Role of Multiple Static Sinks for Supporting Mobile Users in Wireless Sensor Networks

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Abstract

Communication model of wireless sensor networks typically consists of users, sinks, and a number of sensor nodes. The users are remote from wireless sensor networks and they gather data from the sinks via legacy networks. In practical sensor network applications, however there are two types of users: traditional remote users and mobile users such as firefighters and soldiers. The mobile users may move around sensor fields and they communicate with the sinks only via the sensor networks in order to gather data like location information of victims in disaster areas. In this paper, in order to effectively support both the remote users and the mobile users, we propose a novel communication model relying on the typical sensor network model. In the model, multiple static sinks connect with legacy networks and divide a sensor field into the number of the multiple sinks. Through sharing queries and data via the legacy networks, the multiple static sinks provide high throughput through distributed data gathering and low latency through short-hops data delivery. Multiple static sinks deliver the aggregated data to the remote users via the legacy networks. In case of the mobile users, when a mobile user moves around, it receives the aggregated data from the nearest static sink. Simulation results show that the proposed model is more efficient in terms of energy consumption, data delivery ratio, and delay than the existing models[1].

Index Terms — Wireless sensor networks, Remote user, Mobile user, Multiple static sinks, and Information sharing

I. Introduction

Typical communication model of wireless sensor networks consists of users, sinks, and a number of sensor nodes [1], as shown of Fig. 1(a). In the communication model, users are remote from sensor networks and connect with a sink through legacy networks such as Internet or satellite. The sink functions as the gateway between wireless sensor networks and users via legacy networks. However, in practical sensor network applications, there are mobile users [3-6] such as firefighters and soldiers as well the traditional remote users. The mobile users move around sensor fields to perform their own missions like saving life of victims in disaster areas and might not have any direct communication through legacy networks. In other words, wireless sensor networks are the only communication channel between the mobile users and the sink in practical sensor fields. Therefore, in wireless sensor networks without legacy networks, supporting both the remote users and the mobile users is an important issue.

Recently, many researches have been studied to support mobility of the mobile users on sensor networks [2-7]. The studies could be classified into four categories according to communication models with respect to data collection of the mobile users: single static sink model with legacy network, mobile sink model, dynamic sink model, and single static sink model with sensor network. However, these communication models bring many challenges to the traditional sensor network model. First, like the traditional sensor network model, the single static sink model with legacy networks [2] enables the mobile users to receive directly data from a single static sink via legacy networks as the remote users as shown in Fig. 1(b). However, the model requests that sensor networks must have legacy networks and the mobile users must connect with the legacy networks. Otherwise, in the model, the mobile user cannot receive data from the single static sink. We define such problem as disconnection problem of mobile users.

Second, unlike the traditional sensor network model, the mobile sink model [3-5] assumes a mobile user is defined as a mobile sink; thus, the mobile sink is defined as a portable equipment of the mobile user, such as PDA, Laptop, and so on. In other words, the mobile sink model does not consider the traditional static sink which operates as the gateway between the remote users and wireless sensor networks. Hence, in the mobile sink model, the remote users may not gather data from the wireless sensor networks since the mobile sinks are disconnected from legacy networks. We define such problem as disconnection problem of remote users. Also, in the mobile sink model, whenever a mobile sink wants to gather data, it should reconstruct newly a data gathering tree to the whole sensor filed at its current location. After, whenever the mobile sink moves, it constructs relay paths organized by its footprint chaining in order to receive continually data from sources [5]. The relay paths are made as detour paths by random mobility of the mobile user and are congested by a disproportionate amount of data from many sources [5]. Figure 1(c) shows data deliver to a mobile user in the mobile sink model.

In case of the dynamic sink model [6], as shown in Fig.1(d), to avoid long relay paths organized by footprint chaining of the mobile sink model, a mobile user chooses a sensor node as a dynamic sink when the mobile user needs some information. Then, the dynamic sink constructs a data gathering tree and collects data from all sources. The mobile user keeps moving, and requests and receives the data from the dynamic sink at its current location in case of necessity. However, like the mobile sink model, the dynamic sink model also does not rely on the traditional communication model of wireless sensor networks. Hence, the dynamic sink model also has the disconnection problem of remote users. Moreover, if the mobile user wants to gather again, it reselects a new dynamic sink and reconstructs a new data gathering tree from the dynamic sink. Furthermore, actually, the dynamic sink is a sensor node so the sensor node functioning as the sink may suffer from high computation overhead and energy consumption. Finally, as shown in Fig. 1(e), the single static sink model with sensor network [7] supports mobility of the mobile users on the traditional communication model of wireless sensor networks. The single static sink gathers data from sources and it then delivers the collected data to both the traditional remote users and the mobile users. However, the data collection from many sources into the single static sink might cause high congestion and a large amount of energy consumption around the single static sink, i.e. the hot spot problem [5, 8].

In this paper, we introduce a novel communication model that solves the disconnection problem of both static and mobile users, reconstruction overhead of data gathering tree in the mobile sink model and the dynamic sink model, and the hotspot problem and data delivery with both low delivery ratio and high latency of the single static sink, named the multiple static sinks based communication model as shown in fig. 1(f), and propose a novel protocol for supporting the mobile users based on the multiple static sinks model. The communication model relies on the traditional communication model of wireless sensor networks. In the model, multiple static sinks connect with legacy networks and each other by the legacy networks. The wireless sensor network is divided to the multiple static sinks; then, they distributively gather data from their own allocated area. The distributively collected data could be aggregated and shared among the multiple static sinks and then the data would be delivered to remote users. When a mobile user moves around the sensor network, the mobile user requests/gathers interested data to/from the nearest one of the multiple static sinks. In other words, the multiple static sinks model can energy- efficiently support both the remote users and the mobile users with low data delivery latency and high data delivery ratio. Simulation results show that the multiple static sinks model is more efficient in terms of energy consumption, data delivery ratio, and delay than the single static sink model with legacy networks, the mobile sink model, the dynamic sink model, and the single static sink model with sensor network.

The rest of this paper is organized as follows. Section II explains a communication model proposed in this paper and section III describes a communication protocol for supporting user mobility in our communication model. Simulation results are presented in Section IV to evaluate the effectiveness of the proposed model and protocol. Section V concludes the paper.

II. Communication Model Design

Communication models influence considerably in network performances by how to design them. Hence, they must be designed adequately according to models and applications of sensor networks. In this section, we first define two users: a remote user and a mobile user, and next introduce a communication model based on multiple static sinks to support the two users.

A. Definition of Remote Users and Mobile Users

Figure 1(a) shows typical communication model in wireless sensor networks [1]. A user with task manger node in the outside of the sensor field can communicate directly with a static sink in the outskirts of the sensor field via legacy networks such as Internet and satellite. In this paper, we call the user as a remote user. The remote user can gathers data from sensor nodes through the static sink via the legacy networks. Like this, the static sink conducts a gateway function between sensor networks and legacy networks. Hence, if a remote user can be connected with legacy networks, whenever and wherever it can communicate with sensor networks, it can collect data from sensor nodes via the static sink.

In these typical wireless sensor networks, we introduce a mobile user which can move freely inside the sensor networks but cannot connect with legacy networks [6, 7]. This situation happens when the legacy networks do not exist inside the sensor networks because it is damaged due to the result of the war or the disaster in the sensor field such as disaster areas or war zones or when the mobile user cannot have a device for communicating with the legacy networks. Accordingly, the mobile user should communicate with the static sink only via multi-hop communication through sensor nodes. Therefore, by multi-hops communications through sensor nodes, the mobile user requests data collection to the static sink and receives data from the static sink. However, to the mobile user inside the sensor networks, the mobile sink model [3-5] and the dynamic sink model [6] cannot perform a gateway function between sensor networks and remote users when the mobile sink cannot connect with legacy networks.

B. Introduction of Communication Model with Multiple Static Sinks

In this paper, we use multiple static sinks for supporting efficiently mobile users. As shown in fig. 4, static sinks in the outskirts of sensor networks can exist multiple. There are many studies [8, 9] on multiple static sinks to solve problems of single static sink. The first problem is reduction of network lifetime due to fast energy exhaustion of sensor nodes near the sink; the second problem is long delay and low data delivery ratio about query and data dissemination due to long path from the static sink. However, since multiple static sinks can be located in the places connected with legacy networks in the outskirts of sensor field, they can communicate directly with each other via the legacy networks. The multiple static sinks divide the sensor network and dispersively collect data, which can solve the problems of single static sink.

Additionally, multiple static sinks can support effectively the mobility of user inside the sensor field. The mobile user sends queries to the nearest sink from its location and multiples static sinks propagates fast the queries inside the sensor network through sharing the queries via legacy networks. Multiples static sinks also share the collected data from sensor nodes via legacy networks and the nearest sink from the mobile user delivers fast the sharing data to the mobile user. In this manner, through short hops communications, the mobile user sends queries to the nearest sink from its location and receives data from the nearest sink from its location. This reduces energy consumption of sensor nodes, increases data delivery ratio, and decreases delay.

III. Communication Protocol Design

In this section, we describe a communication protocol that supports mobile users in wireless sensor networks based on multiple static sinks. The proposed protocol consists of three phases. The first one is a networks initialization phase which allocates multiple static sinks and divides a sensor network by them .The second one is a phase of data gathering of mobile user which allows mobile users to gather effectively data from the sensor network through the multiple static sinks. The other one is a user mobility support phase which guarantees data delivery to a moving user through mobility management.

A. Network Initialization

1) Allocation of Multiple Static Sinks

The proposed protocol exploits multiple static sinks for supporting user mobility in wireless sensor networks. Via the legacy networks, the multiple static sinks can communicate with each other for sharing information and can communicate with remote users for performing gateway functions between remote users and the sensor network. Various papers [8, 9] related on multiple static sinks also assume the direct communication between sinks and legacy networks and the direct communication via the legacy networks between all sinks.

2) Network Dividing of Multiple Static Sinks

If the allocation of multiple static sinks is finished, every sink flood a *Sink_Annoncement* packet with its ID in the whole sensor field for informing its existence and constructing routing paths from sensor nodes to it. As a result of flooding such *Sink_Announcement* packet, every sensor node has known hop counts and next hop neighbor sensor node toward each sink. Every sensor node has also known the nearest sink from itself through capering hop counts to each sink. Hence, as shown in Fig. 2, every sensor node in the sensor field belongs to the domain of a sink which is closest from its location.

The proposed protocol allows sinks to be allocated in other places with legacy networks if the energy of their any neighbor sensor node falls below some threshold. Sinks, which are allocated in other places, flood again their *Sink_Announcement* packet in the whole sensor field. As a result, the sensor network is divided afresh by multiple static sinks with new locations.

B. Data Gathering of Mobile User

1) Querying of Mobile User

If a mobile user makes a query with its ID for gathering data from sensor nodes, it selects a sensor node nearest from its location as its Primary Agent (PA) and sends the query to the PA as shown in Fig. 3. The PA received the query sends it to a next hop node toward a sink which is nearest (smallest hop counts) from its location. The next hop node also sends it to a next hop node toward the sink. If the next hop node such as G receives same queries from different mobile users, it only sends one query with all IDs of the mobile users to its next hop node toward the sink. This process progresses to the sink and hence the sink receives the queries of the mobile users. The sink saves the query and the IDs of the mobile users in its mobile user management table.

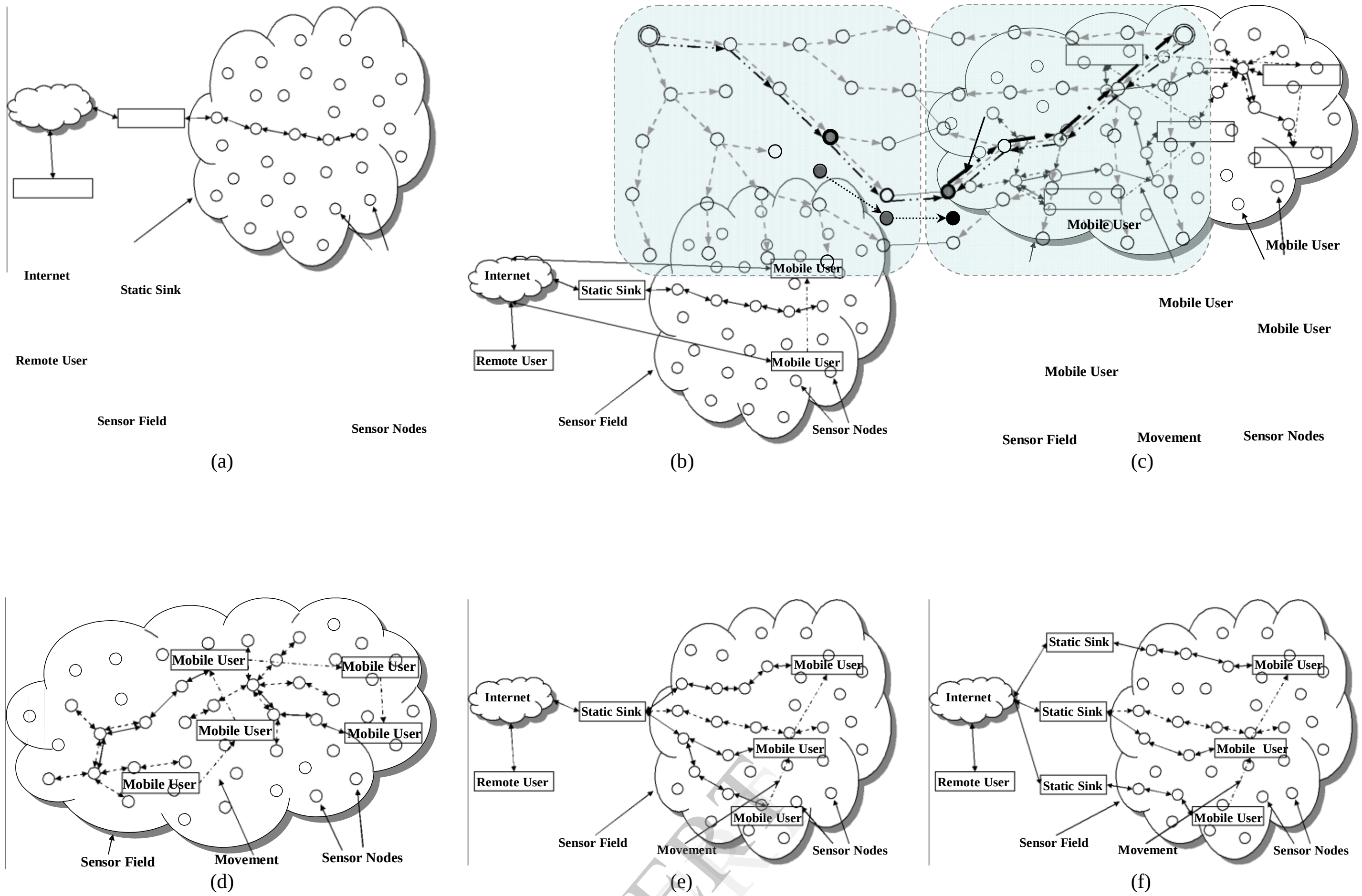


Fig. 1. Models of wireless sensor networks: (a) typical sensor network model, (b) single static sink model with legacy networks (SSSM-LN), (c) mobile sink model (MSM), (d) dynamic sink model (DSM), (e) singe static sink model with sensor network (SSSM-SN), and (f) multiple static sinks model (MSSM)

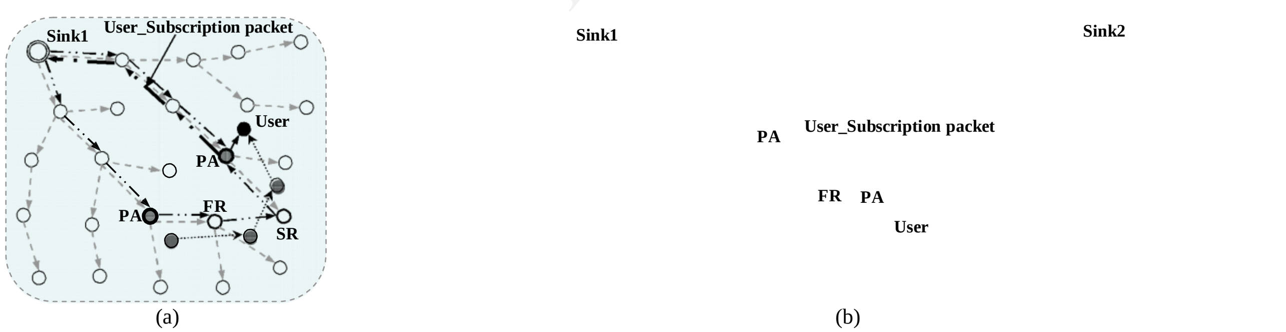


Fig. 5. Data dissemination to a mobile user through user mobility management: (a) Local mobility management and (b) Global mobility management

The sink received the query of the mobile user must disseminate it to the sensor field. Instead of disseminating the query to the whole sensor field by the sink, in the proposed protocol, the sink shares it with the other sinks via legacy networks and they disseminate it to only sensor nodes within their own domain as shown in fig. 6. In other words, each sink disseminates the shared query to sensor nodes which have smaller hop counts from it than hop counts from the other sinks. Hence, with sharing of the query, the proposed protocol can distributedly disseminate it within the whole sensor field by multiple static sinks. The distributed query dissemination by multiple static sinks has two advantages. Firstly, the distributed query dissemination by multiple static sinks can reduce the number of transmitting and receiving than the query dissemination by one sink and hence reducing the energy consumption. Secondly, the distributed query dissemination by multiple static sinks can reduce query receiving times of sensor nodes and hence enabling faster data responses from them.

2) Data Gathering, Sharing, and Disseminating of Sinks

If every sensor node receives a query from the sink in its domain, the sensor network is composed to trees which are rooted at each sink and include sensor nodes in its domain. As shown in fig. 4, every sensor node generates its data about the query and sends it to its parent node on the tree rooted at its sink.

In order to reduce the energy consumption for data transmissions, in the data gathering approach based on tree, parent nodes can receive data from their children nodes, aggregate the data with their data, and send the aggregated data to their parent nodes. Many aggregation schemes based on tree have been proposed [10]. Parent nodes in the proposed protocol aggregates their data and data of their children nodes by exploiting one among the data aggregation schemes based on tree. However, the tree-based data aggregation brings about much delay because parent nodes wait to receive data from all their children [10]. Accordingly, in case of applications requesting emergency of date delivery, the proposed protocol does not execute the tree-based data aggregation.

The applications such as event detection and environment monitoring make a lot of data traffic be generated and flowed toward sinks, they could suffer from data traffic congestion and hence reducing throughput of data. In order to solve data throughput reduction due to the data congestion problem, the proposed protocol proposes a scheme that can achieve data delivery by getting away from data congestion areas. When a sensor node sends data toward the sink in its domain, if it detects data congestion, it sends the data to a next sensor node toward the second nearest sink from it. Because, in the allocation phase of multiple static sinks, every sensor node can be aware of hop counts and a next hop node toward each sink by receiving its *Sink_Announcement* packet.

When multiple static sinks have gathered data from all sensor nodes in their domains, they aggregate the data. In the proposed protocol, we assume that multiple static sinks are located at places connected to legacy networks in the outskirt of sensor fields. Accordingly, all sinks share data from sensor nodes in their domain with each other via the legacy networks and make information data for the user by aggregating the shared data. Hence, all sinks have the same information data about the sensor network. Then, as shown in Fig. 4, the sink received the query from the user deliver the information data to a downstream node toward the PAs of the users. If the downstream node such as G receives queries of users from several downstream nodes, it sends the aggregated data to both of them. This process progresses to the PAs. Since, the mobile users can move out the radio range of their PA, we describe in detail how to guarantee the information data delivery to the moving users in the next section III.C.

C. User Mobility Support

We support user mobility in terms of two mobility managements. One is a local mobility management which supports user mobility inside the domain of a sink. The other one is a global mobility which supports user mobility between the domains of sinks. We present the two mobility managements in next two subsections, respectively.

1) Local Mobility Management

We use a Footprint-Chaining scheme for local mobility management of a user inside the domain of a sink. To support the scheme, when the mobile user selects its PA, it requests and receives neighbors' information of the PA from the PA. If the mobile user moves out the radio range of its PA, it collects neighbors' information in its radio range. Then, among sensor nodes included in both neighbors of the user and neighbors of the PA, the mobile user selects the nearest (the strongest signal strength) one from its location as First Relay (FR) node. The mobile user informs the sensor node of the selection as FR Node and the information of PA, and also requests and receives neighbor's information of the FR node. In next, if the mobile user moves out the radio range of the FR Node, it also selects Second Relay (SR) node by the above mentioned process. As shown in Fig. 5(a), with the consecutive chaining of relay nodes, the proposed protocol manages user mobility inside the domain of a sink.

However, although a mobile user gets near to a static sink which send data to the mobile user because this Footprint-chaining scheme connects continuously relay nodes, it has a problem of long path length from the sink to the mobile user. Thus, to solve the long path length problem of the footprint-chaining scheme, when a mobile user selects a relay node, if a distance from the relay node to the sink is equal or shorter than that from the PA to the sink, we allow the mobile user to select the relay node as new PA. So, our local mobility management reduces path length for data delivery from the sink to the mobile user. To enable this method, when a mobile user selects PAs or RAs we allow the mobile user to acquire hop-count information to sinks in their domains from them. So, when the mobile user selects a relay node the mobile user acquires hop-count information to its sink from it. If the hop-count is equal or smaller than that of PA, the mobile user selects the relay nodes as new PA and sends a *User_Subscription* packet with its ID to the new PA, and then, the new PA sends the *User_Subscription* packet to its sink as shown in Fig. 5(a). Then, the new PA requests data to the sink. If the sink receives the data request, from this point of time, it delivers data to the new PA. So, as shown in Fig. 5(a), before the selection of the new PA, data from the sink are delivered to the mobile user via connected paths of old PA, relay nodes, and new PA and, after the selection of the new PA, data from the sink are delivered to the mobile user through short path via the new PA. Hence, by the footprint-chaining scheme with this function for selecting the nearest PA from a sink, our local mobility management enables a mobile user to receive data from the sink inside its domain through short path.

2) Global Mobility Management

A mobile user can move from a domain of a sink (Old Sink) into a domain of another sink (New Sink). To reduce the energy consumption of delivering the information data, the proposed protocol should allow the mobile user to receive the information data from the new sink with shorter hops. To address this issue, we exploit the handoff concept of Mobile IP [14] in Internet for Global Mobility Management of user between domains of sinks.

When a mobile user moves out the radio range of last relay node and then selects a sensor node as a next relay node, it can be aware of the movement into a domain of new sink by checking ID information of the sink where the next relay node belongs to. Then, as shown in Fig. 5(b), the mobile user also selects the next relay node as a PA in the domain of the new sink and sends a *User_Subscribtion* packet with its ID toward the sink for receiving the information data from the sink. By receiving the packet, the new sink is acquainted with a fact that the mobile user moves into its domain. Then, the new sink saves the ID of the mobile user in its mobile user management table, informs the fact of the old sink, and takes charge of the role for delivering the information data to the mobile user. Then, the old sink deletes the ID of the mobile user in its mobile user management table. Accordingly, the new sink sends the information data toward the reverse of path traveled the *User_Subscribtion* packet from the PA in its domain. If the PA in the domain of new sink receives the information data, it delivers the data to the mobile user. Before the interdomain movement of mobile user from the new sink to the old sink is informed to the old sink, the information data delivered from the old sink are reached to the PA in its domain and next arrived to the PA in the domain of the new sink by the consecutive chaining of relay nodes. The PA in the domain of the new sink delivers the information data to the mobile user. Hence, with the dual paths management from both the old and new sinks, the mobile user in the proposed protocol can seamlessly receive the information data via short hops from sinks in spite of its interdomain mobility.

In handoff concept of Mobile IP, it is a difficult problem for Ping-Pong to deal with, which a mobile user comes and goes boundary lines between the domains of sinks. To relieve this Ping-Pong problem, in the proposed protocol, we use time or distance threshold. Even though the mobile user moves into the domain of a new sink, if it does not stay during a predefined time threshold or reach a predefined hop counts threshold, it does not select a PA in the domain of the sink. Instead of, the mobile user selects a next relay node for extension of the consecutive chaining of relay nodes connected from the domain of the old sink. For the predefined time threshold, when the mobile user enters the domain of the new sink, it starts its timer. If the mobile user stays in the domain up to the predefined time threshold, it then selects a PA in the new domain. For the predefined hop counts threshold, when the mobile user enters the domain of the new sink, it stores hop counts to the new sink from the node. When the mobile user selects a next relay node for its mobility, if a decrease between the stored hop counts and the hop counts of the next relay node is bigger than the predefined distance threshold, it then selects a PA in the new domain. Hence, with these schemes, the proposed protocol can solve frequent user subscription process due to the ping-pong problem.

IV. Performance Evaluation

In this section, we evaluate Multiple Static Sinks Model (MSSM), with the Single Static Sink model via Legacy Networks (SSSM-LN) that a mobile user communicates with the sink via legacy network, a Single Static Sink Model via Sensor Networks (SSSM-SN) that a mobile user communicates with the sink via sensor networks, Mobile Sink Model (MSM), and Dynamic Sink Model (DSM) through simulations. We first describe our simulation model and performance evaluation metrics and next compare the performance of the five communication models though simulation results.

A. Simulation Model and Performance Evaluation Metrics

We implement the five communication models in the Qualnet simulator ver.3.8. The network is 1000m x 1000m area which is deployed by 100 sensor nodes. The energy model of sensor nodes follows the MICA specification [15]. The radio range of sensor nodes is omnidirectionally 100m. A sensor node’s transmitting and receiving power consumption rate are 0.66W and 0.39W, respectively. Each query and data packets are 36 and 64 bytes, respectively. Four multiple static sinks are located in the outskirts of sensor fields and can communicate with each others via legacy networks. A mobile user moves with random way point model and its speed is

10m/sec. A mobile user disseminates a query at an interval of 10 second. Source nodes receive the query, generate only one reporting data for the query, and disseminate the data to the nearest sink. We lasts the simulation for 500 seconds.

We use three metrics to evaluate the performance of the proposed protocol. The **energy consumption** is defined as the communication (transmitting and receiving) energy the network consumes. The **data delivery ratio** is the ratio of the number of successfully received data packets at a user to the total number of data packets generated by every sensor node. The **delay** is defined as the average time between the time a sensor node transmits a data packet and the time a user receives the data packet.

B. Simulation Results for Network Size

We compare the performance of the five models for the network size. Figure 6(a)-(c) shows energy consumption, data delivery ratio, and delay for the network size. As the network size increases, both models increases energy consumption, decreases data delivery ratio, and increases delay because the Since SSSM-LN and SSSM-SN construct data gathering trees to the whole sensor field at the boundary of sensor networks, they has longer tree depth so that they has more energy consumption, lower data delivery ratio, and longer delay. Only, SSSM-SN has more energy consumption, lower data delivery ratio, and longer delay than SSSM-LN because SSSM-SN should disseminate data from a single static sink to a mobile user via sensor nodes. However, MSM and DSM have less energy consumption, higher data delivery ratio, and shorter delay than SSSM-LN and SSSM-SN because they construct data gathering trees in the inside of sensor networks such that the data gathering trees have shorter depth (hop counts). Only, since MSM uses relay nodes on user mobility but DSM uses. On the other hand, MSSM constructs distributedly data gathering trees by multiple static sinks such that the data gathering trees have short depth (hop counts).

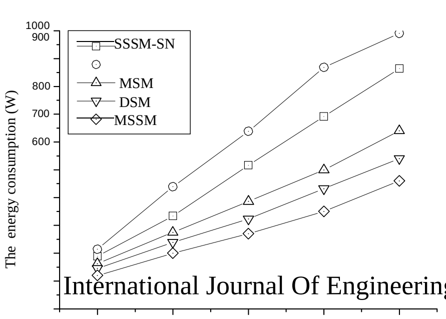
Accordingly, MSSM can gather data from sensor nodes to multiple static sinks and disseminate data from the nearest static sink to a mobile user via short hop counts. MSSM has less energy consumption, higher data delivery ratio, and shorter delay than the other four models.

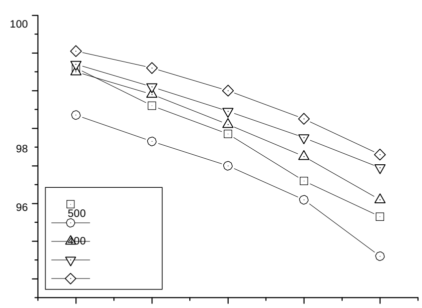
C. Simulation Results for User Speed

In this subsection, we compare the performance of the five models for user speed. Figure 7(a)-(c) show energy consumption, data delivery ratio, and delay for the user speed. SSML-LN and SSSM-SN have high energy consumption, low data delivery ratio, and long delay because they basically construct data gathering trees with long depth (hop counts). Regardless of the user speed, SSSM-LN has the same value in energy consumption, data delivery ratio, and delay because it sends directly data from single sink to a mobile user via legacy networks. In contrast, since SSSM-SN has more relay nodes from the single static sink to the mobile user due to user movement, SSSM-SN has more energy consumption, lower data delivery ratio, and higher delay than SSSM-LN. If use speed increases, MSSM increases energy consumption, decreases data delivery ratio, and increases delay. Since MSM and DSM basically construct data gathering tree with short tree depth (hop counts), they has less energy consumption, higher data delivery ratio, and shorter delay than SSSM-LN and SSSM-SN. If user speed increases, MSM needs more relay nodes due to user movement so that it increases energy consumption, decrease data delivery ratio, and increases delay. However, since a mobile user in DSM requests and receives data from a dynamic sink at its current location, the growth rate of energy consumption, the decline rate of data delivery ratio, and the growth rate of delay in DSM are smaller than that in MSM. If user speed increases, MSSM also requests more relay nodes so that it increases energy consumption, decreases data delivery ratio, and increase delay. However, in MSSM, the length of such relay nodes is limited in a domain of a sink so that MSSM does not have long length of relay nodes. Accordingly, the growth rate of energy consumption, the decline rate of data delivery ratio, and the growth rate of delay in MSSM are smaller than the other four models.

D. Simulation Results for the Number of Sources

We compare performances of the five models for the number of sources. Figure 8(a)-(c) show energy consumption, data delivery ratio, and delay for the number of sources. If the number of sources increases, many data flow in sensor networks and thus generate much congestion. Since such much congestion causes many data collisions, they decrease data delivery ratio. Moreover, due to such data collisions, many retransmissions of data increase energy consumption and delay. Hence, if the number of sources, all model increases energy consumption, decreases data delivery ratio, and increase delay due to mach data congestion. Since both SSSM-LN, SSSM-SN, MSM, and DSM use single data gathering tree of a sink or a agent, they generates much data congestion. On the other hand, since MSSM uses multiple data gathering tree of multiple static sinks, it can distribute data congestion. Accordingly, MSSM has less energy consumption, higher data delivery ratio, and shorter delay than SSSM-LN, SSSM-SN, MSM, and DSM.





1.0

SSSM-LN

SSSM-SN

MSM

DSM

300

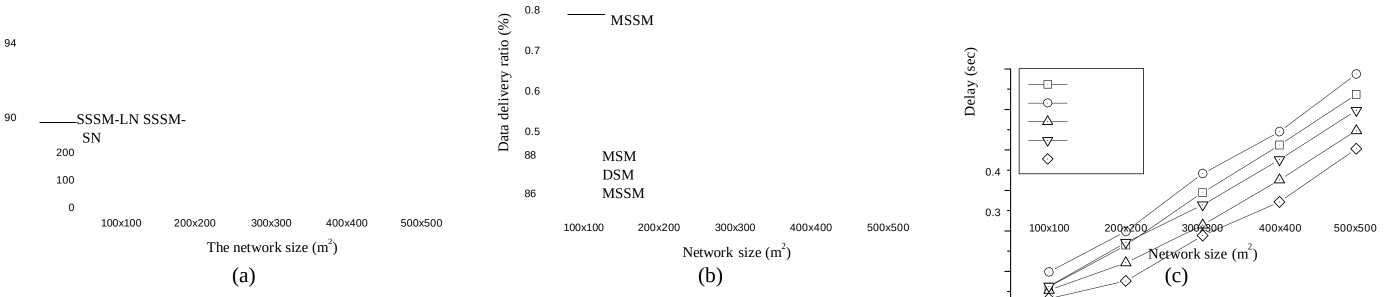


Fig. 6. Simulation results for network size: (a) Energy consumption, (b) Data delivery ratio, and (b) Delay

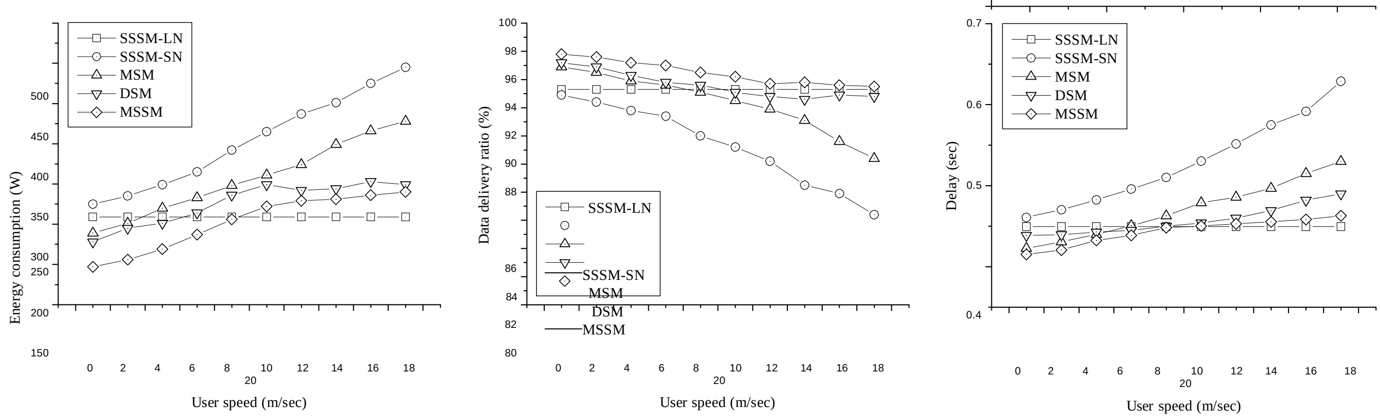


Fig. 7. Simulation results for user speed: (a) Energy consumption, (b) Data delivery ratio, and (b) Delay

allow the width of the data gathering tree to be wide. Hence, MSM and DSM have better performance than SSSM-LN and SSSM-SN. Furthermore, SSSM-SN has worse performance than SSSM-LN because SSSM-SN should deliver data from a single static sink to a mobile user via sensor nodes. MSM has worse performance than DSM because MSM uses many relay nodes from an agent to a mobile user but DSM requests and receives data from a dynamic sink to mobile user.

E. Simulation Results for the Number of Multiple Static Sinks

In this subsection, we examine how the performance of MSSM is affected by the number of multiple static sinks. Figure 9(a) shows the energy consumption for the number of multiple static sinks. As the number of sinks is one, MSSM consumes much energy because it has only one tree which is rooted at single sink, spans all sensor nodes, and thus has long depths (hop counts) from sources to the sink. Moreover, MSSM has many hop counts from the sink to a mobile user due to one tree and hence consumes much energy. If the number of multiple static sink is increases, the sensor network is divided by the sinks such that the hop counts from the sinks to the sensor nodes and the mobile user are reduced. Accordingly, the energy consumption for the data gathering from sensor nodes and the data delivery to the mobile user decreases. However, as the number of sinks is more than six, the energy consumption rather increases in dribs and drabs. Because the sinks are located in the outskirts of sensor network, although the number of sinks increases, MSSM almost never reduces the hop counts from sensor nodes to sinks. Instead of, if the number of sinks increases, the mobile user moves frequently into the domain of new sinks. It increases the energy consumption for performing the interdomain handoffs of the mobile user.

Figure 9(b) shows the data delivery ratio for the number of multiple static sinks. As the number of sinks is one, the data delivery ratio is low value of 91 percent. It is because single sink gathers data from all sources in a sensor network through one tree rooted at it such that many data congestion and collision are generated in the network. In addition, because the data delivery to a mobile user is executed toward inverse path of data gathering, it also aggravates data congestion and collision. As the number of sinks increases, they gather distributedly data of sources through trees of themselves. Accordingly, it reduces data congestion and collision and hence increasing the data delivery ratio. However, as the number of multiple static sinks is more than six, MSSM scarcely increases the decentralization rate of data gathering and hence almost never improves the data delivery ratio. Figure 9(c) shows the delay for the number of multiple static sinks. As the number of sinks is one, the delay of MSSM is high value of o.5 msec. It is because single tree by one sink makes sources have longer depths to the sink and hence increasing hop counts for data gathering. In addition, since many data from sources are delivered from the sources to the sink and from the sink to the mobile user, data congestion raises. As the number of sinks increases, the sensor network is divided by them such that depths from the sources to the sinks are reduced. It reduces hop counts for the data gathering and delivering and hence decreasing the delay in MSSM. However, as the number of multiple static sinks is more than seven, because MSSM has hardly any effect of network distribution by sinks such that hop counts for data gathering and delivering are never almost reduced. On the contrary, since MSSM should perform frequent handoffs of the mobile user into the domains of new sinks, it increases slightly the delay.

V. Conclusion

In this paper, for supporting remote users connecting with legacy networks in the outside of sensor network and mobile users disconnecting with legacy networks in the inside of sensor network, we propose a novel sensor communication model and a novel protocol based on multiple static sinks. In the proposed network model, the multiple static sinks can be located at places with legacy networks in the outskirts of sensor network and communicate directly with each other via the legacy networks. The proposed protocol allows the multiple static sinks to perform the function as gateways for users in other networks via the legacy networks. Through sharing queries and data by the multiple static sinks, the proposed protocol also provides high data delivery ratio through distributed data gathering and low delay through data delivery with short hops. Furthermore, the proposed protocol solves hotspot problems by the multiple static sinks, and hence reduces the energy consumption and prolongs the network lifetime. Simulation results show that the proposed model achieves better performance than the existing model for supporting mobile users in terms of the energy consumption, the data delivery ratio, and the delay.

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