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A new adaptive and flexible communication protocol for long-term operation of ubiquitous sensor networks with multiple sinks and multiple sources

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Abstract: There is growing expectation for a wireless sensor network. A wireless sensor network has great potential as a means of realizing a wide range of applications, such as natural environmental monitoring and environmental control in residential spaces or plants. To facilitate a ubiquitous environment by a wireless sensor network, however, its control mechanism should be adapted to the variety of types of communication, i.e., one-to-one, one-to-many, many-to-one, and many-to-many, depending on application requirements and the context. This paper proposes a new adaptive communication protocol for the long-term operation of such a ubiquitous sensor network. We evaluate the proposed protocol using computer simulation experiments and discuss its development potential.

Keywords: Sensor Networks, Ubiquitous Environments, Adaptive Communication Protocol.

1 INTRODUCTION

Various network services have been provided. They include inter-vehicle communication, which is a network service in intelligent transport systems, environmental monitoring and control, and ad-hoc communication between mobile nodes in such emergent situations as disasters. As a means of realizing the above network services, autonomous decentralized networks, such as a mobile ad-hoc network, a wireless sensor network, and a mesh network, have been intensively researched with great interests. Especially, a wireless sensor network, which is a key network to facilitate ubiquitous information environments, has great potential as a means of realizing a wide range of applications, such as natural environmental monitoring, health monitoring, environmental control in residential spaces or plants, object tracking, and precision agriculture[1-4].

In a general wireless sensor network, hundreds or thousands of static micro sensor nodes, which are compact and inexpensive, are placed in a large scale observation area, and sensing data from each node is gathered to a sink node by inter-node wireless multi-hop communication. Each sensor node consists of a sensing function to measure the status (temperature, humidity, motion, etc.) of an observation point or object around it, a limited function of information processing, and a simplified wireless communication function, and it generally operates on a resource with a limited power supply capacity such as a battery. Therefore, a data gathering scheme capable of meeting the following two requirements is mainly needed to prolong the network lifetime.

(1) Efficiency of data gathering
(2) Balance of communication load among sensor nodes

As data gathering schemes for the long-term operation of a wireless sensor network, clustering-based data gathering[5,6], synchronization-based data gathering[7,8], gradient-based data gathering[9], and bio-inspired data gathering[10,11] are under study, but not all the above requirements are sufficiently satisfied. In a wireless sensor network, the communication load is generally concentrated on sensor nodes around a sink node during the operation process. In cases where sensor nodes are not placed evenly in an observation area, the communication load is concentrated on sensor nodes placed in an area of low node density. The above data gathering schemes[5-11] do not positively ease the communication load concentration to sensor nodes around a sink node, which is the source of problems in the long-term operation of a wireless sensor network. Intensive data transmission to specific nodes, such as sensor nodes around a sink node and sensor nodes placed in an area of low node density, results in concentrated energy consumption by them, and causes them to break away from the network early. This makes long-term observation by a wireless sensor network difficult. To solve this communication load concentration problem, data gathering schemes for a wireless sensor network with multiple sink nodes have been proposed[12,13]. In comparison with the case of a one-sink wireless sensor network, the communication load of sensor nodes around a sink node can be reduced. Especially, the scheme in Utani et al.[13] can actualize autonomous load-balancing data transmission to multiple sink nodes and can sufficiently reduces the load of load-concentrated sensor nodes. This balances the load of nodes autonomously.

To facilitate a ubiquitous environment by a wireless sensor network, however, its control mechanism should be adapted to the variety of types of communication, i.e., one-to-one, one-to-many, many-to-one, and many-to-many, depending on application requirements and the context. This paper proposes a new adaptive communication protocol for the long-term operation of such a ubiquitous sensor network. We evaluate the proposed protocol using computer simulation experiments and discuss its development potential. In simulation experiments performed, the effectiveness of the proposed protocol is investigated in detail. The rest of this paper is organized as follows. In Section 2, the existing representative protocol for adaptive communication in a wireless sensor network is outlined. In Section 3, the proposed protocol is described. In Section 4, the experimental results are reported, and the effectiveness of the proposed protocol is demonstrated by comparing its performances with those of existing protocols. Finally, we give our conclusions and ideas for further study in Section 5.

2 DIRECTED DIFFUSION

Recently, a few adaptive wireless sensor network protocols to facilitate ubiquitous information environments, which are directed diffusion[14] and rendezvous-based communication protocols[15,16] have been proposed. This paper focuses on directed diffusion that is a most representative protocol for adaptive communication in a wireless sensor network and applicable to various requirements from many sensor nodes constructing a network. The purpose of directed diffusion is to establish efficient *n*-way communication between one or more sink nodes and source nodes. Directed diffusion, which is also a data centric communication protocol, consists of the following protocol family,

(1) Two-phase pull diffusion and one-phase pull diffusion

(2) Push diffusion

where the above protocol family in directed diffusion are introduced by considering the types of communication.

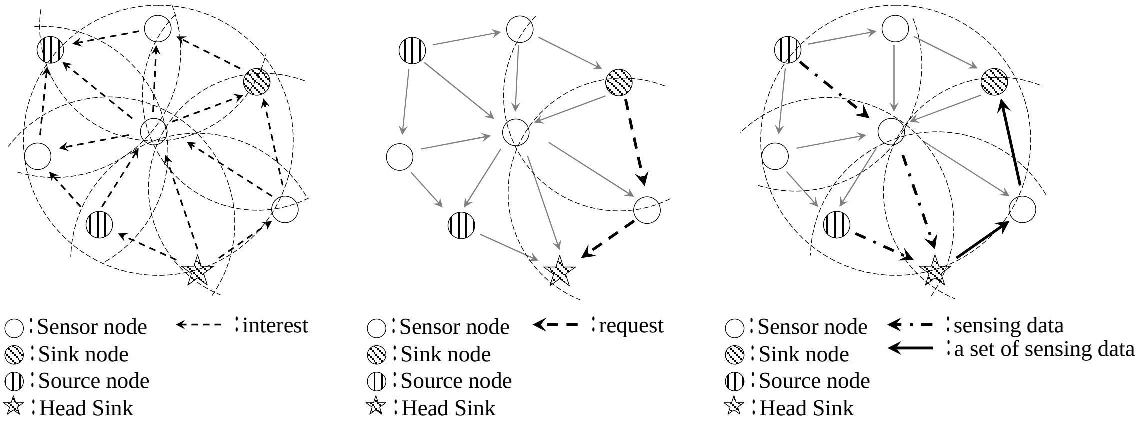
In two-phase pull diffusion and one-phase pull diffusion, each sink node firstly broadcasts a message (a query) which specifies what it wants throughout the network, and afterward it gathers sensing data from each source node capable of meeting its query. In push diffusion, on the other hand each source node firstly broadcasts a message which specifies what it has measure and can provide throughout the network, and afterward it transmits sensing data to each sink node that wants sensor information included in its message. Pull types, which are two-phase pull diffusion and one-phase pull diffusion, adapt themselves to cases where the number of source nodes is more than the number of sink nodes, and push diffusion adapts itself to their contrary cases. In cases where communication between sink nodes and source nodes dynamically changes, therefore, it is difficult to use directed diffusion effectively. Directed diffusion includes the following problems.

1. Since flooding is frequently used for disseminating messages (or queries), each sensor node is loaded with loads of energy consumption.
2. Since the function for autonomously selecting the effective protocol from the above protocol family according to the situations of communication is not arranged, directed diffusion can not always achieve efficient communication in changing communication environments.
3. The communication load of each sensor node is not sufficiently balanced

3 PROPOSED PROTOCOL

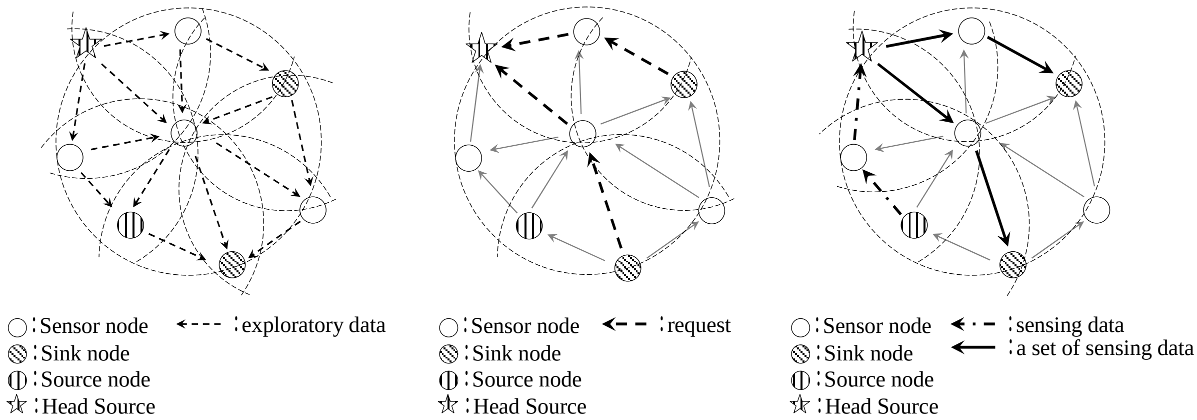
The proposed protocol, which is an adaptive communication protocol for a ubiquitous sensor network, is devised for improving the above-mentioned problems included in directed diffusion. In the proposed protocol, the first node that disseminated a query in sink nodes, called *head sink*, functions for efficient data gathering, and the first node that disseminated a message, the contents of which is outlined in section 2, in source nodes, called *head source*, functions for efficient data providing in the same way. In addition, the mechanism of autonomous load-balancing communication[13] is introduced in the proposed protocol. By realizing efficient and load-balancing communication between sink nodes and source nodes, the proposed protocol can prolong the lifetime of a ubiquitous sensor network.

The proposed protocol is composed of two protocol family: sink-oriented communication protocol and source-oriented communication protocol. In the proposed protocol, each node has a connective value named *value to self*, which is not updated by transmitting and/or receiving messages or sensing data, and this is used for autonomous load-balancing communication between sink nodes and source nodes, where parts on autonomous load-balancing communication in the proposed protocol is outlined in the following subsections. The mechanism is detailed in Utani et al.[13].



1) Interest propagation 2) Request transmission 3) Data delivery

Fig.1. Flow of communication based on sink-oriented communication protocol.



1) Exploratory data propagation 2) Request transmission 3) Data delivery

Fig.2. Flow of communication based on source-oriented communication protocol.

3.1. Sink-Oriented Communication Protocol

The flow of communication based on sink-oriented communication protocol consists of the following steps. In **Fig.1**, the communication flow is illustrated.

1) A sink node broadcasts a message (a query) which includes what it wants named *interest* and its own *value to self* throughout the network with hop counts updated, where this node, which is the first sink node that broadcast a query in sink nodes, becomes the head sink. Each node that repeatedly receives this message stores the connective values computed from *value to self*, "hop counts" and "residual energy" in the matching neighborhood node fields of its own routing table. In each node, the connective values updated by "residual energy" are used as the only index to evaluate the relay destination value of each neighborhood node.
2) Each sink node, which wants to gather the same sensing data (sensor information) as what the head sink wants, transmits a message named *request* to the head sink according to the above connective values which are the only route information. Therefore, the path between the head sink and each sink node is constructed.
3) Each source node, which has measure and can provide sensing data (sensor information) specified in *interest* that is propagated by the head sink, transmits sensing data to the head sink according to the above connective values, and then the head sink transmits a set of data consisting of sensing data gathered from source nodes to each sink node along the constructed path.

3.2 Source-Oriented Communication Protocol

Next, the flow of communication based on source-oriented communication protocol is described. In **Fig.2**, the communication flow is similarly illustrated.

1) A source node broadcasts a message which includes what it has measure and can provide named *exploratory data* and its own *value to self* throughout the network with hop counts updated, where this node, which is the first source node that broadcast a message in source

nodes, becomes the head source. Each node that repeatedly receives this message stores the connective values computed from *value to self*, "hop counts" and "residual energy" in the matching neighborhood node fields of its own routing table. As in the above-mentioned sink-oriented communication protocol, the connective values updated by "residual energy" are used as the only index to evaluate the relay destination value of each neighborhood node in each node.

2) Each sink node, which wants to gather sensing data (sensor information) specified in *exploratory data* that is propagated by the head source, transmits a message named *request* to the head source according to the above connective values which are the only route information. As in step 2) of sink-oriented communication protocol, therefore, the path between the head source and each sink node is constructed.

3) Each source node, which has measure the same sensing data (sensor information) as what the head source can provide, transmits sensing data to the head source according to the above connective values, and then the head source transmits a set of data consisting of its own sensing data and sensing data transmitted from the other source nodes to each sink node along the constructed path.

4 SIMULATION EXPERIMENT

Through simulation experiments on a large scale and dense ubiquitous sensor network, the performance of the proposed protocol, i.e., the adaptability of the proposed protocol in a changing communication environment, is investigated in detail to verify its effectiveness.

4.1. Conditions of Simulation

A ubiquitous sensor network composed of many static sensor nodes with global positioning system placed in a large scale square field was assumed. The conditions of the simulation which were used in the experiments performed are shown in **Table1**, where a thousand static sensor nodes were randomly arranged in the set simulation area as in **Fig.3**. The *value to self* of each node and the connective value attenuation factor accompanying hop[13] for autonomous load-balancing communication were set to 100.0 and 0.5 from a preliminary investigation, respectively. As in Intanagonwiwat et al.[14], messages which include *interest* were modeled as 36-byte packets, and messages which include *exploratory data* as 64-byte packets, where the size of sensing data of each node was set to 10 byte. The battery capacity of each node was modeled as 0.5J, and energy consumption was computed as in Heinzelman et al.[17]. In the following experimental results reported, the proposed protocol is evaluated through a comparison with "one-phase pull diffusion" and "push diffusion" in directed diffusion.

Table1. Conditions of simulation.

Simulation size	2,400[m]×2,400[m]
Operation time	1,000[s]
Number of sensor nodes	1,000
Range of ratio wave	150[m]
Value to self of each node	100.0
Connective value attenuation factor	0.5
Interest message	36-byte packet
Exploratory data message	64-byte packet
Size of sensing data	10[bytes]
Battery capacity of each node	0.5[J]

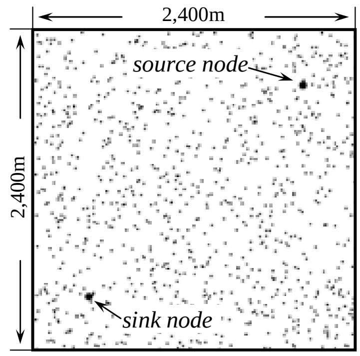
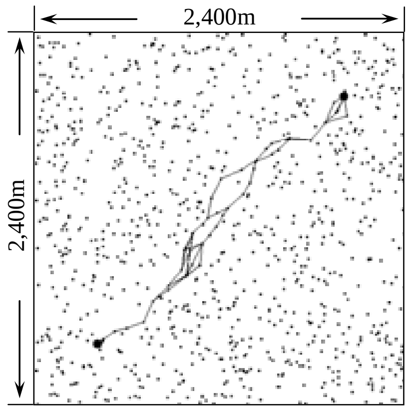


Fig.3. Arrangement of sensor nodes in the set simulation area.

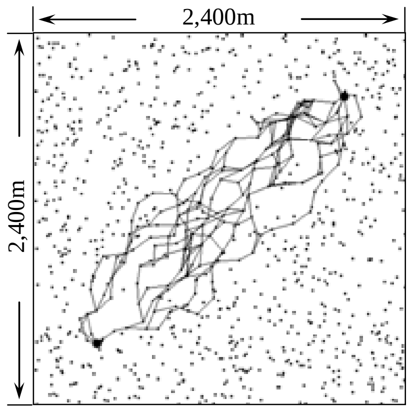
4.2. Experimental Results

In the first experiment, it was assumed that the sink node marked in **Fig.3** transmitted the data packet with sensing data measured to the source node similarly marked in **Fig.3**, where the data packets were periodically transmitted every 10sec and the network operation duration was 1,000sec. The routes used by applying the proposed protocol are shown in **Fig.4**. Of the 100 data packets transmitted from the sink node, the routes used by the first 25 data packets are illustrated in **Fig.4**(1), those used by the 50 data packets are in **Fig.4**(2), and those used by a total of 100 data packets are in **Fig.4**(3). **Fig.4** indicates that the proposed protocol enables the autonomous load-balancing transmission of data packets using multiple routes. By this autonomous load-balancing communication, to prolong the network lifetime can be expected.

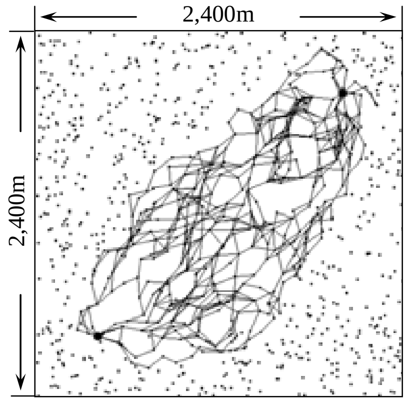
Next, the sustainability of the proposed protocol was evaluated in a changing communication environment. Here, it was assumed as a changing communication environment that sinks to sources was periodically transformed from *one-to-one* to *one-to-ten*, from *one-to-ten* to *ten-to-one*, and from *ten-to-one* to *ten-to-ten* every 250sec, where all sink nodes and all source nodes were randomly selected from a total of 1,000 nodes shown in **Fig.3**. In the same way as in the above experiment, all data packets were periodically transmitted every 10sec and the operation duration was 1,000sec. In **Figs.5** and **6**, the transition of total energy consumption of all nodes arranged in the set simulation area is shown, and total energy consumption in applying the proposed protocol is compared with it in directed diffusion. From **Figs.5** and **6**, it can be confirmed that the proposed protocol always realizes efficient communication between one or more sink nodes and source nodes accompanying the variety of types of communication. In **Figs.7** and **8**, the transition of the average data delivery ratio of fifty trials is shown, and the network lifetime in a changing communication environment is compared. From **Figs.7** and **8**, it can be confirmed that the proposed protocol achieves a longer-term operation of a ubiquitous sensor network than directed diffusion because it improves and balances the load of each node by the communication load reduction for network control and data gathering, and the load-balancing communication. Through simulation experiments, it was verified that the proposed protocol is substantially advantageous for the long-term operation of an ubiquitous sensor network.



(1) 1 to 25 data packets.



(2) 1 to 50 data packets.



(3) 1 to 100 data packets.

Fig.4. Routes used by applying the proposed protocol.

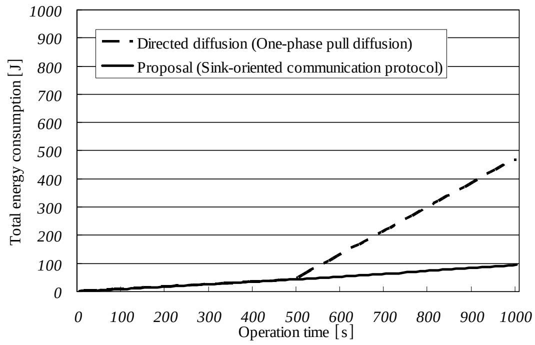


Fig.5. Transition of total energy consumption (Sink-oriented protocol).

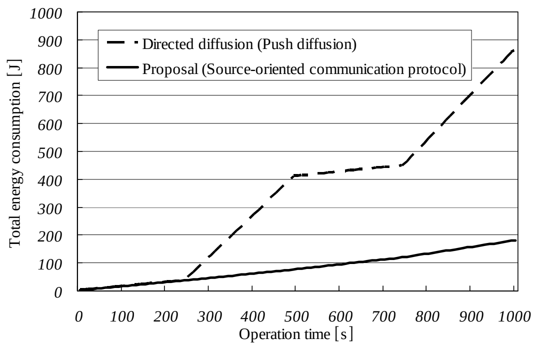


Fig.6. Transition of total energy consumption (Source-oriented protocol).

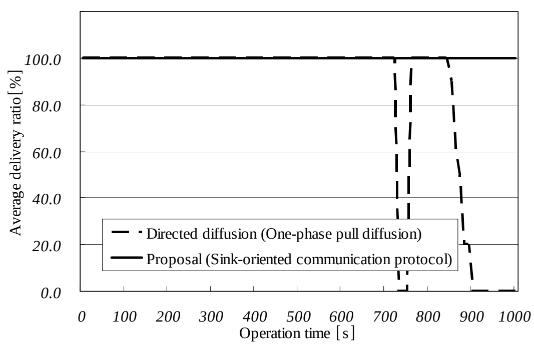


Fig.7. Transition of average data delivery ratio (Sink-oriented protocol).

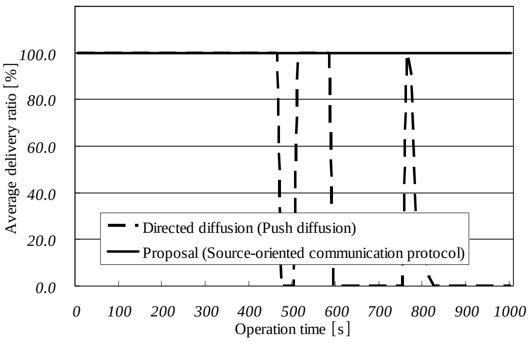


Fig.8. Transition of average data delivery ratio (Source-oriented protocol).

5. CONCLUSIONS

In this paper, a new adaptive communication protocol for a wireless sensor network, which adapts itself to the variety of types of communication, has been proposed. The proposed protocol can improve several problems in directed diffusion, which is the existing representative protocol for adaptive communication in a wireless sensor network. In simulation experiments performed, the performances of the proposed protocol were compared with those of directed diffusion. The experimental results indicate that the proposed protocol is superior to directed diffusion from the viewpoint of the long-term operation of a ubiquitous wireless sensor network, and has the development potential as a promising one. Future work includes a detailed evaluation of the adaptability of the proposed protocol in dramatically changing communication environments.

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