Collaboration Projects

R&D Toward a Connecting Service Between Mobile Terminals and Sensor Networks

With the aim of achieving a connecting service between mobile terminals and sensor networks, we developed sensor-network middleware and performed a demonstration experiment with a prototype system. This research was conducted jointly with Hewlett-Packard Laboratories.

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1. Introduction

Today, embedded sensors are commonplace in devices and equipment installed in homes, offices, hospitals, and elsewhere. They are used in a wide variety of fields including temperature sensors in air conditioners and refrigerators, infrared sensors for automatic doors, FeliCa®[*1] readers for automatic ticket gates, and security cameras. A sensor is a device equipped with functions for detecting and evaluating information in the surrounding environment and for converting that information to electrical signals. Its task may be to simply measure a physical quantity like temperature, pressure, magnetism, or acceleration, or to obtain ID information through Radio Frequency IDentification (RFID)[*2], obtain images by a camera, or obtain location information through Global Positioning System (GPS)[*3].

Recent advances in microprocessors and wireless communication technology have also made possible sensor networks in which sensors equipped with wireless communication functions communicate with each other. A sensor network can be used to perform integrated control of many sensors, and applications making use of this capability are increasing. For example, systems are being developed to interconnect human sensors, vibration sensors, smoke sensors, cameras, and other sensors installed throughout a house for the purpose of crime prevention, fire detection, and even supervision of elderly family members. There are also systems under development that plan to install RFID readers in retail stores, on distribution routes, and in trucks to perform such tasks as inventory management and baggage tracking. In the near future, we can expect such systems to evolve into a true "ubiquitous computing environment" in which many embedded computers and sensors communicate with each other.

In the research described here, we investigated technology for achieving an application whereby mobile terminals connected to a mobile network system can control nearby sensor networks and make sensor nodes connected to different network systems connect and interface with each other. We also designed and implemented sensor network middleware to provide an execution environment for that application. Finally, to test the proposed system, we conducted a demonstration experiment with a prototype system consisting of DoCoMo FOMA M1000 mobile terminals, Linux-based terminals[*4], and microsensor devices.

2. Sensor Network System Technology

Technology for sensor network systems can be broadly clas-

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*1 FeliCa®: A contactless smart card system developed by Sony; a registered trademark of Sony Corporation.

*2 RFID: A mechanism for wirelessly obtaining ID information embedded in small IC chips to identify and manage people and things.

*3 GPS: A system for measuring location in terms of latitude, longitude, and altitude with high accuracy using information transmitted from orbiting satellites.

*4 Linux-based terminal: An application-specific device such as a PDA or digital appliance equipped with a CPU and software operating under Linux OS (see *19).

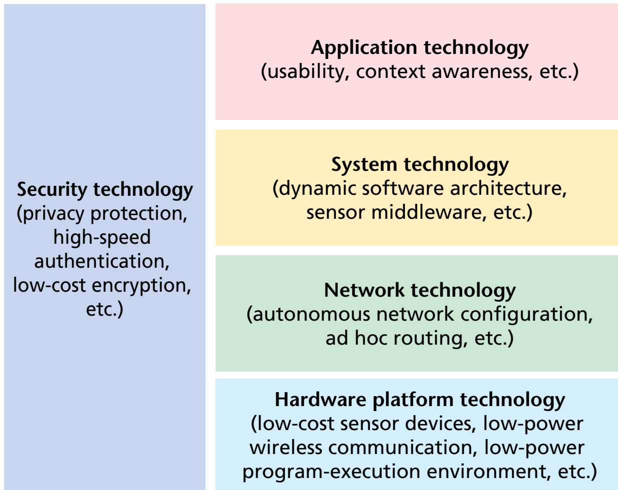


Figure 1 Technology areas for sensor network systems

sified into the areas shown in **Figure 1**.

- Hardware Platform Technology

  This includes device technology optimized for sensors as well as operating systems and wireless communication technology. For sensors and operating systems, R&D themes include SmartDust®[*5] [1], a system for collecting sensing data by multihop communication[*6] between several-millimeter-square modules each equipped with a microsensor and communication functions, and MOTE®[*7], a general-purpose sensor device operating TinyOS[*8]. For wireless communication technology, R&D is active in wireless LAN and Bluetooth®[*9] and in ZigBee®[*10] and Ultra Wide Band (UWB)[*11].

- Network Technology

  Ad hoc networks[*12] are being extensively researched and developed to perform autonomous distributed routing control for multihop communication between sensor nodes [2]-[4].

- System Technology

  Middleware[*13] is also being extensively researched and developed as a platform technology for developing sensor network applications. A typical example is TinyDB[*8] [5], which treats multiple sensors as a single virtual database and provides a mechanism for performing integrated control of those sensors using a query language[*14] derived from Structured Query Language (SQL)[*15]. Another example is SensorWare[*16] [6] that enables an entire sensor network to be controlled by having sensor nodes send scripts[*17] that describe sensor operating conditions to neighboring nodes.

- Application Technology

  To process and actually use the information obtained from a sensor network, R&D in this area is focusing on usability technology and context-awareness technology. The former aims to raise the level of user convenience such as by devising novel user interfaces, and the latter aims to provide services that take various user and environmental conditions into account.

- Security Technology

  High-speed authentication, low-cost encryption, privacy protection, and other security technologies are needed to provide actual services.

Among the technologies for achieving a connecting service between mobile terminals and sensor networks in a ubiquitous computing environment, DoCoMo is researching and developing the following technologies as part of "system technology" and "application technology":

1) Middleware technology that can provide a general-purpose application-execution environment for sensor networks
2) Information-processing technology for integrated processing of diverse types of information obtained from sensor networks

This article focuses on item 1) above. Please see the article titled "Sensor Information Processing System for Flexible Ubiquitous Services" for a description of item 2).

*5 SmartDust®: The name of a sensor-network project at University of California, Berkeley, or of the device developed by this project. Features multiple sensor devices arranged in clusters, and was the first sensor project to establish the basic concept of sensor networks. Some project results have been commercialized as products that are known by this name. A registered trademark of Sumitomo Precision Products Co., Ltd.

*6 Multihop communication: A communication system that enables two remote terminals to exchange data through intermediate terminals that act as relays in a network where communication terminals are connected in multiple stages, in addition to allowing two terminals to communicate directly.

*7 MOTE®: A sensor network system manufactured and sold by Crossbow Technology, Inc. It can be used to construct a sensor network using small general-purpose sensor devices (motes) operating TinyOS. Research on motes and TinyOS began at UC Berkeley in collaboration with Intel Research.

*8 TinyOS/DB/SQL: TinyOS is an operating system for wireless sensor nodes designed to perform highly efficient processing with limited resources. TinyDB is a query system (database system) for collecting data from a group of sensor nodes operating TinyOS. It collects this data by issuing TinySQL, a data query language similar to SQL (see *15). Research on TinyOS began at UC Berkeley in collaboration with Intel Research.

*9 Bluetooth®: A short-range wireless communication standard for interconnecting mobile terminals such as cell phones, notebook computers, and PDAs. A registered trademark of Bluetooth SIG Inc. in the United States.

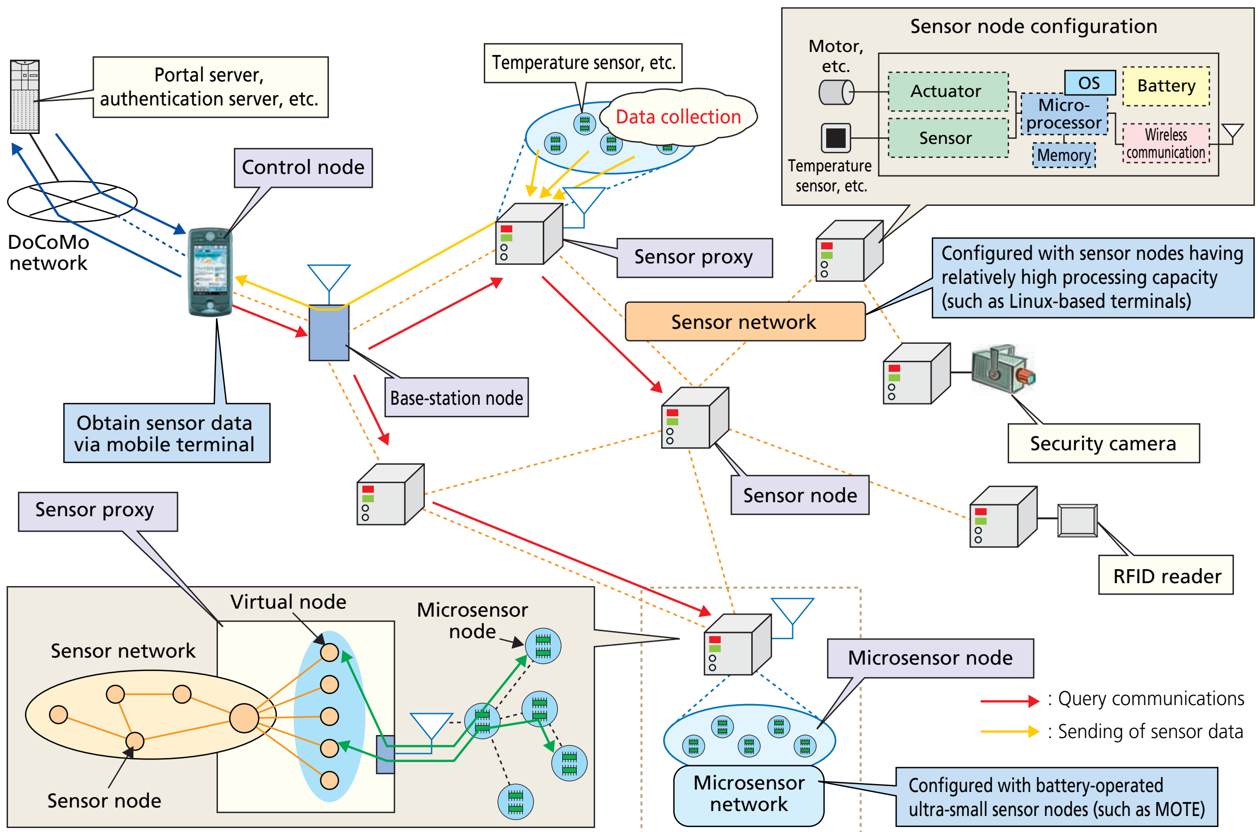


Figure 2 Sensor network architecture

3. Middleware Requirements for Achieving a Connecting Service Between Mobile Terminals and Sensor Networks

As shown in **Figure 2**, a sensor network consists of sensor nodes, a base-station node for collecting sensor data from sensor nodes, and a control node for requesting sensor data. There are sensor nodes with relatively high processing capability to handle a device like a camera or RFID reader, and there are microsensor nodes with a very small form factor and low processing capability suitable for sensors that detect temperature, brightness, etc. Either type of sensor node generally incorporates a sensing function, an actuator*18 control function, an information-processing function, a wireless communication function, and a power supply. A sensor node possesses a mechanism for networking with other sensor nodes by wireless means. It can send sensor data to the base-station node by multihop communication through intermediate sensor nodes, or it can control its actuator according to sensor data. A control node obtains sensor data from a sensor node via the base-station node. Of significance here is that a mobile terminal may be used as a control node, which should lead to a wide variety of applications that link mobile terminals with nearby sensor networks as previously mentioned.

The following technical issues must be considered in the development of middleware for the above type of sensor network system.

1) Interconnectivity

*10 ZigBee®: A short-range wireless communication standard for digital appliances specified as IEEE802.15.4. Although data transfer rate is low and transmission distances short, it features a compact, low-cost, and low-power configuration. A registered trademark of Koninklijke Philips Electronics N. V.

*11 UWB: A wireless communication system featuring location-measurement, radar, and high-speed-communication functions capable of several hundred Mbit/s to several Gbit/s at short range.

*12 Ad hoc network: A network configured by interconnecting mobile terminals without the need for base stations or access points.

*13 Middleware: Software positioned between the OS and actual applications providing common functions for diverse applications thereby making application development more efficient.

*14 Query language: A language used for inquiring and manipulating data in a database: SQL is a typical query language.

*15 SQL: A programming language developed by International Business Machines Corp. in the United States for defining and manipulating databases.

*16 SensorWare: General-purpose sensor middleware technology researched by the University of California, Los Angeles. Sensor operating conditions are described in the form of scripts (see *17). Many sensors can be controlled by dynamically transferring and copying scripts within the sensor network.

*17 Script: A simple programming language for describing a program that performs a simple process. A program described by a script may also be called a script.

A sensor network includes power-saving control methods specialized for specific sensor devices and routing systems oriented to the processing capabilities of different types of sensor devices. It consists of a variety of transport and routing protocols. A mechanism for achieving interconnectivity among the above systems and protocols is necessary.

2) Application Independent

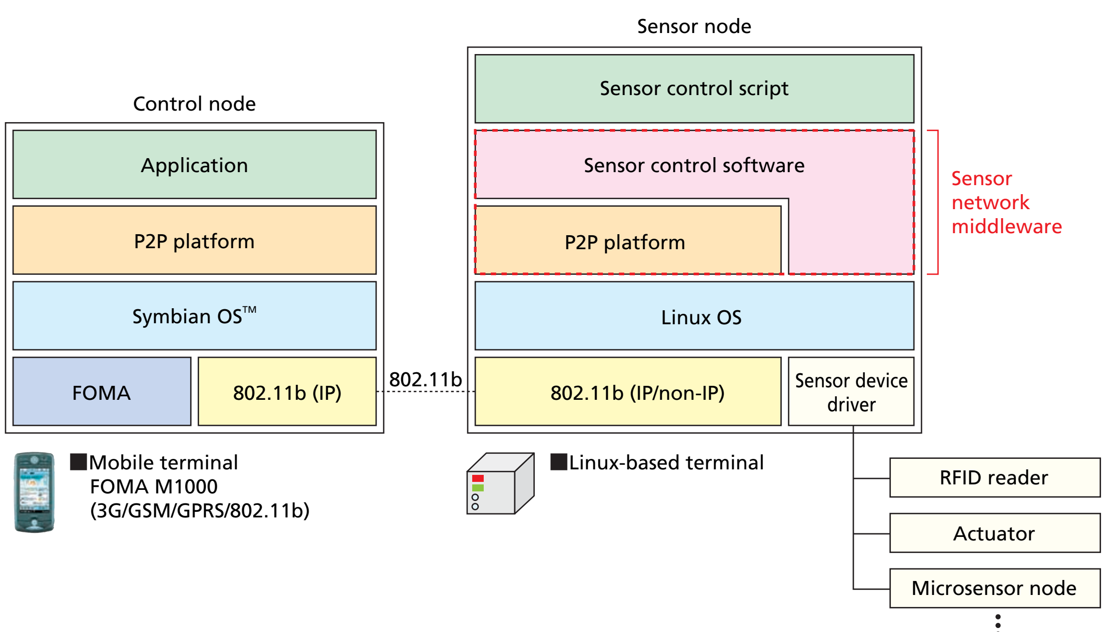
To reduce the cost of deployment and to make deployment easier, the system must not be dependent on a specific application, i.e., it must be able to accommodate diverse applications. And to simplify application development, a general purpose common interface for controlling the sensor network must be provided.

4. Design and Implementation of Sensor Network Middleware

In this chapter, we describe the design and implementation of sensor network middleware satisfying the above requirements.

4.1 Middleware Implementation

To implement middleware, we used small Linux-based terminals operating Linux OS[*19] as sensor nodes and MOTEs operating TinyOS as microsensor nodes. The Linux-based terminals were equipped with a 400 MHz CPU, a 32 MB flash ROM, and a 64MB Synchronous Dynamic Random Access Memory (SDRAM), and the MOTEs with a 7.4 MHz CPU, a 512 KB flash ROM, a 128 KB RAM, and low-power 315 MHZ Frequency Shift Keying (FSK)[*20] for the communication module. We used a FOMA M1000 terminal for the control node and loaded application software on it. **Figure 3** shows software architecture for the control node and sensor node. The sensor network middleware implemented on the sensor node consists of a Peer-to-Peer (P2P)[*21] platform and sensor-control software.



Symbian OS™ : An operating system for mobile terminals developed and licensed by Symbian Ltd. (U.K.).
"Symbian OS" and all other Symbian-based marks and logos are trademarks or registered trademarks of Symbian Ltd.

Figure 3 Software architecture

*18 Actuator: Equipment for converting electricity, heat, pressure, and other kinds of energy into mechanical motion as in train and electric-car motors, automatic doors and ticket gates, and hydraulic cylinders.

*19 Linux OS: An open source operating system of the Unix family that can be redistributed freely under GNU Public License (GPL).

*20 FSK: A digital modulation method in which digital signals are transmitted using different frequencies (different phase-transition speeds).

*21 P2P: A communication model in which computers exchange information on equal footing in contrast to the server-client model. In this article, mobile terminals and surrounding digital devices all exchange information on equal footing.

The following describes middleware design.

4.2 P2P Platform

In this research, we decided to use P2P technology as a means of solving problem 1) described in Chapter 3 because of its ability to communicate across different networks. We have previously researched and developed a P2P platform [7] to achieve seamless connections between devices (e.g. PCs, digital appliances, mobile terminals) distributed over a heterogeneous network environment (having a mixture of communication formats like Internet, IEEE1394[*22], and Bluetooth) and to execute various types of applications using mobile terminals. This platform is an overlay network that sends, receives, and transfers messages on the application layer. The communication functions that this platform provides enable seamless connections between mobile terminals and sensor nodes. It is difficult, however, to implement this P2P platform in ultra-small microsensor nodes equipped with temperature and brightness sensors because of their low processing capability and because of the protocol that they adopt based on original power-savings control methods specific to certain devices. For this reason, we investigated the use of a sensor-proxy mechanism. As shown in Fig. 2, a sensor proxy is assumed to have a communication interface for connecting to a microsensor network and a communication interface for connecting to a regular sensor network. The sensor proxy instantiates virtual nodes corresponding to individual microsensor nodes and presents those virtual nodes as independently operating sensor nodes. In the event that a sensor node on the sensor network wishes to communicate with a certain microsensor node, it must communicate with the virtual node corresponding to that microsensor node. Then, based on the message sent or received by that virtual node, the sensor proxy performs an exchange of data with the actual microsensor node thereby enabling a sensor node to communicate with a microsensor node.

4.3 Sensor Control Software

Sensor control software, which is needed to solve issue 2) described in Chapter 3, has two main functions as described below.

1) Setting of Sensor Operating Conditions

Needless to say, it would be difficult to individually control each of the many sensor nodes making up a sensor network. It is therefore preferable that each sensor node operates in an autonomous manner. That is to say, it must be easy to set operating conditions based on sensor data and request messages, as in “send an alarm message to surrounding sensor nodes when temperature rises above 30°C” or “return a reply on receiving a request message for inventory data managed by the RFID.” To this end, we have introduced a script execution environment for sensor nodes that enables operating conditions to be programmed. Sensor nodes therefore operate according to scripts distributed throughout the sensor network.

2) Processing of Queries for Sensor Data

The control node obtains sensor data from the sensor network as needed. We tried applying an SQL subset as an interface for requesting sensor data in the same way that TinySQL[*8] is used in TinyDB. The idea here was to treat the sensor network as a virtual database so that data stored on many sensor nodes could be requested from the application side by a uniform process. To this end, we introduced a database for sensor nodes that would manage sensor data and, on receiving a query for sensor data, would extract that data and return a reply.

Figure 4 shows an example of a message sequence in which the control node requests a sensor node for sensor data. First, the control node sends out a query message to a sensor node. The query message is then transferred to the appropriate sensor node or sensor proxy on the sensor network (Fig. 4 (1) and (2)). Next, the sensor proxy receiving the query message performs control processing specific to the sensor system of the microsensor-node group targeted by the query (Fig. 4 (3)). Finally, the sensor data obtained from the microsensor-node

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*22 IEEE1394: A high-speed serial bus specification standardized by IEEE in 1995. It is loaded on many types of digital appliances such as video cameras, video decks, and televisions and on printers, personal computers, and other devices enabling video streaming and other forms of data transfer between devices.

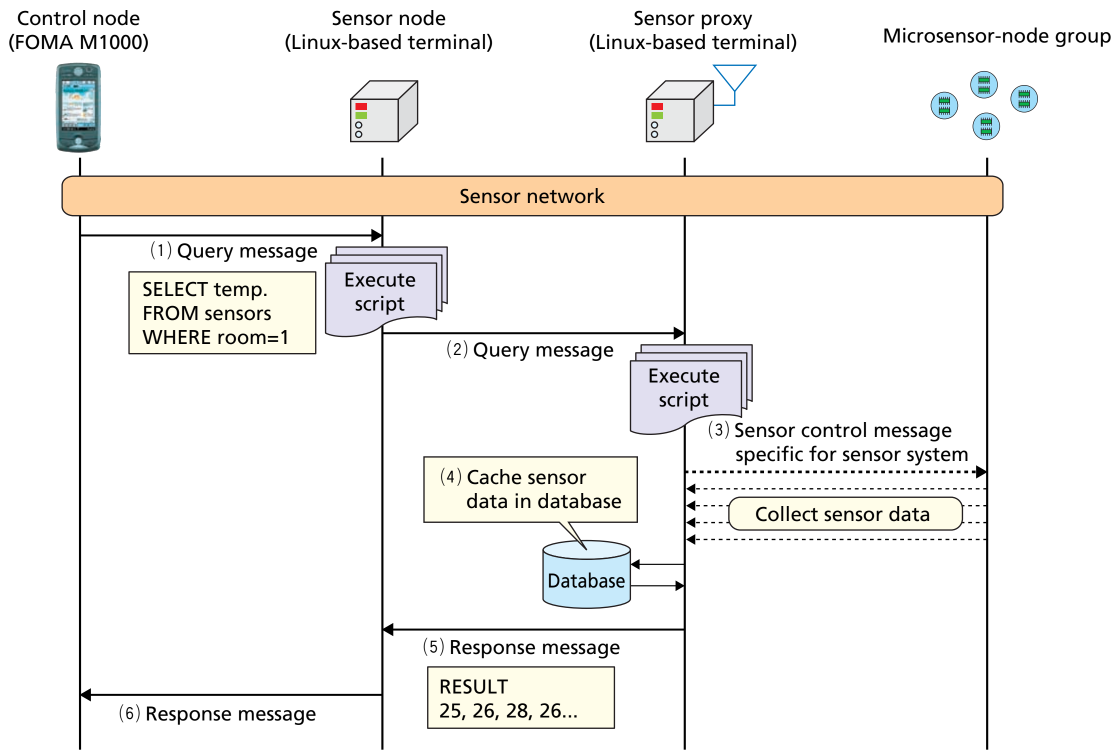

Figure 4 Message sequence example

group is cached in the sensor proxy's database (Fig. 4 (4)) and delivered to the control node by a Response message (Fig. 4 (5) and (6)).

5. Demonstration Experiment With a Prototype System

Figure 5 shows the overview of the experimental system, which presumes a retail store environment. In the store, an electronic Point Of Purchase (POP) advertising[*23] mechanism having built-in microsensor nodes registered with sale information are connected with product shelves equipped with RFID readers and microsensor-node base stations to form a sensor network that can manage advertising and inventory data. At the same time, the store network interconnects a store-management server, mobile terminals, and advertising displays as well as mobile terminals belonging to customers. In this experiment, the following usage scenarios were tested as examples of applications where sensor data obtained from the store's sensor network are used in real time on mobile terminals.

1) Shopping Assistance Application for Mobile Terminals

This application assists the user in shopping. It connects the user's mobile terminal with the store's sensor network and the user's home sensor network, selects needed products by comparing store advertising information with information on food supplies at home, and guides the user around the store. The user first gets information on the current contents of the refrigerator at home using a mobile terminal from an outside location. Then, once inside the store, the user sends a query to the store's sensor network to request advertisements on products not in the refrigerator at home. Next, product shelves, on detecting a request for electronic POP advertising, sends advertisements to the user's mobile terminal in accordance with the contents of the refrigera-

*23 Electronic POP advertising: A means of advertising products directly at sales counters, sales floors, and other places where purchases are made. It is used to inform the consumer a product's display location, functions, price, and features to promote purchase. Using an embedded terminal, it can dynamically present advertisements on a display, and if equipped with communication functions, it can update display content in real time for more effective advertising.

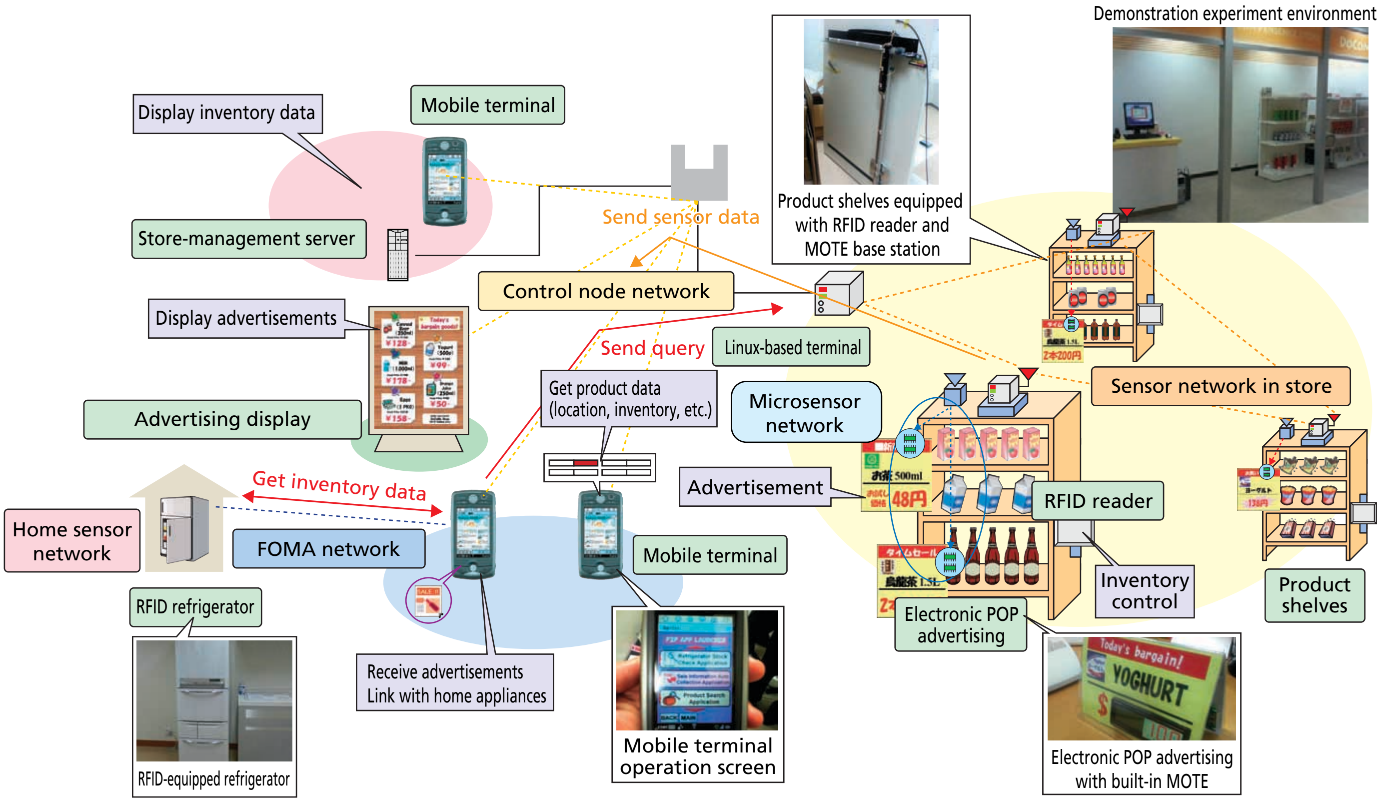

Figure 5 Experimental system

tor at user's home. The user can then use those advertisements to ask the store's sensor network where those shelves with those products are located in the store. The user can then proceed to those product shelves and purchase the products in question.

2) Store Management Application Using Mobile Terminals

This application assists store clerks with store management. It can collect inventory data and advertising information from product shelves and send that information to the store server and to store clerks' mobile terminals. It can also automatically display ads on store-front advertisement displays. This application enables product shelves to automatically inform the store server and store clerks' mobile terminals of changes in inventory, and enables a shelf to detect the installation of electronic POP advertising by a store clerk and obtain advertising information. The advertisements so obtained can be automatically shown on information displays to achieve real-time advertising.

The results of the above demonstration experiment show that applications that manipulate sensor nodes and use sensor data can be easily loaded on mobile terminals using a simple query language. They also show that the proposed middleware can be used to achieve sensor network applications that adopt actual sensor devices such as RFID readers and electronic POP advertising installed in a store environment.

6. Conclusion

We described technical trends in sensor networks and sensor-network middleware technology for achieving a connecting service between mobile terminals and sensor networks. We demonstrated experiment to examine the operation of a prototype system equipped with the proposed middleware. In the future research, with the aim of introducing a practical system, we plan to investigate security systems such as for privacy protection and system operation schemes. We will also conduct more technology tests and demonstration experiments to explore the application of this technology to other applications such as advertisement delivery and facility/building guidance that use sensor networks and mobile terminals.

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