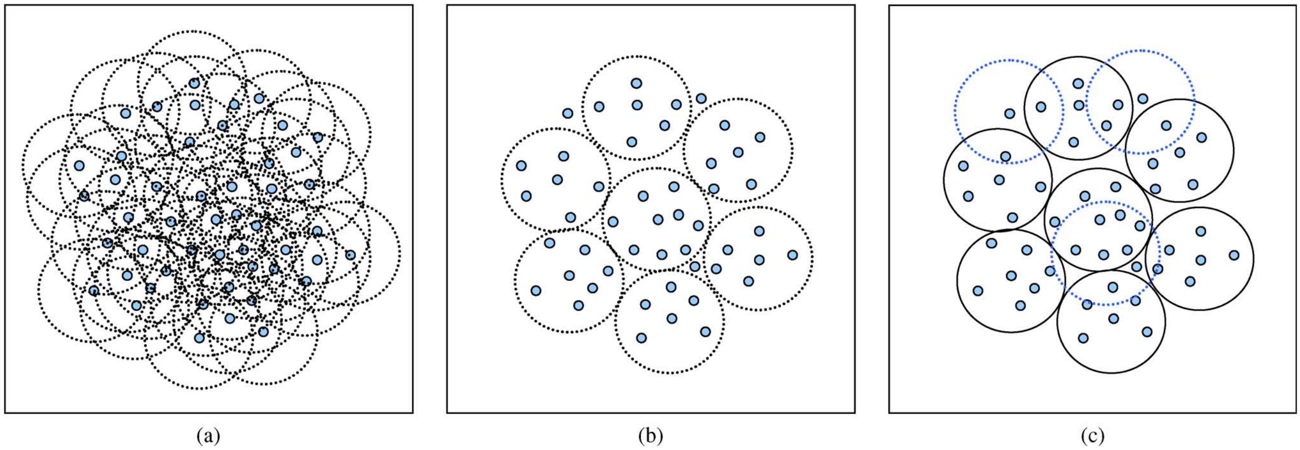

Fig. 4. Proposed clustering procedure. (a) There are n clusters in the first stage. (b) Chosen clusters by set packing algorithm in the second stage. (c) Clusters added to cover all of the nodes (dotted circles).

less than H_k times the optimal solution. The best improvement achievable by the greedy algorithm, to our best knowledge, is the $(H_k - 196/390)$-approximation algorithm [20]. Our envisioned SPAT scheme adopts the maximum set packing problem which can be solved by this greedy algorithm to approximate the optimal solution.

B. Proposed Mobility Scheme

Our proposed SPAT mobility scheme functions in four phases. In the first phase, SPAT generates clusters of sensor nodes. The redundant clusters are eliminated by SPAT in the second stage by employing the set packing algorithm. In the third stage, SPAT adds the least number of clusters required to guarantee that mobile sinks are able to communicate with all the sensor nodes deployed in the target WSAN topology. Finally, in the fourth phase, SPAT computes the traveling salesman path amongst all of the cluster heads. The mobile sinks move along this computed path and gather data from the sensors belonging to various clusters.

1) Clustering Algorithm: Many clustering techniques can be adopted to classify the given data in WSANs. For instance, in a static sink scheme, LEACH adopts a clustering mechanism, which assigns cluster heads, i.e., representative sensor nodes of respective clusters. On the other hand, in a mobile sink scheme, KAT mobility adopts a simpler clustering technique referred to as k-means method [21], without resorting to assignment of cluster heads. In our envisioned SPAT scheme, we first extract C_i as a cluster whereby a sensor node n_i can communicate with, and regard this n_i as the cluster head of cluster C_i. First, we compute the cost between the initial node n_i and each of the other nodes denoted by $n_j (j \neq i)$. Next, the lowest cost node, n_j, joins as a member of cluster C_i. The cluster members depend upon various parameters such as adopted protocols of sensor networks and the communication range of a sensor node. From the viewpoint of each cluster head, the mobile sink can communicate with all members belonging to the cluster in question. This clustering applies to every sensor node. Therefore, in this first stage, there are n clusters as well as n cluster heads when the number of sensor nodes is n, as shown in Fig. 4(a). We can see that this clustering is basically based on the Dijkstra's algorithm.

2) Elimination of Redundant Clusters: As evident from Fig. 4(a), there are many sensor nodes in the considered WSAN topology that belong to more than a single cluster. These nodes are referred to as the "duplicated" ones. In order to obtain the number of clusters with the smallest number of duplicated nodes, we apply the set packing algorithm as follows. First, the algorithm assigns a score, which equals the number of clusters that the node belongs to, to each node of the network. At this moment, the list of possible clusters contains all of the clusters; i.e., n clusters. This score indicates the number of duplications because it indicates the number of times a node is covered by clusters. Second, the algorithm chooses the node, which has the minimum score, from the list of possible clusters. Third, the algorithm eliminates the clusters, which contain the node already selected in the previous step (Step 2), from the list of possible clusters. Finally, the algorithm repeats these procedures until the list of possible clusters becomes empty. Continuing from the example depicted in Fig. 4(a), the result at the end of this stage is shown in Fig. 4(b).

It is worth noting that there is a possibility that some sensor nodes may still exist in the target WSAN that are not covered by any cluster. The reason behind is that the set packing algorithm only generates the smallest number of clusters without duplicated nodes.

3) Adding Clusters: In order to guarantee data gathering from all of the sensor nodes, we add clusters until all of the sensor nodes are covered. Indeed, there are various options to choose the additional clusters. If we focus on the fairness in gathering data from the deployed sensor nodes, we need to take into account of the additional clusters with the least number of duplicated sensor nodes. In this paper, we define the number of duplications with respect to a sensor node as the number of clusters to which the sensor node belongs. Indeed, this is a good metric for evaluating the fairness. Eventually, our envisioned SPAT mechanism is capable of choosing additional clusters with the least number of duplications, as shown in Fig. 4(c).

4) Calculating the TSP Path for Data Gathering: In the final stage of our proposed mobility method, the trajectory among the cluster heads of selected clusters is calculated by using the traveling salesman algorithm. Similar to the set packing problem, it is also difficult to find the optimal solution for the traveling salesman problem. Among the already available approximation algorithms of TSP [22], [23], we adopt the well known approximation algorithms, namely 2-opt [24] and Or-opt [25], which are the special cases of the 3-opt approach [26], that can be executed practically within an acceptable time.

After having determined the trajectory, the mobile sinks can move along the calculated path, taking turns to gather data from the sensor nodes.

IV. Performance Evaluation

We used the QualNet 3.9.5 [27] simulator to evaluate the performance of our proposed SPAT method. In this simulation, a mobile sink moves to the position of each cluster head and gathers data for a certain period of time via multi-hop communication. It is worth mentioning that the mobile sink gathers data not only when it pauses at a cluster head, but also when it is in transit to the next cluster head.

A. Simulation Set-Up

1) Network Model: Directed Diffusion [28], which is one of the most popular protocol stacks adopted in WSNs/WSANs, is implemented in our simulations. Especially, we implement the One Phase Pull model [29] in this protocol stack because of its simplicity. The link layer and the physical layer correspond to those of IEEE 802.11b, which is the global standard used in wireless communications.

2) Battery Model: We adopt the LCP (Load Current Profile) based battery model, which is widely utilized in simulating sensor networks. This model is approximated by an N-step staircase function.

B. Performance Metrics

First, we evaluate the fairness of the received data by using the following Fairness index F [30]:

$$F = \frac{\left(\sum_{i=1}^{n} d_i\right)^2}{n \sum_{i=1}^{n} d_i^2} \tag{1}$$

where d_i denotes the data received by the i^{th} sensor node. Note that this index is equal to one when the data received from all of the nodes are the same, and is close to zero when the variance of data received from different nodes becomes extremely large.

Second, we take into account of the trade-off between the throughput and energy consumption by adopting the efficiency index defined below. This index was first used in the KAT mobility scheme introduced in [8]

$$R\,[\text{KB}] = \frac{\text{Received Bytes by all mobile sinks}}{N \times M} \tag{2}$$

$$C\,[\text{mWhr}] = \frac{\text{Consumed Energy by all sensors}}{M} \tag{3}$$

$$E\,[\text{KB/mWhr}] = \frac{R}{C} \tag{4}$$

where the parameters N and M denote the number of nodes and the number of mobile sinks, respectively.

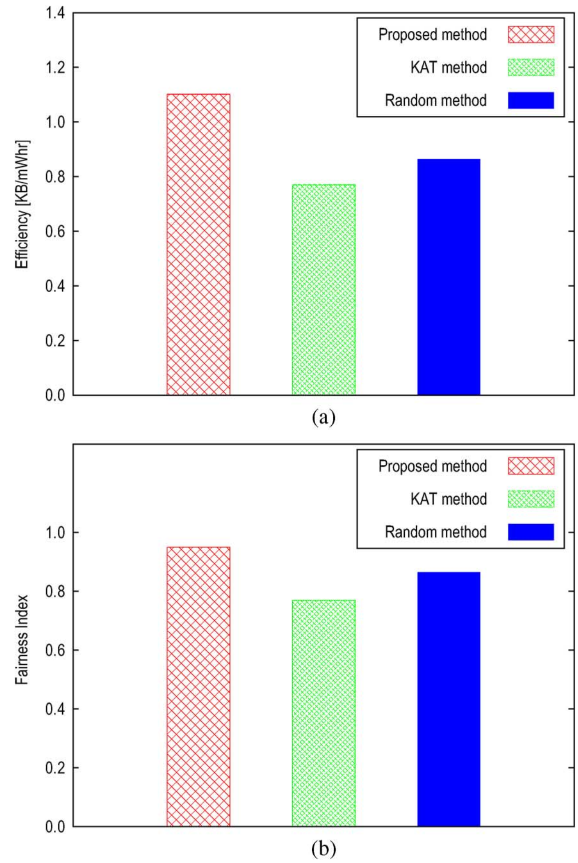

Fig. 5. Results when the node density is sparse. (a) Efficiency of three mobility schemes. (b) Fairness of three mobility schemes.

C. Parameter Settings

Most of the parameters adopted in this simulation are the same as those used in the conventional simulations [8]. The simulation time is fixed to 80 minutes, and an area of 5,000 [m] × 5,000 [m] is considered where the sensor nodes are deployed. The number of mobile sinks is set to one without any specific purpose in mind. The pause time of the mobile sink after having arrived at the destination is set to be 20 seconds. The velocity of the mobile sink is randomly varied from 20 m/s to 30 m/s. The number of deployed sensor nodes is varied from 20 to 200. The number of clusters used in the KAT mobility scheme is set to ten. This number was demonstrated to achieve good performance in experiments conducted in contemporary works [8]. These parameter settings were chosen generally by trials and errors, and they were also similarly used in KAT mobility except for the simulation time [8]. We have conducted ten simulations with different locations of sensor nodes, and Figs. 5(a)–7(b) demonstrate the results averaged over these ten simulations.

From the point of view of security and energy efficiency, a small number of hops for communication is recommended. Therefore, the number of communication hops of up to three is adopted in this simulation.

D. Experimental Results

Two types of situations in the considered WSAN topology are considered, namely, the sparse and dense situations. The former is the case where the number of nodes in the sensing field is

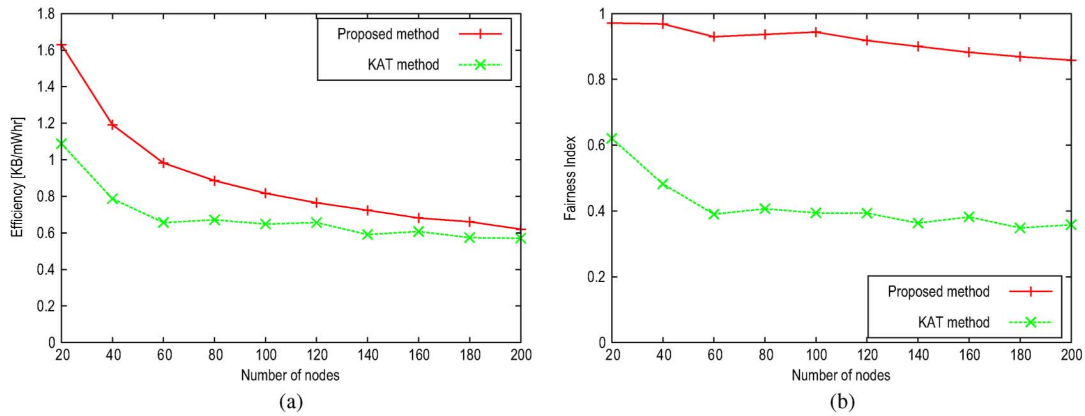

Fig. 6. Results in the case of dense situations when TTL is 1. (a) Efficiency of the two respective mobility schemes. (b) Fairness of the two respective mobility schemes.

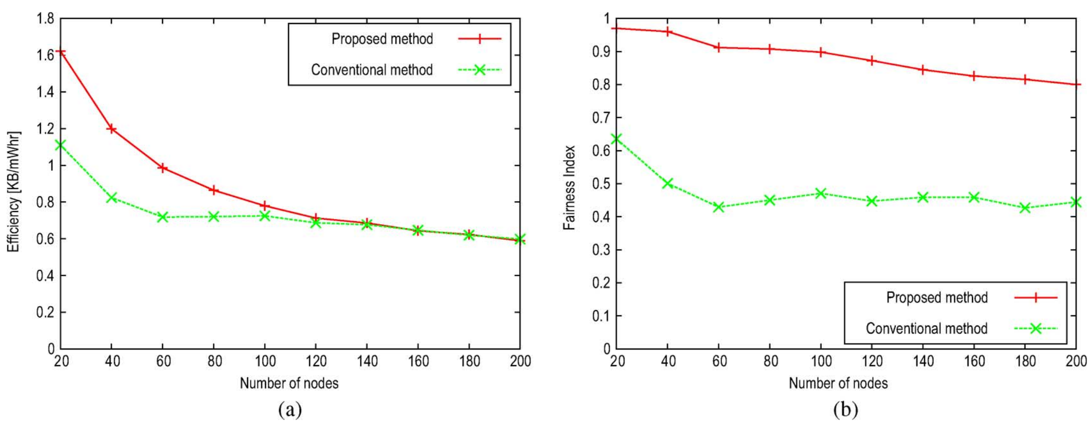

Fig. 7. Results in the case of dense situations when TTL is 3. (a) Efficiency of the two respective mobility schemes. (b) Fairness of the two respective mobility schemes.

relatively small. In this case, mobility is deemed to be more important since it is difficult for a mobile sink to gather data of most of the sensor nodes from limited positions. The latter takes into account of the case with a large number of nodes in the sensing field. We can evaluate the scalability of mobility schemes from this case.

1) Results in Case of Sparse Situations: Figs. 5(a) and 5(b) demonstrate the comparison results in terms of efficiency and fairness among the proposed mobility, KAT mobility, and random mobility. These figures show the average values when the node density varies from 20 to 100 nodes. As we can see from these figures, the proposed method (i.e., SPAT) achieves the best performance in terms of both efficiency and fairness. Given that the proposed method can gather data from all sensor nodes and has relatively good fairness, we will mainly focus on the efficiency issue hereafter. Also, since KAT mobility outperforms the random mobility method with respect to gathering data from sensor nodes without unexpected delay due to its random nature, we will only use KAT mobility as the reference for subsequent comparisons.

2) Results in the Case of Dense Situations: Fig. 6(a) and (b) depict the simulation results in terms of efficiency and fairness when the number of hops is set to one, i.e., when the mobile sink directly collects data from sensor nodes with relay. TTL (Time To Live) indicates the number of communication hop(s).

In Fig. 6(a), we can clearly see that the proposed mobility scheme outperforms KAT mobility. The smaller the node density, the more pronounced the effect produced by the proposed method. The difference results from the better cluster allocation of the proposed mobility. For the sake of saving resources, allocating sensors sparsely is rational, and our proposed method is able to demonstrate this capability.

Fig. 6(b) shows that the proposed mobility scheme achieves better fairness than that of KAT mobility for different numbers of sensor nodes. This has validated again that the adoption of the set packing algorithm is viable for generating a proper number of clusters.

Fig. 7(a) and (b) demonstrate the simulation results when the number of hops is constrained to three, i.e., the mobile sink can accept data from nodes relayed in up to two hops.

From Fig. 7(a), we can clearly observe that the proposed mobility scheme is superior to KAT mobility also when the number of hops is constrained to three. In this case, the mobile sink has a wider communication range and is therefore able to go around all the cluster heads in a short time.

Fig. 7(b) shows the fairness of the proposed method and KAT mobility when the value of TTL is set to three. By considering Fig. 6(b) where the hop number is one, we may conclude that regardless of the communication range, the proposed mobility outperforms KAT mobility.

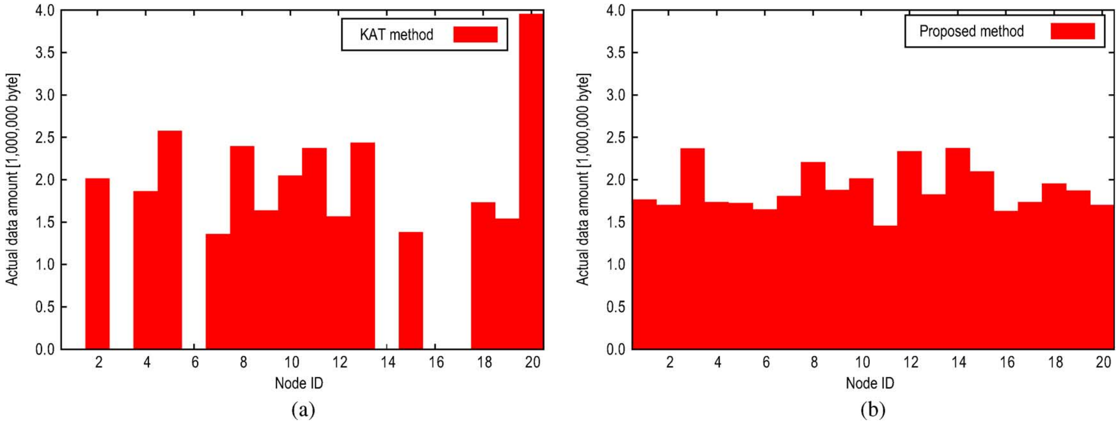

Fig. 8. Amount of data when the number of nodes is 20. (a) Gathered by KAT mobility; (b) Gathered by the proposed mobility.

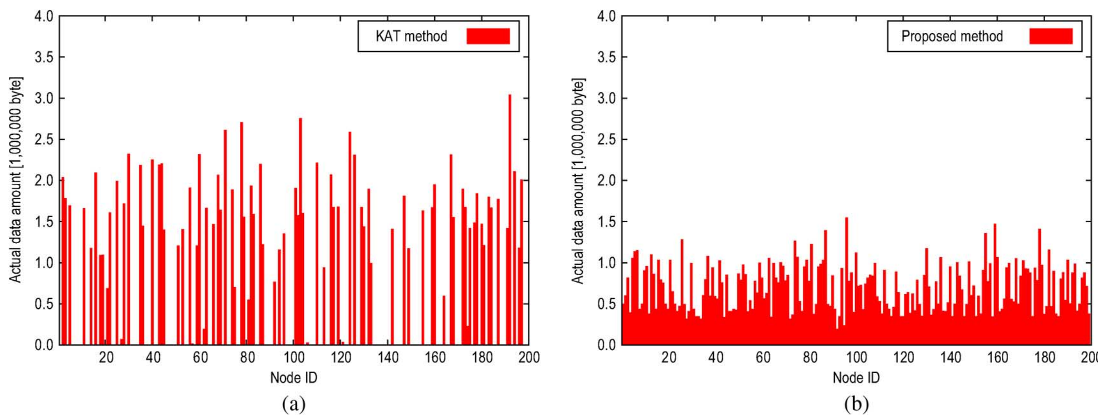

Fig. 9. Amount of data when the number of nodes is 200. (a) Gathered by KAT mobility; (b) Gathered by the proposed mobility.

In order to see whether each mobility scheme can gather data from all of the sensor nodes, results pertaining to the amount of data received by the mobile sink are presented in Figs. 8(a) and 9(b). Fig. 8(a) and (b) compare the amount of data gathered by the sink when the number of sensor nodes is 20, which is a typical sparse situation. Fig. 9(a) and (b) show the results of the densely distributed case where the number of sensor nodes is 200.

We can see that in both cases, the sink in the proposed mobility does not miss any sensor in gathering data, while many sensor nodes cannot be reached by KAT mobility. This validates the effectiveness of the proposed scheme based on the set packing algorithm with supplementary clusters to augment the family of clusters in covering all the sensing area.

Therefore, we can conclude that the proposed mobility scheme can achieve better fairness with high efficiency, and it can moreover guarantee the full coverage of data gathering.

Fig. 10 shows the number of clusters obtained by our proposed method. The solid line shows the results with error bars, and the dotted line shows the maximum possible number of clusters which equals to the number of nodes. As evident from the figure, when the number of nodes is relatively small, e.g., below 60, the number of clusters are quite close to the number of nodes because the sensor nodes are distributed sparsely. Therefore, more clusters are needed to cover the whole area. On the other hand, when the number of nodes is large (e.g., 60 and above), more nodes are contained in one cluster so that the mobile sink

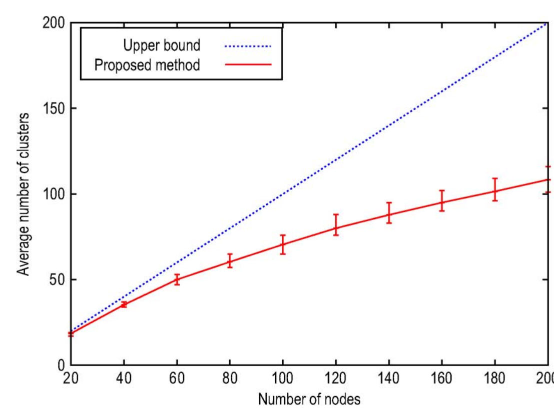

Fig. 10. Number of clusters formed by the proposed mobility.

with, only one stop at the cluster center, can collect data from a larger number of nodes.

V. Conclusion

It is essential to enable reliable and efficient data gathering by the mobile sinks in WSNs and/or WSANs. In this paper, we have proposed a new data gathering scheme, SPAT, to realize this goal. The features of SPAT are threefold. First, it guarantees the mobile sink to collect data from all sensor nodes. Second, it is more efficient in terms of collecting data by using less energy. Third, it ensures fairness regarding to equally collecting data from the sensor nodes. As a consequence, the users will be able to control all sensor hosts in an effective and real-time manner.

We have conducted extensive computer simulations by taking into account of different distribution patterns. The results have demonstrated the viability of the proposed mobility. To minimize the time for collecting data or reducing the consumed energy of the mobile sink, our future work may also take into account of investigating mobile sensors or multiple sinks in the considered WSAN topology. In addition, designing a system that incorporates cooperation between sensors and actuators is a very challenging task. He *et al.* [31] analyzed the optimal information capture function of the event type, the event dynamics, and the speed of the mobile sensor. Cao *et al.* [32] investigated the ability of a control system of WSANs based on their optimal control method. As our future work, we plan to incorporate these analytical approaches into SPAT for a better controlled and enhanced WSAN.

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Hidehisa Nakayama (M'06) received the B.E. degree from the Department of Information Engineering, Tohoku University, Sendai, Japan, in 2000, and the M.S. and Ph.D. degrees from the Graduate School of Information Sciences (GSIS), Tohoku University, Sendai, Japan, in 2002 and 2005, respectively.

He joined the GSIS as an Assistant Professor in 2005. He has been a Senior Assistant Professor in the Department of Electronics and Intelligent Systems, Tohoku Institute of Technology, Sendai, since 2008, and has been an Assosiate Professor since 2011. He has been engaged in research on intelligent sensor technology, wireless mobile ad hoc network, computer networking, character string analysis, pattern recognition, and image processing.

Dr. Nakayama received the Paper Award for Young Researcher of IPSJ Tohoku Chapter in 2000, the Best Paper of Pattern Recognition Award in SCI 2003, the 8th Network System Award of IEICE Technical Committee on Network Systems in 2009, the 20th NEC TOKIN Contribution Award in 2010, and the Best Paper Award of IEEE GLOBECOM 2010. He is a member of the IEEE Communications Society, the Institute of Electronics, Information and Communication Engineers (IEICE), and the Information Processing Society of Japan (IPSJ).

Zubair Md. Fadlullah (S'06) received B.Sc. degree in computer sciences from the Islamic University of Technology, Dhaka, Bangladesh, in 2003 and the M.S. and Ph.D. degrees from the Graduate School of Information Sciences (GSIS), Tohoku University, Sendai, Japan, in 2008 and 2011, respectively.

Currently, he is serving as an Assistant Professor at GSIS. His research interests are in the areas of network security, specifically intrusion detection/prevention, traceback, quality of security service provisioning mechanisms, ad hoc networking, and smart grid communications.

Dr. Fadlullah received the prestigious Dean's and President's awards from Tohoku University in 2011

Nirwan Ansari (S'78–M'83–SM'94–F'09) received the B.S.E.E. (with highest honors) from the New Jersey Institute of Technology (NJIT), Newark, in 1982, the M.S.E.E. degree from University of Michigan, Ann Arbor, in 1983, and the Ph.D. degree from Purdue University, West Lafayette, IN, in 1988.

He joined NJIT's Department of Electrical and Computer Engineering as Assistant Professor in 1988, became a tenured Associate Professor in 1993, and has been a Full Professor since 1997. He has also assumed various administrative positions at NJIT. He was Visiting (Chair) Professor at several universities. He co-authored *Computational Intelligence for Optimization* (Springer, 1997, translated into Chinese in 2000) and co-edited *Neural Networks in Telecommunications* (Springer, 1994). He has also contributed over 350 technical papers, over one third of which were published in widely cited refereed journals/magazines. He has also guest-edited a number of special issues, covering various emerging topics in communications and networking. His current research focuses on various aspects of broadband networks and multimedia communications.

Dr. Ansari received a 2007 IEEE Leadership Award from the Central Jersey/Princeton Section, the NJIT Excellence in Teaching Award in Outstanding Professional Development in 2008, a 2008 IEEE MGA Leadership Award, the 2009 NCE Excellence in Teaching Award, a couple of best paper awards (IC-NIDC 2009 and IEEE GLOBECOM 2010), a 2010 Thomas Alva Edison Patent Award, and designation as an IEEE Communications Society Distinguished Lecturer (2006–2009, two terms). He has served on the Editorial Board and Advisory Board of eight journals, including as a Senior Technical Editor of the *IEEE Communications Magazine* (2006–2009). He has served the IEEE in various capacities such as Chair of the IEEE North Jersey Communications Society (COMSOC) Chapter, Chair of the IEEE North Jersey Section, Member of the IEEE Region 1 Board of Governors, Chair of the IEEE COMSOC Networking Technical Committee Cluster, Chair of the IEEE COMSOC Technical Committee on Ad Hoc and Sensor Networks, and Chair/Technical Program Committee Chair of several conferences/symposia.

Nei Kato (M'03–A'04–SM'05) received the M.S. and Ph.D. degrees in information engineering from Tohoku University, Sendai, Japan, in 1988 and 1991, respectively.

He joined the Computer Center, Tohoku University, in 1991, and has been a Full Professor at the Graduate School of Information Sciences since 2003. He has been engaged in research on computer networking, wireless mobile communications, image processing and neural networks. He has published more than 200 papers in journals and peer-reviewed conference proceedings.

Dr. Kato received the Minoru Ishida Foundation Research Encouragement Prize (2003), the Distinguished Contributions to Satellite Communications Award from the IEEE Communications Society, Satellite and Space Communications Technical Committee (2005), the FUNAI information Science Award (2007), the TELCOM System Technology Award from Foundation for Electrical Communications Diffusion (2008), the IEICE Network System Research Award (2009), and best paper awards from many prestigious international conferences such as IEEE GLEBECOM, IWCMC. He currently serves as the Chair of *IEEE Satellite and Space Communications* TC, the Secretary of *IEEE Ad Hoc & Sensor Networks* TC, the Vice Chair of *IEICE Satellite Communications* TC, a Technical Editor of *IEEE Wireless Communications*(2006-), an Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS(2008-), an Associate Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY (2009-). He served as a co-guest-editor for the *IEEE Wireless Communications Magazine* SI on "Wireless Communications for E-healthcare," a symposium co-chair of GLOBECOM'07, ICC'10, ICC'11, ChinaCom'08, ChinaCom'09, and WCNC2010-2011 TPC Vice Chair. He also serves as a member on the expert committee of Telecommunications Council, the special commissioner of Telecommunications Business Dispute Settlement Commission, Ministry of Internal Affairs and Communications, Japan, and as the chairperson of ITU-R SG4, Japan. Nei Kato is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) and a senior member of IEEE.