

Attribute-Aware Data Aggregation Using Potential-Based Dynamic Routing in Wireless Sensor Networks

Fengyuan Ren, *Member, IEEE*, Jiao Zhang, Yongwei Wu, Tao He, Canfeng Chen, and Chuang Lin, *Senior Member, IEEE*

Abstract—The resources especially energy in wireless sensor networks (WSNs) are quite limited. Since sensor nodes are usually much dense, data sampled by sensor nodes have much redundancy, data aggregation becomes an effective method to eliminate redundancy, minimize the number of transmission, and then to save energy. Many applications can be deployed in WSNs and various sensors are embedded in nodes, the packets generated by heterogenous sensors or different applications have different attributes. The packets from different applications cannot be aggregated. Otherwise, most data aggregation schemes employ static routing protocols, which cannot dynamically or intentionally forward packets according to network state or packet types. The spatial isolation caused by static routing protocol is unfavorable to data aggregation. To make data aggregation more efficient, in this paper, we introduce the concept of *packet attribute*, defined as the identifier of the data sampled by different kinds of sensors or applications, and then propose an attribute-aware data aggregation (ADA) scheme consisting of a packet-driven timing algorithm and a special dynamic routing protocol. Inspired by the concept of potential in physics and pheromone in ant colony, a potential-based dynamic routing is elaborated to support an ADA strategy. The performance evaluation results in series of scenarios verify that the ADA scheme can make the packets with the same attribute spatially convergent as much as possible and therefore improve the efficiency of data aggregation. Furthermore, the ADA scheme also offers other properties, such as scalable with respect to network size and adaptable for tracking mobile events.

Index Terms—Wireless sensor network, data aggregation, attribute-aware, dynamic routing, potential field

1 INTRODUCTION

WIRELESS sensor networks (WSNs) can be readily deployed in various environments to collect information in an autonomous manner, and thus can support abundant applications such as habitat monitoring [1], moving target tracking [2], and fire detection [3]. WSNs are generally event-based systems, and consist of one or more sinks which is responsible for gathering specific data by sending queries. Usually, sensor nodes are densely deployed and responsible for detecting interesting events and sending related data to sinks. The collaborative signal processing algorithms can be designed in WSN applications to improve the sensing performance. A data fusion technique, which can merge raw data from multiple sources to achieve improved accuracies and more specific inferences than could be achieved by use of a single sensor alone [4], has been employed in sensor network systems for target detection [5], [6], localization [7], and classification [8].

Generally, data fusion involves hierarchical transformation between sensory raw data and decision, which constitutes statistical and sequential estimations, or weighted decision problems [4]. Thus, data fusion often requires intensive computing, which may be unaffordable for the nodes in WSN with the limited resources including computing, storage and especially energy, which is usually difficult to be supplemented due to unattended operation in remote or even hostile locations. Hence, it is a key research issue to design energy efficient protocol for WSNs.

Most phenomena or events are spatially and temporally correlated, which imply data from adjacent sensors are often redundant and highly correlated. To exploit both spatial and temporal correlations, the data aggregation, which can be regarded as simple data fusion, is introduced by Heidemann et al. [9] to conduct some simple operation on raw data at intermediate nodes, such as MAX, MIN, AVG, SUM, etc., and then only the abstracted data are transmitted to the sink, and thus save energy consumption by avoiding redundant transmissions. Following this paradigm, numerous data aggregation schemes [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26] have been proposed to save the limited energy on sensor nodes in WSNs.

In WSN community, most investigations on data aggregation schemes focus on designing proper strategies to drive the packets carrying redundant and correlated data converge spatially and temporally, which will provide more chances and more sufficient conditions for actual aggregation operations. Accordingly, the data aggregation schemes can

- F. Ren, J. Zhang, Y. Wu, T. He, and C. Lin are with the Department of Computer Science and Technology, Tsinghua University, Beijing 100084, China. E-mail: {renfy, wuyw, chlin}@tsinghua.edu.cn, zhangjiao08@csnet1.cs.tsinghua.edu.cn, qtmssa@gmail.com.
- C. Chen is with the NRC Radio Systems Lab, Nokia Research Center, Nokia Building 5 Dong Huan Zhonglu, Beijing 100176, China. E-mail: canfeng-david.chen@nokia.com.

Manuscript received 19 Sept. 2011; revised 19 June 2012; accepted 20 June 2012; published online 5 July 2012.

Recommended for acceptance by X.-Y. Li.

For information on obtaining reprints of this article, please send e-mail to: tpds@computer.org, and reference IEEECS Log Number TPDS-2011-09-0674. Digital Object Identifier no. 10.1109/TPDS.2012.209.

be broadly classified into two categories, i.e., temporal and spatial solutions, respectively. The work in [10], [11], [12], [13], [14], [15], [16], [17], [18], [19] belongs to the former and the investigation in [20], [21], [22], [23] refers to the latter. Otherwise, data aggregation is ordinarily accomplished in data gathering paradigm where the sink usually transmits a query message to sensor nodes (e.g., via flooding) and the sensor nodes, which have data matching the query, send response messages back to the sink. Obviously, the underlying data collection routing protocol is crucial to drive packets converge spatially. Hence, most of the existing work [10], [11], [12], [13], [14], [15], [16], [17], [18], [19] mainly focus on the development of an efficient routing mechanism for data aggregation. Although the existing data aggregation schemes can effectively make packets more spatially and temporally convergent to improve aggregation efficiency, most of them assume that there are homogeneous sensors and only one application in WSNs, and ignore considering whether the packets really carry redundant and correlated information or not. Actually, nodes are equipped with various sensors (i.e., pressure, temperature, humidity, light intensity, etc.) and different applications can also run in the same WSN simultaneously. It is impossible to conduct simple aggregation operations on the packets from heterogeneous sensors even if all packets can be transmitted along the same preconstructed aggregation trees and timing control schemes can also ensure packets have a high probability to meet with each other. Even data fusion can merge multiple heterogeneous raw data to produce new data, which is expected to be more informative and synthetic than input raw data, it is meaningless to make data fusion on raw data from different applications.

In this work, we introduce the concept of *packet attribute*, which is used to identify the packets from different applications or heterogeneous sensors according to specific requirements, then design an attribute-aware data aggregation (ADA) scheme, which can make the packets with the same attribute convergent as much as possible to improve the efficiency of data aggregation. The routing protocols employed by most of existing data aggregation schemes are static. They properly support data aggregation in the network with homogeneous sensors and a single application, but cannot conduct effective data aggregation when the data from heterogeneous sensors or various applications are forwarded along the same static path. Events always occur randomly in time and space, the information of packet attribute at each node is hardly predicted. It is costly to predetermine the proper routing path for each packet attribute. Therefore, a distributed and dynamic routing protocol is expected to adapt to the frequent variation of packet attribute distribution at each node.

Enlightened by the concept of *pheromone*, which will be left along the path where ants pass and evaporate with time, in ant colony [27], we draw an analogy between pheromone and packet attribute. A packet will leave attribute-dependent pheromone when passing a node to attract the afterward packets with the same attribute, which will make the packets generated by the same applications more spatially convergent. With respect to routing decisions, we borrow the concept of *potential* in physics and follow the potential-based routing paradigm in the context

of traditional networks [28] to develop a dynamic routing algorithm. The packets are driven by a hybrid virtual potential field to move toward the sink, at the same time the packets with identical attribute are attracted by attribute-dependent pheromone to move along the same path, which will provide more chances to conduct data aggregation effectively. In addition, the potential-based routing is scalable and easy to be implemented since only local information are required and can be easily obtained. To further improve the performance of data aggregation scheme, the packets should also be temporally convergent so as to meet with each other at the same node as well as at the same time. Thus, we also design an adaptive packet-driven timing control algorithm to improve temporal convergence. In summary, the main contributions in this work are threefold:

- An ADA scheme is proposed to intentionally drive the packets with the same attribute convergent as much as possible in the WSNs with heterogeneous sensors or various applications.
- Inspired by the concepts of both potential field in physics and pheromone in ant colony, a dynamic routing protocol is elaborately designed to support the ADA scheme.
- An adaptive packet-driven timing control algorithm is proposed to provide more chances for data aggregation on nodes.

The remainder of the paper is organized as follows: Related work and motivation are introduced in next section. In Section 3, the details of ADA, including the potential-based dynamic routing (PBDR) and the packet-driven timing scheme, are presented. In Section 4.2, the simulations are conducted to evaluate the performance of our ADA mechanism. Finally, the paper is concluded in Section 5.

2 RELATED WORK AND MOTIVATION

2.1 Related Work

As aforementioned, data aggregation can be broadly classified into temporal and spatial solutions. The former makes packets more temporally convergent and the latter makes packets more spatially convergent. Next, the related work in these two aspects will be introduced.

As for timing control scheme, TAG [20] proposes a simple SQL-like declarative language for expressing aggregation queries over streaming sensor data and identifies the key properties of aggregation functions which affect whether data aggregations can be efficiently processed at some extent. The semantics of the query language partition time into epochs. Nodes transmit packets along a tree rooted at the sink in the corresponding epoch, which is decided by the depth of node; thus, each parent will receive packets from its children in the same epoch. Cascading timeout (CT) [21] is also based on a rooting tree in which nodes need wait some time determined by the depth of nodes before transmitting packets. In these two schemes, the transmission scheduling at a node is fixed once the aggregation tree is constructed, and is hardly adjusted dynamically according to the state of both load and network. Afterward, there are some aggregation schemes

with dynamic timing control. Hu et al. [22] proposed a simple centralized feedback timing control algorithm for tree-based aggregation. The sink determines the maximal interval for one data aggregation operation with the knowledge of the information quality in the previous operation. Fan et al. proposed a random waiting timing scheme in which each node aggregates and forwards incoming packets after waiting a randomized interval [19]. A distributed scheme employing a semi-Markov decision process model is developed in [23], and the decisions are made at available transmission epochs combining with the current state of nodes, such as the number of collected samples, and the elapsed time at a node.

The second category focuses on designing a proper routing protocol for data aggregation. The sensor nodes are organized into clusters, a chain or a tree. In cluster-based solutions, each cluster has a designated sensor node as the cluster head, which aggregates data from all sensors in the cluster and directly transmits concise digest to the sink. LEACH [10] and HEED [12] are two typical examples. The difference between them is the method of selecting cluster heads. LEACH assumes that all nodes have the same amount of energy capacity in each election round, while HEED aims to form efficient clusters to maximize network lifetime. All cluster-based data aggregation schemes assume that each node in networks can reach the sink directly in one hop, which limits its scalability. In [29], Liu et al. proposed a poller/pollee-based architecture with the objective of minimizing the number of overall pollers while bounding the false alarm rate for the applications capable of monitoring the sensor statuses such as liveness, node density, and residue energy. Wang et al. proposed a distributed multicluster coding protocol [30] to partition the entire network into a set of coding clusters such that the global coding gain is maximized. In cluster-based routing protocols, if the cluster head is far away from nodes, they might expend excessive energy in transmissions. Therefore, the chain-based scheme is introduced to further improve energy efficiency.

The key idea behind the chain-based data aggregation is that each sensor only transmits data to its closest neighbor. The chain can be constructed by employing a greedy algorithm or determined by the sink in a centralized mode. All nodes are assumed to have the global knowledge of the whole network when the greedy chain is formed. PEGASIS [11] is a typical chain-based data aggregation protocol, and employs the greedy algorithm to construct the chain. In PEGASIS, the transmission distances among nodes are much shorter than those in LEACH [10]. Hence, PEGASIS can save more energy than LEACH does. However, the global information required by chain-based routing protocols results in the relatively high overhead especially for the large-scale network. Based on both LEACH and PEGASIS, a hybrid scheme HIT is proposed in [31], which organizes sensor nodes into clusters, but the multihop indirect transmissions between cluster head and nonhead nodes are allowed.

In tree-based routing protocols, data aggregation is performed at intermediate nodes along the tree and a concise representation of data is transmitted to the root node, i.e., sink. One of main tasks for tree-based scheme is

to construct an energy efficient data aggregation tree. For example, Steiner minimum tree has been used in designing data aggregation protocols in [16]. Since the tree constructed in advance is static, most tree-based schemes can only be suitable for applications in which source nodes are known. Energy-aware distributed heuristic (EADAT) [13] and power-efficient data gathering and aggregation protocol (PEDAP) [14] are two typical examples of tree-based data aggregation schemes. The main advantage of EADAT is that the node with higher residual energy has the higher probability to become nonleaf tree node, and thus the network lifetime can be extended in terms of the number of alive nodes. PEDAP computes a minimum spanning tree using transmission overhead as the link cost, and thus minimizes the total energy consumption in each communication round. However, it is costly to reconstruct the spanning tree for each communication round. In [18], a set of routes is preconstructed and one of them keeps active in round-robin fashion, which can save energy by avoiding reconstructing route and balance energy consumption. However, each node needs to maintain the predetermined path to guarantee successful transmissions. When the network topology changes due to energy exhaustion on some nodes, the route needs to be reconstructed and the topology information maintained by each node needs to be updated, which will introduce considerable overhead. In [32], Park et al. combined the shortest path tree with the cluster method and developed a hybrid routing protocol to support data aggregation. A head node in each minimum dominating set performs data aggregation and all head nodes are connected by constructing a global shortest path tree.

Most of existing routing protocols employed by data aggregation schemes are static. They are unsuitable for applications tracking amorphous event, such as mobile target, and so on. Identifying this limitations, Zhang et al. proposed a dynamic convoy tree-based collaboration (DCTC) to reduce the overhead of tree reconstruction in event-based applications, such as detecting and tracking a mobile target [17]. DCTC assumes that each node knows the distance to events and the node near the center of events acts as the root to construct and maintain the aggregation tree dynamically. How to obtain the information of event location and distance is still an open issue, which also restricts the applicability of DCTC. In addition, most existing data aggregation scheme can properly work in homogeneous environment, i.e., identical sensor data or a single application, but rarely considers the impact of heterogeneity, including heterogeneous sensors or different applications in the same WSN.

2.2 Motivation

Assume there are two different applications in a WSN, the data generated by different applications are heterogeneous, and cannot be aggregated. Fig. 1 illustrates a small part of the whole network. The solid circles and empty circles denote the source nodes of applications App1 and App2, respectively. The empty circles with plus signs are intermediate nodes.

Fig. 1a illustrates a typical tree-based routing protocol, which consists of the shortest path tree rooted at the sink with metric such as hop count. Regardless of event locations

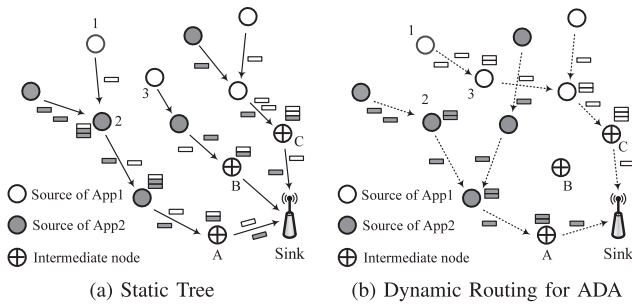


Fig. 1. Basic idea of the ADA scheme.

and data type, the packets from different applications will move along the predetermined aggregation tree. Objectively, this static tree can converge packets in space, which provides chances for nodes to perform aggregation operation. However, the efficiency of data aggregation depends on the degree of matching between the tree structure and the distribution of source nodes. For example, although node B forwards the packets from both App1 and App2, it nearly does nothing for data aggregation because the mismatch between tree structure and source distribution results in few redundant packets passing through node B. On the other hand, node A or node C can aggregate the redundant packets from App2 or App1, respectively, but provide little contribution for App1 or App2, respectively. The static and predetermined routing protocol hardly adapts to dynamic and heterogeneous environment, and irregular events. If the dynamic routing would be constructed according to the network state and the data features as shown in Fig. 1b, for example, node 1 sends packets to node 3 instead of node 2, the packets from App1 could be gathered together as much as possible, and thus the aggregation efficiency would be improved drastically. Comparing with the static routing in Fig. 1a, the dynamic routing in Fig. 1b intentionally drives the packets from the same application to converge spatially during their transmission procedure, but the static routing can only utilize the spatial correlation in the predetermined forwarding paths. In addition, the limited buffer resources on nodes can be reserved to cache more packets from the same application, and then conduct more effective aggregation at the proper time. Otherwise, the intermediate nodes with little contribution on data aggregation can be excluded from the forwarding path to avoid energy consumption caused by pure forwarding operations, just like node B in Fig. 1a.

Obviously, the dynamic routing protocol is the cornerstone of ADA suitable for heterogeneous data or various application in the same WSN. The concept of pheromone in ant colony [27] inspires us to design the dynamic routing algorithm for our ADA scheme. In nature, ants leave pheromone, which can emanate an odor and evaporate with time, along the paths that they have passed. The afterward ants will select their paths according to the amount of pheromone on different paths. If the packets in WSNs are treated as the ants in nature by analogy, and then the attribute-dependent pheromone is left on the nodes through which packets with different attributes pass. Subsequently, the node with different pheromone will emanate different odors. The more is the pheromone, the more intense is the

odor. The packets just follow the odor to meet with other packets with the same attribute. In this way, the packets can be gathered together by intentional forwarding, which will assist in achieving the goal of our ADA scheme. Applying the principle that ants select the paths to find food based on pheromone, the routing protocols are designed for wired network [33] and wireless ad hoc network [34], respectively. However, to search the proper path between a pair of nodes, the ant routing protocol needs to inject extra packets (i.e., forward “ants” and backward “ants”) into networks to update routing tables and distribute state information of network; moreover, the convergence of routing depends on the number of “ants.” The excessive overhead is unaffordable for WSNs with limited energy. Therefore, in this work, we only use the concept of pheromone in ant colony to identify data attributes from different applications or heterogeneous sensors, and borrow another concept in physics (i.e., potential field) to construct the dynamic routing for the ADA scheme. In [28] and [35], the steepest gradient search method is used to design a potential-based routing paradigm in the context of traditional networks and mobile ad hoc network, respectively. However, it is expensive to build an exclusive virtual field for each destination in traditional networks where numerous destinations distribute arbitrarily. The huge management overhead degrades their practicality. On the contrary, the potential-based routing algorithm is much proper for the centralized traffic pattern in WSNs with a single (at most several) sink(s), namely destinations.

Motivated by the above understanding and enlightened by the two concepts in other disciplines, we construct two independent virtual potential fields. One potential field is built using the parameter related to network topology to guarantee packets reaching the sink at last, and the other potential field is constructed using the pheromone left by packets to purposely attract the packets with the same attribute, and then these independent virtual potential fields are combined together to form a hybrid potential field acting on the routing decisions. Since the information for making dynamic routing decisions can be easily gotten by each node, our PBDR scheme not only makes the packets with the same attribute more spatially convergent but also is simple and scalable. In addition, to make packets more temporally convergent, a packet-driven adaptive timing control scheme is proposed to cooperate with the basic dynamic routing, namely our completed ADA scheme includes a PBDR and a packet-driven timing control algorithm. Next, we will introduce their details.

3 DESIGNING ADA

In this section, the PBDR protocol will be presented, followed with some analysis of key parameters, then a packet-driven timing scheme which cooperates with the dynamic routing will be developed. For a legible description, we first introduce some definitions

3.1 Definition

Depth: The *depth* of a node is the number of hops that it is away from the sink.

Neighbor: The neighbor of node i is all nodes in the radio coverage disk of node i except for i itself, denoted by $\Omega(i)$.

Attribute: The *attribute* of data packet is its identification. The heterogenous sensors and nodes involved in different applications may generate data packets with different attributes. The identical sensors on the nodes involved in the same applications will generate the packets with identical attribute. We use different natural numbers to identify different attributes, and extend the packet header to carry this value.

3.2 PBDR

Before starting to describe the concrete routing algorithm, we first show how it works. Intuitively, the depth potential field in the PBDR can be viewed as a *bowl*. The sink resides at the bottom, and all packets in most of existing tree-based data aggregation schemes flow down along the surface directly just like water does without interacting with each other. However, the packets with correlated information should be gathered together for more efficient data aggregation. To realize this goal, the pheromone potential field is constructed. Packets with different attribute leave different *odor* at every node that it passed, and the *odor* will volatilize with the time. Each packet is transmitted to the neighbor in response to the amount of the same *odor* as that of itself, so that the packets with the same attribute can attract each other and gather together in space. Intuitively, the pheromone potential field forms the valleys in the surface of the *bowl*. The more intense is the odor, the deeper is the valley. Each packet is transmitted to the deepest valley with the same odor as that of itself, rather than be sent along a fixed path such as the shortest tree. In this way, the packets with the same attribute can intentionally follow the same path and converge as much as possible.

3.2.1 Potential Field Model

In the *bowl* model, we can view the whole network as a gravitational field. A packet can be viewed as a drop of water, moving down to the bottom along the bowl surface. The trajectory is determined by the force from the gravitational potential field.

A single-valued potential, $V(u)$, is assigned to node u on the bowl surface to form a scalar potential field. Now, consider a packet p at node u , to reach the sink, it will be forwarded to one of the neighbors of u . Let $\Omega(u)$ be the neighbor set of node u . To determine the next hop of packet p , following the concept of force given in [28], we define the force acting on packet p at node u based on the potential difference between node u and its neighbors as follows:

$$F_{u \rightarrow v} = V(u) - V(v). \quad (1)$$

The packet will be forwarded to the neighbor x in the direction of the steepest gradient, namely, the force from nodes u to x , $F_{u \rightarrow x}$, is maximum.

3.2.2 Depth Potential Field

The depth potential field aims to ensure that packets will be transmitted to the sink. Let $D(u)$ be the depth of node u . The depth potential $V_d(u)$ is defined as $V_d(u) = D(u)$. Hence, the force from node u to one of its neighbors $v \in \Omega(u)$ in the depth potential field is

$$F_{u \rightarrow v}^d = D(u) - D(v). \quad (2)$$

The depth differences between node u and its neighbors $v \in \Omega(u)$ can only be one of $-1, 0$, or 1 since the nodes two

hops away from a node cannot become its neighbors. Thus, we have $F_{u \rightarrow v}^d \in \{-1, 0, 1\}$. Theorem 2.1 given in [28] states that the route in a time-invariant potential field is loop free. The depth field should satisfy this condition. In a word, the depth potential field will drive packets move to the sink along the shortest path without any loops; thus, it can provide the basic routing function.

3.2.3 Pheromone Potential Field

Pheromone potential field is constructed to gather the packets with the same attribute together. If the packets in WSN are treated as the ants leaving volatile pheromone at each passed node, a path selected by more packets will have more pheromone and can attract more packets with the same attribute.

Define $\tau(i, \delta)$ as the amount of pheromone where i is the ID of node and δ is the attribute of data packet. $\tau(i, \delta)$ is initialized to 0. Each packet will leave constant pheromone τ when passing a node. Naturally, in ant colony, the pheromone will not only increase after ants passing but also continuously evaporate with the time. Here, in order to reduce overhead, only when a packet with attribute δ reaches node v or after an aggregation operation at node v , $\tau(v, \delta)$ will be updated as follows:

$$\tau(v, \delta) = \rho \times \tau(v, \delta) + I \times \Delta\tau, \quad (3)$$

where $\rho \in (0, 1)$ reflects pheromone evaporation, and I is an indicative function. When a new packet with attribute δ reaches node v , $I = 1$, and else $I = 0$.

Since the packets will be forwarded to the sink in the steepest gradient direction, the nodes with more intense pheromone should have lower pheromone potential. Therefore, the pheromone potential field force $V_p(u, \delta)$ of node u is defined as $V_p(u, \delta) = 1 - \tau(u, \delta)$. Hence, according to (6), the pheromone potential field force from node u to one of its neighbor $v \in \Omega(u)$ is

$$F_{u \rightarrow v}^p(\delta) = V_p(u, \delta) - V_p(v, \delta). \quad (4)$$

Since $0 \leq \tau(i, \delta) < 1$ for any node i and attribute δ , both the pheromone potential field force $F_{u \rightarrow v}^p(\delta)$ and the depth potential field force $F_{u \rightarrow v}^d(\delta)$ have the same order of magnitude. Hence, we define $\Delta\tau = \frac{1}{S}$, where S is the buffer size of nodes in unit of packets. This definition guarantees that $\tau(u, \delta)$ will always not be greater than 1.

3.2.4 Hybrid Potential Field

To ensure packets reach the sink as well as be more spatially convergent, we linearly combine the depth potential field and the pheromone potential field to form a hybrid potential field as follows:

$$V_h(u, \delta) = (1 - \alpha)V_d(u) + \alpha V_p(u, \delta). \quad (5)$$

$V_h(u, \delta)$ is the potential value of the hybrid field at node u with attribute δ . The parameter $\alpha \in [0, 1)$ is a weight. As $\alpha = 0$, the routing constructed by the hybrid potential field degenerates the shortest path tree with the hop count as the metric. Accordingly, the force from nodes u to v in the hybrid potential field with attribute δ should be

$$F_{u \rightarrow v}^h(\delta) = (1 - \alpha)F_{u \rightarrow v}^d + \alpha F_{u \rightarrow v}^p(\delta). \quad (6)$$

The PBDR selects the next hop for node u according to the force given by node $v \in \Omega(u)$ in the hybrid potential field. A packet p with attribute δ at node u will be transmitted to the neighbor node x to which the hybrid potential force from node u with attribute δ , $F_{u \rightarrow x}^h(\delta)$, is maximum.

It is noted that each node in networks can obtain its depth through receiving the routing update message sent by the sinks periodically. The nodes one hop away from the sink will get their depth by adding 1 to the depth value in the update message. Then, the other nodes will also obtain their own depth by receiving update message from its neighbors who already have a depth just in the same way as the nodes one hop away. Certainly, multiple sinks might be deployed in a WSN with some special purposes. Since each node in networks obtains the depth value through receiving the routing update message sent by sinks periodically, nodes can maintain the least depth value to the nearest sink or multiple depth values to different sinks according to application requirements. Combining with the pheromone values from its direct neighbors, the node can make dynamic routing decisions. In this way, our PBDR can be straightforwardly extended to normally work in the WSN with multiple sinks. The overhead is that different depth values with respect to different sinks need to be maintained by nodes.

3.2.5 Analysis of Parameters

In this section, we will conduct the analysis on impact of the parameters on the PBDR routing protocol for our ADA scheme, and present some guidelines towards proper parameter settings. First, two lemmas are introduced.

Lemma 1. *The range of the pheromone potential field at node u with attribute δ should be*

$$V^p(u, \delta) \in \left[0, \frac{1 - \rho^s}{1 - \rho} \Delta\tau\right]. \quad (7)$$

Proof. We have stated that the pheromone potential field at node u will be updated after receiving a new packet or after an aggregation at node u as given in pseudocodes. It is obvious that when the buffer is fully occupied by continuous coming packets with attribute δ , namely without any data aggregation operations, the pheromone potential field reaches the maximum. According to the update function after receiving a packet $\tau(v, \delta) = \rho \times \tau(v, \delta) + \Delta\tau$, we can get

$$\max\{\tau(v, \delta)\} = \sum_{i=0}^S \rho^i \Delta\tau = \frac{1 - \rho^S}{1 - \rho} \Delta\tau. \quad (8)$$

□

Lemma 2. *Define $V_m = \{x|x \in \Omega(u), D(x) = D(u) + k(k = 0 \text{ or } 1)\}$, $V_n = \{x|x \in \Omega(u), D(x) = D(u) - 1\}$. Let nodes $v_m, v_n \in \Omega(u)$ be the node with the maximum pheromone with attribute δ in V_m and V_n , respectively, and $\Delta\tau_{mn}(\delta) = \tau(v_m, \delta) - \tau(v_n, \delta)$. If $\Delta\tau_{mn}(\delta) > \frac{(1+k)(1-\alpha)}{\alpha}$, then node u will send packet p with attribute δ to node v_m rather than node v_n .*

Proof. If u does not choose v_n as the next hop of packet p , it will not choose any other nodes in V_n since the

pheromone of v_n with attribute δ has already been the maximal. The potential values at different node are

$$V_h(u, \delta) = (1 - \alpha)D(u) + \alpha[1 - \tau(u, \delta)] \quad (9)$$

$$V_h(v_m, \delta) = (1 - \alpha)[D(u) + k] + \alpha[1 - \tau(v_m, \delta)] \quad (10)$$

$$V_h(v_n, \delta) = (1 - \alpha)[D(u) - 1] + \alpha[1 - \tau(v_n, \delta)]. \quad (11)$$

Then, we get the force at node u given by nodes v_m and v_n as follows:

$$F_{u \rightarrow v_m}^h(\delta) = -k(1 - \alpha) + \alpha[\tau(v_m, \delta) - \tau(u, \delta)] \quad (12)$$

$$F_{u \rightarrow v_n}^h(\delta) = (1 - \alpha) + \alpha[\tau(v_n, \delta) - \tau(u, \delta)]. \quad (13)$$

Since $\Delta\tau_{mn}(\delta) > \frac{(1+k)(1-\alpha)}{\alpha}$, we have $F_{u \rightarrow v_m}^h(\delta) > F_{u \rightarrow v_n}^h(\delta)$. The pheromone with attribute δ of node v_m is the maximum in the set V_m ; thus, v_m will be selected as the next hop of packet p at node u according to the steepest gradient rule. □

Based on these two lemmas, we provide two propositions to describe the impact of parameters on the performance of PBDR.

Proposition 1. *As $\alpha < \frac{S(1-\rho)}{1+S(1-\rho)}$, the neighbor nodes with the same depth are never chosen as the next hop by the PBDR.*

Proof. Let $V_m = \{x|x \in \Omega(u), D(x) = D(u)\}$, $V_n = \{x|x \in \Omega(u), D(x) = D(u) - 1\}$, and nodes $v_m, v_n \in \Omega(u)$ be the node with the maximum pheromone and attribute δ in V_m and V_n , respectively. $\Delta\tau_{mn}(\delta) = \tau(v_m, \delta) - \tau(v_n, \delta)$. Assume that node u select neighbor v_m but not v_n as its next hop. According to the conclusion in Lemma 2, we have $\Delta\tau_{mn}(\delta) > \frac{1}{\alpha} - 1$. If $\alpha < \frac{S(1-\rho)}{1+S(1-\rho)}$, then

$$\Delta\tau_{mn}(\delta) > \frac{1 + S(1 - \rho)}{S(1 - \rho)} - 1 > \frac{1 - \rho^S}{1 - \rho} \Delta\tau.$$

Lemma 1 tells that it is impossible. Thus, the sufficient condition that the node does not select the neighbors nodes with the same depth as the next hop is $\alpha < \frac{S(1-\rho)}{1+S(1-\rho)}$. □

Proposition 2. *As $\alpha < \frac{2S(1-\rho)}{1+2S(1-\rho)}$, the neighbor nodes with high depth are never chosen as the next hop by the PBDR.*

Proof. Similar to the proof of Proposition 1. □

3.3 Packet-Driven Adaptive Timing Scheme

The packets following the same path cannot ensure to be aggregated. They should meet with each other at the proper time. To increase the possibility that the packets meet with each other, a proper timing scheme is necessary. The timing control algorithm used in CT [21] exploits the relationship between the delay T required by applications and the depth h_i of node u . Node u aggregates packets and forwards abstracted data after waiting time $W_i = (T - shd \times h_i)$, where shd represents the delay in a single hop. It is a typical solution of fixed timing schemes. The end-to-end delay is always constant T wherever source nodes locate. For example, the source nodes that are at most two hops away from the sink have to wait $T - 2 \times shd$ and then forward packets. This will introduce the avoidable delay

TABLE 1
Parameters Setting: Random Deployment

Para.	Value	Para.	Value
Deployment type	random	Rate in MAC	8 Kbps
Buffer size	32	App delay bound	10s
ρ	0.9	Packet size	25 Byte
T_F	0.3s	ϕ	0.9

and degrades the performance. Besides, the waiting time is sometimes so long that some packets possibly overflow buffer. Furthermore, most of timing schemes will start up a timer at every node at the beginning of an application no matter whether the node will participate in applications, which is costly and waste energy.

To adapt to our dynamic routing protocol and overcome the drawbacks in existing timing schemes, we propose a packet-driven adaptive timing scheme. The node maintains a timer for the packets with the same attribute in its queue. When the timer fires, the corresponding aggregation is performed. When receiving one new packet, the value of timer $T_u(t)$ at node u is initialized or updated dynamically as follows:

$$T_u(t) = T_F \times \left[1 - \frac{N_u(t)}{S \times \phi} \right], \quad (14)$$

where $N_u(t)$ is the number of packets in the queue of node u , and the parameter ϕ ($0 < \phi < 1$) is ratio factor and T_F is a time constant. Equation (14) indicates that when the queue occupancy ratio reaches to ϕ , the timer fires since $T_u(t)$ approaches 0, and the aggregation is conducted immediately. The ratio factor ϕ is introduced to accommodate burst arrival of packets in the reserved buffer with room $(1 - \phi)S$ to avoid excessive packet dropping. Equation (14) also states that the more the packets wait in the queue, the shorter is the interval of the timer. Generally, an event is monitored by some adjacent nodes nearly at the same time. Hence, if some downstream nodes monitor an event, the upstream node can receive the packets sent by its direct downstream nodes at about $t + shd$; thus, it is responsive enough to set T_F as the delay in a single hop. Naturally, the larger T_F is beneficial for data aggregation but will increase the end-to-end delay. Because the value of timer for aggregation operation is updated according to the number of the packets in queue when one packet arrives, the timing control algorithm for our ADA is packet driven and adaptive.

4 PERFORMANCE EVALUATION

In this section, we conduct series of simulation experiments to evaluate the performance of the ADA scheme and compare it with some typical data aggregation schemes.

4.1 Performance Metrics

To make a performance evaluation, we introduce two special metrics except for common performance metrics, such as delay and dropping ratio

- *Average number of transmission per received packet (ANTRP)* is defined as the ratio of the total number

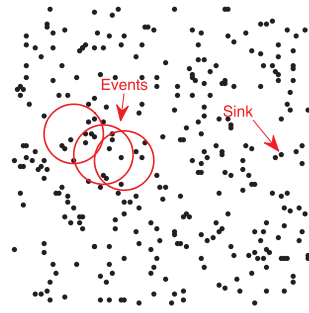


Fig. 2. A WSN with 300 sensors and three circular events.

of transmissions to the total number of packets received by the sink. Without data aggregation, every packet generated at the node whose depth is d can reach the sink after at least d transmissions. An efficient data aggregation mechanism will reduce transmissions by aggregating packets at intermediate nodes. Thus, ANTRP is a proper metric to evaluate the efficiency of data aggregation schemes.

- *Aggregation ratio (AR)* is define as the ratio of the total number of packets received by the sink to the difference between the total number of packets generated by applications and the number of dropped packets. If there are only packets with the same attribute and most packets are aggregated near events and then forwarded to the sink, the sink will receive a few packets. Conversely, the fact that more packets are received at the sink indicates that fewer aggregation operations are performed in networks.

4.2 Experimental Setup

We implement the ADA scheme in nesC and use the TOSSIM simulator integrated in TinyOS to evaluate its performance. Assume that an aggregation function can merge the packets with correlated information into one packet regardless of its actual operators. This assumption can be held for some common aggregation operators, such as MAX, MIN, SUM, AVG, STD, and VAR [36]. The deployment of network and the key parameters in experiments are listed in Table 1. The other particular parameters in different scenarios will be introduced in the related sections. Fig. 2 shows a randomly deployed network with three circular monitoring areas. With regard to the setting of parameters α , ρ , and S , we set $S = 32$, $\rho = 0.9$, and $\alpha = 0.78$. A relatively large ρ indicates that the pheromone evaporates more slowly, which is propitious to make the packets with identical attribute be transmitted along the same path to the sink. Otherwise, in our simulations, three different scenarios where node density and scale vary, respectively, and a mobile event is introduced, are designed to conduct a comprehensive performance evaluation and comparison with the following typical schemes:

- *SPT*: Packets are forwarded to the sink along the shortest path. Aggregation is opportunistic and happens only if two packets with the same attribute encounter at the identical node as well as at the same instant.
- *CT*: The shortest path tree with CT scheme proposed in [21].

TABLE 2
Parameters in the First Experiment

Application	$x(m)$	$y(m)$	$r(m)$	Attribute
App1	300	600	100	1
App1	374	583	100	1
App2	207	675	100	2

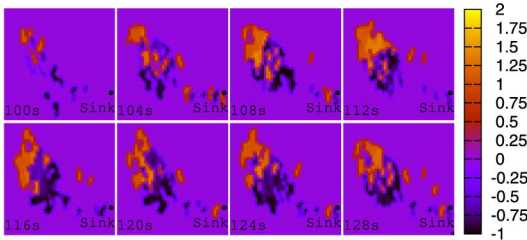


Fig. 3. Snapshot of normalized queue length in ADA.

- *DDS*: A special dominating set is constructed first and then a connected dominating set is constructed to connect dominators and the other nodes [37], and the resultant tree can act as the aggregation tree in [38].
- *WCDS*: A directed tree over the sensor network nodes is constructed to compress the value of a node using the value of its parent proposed in [39].

To the best of our knowledge, little work focus on the data aggregation in WSN with heterogenous sensor and various applications. Actually, in the homogeneous environment, our ADA scheme should have advantage over the existing data aggregation scheme employing the static routing protocol. To verify this prediction, the above four schemes are chosen to make comparison with the ADA scheme. It is noted that the DDS in [38] only provides an aggregation tree. To make proper comparison, the adaptive timing control scheme presented in this work is combined with the aggregation tree of DDS in simulation experiments.

4.3 Results

4.3.1 General Results

A WSN with 999 sensor nodes is randomly deployed in a $1,000\text{ m} \times 1,000\text{ m}$ rectangular region. The communication range of a node is 18 m and the sink locates at (874 m, 550 m). There are two different applications. The packets are randomly generated with average interval 30 ms. All applications start at 100 s and end at 130 s. Table 2 shows the application parameters. (x, y) is the coordinate of the center of the circle where the event happens and r is the radius of the circle.

To vividly demonstrate that the packets with the same attribute are more spatially convergent in ADA, we take a series of snapshots of the normalized queue length, and present them in Figs. 3, 4, 5, and 6. To identify the packets with different attributes, the values of the normalized queue length of packets from two applications are artificially added by 1 or multiplied by -1 , respectively. Apparently, the distribution of packets in space is centralized in ADA so that the normalized queue length is smaller than those in other schemes. This phenomena occurring in the queue indicate that ADA does more efficient aggregation than CT, DDS, and WCDS since ADA always attracts the packets

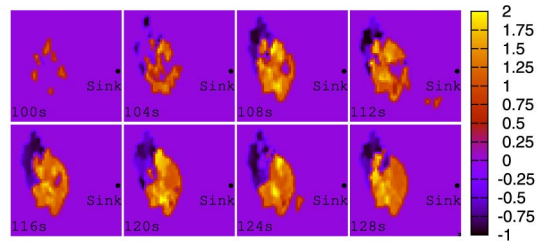


Fig. 4. Snapshot of normalized queue length in CT.

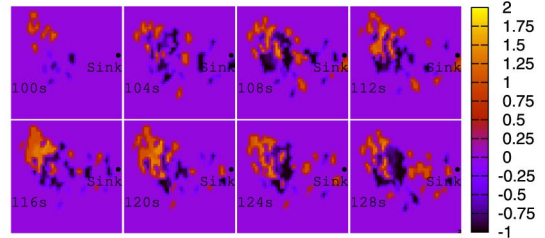


Fig. 5. Snapshot of normalized queue length in DDS.

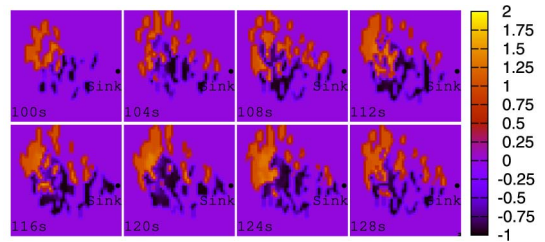


Fig. 6. Snapshot of normalized queue length in WCDS.

with the same attribute together, the limited buffer on nodes only caches the packets from one applications, which can be inferred from the following fact, namely, in ADA, the packets with the same attribute are transmitted to the sink along relatively constant paths, while in CT, DDS, and WCDS, the distribution of packets in space are decentralized. Both sharing buffer and decentralized paths are not beneficial for data aggregation.

4.3.2 Node Density

Generally, the density of nodes in WSNs is initially much dense, gradually decrease as some nodes die due to energy exhaustion or other factors. An efficient data aggregation scheme should perform well as long as the WSN is connected and no matter the node density is high or low. To evaluate the performance of ADA with different node density, nodes are deployed in a $100\text{ m} \times 100\text{ m}$ square where the sink locates at (90 m, 50 m). The number of sensors changes from 100 to 450. In this way, the average number of neighbors of a node increases, i.e., the node density increases. Three different applications happens in a circle and the packets are randomly generated with average interval 10 ms. All three applications start at 110 s and end at 120 s. Table 3 lists the parameters related to applications. (x, y) is the coordinate of the center of the circle where the application happens and r is the radius of the circle.

The ANTRP with different node density in different schemes is shown in Fig. 7a. We can observe that all the curves decline as the number of nodes increases. It is reasonable since the average number of neighbors of a node

TABLE 3
Parameters of Apps with Different Node Density

Application	$x(m)$	$y(m)$	$r(m)$	Attribute
App1	20	57	5	3
App2	30	50	5	2
App3	37	48	5	1

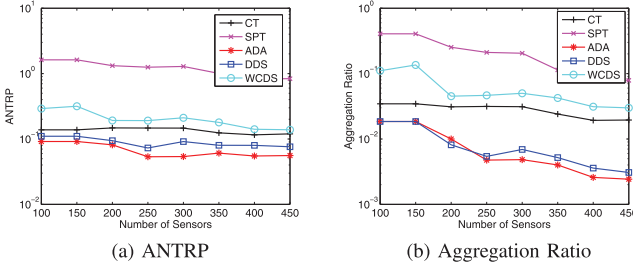


Fig. 7. Different node density.

increases as nodes become denser, which is helpful to improve spatial convergence degree and then reduce ANTRP. SPT performs the worst since it does nothing to make packets spatially convergent and temporally convergent. We can also see that ADA outperforms the other schemes at any node density.

Fig. 7b illustrates the AR of different schemes in the same scenario. As the node density increases, all schemes perform better, and both ADA and DDS are prominent. It seems that ADA obtains more gains in Fig. 7b than that in Fig. 7a. The reason is that ADA indeed improves spatial and temporal convergence remarkably and thus the number of the packets received by the sink is rather small. However, with respect to the average number of transmissions per received packet as shown in Fig. 7a, the packets sometimes will be forwarded to the next hop with the same depth or even with a deeper depth to improve spatial convergence degree. Although this detour transmission increases the number of transmissions, it is indeed beneficial for data aggregation. Hence, the advantages of ADA in Fig. 7b is more obvious than that in Fig. 7a.

4.3.3 Scalability

The scale of WSNs could be very large. For example, a WSN could be deployed on an island for biological investigation or in the forest to detect fire. The scalability of protocols in WSN is very important, at least, the performance should gracefully degrade as the network size increases. To evaluate the scalability of our ADA, we enlarge the WSN into a $1,000\text{ m} \times 1,000\text{ m}$ rectangular area with 1,000 sensors and the radio range becomes 50 m. The sink locates at (950 m, 500 m). Only one application happens in a circle with radius of 40 m and the center of the circle is (x, y) where $y = 500\text{ m}$ and $x = (150 + 100 * i)\text{ m}$ ($i = 1, 2, \dots, 7$), namely the different distances between the event and the sink denote WSNs with different scale. The packets are randomly generated with average interval of 100 ms.

The average number of transmissions per received packet and AR with different distance to the sink are presented in Fig. 8. As for ANTRP, the advantage of ADA compared with the other schemes is impressive as shown in Fig. 8a. As for AR, Fig. 8b shows that when the distance

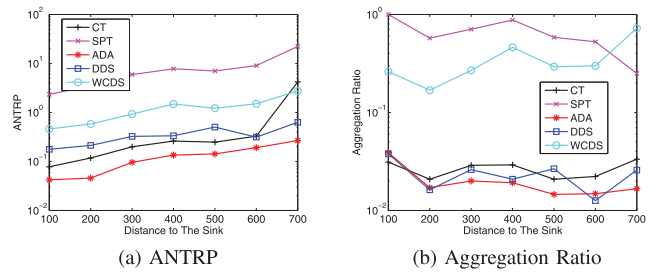


Fig. 8. Different scale.

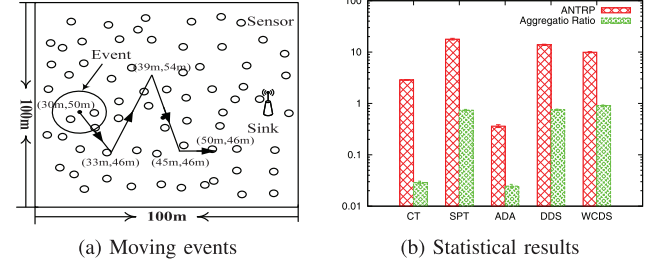


Fig. 9. Mobile scenarios.

from the center of the event to the sink is 100 m, CT performs better than ADA. It is reasonable that when the event is much closer to the sink, there are few chances for ADA to collect packets and aggregate them before they reach the sink. However, in CT, the packets at the upstream nodes will wait the packets forwarded by their downstream nodes and then aggregate them, which results in fewer packets received by the sink. When the distance between the center of the event and the sink becomes longer than 100 m, both ADA and DDS perform better than CT, SPT, and WCDS. Only at several sporadic points, the AR of ADA is larger than that of DDS.

4.3.4 Mobile Scenario

To evaluate the performance of ADA in mobile scenario, we configure an event moving at the speed of 0.1 m/sec in a $100\text{ m} \times 100\text{ m}$ WSN with 100 sensors as shown in Fig. 9a. The radius of the circle is 4 m. The event starts to move from (30 m, 50 m) and stops at (50 m, 46 m), and the moving trajectory is also depicted in Fig. 9a. The experiment is repeated 10 times and the statistical results are calculated. Both ANTRP and AR are presented in Fig. 9b. The average number of transmissions per received packet and AR of ADA is the smallest among all schemes. The obvious advantage of the dynamic routing protocol and adaptive timing control scheme in ADA implies that it is critical to dynamically forward packets in response to the state of both network and event in mobile scenario. Specifically, in Fig. 9a, the event moves along a curve. ADA can dynamically send packets along the curve to make packets more convergent in space. However, the static routing schemes only send packets along the predetermined route path. Although the AR of ADA is nearly same as that of CT, the average number of transmissions per received packet in CT is much larger. The reason is that although most of packets are aggregated in CT, they are aggregated much later than that in ADA. Hence, ANTRP is relatively large. The obvious advantage is obtained by our ADA scheme; moreover, it does not need any extra mechanisms to

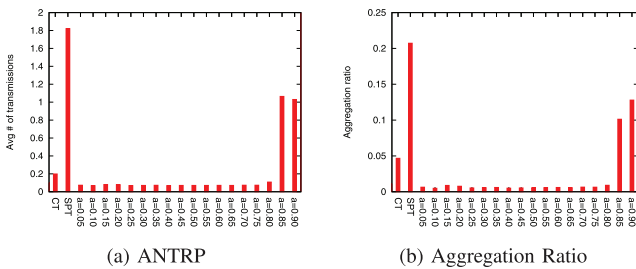


Fig. 10. Different parameter α .

monitor or maintain necessary information for dynamic routing, such as event locations required by the dynamic routing in [17]. In addition, the small standard deviation presented by bars in Fig. 9a shows that our proposed scheme is stable.

4.3.5 Impact of α

The parameter α plays an important role in our ADA scheme; we conduct a series of experiments to evaluate the impact of α on the performance. The configuration of both network and applications is almost the same as that in the scenario of different node density except that the radius of three circles where the applications happen is all 7 m. To compare with other two schemes, we also conduct experiments in the same scenario when CT and SPT are employed, respectively.

The ANTRP with different α values is shown in Fig. 10a. Obviously, ADA performs better than both SPT and CT in most cases. However, when $\alpha > 0.85$, ANTRP increases drastically, even exceeds the corresponding value in SPT. AR presented in Fig. 10b follows the similar trend. Applying the results from theoretical analysis in Section 3.2.5, we can provide a reasonable explanation about this point. Since $S = 32$, $\rho = 0.9$, thus $\frac{2S(1-\rho)}{1+2S(1-\rho)} = 0.86$ and $\frac{S(1-\rho)}{1+S(1-\rho)} = 0.76$. According to the conclusions presented in Propositions 1 and 2, the PBDR routing protocol with $\alpha > 0.76$ allows nodes forward packets in parallel to the neighbor nodes with the same depth but not backward to the neighbor nodes with the higher depth, and the PBDR routing protocols with $\alpha > 0.86$ allows the node transmit packets to its arbitrary neighbor nodes, including forward, parallel, and backward. Theoretically, the backward transmission maybe make packets more spatially convergent to improve the efficiency of data aggregation, but it also implies that there is a local loop in the routing path, which will result in the frequent and useless transmissions between two nodes. This should be the reason that both ANTRP in Fig. 10a and AR in Fig. 10b increase after the parameter α exceeds 0.85. Therefore, in practice, the routing loop need to be avoided through keeping α be less than 0.85.

5 CONCLUSIONS

The data aggregation is an effective mechanism to save limited energy in WSNs. Heterogenous sensors and various applications likely run in the same network. To handle this heterogeneity, in this paper, we introduce the concept of packet attribute to identify different packets generated by heterogenous sensors and different applications, and then propose an attribute-ware data aggregation

scheme consisting of PBDR protocol and packet-driven timing control algorithm. Packets are treated as ants, and then the basic mechanism for finding paths based on pheromone in ant colony is borrowed to attract the packets with the same attribute to gather together. Enlightened by the concept of potential in physics, a PBDR protocol is developed. Combining with the adaptive timing control algorithm, the attribute-ware data aggregation scheme can make the packets with the same attribute spatially convergent as much as possible, and therefore improve the efficiency of data aggregation. The simulation experiments validate the effectiveness of our ADA scheme and demonstrate that it also has some properties required by actual applications in WSNs, such as scalable with respect to network size and suitable for tracking mobile events, and so on. In addition, the theoretical analysis provides some guidelines on parameter settings.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the anonymous reviewers for their constructive comments which helped significantly improve the quality of the manuscript. This work was supported in part by the National Grand Fundamental Research Program of China (973) under Grant Nos. 2012CB315803, 2010CB328105, and 2009CB320504, and the National Natural Science Foundation of China (NSFC) under Grant No. 61225011 and the National Science and Technology Major Project of China (NSTMP) under Grant No. 2011ZX03002-002-02.

REFERENCES

- [1] R. Szcwzyk, A. Mainwaring, J. Polaster, and D. Culler, "An Analysis of a Large Scale Habitat Monitoring Application," *Proc. ACM Int'l Conf. Embedded Networked Sensor Systems (SenSys)*, 2004.
- [2] Q. Fang, F. Zhao, and L. Guibas, "Lightweight Sensing and Communication Protocols for Target Enumeration and Aggregation," *Proc. Fourth Int'l ACM Symp. Mobile Ad Hoc Networking and Computing*, 2003.
- [3] M. Hefeeda and M. Bagheri, "Forest Fire Modeling and Early Detection Using Wireless Sensor Networks," *Ad Hoc and Sensor Wireless Networks*, vol. 7, nos. 3/4, pp. 169-224, Apr. 2009.
- [4] D.L. Hall and J. Llinas, "An Introduction to Multisensor Data Fusion," *Proc. IEEE*, vol. 85, no. 1, pp. 6-23, Jan. 1997.
- [5] D. Li, K. Wong, Y.H. Hu, and A. Sayeed, "Detection, Classification and Tracking of Targets in Distributed Sensor Networks," *IEEE Signal Processing Magazine*, vol. 19, no. 2, pp. 17-29, Mar. 2002.
- [6] T. Clouqueur, K.K. Saluja, and P. Ramanathan, "Fault Tolerance in Collaborative Sensor Networks for Target Detection," *IEEE Trans. Computer*, vol. 53, no. 2, pp. 320-333, Mar. 2004.
- [7] X. Sheng and Y.H. Hu, "Energy Based Acoustic Source Localization," *Proc. IEEE Int'l Conf. Information Processing in Sensor Networks*, pp. 285-300, 2003.
- [8] M. Duarte and Y.H. Hu, "Vehicle Classification in Distributed Sensor Networks," *J. Parallel and Distributed Computing*, vol. 64, no. 7, pp. 826-838, 2004.
- [9] J. Heidemann, F. Silva, C. Intanagonwiwat, R. Govindan, D. Estrin, and D. Ganesan, "Building Efficient Wireless Sensor Networks with Low-Level Naming," *Proc. ACM Symp. Operating Systems Principles*, pp. 146-159, 2001.
- [10] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Application-Specific Protocol Architecture for Wireless Networks," *IEEE Trans. Wireless Comm.*, vol. 1, no. 4, pp. 660-670, Oct. 2002.
- [11] S. Lindsey, C. Raghavendra, and K.M. Sivalingam, "Data Gathering Algorithms in Sensor Networks Using Energy Metrics," *IEEE Trans. Parallel and Distributed Systems*, vol. 13, no. 9, pp. 924-935, Sept. 2002.

- [12] O. Younis and S. Fahmy, "HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad Hoc Sensor Networks," *IEEE Trans. Mobile Computing*, vol. 3, no. 4, pp. 366-379, Dec. 2004.
- [13] M. Ding, X. Cheng, and G. Xue, "Aggregation Tree Construction in Sensor Networks," *Proc. IEEE 58th Vehicular Technology Conf.*, pp. 2168-2172, Oct. 2003.
- [14] H.O. Tan and I. Korpeoglu, "Power Efficient Data Gathering and Aggregation in Wireless Sensor Networks," *SIGMOD Record*, vol. 32, no. 4, pp. 66-71, Dec. 2003.
- [15] R. Cristescu, B. Beferull-Lozano, and M. Vetterli, "On Network Correlated Data Gathering," *Proc. IEEE INFOCOM*, pp. 2571-2582, Mar. 2004.
- [16] J. Li, A. Deshpande, and S. Khuller, "On Computing Compression Trees for Data Collection in Wireless Sensor Networks," *Proc. IEEE INFOCOM*, 2010.
- [17] W. Zhang and G. Cao, "DCTC: Dynamic Convoy Tree-based Collaboration for Target Tracking in Sensor Networks," *Ad Hoc and Sensor Wireless Networks*, vol. 3, pp. 1689-1701, Sept. 2004.
- [18] Y.-K. Kim, R. Bista, and J.-W. Chang, "A Designated Path Scheme for Energy-Efficient Data Aggregation in Wireless Sensor Networks," *Proc. IEEE Int'l Symp. Parallel and Distributed Processing with Applications*, pp. 408-415, 2009.
- [19] K. Fan, S. Liu, and P. Sinha, "On the Potential of Structure-Free Data Aggregation in Sensor Networks," *Proc. IEEE INFOCOM*, pp. 1-12, Apr. 2006.
- [20] S.R. Madden, M.J. Franklin, J.M. Hellerstein, and W. Hong, "TAG: A Tiny Aggregation Service for Ad-hoc Sensor Networks," *Proc. Symp. Operating Systems Design and Implementation (OSDI)*, pp. 131-146, Dec. 2002.
- [21] I. Solis and K. Obraczka, "In-Network Aggregation Trade-offs for Data Collection in Wireless Sensor Networks," *Int'l J. Sensor Networks*, vol. 1, nos. 3/4, pp. 200-212, 2006.
- [22] F. Hu, X. Cao, and C. May, "Optimized Scheduling for Data Aggregation in Wireless Sensor Networks," *Proc. Int'l Conf. Information Technology: Coding and Computing (ITCC '05)*, pp. 156-168, 2005.
- [23] Z. Ye, A. Abouzeid, and J. Ai, "Optimal Policies for Distributed Data Aggregation in Wireless Sensor Networks," *Proc. IEEE INFOCOM*, pp. 1676-1684, May 2007.
- [24] X. Xu, X. Li, P. Wan, and S. Tang, "Efficient Scheduling for Periodic Aggregation Queries in Multihop Sensor Networks," *ACM/IEEE Trans. Networking*, vol. 20, no. 3, pp. 690-698, June 2012.
- [25] H. Luo, H. Tao, H.M. Sajal, and K. Das, "Data Fusion with Desired Reliability in Wireless Sensor Networks," *IEEE Trans. Parallel and Distributed Systems*, vol. 22, no. 3, pp. 501-513, Mar. 2011.
- [26] H. Tan and I. Korpeoglu, "Power Efficient Data Gathering and Aggregation in Wireless Sensor Networks," *ACM SIGMOD Record*, vol. 32, no. 4, pp. 66-71, 2003.
- [27] G. Theraulaz and E. Bonabeau, "A Brief History of Stigmergy," *Artificial Life*, vol. 5, no. 2, pp. 97-116, 1999.
- [28] A. Basu, A. Lin, and S. Ramanathan, "Routing Using Potentials: A Dynamic Traffic-Aware Routing Algorithm," *Proc. ACM SIGCOMM*, pp. 37-48, 2003.
- [29] C. Liu and G. Cao, "Distributed Monitoring and Aggregation in Wireless Sensor Networks," *Proc. IEEE INFOCOM*, 2010.
- [30] W. Pu, D. Rui, and I. Akyildiz, "Collaborative Data Compression Using Clustered Source Coding for Wireless Multimedia Sensor Networks," *Proc. IEEE INFOCOM*, pp. 1-9, 2010.
- [31] B.J. Culpepper, L. Dung, and M. Moh, "Design and Analysis of Hybrid Indirect Transmissions for Data Gathering in Wireless Micro Sensor Networks," *ACM SIGMOBILE Mobile Computing and Comm. Rev.*, vol. 8, pp. 61-83, 2010.
- [32] S.J. Park and R. Sivakumar, "Energy Efficient Correlated Data Aggregation for Wireless Sensor Networks," *Int'l J. Distributed Sensor Networks*, vol. 4, no. 1, pp. 13-17, 2008.
- [33] G.D. Caro and M. Dorigo, "AntNet: Distributed Stigmergetic Control for Communication Networks," *J. Artificial Intelligence Research*, vol. 9, no. 1, pp. 317-365, 1998.
- [34] F. Ducatelle, G.D. Caro, and L. Gambardella, "Ant Agents for Hybrid Multipath Routing in Mobile Ad Hoc networks," *Proc. Second Ann. Conf. Wireless Demand Network Systems and Services (WONS)*, 2005.
- [35] D.Y. Kwon, J. hwa Chung, T. Suh, W. gyu Lee, and K. Hury, "A Potential Based Routing Protocol for Mobile Ad Hoc Networks," *Proc. IEEE Int'l Conf. High Performance Computing and Comm.*, pp. 273-280, 2009.
- [36] S. Yoon and C. Shahabi, "The Clustered AGgregation (CAG) Technique Leveraging Spatial and Temporal Correlations in Wireless Sensor Networks," *ACM Trans. Sensor Networks*, vol. 3, no. 1, pp. 1-39, Mar. 2007.
- [37] X. Xu, X.-Y. Li, X. Mao, S. Tang, and S. Wang, "A Delay-Efficient Algorithm for Data Aggregation in Multihop Wireless Sensor Networks," *IEEE Trans. Parallel Distributed Systems*, vol. 22, no. 1, pp. 163-175, Jan. 2011.
- [38] P.J. Wan, K. Alzoubi, and O. Frieder, "Distributed Construction of Connected Dominating Set in Wireless Ad Hoc Networks," *Mobile Networks and Applications*, vol. 9, pp. 141-149, 2004.
- [39] J. Li, A. Deshpande, and S. Khuller, "On Computing Compression Trees for Data Collection in Wireless Sensor Networks," *Proc. IEEE INFOCOM*, pp. 2115-2123, 2010.



Fengyuan Ren received the BA, MSc, and PhD degrees from Northwestern Polytechnic University, China, in 1993, 1996, and 1999, respectively. He is a professor in the Department of Computer Science and Technology, Tsinghua University, Beijing, China. In January 2002, he joined the Computer Science and Technology Department, Tsinghua University. His research interests include network traffic management and control, control in/over computer networks, wireless networks and wireless sensor networks. He authored and coauthored more than 80 international journal and conference papers. He is a member of the IEEE.



Jiao Zhang received the bachelor's degree in computer science and technology from the Beijing University of Posts and Telecommunication in 2008. She is currently working toward the PhD degree in the Department of Computer Science and Technology, Tsinghua University, China. She is now conducting researches in networking under the direction of Prof. Fengyuan Ren. Her recent research focuses on traffic management in data center networks. She also has done some work on data aggregation and energy-efficient routing in wireless sensor networks before.



Yongwei Wu received the PhD degree in applied mathematics from the Chinese Academy of Sciences in 2002. He is currently a professor of computer science and technology, Tsinghua University, Beijing, China. His research interests include data center, cloud computing, distributed processing, and parallel computing.



Tao He received the MS degree in computer science and technology from Tsinghua University of China in 2008. He has been an assistant researcher at NEC Labs, China, since his graduation. His research interests include wireless sensor networks and recommendation systems.



Canfeng Chen received the BEng degree in information engineering and the PhD degree in signal and information processing from the Beijing University of Posts and Telecommunications, Beijing, China, in 2000 and 2005, respectively. Since July 2005, he has been with the Nokia Research Center in Beijing, where he is currently a research leader in Sensor Radio Networks and Prototyping team. His main research interests cover Bluetooth Low Energy

wireless sensor networks, mobile and Internet computing, and context-aware services.



Chuang Lin received the PhD degree in computer science from Tsinghua University, China, in 1994. He is a professor in the Department of Computer Science and Technology, Tsinghua University, Beijing, China. He is an honorary visiting professor at the University of Bradford, United Kingdom. His current research interests include computer networks, performance evaluation, network security analysis, and Petri net theory and its applications. He

has published more than 300 papers in research journals and IEEE conference proceedings in these areas and has published four books. He is a senior member of the IEEE, and an associate editor of *IEEE Transactions on Vehicular Technology* and an area editor of *Computer Networks* and the *Journal of Parallel and Distributed Computing*.

▷ **For more information on this or any other computing topic, please visit our Digital Library at www.computer.org/publications/dlib.**