A Semantic-based architecture for sensor networks

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Abstract

With rapid development of sensor networks technology, it becomes feasible to deploy multiple sensor networks in relevant area to collect interested information. Sensor nodes that are co-located but belong to different sensor networks may not be able to collaborate properly to gain the capacity or performance. In this paper we propose a semantic-based sensor networks architecture that enables inter-networking of sensor networks. In this Semantic Sensor Net (SSN), a semantic tag is attached to the sensory data so that the sensor networks are able to exchange information and work collaboratively. The process of semantic creation and maintenance is described. We also introduce the concept of InterSensorNet. This infrastructure enables efficient information exchange and information extraction among multiple sensor networks.

Key words: semantics, wireless sensor networks, InterSensorNet.

TITRE FRANÇAIS

Résumé

Mots clés :

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Contents

I. *Introduction*
II. *Related works*
III. *Why we need semantic sensor networks*
IV. *Semantics in sensor networks*
V. *Semantic-based query processing*
VI. *Conclusion and future work*
References (28 ref.)

I. INTRODUCTION

Over the last few years, wireless sensor networks have attracted a great deal of research attention due to their wide-range of potential applications. Sensor networks introduced a new class of computer systems and expand the ability of individuals to remotely interact with the physical world. We can envision that in the near future sensor networks composed of hundreds or thousands of sensors will be used for numerous applications including battlefield surveillance, detection of biological attack, home appliances, precision agriculture, smart spaces, and targets tracking. Sensor networks will transform the way we manage our homes, factories, and environment.

The sensor network is a data-centric network. Data management is one of the most important components in sensor networks. A variety of data such as light, humidity, audio and magnetic sensory data can be collected by sensor networks. When the scale of sensor networks becomes larger the amount of sensory data increases quickly. The raw data gathered by the sensor nodes are sent back to the base station after in-network processing. Data aggregation methods which focus on energy efficiency and data integrity have been studied [1, 2]. The network topology controls [3], routing protocols [4], clustering and leader election algorithms have been proposed. However, existing researches suffer some critical drawbacks which have significantly restricted the wide deployment of sensor networks.

Most proposed architectures or protocols only consider simple homogeneous sensor networks. Moreover, each solution is usually for a specific application and is usually an engineering approach without a common framework. These solutions have shortcomings when a large-scale sensor network or a heterogeneous sensor network is deployed which is more common in real application systems. Sometimes useful information is lost while redundant data is collected and send back to the base station. Then the base station must do extra work to correct and classify the sensory data and extract the useful information from large amount of data. If these sensor networks collaborate with each other when processing the sensory data, the network capacity and capability could be increased. However, we have lack of standards that allow collaboration among different sensors networks.

A self-description of the sensor is stored in each sensor, including the sensor type, the current location and current time, the remaining power, etc. When raw sensory data are created, semantics of the data can be produced based on these descriptions. The semantics are crucial for sensory data. Without theses semantics, the sensory data cannot be processed and interpreted properly. In the current form of most sensor networks, some of the semantics are explicit such as the location where the data have been sensed and the time when the data captured; some of them are implicit such as the unit of data. For the same information, the expression can be different. Sometimes the same information is encapsulated by different data formats. For example, the measurement of temperature can be in Fahrenheit or Celsius. When two temperature sensor networks are deployed and the sensory data measurement designed differently, the same temperature is expressed differently. To interpret these data, the semantics of the data are necessary. Furthermore, for the purpose of energy efficiency, these data may be processed in network before they are sent back to the base station. Semantics of the data can enable the coordination of in-network processing.

To enable the coordination among multiple sensor networks, standards and semantics are necessary. This paper focuses on the semantics of the sensor network. Note that the semantics are also an important part of the sensor network standard. Our research provides a semantic-based architecture of sensor networks. In this architecture, there are low-level semantics in raw sensory data which are the mapping of the physical world. Semantics will be attached to the data to make the sensory data be understood more easily. It enables information exchange between sensors in multiple sensor networks. On the other hand, queries may have complex, high-level semantics. High-level semantics are created by the demand of applications. The high-level semantics should be matched with the low-level semantics of the sensory data to extract useful information. In the process of matching, aggregated data are generated and semantics are attached to the aggregated data. The advantage of semantic-based architecture is that it can solve the problems in more complex situations. It makes the exchange of sensory data in multiple sensor networks possible. In this cross-layer architecture, semantic routing protocols are more robust and efficient. Semantics will simplify data processing and interpretation, and make the solution of some critical problems possible. We will define these semantics and give the description of them in this paper.

This paper is organized as follows: Section II discusses related works. Section III considers multiple sensor networks and introduces the concept of InterSensorNet. Section IV describes the semantic-based architecture and a pollution monitoring example illustrates the process of semantics generation. Semantic query processing is presented in Section V. Section VI concludes the paper.

II. RELATED WORKS

The sensor node contains sensors and processing devices. With the rapid advancement in wireless communications and microelectromechanical systems (MEMS), many research institutes and companies have produced tiny sensor nodes such as the Mica Motes serial developed by UC Berkeley [5, 6]. Motes are powered by the TinyOS operating system [7, 8] that is specifically tailored to this type of devices. The design of TinyOS is based on the specific sensor network characteristics. TinyOS follows an event model approach instead of a stack-based threaded approach. Many tools such as NS2 [9], TOSSIM [10] are used to simulate sensor networks.

The sensor network is data-centric. The data collection [11, 12] and storages strategy [13], power efficient data dissemination algorithm [14] and data aggregation methods [15] have been popularly researched. Data aggregation combines data from different sources by using functions such as suppression, minimization, maximum and average [15]. Some of these functions can be performed either partially or fully in each sensor node, by allowing sensor nodes to conduct in-network data reduction [16, 17, 18]. The wireless communication protocol includes blue tooth, IEEE 802.11 and IEEE 802.15.4. And now ZigBee [19] is recommended to be used in sensor networks because it can transport high rate data for longer distance by lower power. When a sensor network is first activated, various tasks must be performed to establish the necessary infrastructure that will allow useful collaborative work to be performed. Topology control [20], clustering [21], time synchronization [22] and localization [23] are the main issues.

There are many application systems now. System for European Water Monitoring has been researched in the past three years [24]. It is Application-oriented system for monitoring water quality with sensor networks. The main goal of SEWING project is to create a relatively cheap and generally accessible system for monitoring and early warning of water pollution. On Great Duck Island [25], biologists put sensor devices in the underground nests of the storm petrel to monitor their habit. The sensor networks are also used in battlefield detect systems.

III. WHY WE NEED SEMANTIC SENSOR NETWORKS

Sensor networks are expected to find widespread use in a variety of applications including environmental monitoring, security, battlefield sensing, and intelligence data-gathering. In the near future, more and more sensor networks will be deployed for different services in a surrounding area, resulting in a heterogeneous sensor system consisting of multiple sensor networks.

III.1. Multiple sensor networks

New issues will arise due to deployment of multiple sensor networks. Multiple sensor networks may overlap or partially overlap in the same area with different sensing tasks. Imagine this phenomenon in a battlefield. Air Force, Army and Marine deploy their own sensor networks. Each of them may also deploy different networks for various sensing purposes such as moving targets, radiation, temperature, light, or pressure. Thus, tens of sensor networks, each of different sensor types, on the battlefield may interfere with each other, decreasing the signal-to-noise ratio (SNR).

It is possible to change the drawback into an advantage with interoperability of sensor networks. With collaboration of multiple sensor networks, connectivity and robustness can be improved and energy dissipation reduced. Possible interference can be reduced too. We use an example of connectivity to illustrate this point. The sensors can be placed to a predefined location or randomly distributed randomly. Although our scheme can be applied to both cases, we only consider the situation that sensors are randomly deployed. When a sensor is deployed to some location, it is possible that the sensor cannot attach to the wireless network at all because it cannot find a neighbor. The percentage of sensors that do not get connected involve with sensor node density, transmit power, and terrain type. Here we call a node in a local sensor net the *local node* and a node in a foreign sensor net the *foreign node*. When a sensor node cannot find a neighbor in its local network, it may find a neighbor in a foreign network. The connection percentage can be significantly improved by routing data through foreign nodes. Furthermore, even if a sensor node can find a neighbor in its local network, these two nodes may be far apart and communication power required can be very high. In this situation, a foreign node can help to reduce the power dissipation. As shown in Figure 1, where there are two sensor networks, one is temperature sensor net and the other is humidity sensor net. Without collaboration of the two sensor nets, each homogeneous sensor net builds its query topology tree. In this way, more power will be consumed. With collaboration, these sensor networks may share the routing function so one sensor net can transmit sensory data for the other sensor net. For example, node *H* needs 4 hops to connect to the base station in its local net but just 3 hops with the help of node *f*. Also can be seen in the figure, node I is unable to connect to the base station in its local net because it is out of the transmission range of any other node of the temperature sensor net. However, it can send data back with the help of node *a*. In this figure, the solid line illustrates the initial query topology of the sensor networks. The broken line illustrates the new topology.

III.2. InterSensorNet

In this section, we introduce the concept of InterSensorNet. *An InterSensorNet is a heterogeneous sensor system consisting of multiple sensor networks that are able to collaborate*

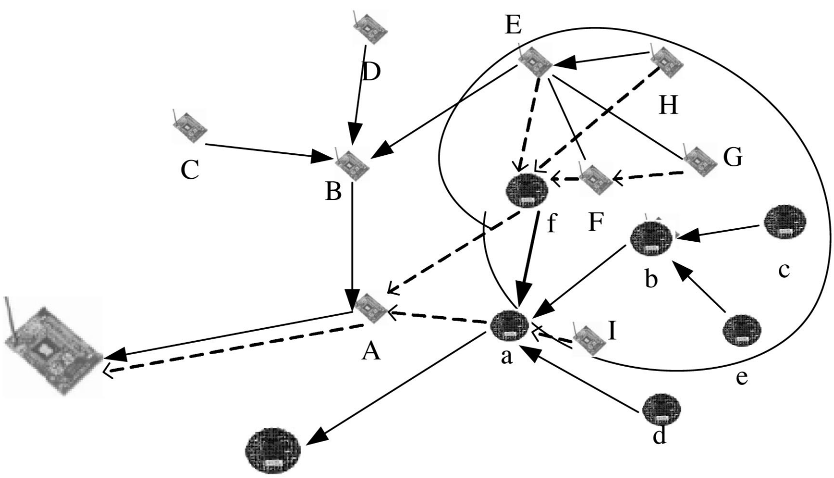

FIG. 1 – Heterogeneous sensor network query tree.

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with each other. In an InterSensorNet, sensor networks relay data, process data, and perform many other tasks for each other.

Different sensor networks may overlap or partially overlap with each other, and may interfere with each other. However, it also provides an opportunity to make a low energy, high connectivity, reduced interference, and more robust sensor network. An InterSensorNet scheme is a federation of multiple sensor networks where a unified protocol allows sensor networks collaborate together.

We advocate that an InterSensorNet scheme can model the situation of multiple sensor networks and bring many new research issues. Some of these are listed below:

- **Localization and location service.** A local node can determine its location more accurately with the help of foreign nodes. It can also obtain the location service from foreign networks.
- **Synchronization.** Synchronization could be more accurate with the help from foreign networks, and sometimes a node cannot get synchronization without the help of foreign networks as a foreign anchor node is close by.
- **Topology control.** Topology control can be more efficient with cooperation of sensor nets. As shown in previous example, when a node cannot find a neighbor in its local network, it may find a neighbor in a foreign network. Two nodes may be far apart and a higher communication power is required and foreign nodes can help to reduce the power dissipation.
- **In-network processing.** A foreign node can help the in-network processing because it is in a better location or has necessary information to process the data. Some foreign nodes may have a higher capacity to process data.

To promote methodology of the InterSensorNet, two major components are necessary: an internetworking protocol and a mechanism for incentives. The internetworking protocol enables communication between different sensor networks and the mechanism for incentives encourages cooperation. The success of InterSensorNet depends on whether a node is willing to perform necessary tasks for other sensor networks, however, we will not study the mechanism for incentives in this paper. Instead, we will mainly consider the semantics in protocols and standards. The collaborative sensor networks must follow some standard so they can exchange information with each other. Current standards of the MAC layer and network layer include IEEE 802.15.4 and ZigBee [19]. More standards are needed to enable collaboration of sensor networks. As we will discuss later, standard of semantics will be crucial for heterogeneous sensor systems. Without properly defined semantics, interoperability of multiple sensor networks is impossible.

The multiple sensor networks might be overlapped or non-overlapped. The utilization of semantics for interoperability of overlapped sensor networks has been described above. Even if the sensor networks are not overlapped, semantics are necessary to enable the sensory information extraction and processing. Sensory data from different sensor networks may have variant semantics. These semantics might be implicit in the current form of sensor networks so it is difficult to process them. Unifying the semantics expression of the sensory data will make the information extraction from multiple sensor networks possible.

IV. SEMANTICS IN SENSOR NETWORKS

In the past, researches in sensor networks focus on the methods to construct the sensor networks, which include routing, clustering, localization, and synchronization. Most of the approaches emphasize on the basic functions such as the energy saving problem. Not much attention has been paid to the semantics of the sensor networks. When talking about the semantics, people mostly consider the semantics in the queries. The semantics of a query to a sensor network states what information a user is willing to know. However, the semantics in queries themselves do not answer the question of how to map the physical world to the virtual world. This semantics must be matched to the semantics of the sensory data so requested information can be delivered to the user. Since people did not consider the semantics as an important issue in the sensor network research, the existing semantics in sensor networks are either incomplete or implicit. In fact, some semantics exist in the current sensor networks, such as the location of the sensor, the time when the data are captured, and sometimes the type of the sensory data. These semantics are fragmented and far from complete. Some semantics are implicit, such as the unit of the sensory data or the accuracy of the data. These incomplete or implicit semantics lead to the difficulty of processing and interpreting the sensory data, especially in heterogeneous sensor systems.

In this section we will provide a formal definition of the semantic sensor net and describe how the semantics are represented, created, and maintained.

IV.1. The Semantic Sensor Net

A Semantic Sensor Net (SSN) is a heterogeneous sensor network that enables dynamic tagging of semantic information to sensory data and creates semantics in the process of aggregation and abstraction of sensory data to allow more efficient and systematic monitoring and handling of the environmental dynamics to provide demanded services. SSN has the following advantages:

- The tagging of semantic information to sensory data and aggregated data allows efficient handling of large-scale distributed heterogeneous sensory data.
- SSN can provide a sound theoretical foundation to research in sensor networks at different levels.
- SSN can help to develop a semantic-based framework to systematically solve various applications.

IV.2. Semantics in sensor networks

The semantics of sensory data are created when the data are captured from the environment. It is difficult to exchange, process or interpret the sensory data without explicit semantics. Each sensor generates some kind of sensory data. To make the data meaningful, we need to attach the semantics to it. This is done by attach a *semantic tag* to the sensory data. The semantic tag of sensory data is the necessary description about data generation environment where the sensory data was generated and the description of the sensory data itself. The semantic tag should include:

1. **Meta data**. These are the necessary description about the sensory data itself. Take the sensory data produced by a temperature sensor for example. The meta data may include the type of measurement which is temperature, the unit of measurement which can be Fahrenheit or Celsius, and the accuracy of the measurement. Meta data usually depends on the capability of sensing devices. Different sensing devices may have different kinds of meta data.
2. **Context information**. These are about the context information in which the sensory data was generated, which are usually related to the sensor node which the sensing device is attached to. Take the above example. The context information should include the location of sensor node (i.e., where the temperature measurement was made), the ID of sensor node (i.e., which node took the measurement), and the timestamp (i.e., when it was captured).

IV.3. Semantic description

The semantic tag is defined by *Semantic Sensory Data Language (SSDL)*. The semantic description is in the XML style. Two simple examples are given below to illustrate the semantic description. The following description shows the semantic tag for temperature data., the measurement unit is Celsius:

<sensor type> temperature </sensor type>
<measurement unit>Celsius</ measurement unit>
<data>19</data>
………

In the next description, the measurement unit is Fahrenheit:

<sensor type> temperature </sensor type>
< measurement unit>Fahrenheit</ measurement unit>
<data> 66.2</data>
………

Though the data values are different, the temperature detected by these two sensor networks is the same. The data has the same semantic information.

Generating and processing the semantic tags requires extra processing time and more storage space. The overhead can be large and some methods need to be researched to minimize it. We may embed the semantic tag into hardware. Moreover, attaching only selected semantic tags to the sensory data can reduce the overhead. For example, if the semantics are used only in the base station of each sensor net, the semantic tags can be used per net instead of per node.

IV.4. Data model

There are two types of semantics in the sensor networks, the semantics in the query and the semantics for sensory data. The query semantics are provided by applications. We will discuss this later. Here we present the semantic tags for raw sensory data and the aggregated data that are generated from the raw data.

The data model in sensor networks is the model that describes how data are represented. When the scale of sensor networks becomes larger, there will be more data types in sensor networks. We need to provide a scalable method to represent different sensory data in a consistent and flexible framework. The data format is shown in Figure 2, where the sensory data are self-described. The data contain two parts: the sensory data and the semantic tag.

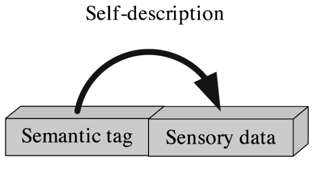

FIG. 2 – Semantic data model.

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The semantic tags in sensory data and aggregated data can be different as shown in Figure 3. The semantic tags for the raw sensory data represent the physical characteristics of sensor nodes such as time, position, and various data types. The semantic tags for the data aggregated from the raw data also depend on the applications since they are created when query's semantics are processed. The tags may include velocity, boundary, amount of raw data, and the maximum, minimum, average values of certain types of raw data, and so on.

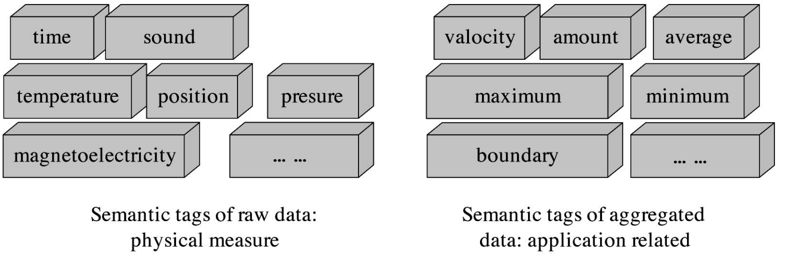

FIG. 3 – Various semantic tags.

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IV.5. A pollution monitoring system

Figure 4 illustrates the semantics generation process in a pollution monitoring system. Two sensor networks are deployed in the monitoring area. One of them detects the degree of pollution, and the other one detects the degree of acidity. Semantic tags are dynamically generated and attached to the sensory data. They coordinate each other. Location and time semantics are exchanged between them. New semantics are generated based on raw sensory data. Average pollution degree of the area can be calculated from pollution degrees. A boundary calculation algorithm is applied to determine the boundary of the pollution area with pollution degree, location of sensors and sensing time. The scope of pollution can be obtained from the boundary. The diffusion rate of pollution can be calculated from boundary and time information. An even higher-level abstraction can be produced as a survey of pollution and the impact of pollution combined with the acidity information. When a new query wants to acquire the content information such as the pollution boundary, diffusion rate, or survey of pollution, it can be answered quickly with the help of these abstracted semantics.

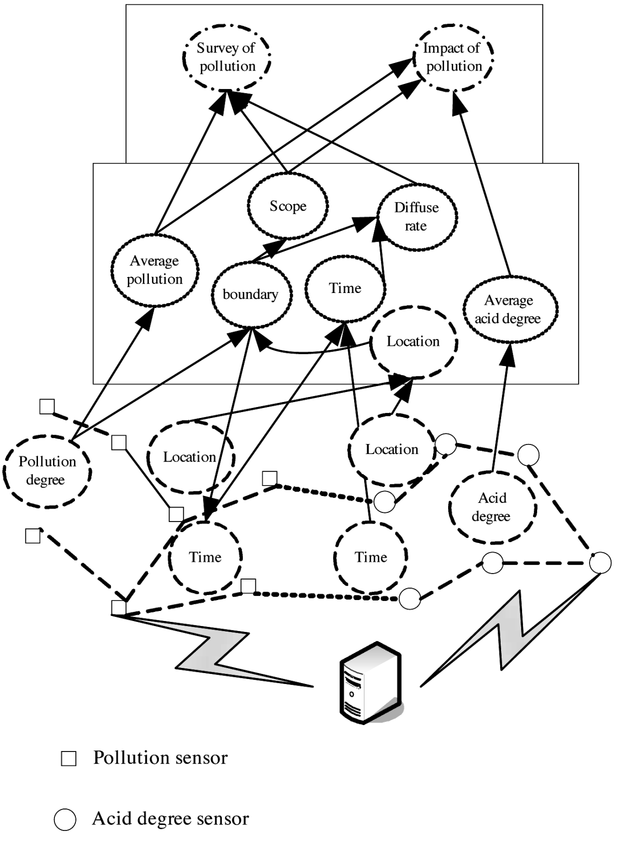

FIG. 4 – Semantic sensor network in pollution monitoring system.

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IV.6. Semantics maintenance

Sensory data and their semantics can be stored in local at the sensor node or stored in external storage. Yet another approach is the data-centric storage. Here, the data are stored by name (i.e., at a storage node that needs not be the same as the node where the data are captured).

The maintenance of semantics is to maintain a consistent semantics in multiple sensor networks. The semantics should be maintained to be consistent and easy to understand. The semantic tags must be easy to search with a semantic catalog. Due to the limitation of storage space in sensor nodes, a mechanism needs to be designed to determine at real time which semantics are retained and which ones discarded, as well as where to store these semantics.

IV.7. The semantics in protocols and architecture

The semantics in sensor networks make the collaboration of multiple sensor networks possible. The data can be exchanged and processed across individual sensor network boundaries. It greatly influences the sensor network protocols, data processing and architecture.

One of the goals of sensor network routing protocol is to reduce power consumption. Many routing protocols for wireless sensor networks are based on homogeneous sensor networks. Some routing protocols are energy-aware protocols [26] and some are geographic routing protocols [27]. In a heterogeneous sensor system consisting of multiple sensor networks, a sensor network normally routes its own data by the same type of sensor nodes. In semantic sensor networks, the sensor nodes can exchange their routing information and relay the data for other sensor networks.

Semantics enable more sophisticated routing protocols in the InterSensorNet. Semantic routing is not a specific routing algorithm. Instead, it is rather a framework, which combines the existing protocols over large-scale heterogeneous sensor systems. In semantic routing, an algorithm could be chosen based on semantic information such as the location or type of data. Real-time data such as audio signals are different from the discrete data and a real-time routing algorithm might be applied. Different routing algorithms such as that based on global ID or based on locations can be used in different situations. Based on semantic information, sensor nodes are able to determine if an in-network processing is necessary. For example, to track a target, a few sensor nodes in the target area can process their data to track the target mode accurately. In addition, semantics enable the collaboration among multiple sensor networks. The routing can become more efficient as we consider all of the sensor networks as a heterogeneous sensor system. The collaboration can provide more efficient data dissemination, longer network lifetime and more flexible application environment.

V. SEMANTIC-BASED QUERY PROCESSING

The query processing can be divided into two major parts, on the server and on the sensor nodes. On the server, the query request submitted by the user is processed and forwarded to the sensor field. The query is normally parsed into multiple lower-level queries. The server also performs the query optimization. On the sensor nodes, when a query reaches the interesting area the sensors response to the query and sense the field to capture the information according to the query condition. On the way routing back to the base station, the sensory data may be aggregated by in-network processing [28].

The semantic-based query processing is shown in Figure 5. Using the Query Service interface, the users submit their queries written in the *SSN Query Language (SSNQL)*. The SSNQL must have a sufficient expressive power and easy to parse. Then the query is parsed into an executable query program with the *SSN Execution Language (SSNEL)*. The executable program is a sequence of basic queries that is defined by the underlying sensor networks. Conditional structures are also included in SSNEL. Each statement in the program is able to be executed by one or more sensor networks in the InterSensorNet. Query route and the way to route the result back are constructed in this process too. To be able to parse the SSN queries, a description of the SSN is required. An *SSN Description Language (SSNDL)* is used to describe the underlying sensor networks. An SSN description is the description of each sensor network including the number of sensors, sensor types, deployed area, health of the sensor nodes, remaining power, and other parameters. Obviously, a same query could be parsed into diffe-

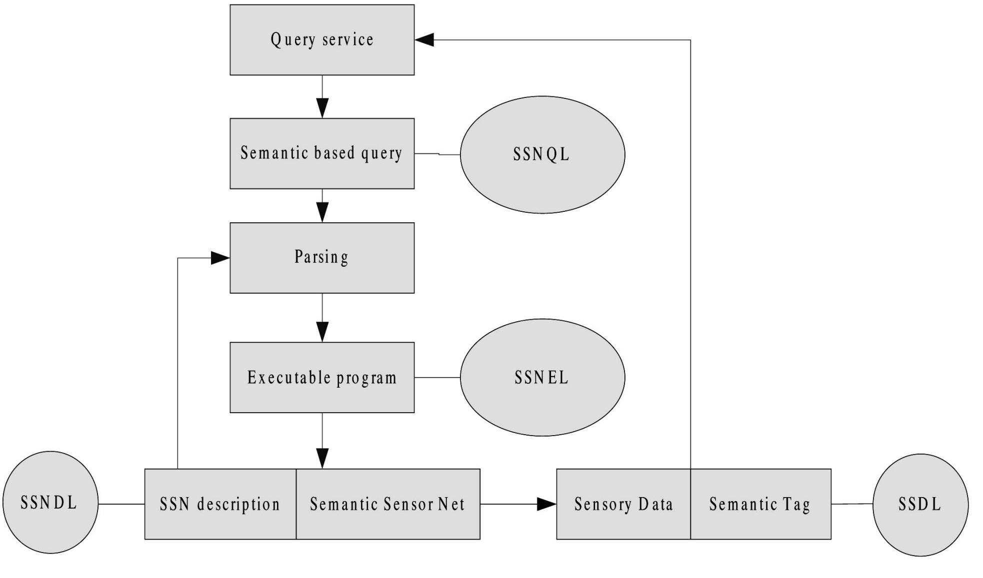

FIG. 5 – Semantic-based query processing.

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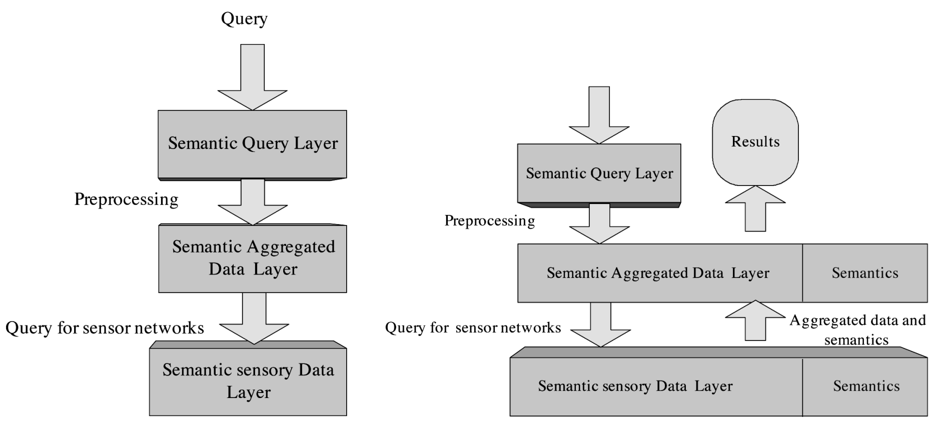
rent executable programs depending on the sensor network description. Different from computer programs, it is possible that a query cannot be parsed due to limited sensor network capability and an error will be returned to the user. The InterSensorNet executes the program, captures the data from the field, and delivers the result back to the user. As mentioned before, semantic tags are attached to the sensory data for further processing. Aggregated data will be attached semantic tags too.

The typical semantic-base query workflow is illustrated in Figure 6. A query is preprocessed into multiple sub-queries in the semantic query layer. The sub-queries are then matched with the data in the semantic aggregated data layer. Unmatched sub-queries are then sent to the semantic sensory data layer for processing. When the queries are executed in the sensory data layer, the raw data are captured and semantic tags are created and attached to the sensory data. As stated before, the semantics in this layer represent the physical characteristics of sensor networks. The raw data are then aggregated through in-network processing. This aggregation process depends on the semantics in the queries. Thus, the semantics created during the aggregation process not only depend on the physical characteristics of the sensor nodes but also the semantics in the queries. These aggregated semantic tags are attached to the aggregated data. The raw data and aggregated data along with their semantic tags are stored in various locations in the InterSensorNet, as well as in the base station. Where and how much the data can be stored depend on the storage capacity and the usefulness of the data under the help of the semantic tags.

When a query sent to the aggregated data layer, it tries to match as much as possible the existing information data. Sometimes the information data only satisfy a query partially. Then a sub-query is generated to acquire information from the lower layer. As an example, a query for the average temperature in the past 24 hours may only match the data of 23 hours. A query for the recent 1-hour temperature is sent to the lower layer and the returned data will



Query processing

Data and semantic

tag creation

FIG. 6 – Workflow of semantic-based query processing.

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be aggregated with the existing data to satisfy the original query. In this way, network traffic as well as energy consumption will be reduced.

Figure 7 illustrates the process of semantics generation. Two sensor networks are deployed in the same area. By the semantic routing protocol, these two sensor networks coordinate as an InterSensorNet. When the query is flooding from the base station, the query routing tree is constructed by two types of sensor nodes. The captured data are aggregated along the way back to the base station. The semantic tags are generated for the sensory data as well as the aggregated data. For example, when temperature data from four sensor nodes are aggregated, a semantic tag of "average temperature, four nodes" will be generated and attached to the average temperature data along with other tags from the original data. More and more semantic tags are generated in the system. Finally, the result is produced.

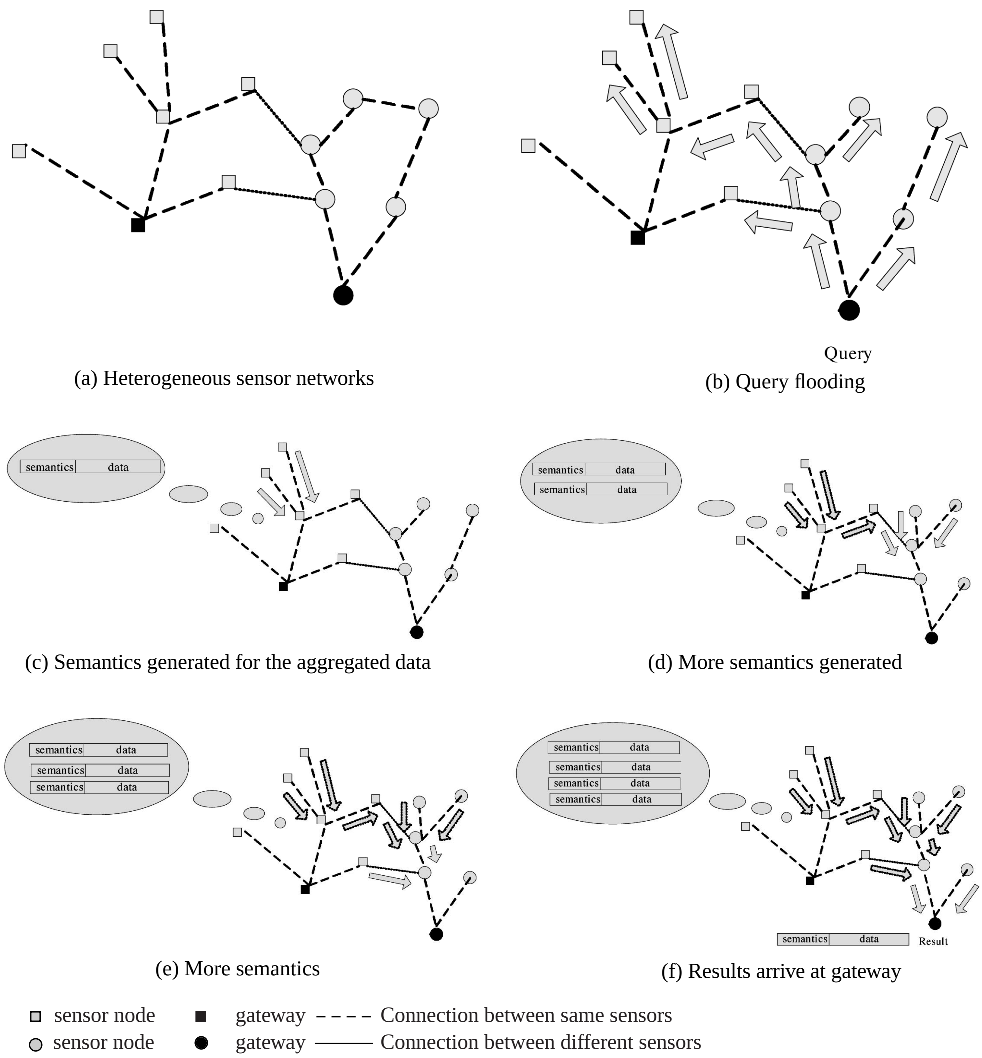

FIG. 7 – Semantics generation

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VI. CONCLUSION AND FUTURE WORK

In this paper, we described a semantic sensor networks architecture. Deployment of multiple sensor networks results in large-scale heterogeneous sensor systems. The collaboration makes the sensor networks more robust and power efficient. Semantics are one of the most important components that enable the inter-sensor networking. The semantics are created initially when raw sensory data are generated. The aggregated semantics are formed when generating the aggregated data. The query process can be more flexible with the help of the semantics in sensor networks. Under the semantic sensor network framework, new semantic based routing protocols and new semantic based data management become more efficient. Currently efforts are being directed to implement the concepts in a sensor network testbed. The semantic sensor net provides a new research direction of sensor networks.

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