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An Extensible Interworking Architecture (EIA) for Wireless Sensor Networks and Internet

Min Zhang, Sangheon Pack, Kideok Cho,
Dukhyun Chang, Yanghee Choi, and Taekyoung Kwon

Multimedia and Mobile Communication Laboratory
School of Computer Science and Engineering
Seoul National University, Seoul, Korea

Email: {mzhang, shpack, kdcho, dhchang, yhchoi, tk}@mmlab.snu.ac.kr
http://mmlab.snu.ac.kr/

서울대학교
SEOUL NATIONAL UNIVERSITY

MMLab
Multimedia and Mobile communications Laboratory

Abstract

One of representative applications of wireless sensor networks (WSNs) is a data collecting system that monitors and gathers physical phenomena in an area of interest. To build an end-to-end data collecting system, how to efficiently integrate WSNs with the Internet should be investigated. In this paper, we first present important design considerations regarding interworking between these two networks and review the existing interworking approaches: gateway-based and overlay-based approaches. Then, we propose a new interworking architecture, extensible interworking architecture (EIA), which forms overlay sensor networks (OSNs) over Internet. EIA employs two advanced functions to improve the data gathering efficiency: application layer graph (ALG) and distributed caching. Compared with previous works, EIA can meet the design requirements on the WSN/Internet interworking more efficiently.

Introduction

- Wireless sensor network (WSN)
  - A key enabling technology for ubiquitous computing
- WSNs-Internet Interworking
  - Design Considerations
    - Scalability, Extensibility, Distributed, Efficiency, Reliability, etc.
  - Existing Interworking Approaches
    - Gateway-based Approach
    - Overlay-based Approach
- EIA: Extensible Interworking Architecture
  - Wireless sensor network (WSN) and Overlay sensor network (OSN).
  - Application layer graph (ALG) and Distributed caching

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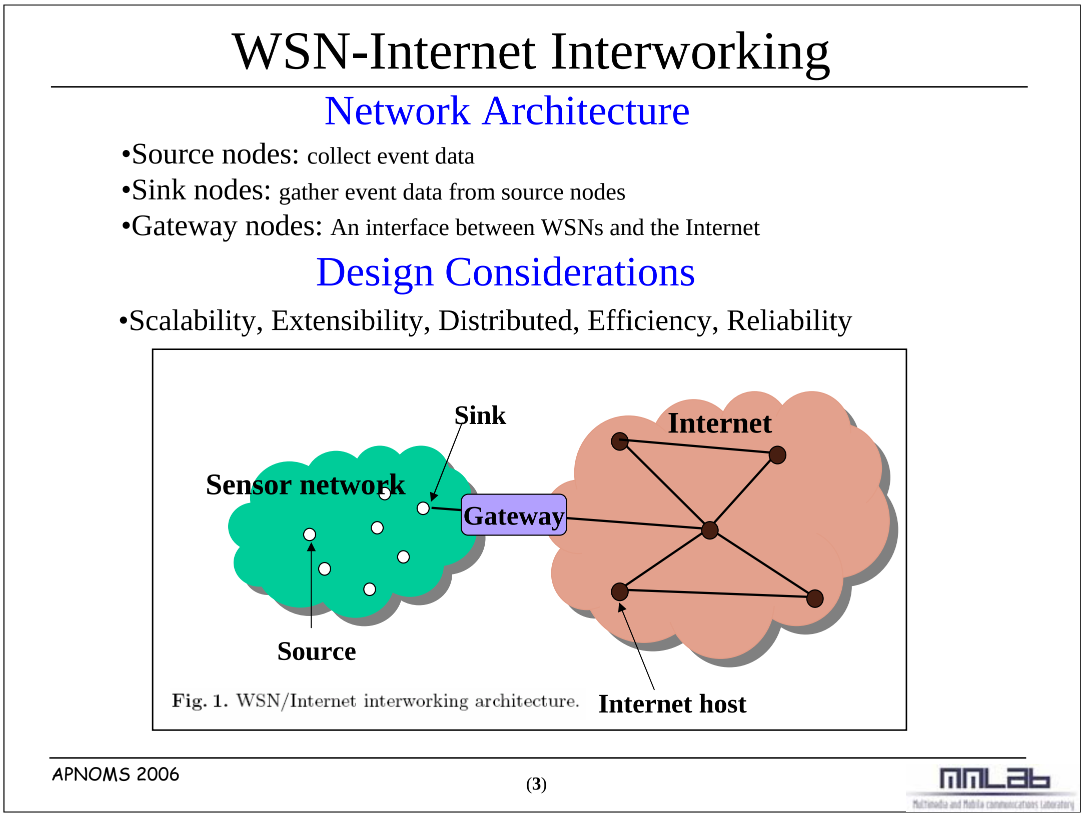
1 Introduction

Wireless sensor networks (WSNs) are expected to be key technologies for enabling ubiquitous computing. With the development in micro-sensor hardware technologies such as micro-electro-mechanical systems (MEMS) and nano-technology, diverse WSN applications are emerging. One of the most representative applications is a data collection or surveillance monitoring system, such as enemy detection in battle fields, rainfall monitoring system, intelligent traffic control system, habitat monitoring, etc [1]. Furthermore, WSNs can be utilized in a form of wireless sensor and actor networks (WSANs), which takes a specific action based on sensory data [2]. These various developments of sensor networks will bring ubiquitous computing environments much closer to our daily lives.

WSNs have quite different characteristics from the existing wireless networks. For instance, sensor nodes in WSNs have limited battery and computation power. In addition, sensor nodes communicate with each other in a multi-hop fashion to reduce energy consumption for communications (lower transmission range means lower energy consumption). Because of these characteristics of WSNs, a lot of studies have been focused on energy efficiency. Especially, the design of medium access control (MAC) and routing protocols is the most active research area.

Most WSN applications, especially surveillance monitoring systems, are based on the publish/subscribe mechanism [3]. In other words, an entity registers its interest with WSNs (Subscribe phase) and sensor nodes in WSNs monitor some information from the physical world and deliver the interesting information to the entity (Publish phase). In most cases, the entity triggering subscribe/publish phases will be an Internet host. Accordingly, WSNs should interwork with the Internet to build end-to-end application systems for customers. However, compared with other areas (e.g., MAC and routing protocols), little attention has been paid for interworking between WSNs and the Internet. Even though there are a few researches for interworking mobile ad hoc network (MANET) and the Internet (e.g., [4]), these schemes cannot be directly applied to WSNs due to different characteristics. Consequently, it is necessary to investigate efficient WSNs-Internet interworking architecture and protocol.

In this paper, we focus on the issue, how to efficiently interwork WSNs with the Internet?. To address this issue, we propose a new interworking architecture: extensible interworking architecture (EIA). EIA supports two advanced functions to improve the data gathering performance: application layer graph (ALG) and distributed caching. The ALG is the connectivity graph over an overlay sensor networks (OSNs), which enables the data centric routing. Unlike routing protocols in WSNs (e.g., directed diffusion [5]), the ALG is formed in a proactive manner. Distributed caching prolongs the lifetime of wireless sensor nodes by locally processing queries within the Internet.



2 WSN-Internet Interworking

2.1 Network Architecture

As mentioned before, one of representative WSN applications is the data gathering application that collects data using a number of sensor nodes and sends the collected data to a host located in the Internet [6]. In the data gathering application, WSN can be considered as a kind of database. Namely, when a WSN receives a query from an Internet host, the WSN interprets this query and sends back the result to the Internet host after gathering the corresponding information.

Figure 1 illustrates a typical architecture for interworking of WSN and the Internet. A WSN consists of source nodes collecting event data monitored around their vicinity and sink nodes gathering these event data. Since sensor nodes have a limited processing capability, all sensor nodes cannot be equipped with the IP protocol stack and therefore only several selected nodes (e.g., cluster heads) implement the IP protocol stack. At the Internet part, hosts are operated to send the query for data collection and process the received query responses. A host can communicate with WSNs through gateway nodes, which provides an interface between WSNs and the Internet. A typical database query language (e.g., structured query language (SQL)) can be used for the Internet part, whereas a light-weight query.

2.2 Design Considerations

To support diverse WSN applications in a scalable manner, a more efficient interworking architecture should be developed. Specifically, the following features should be satisfied for efficient WSN-Internet interworking.

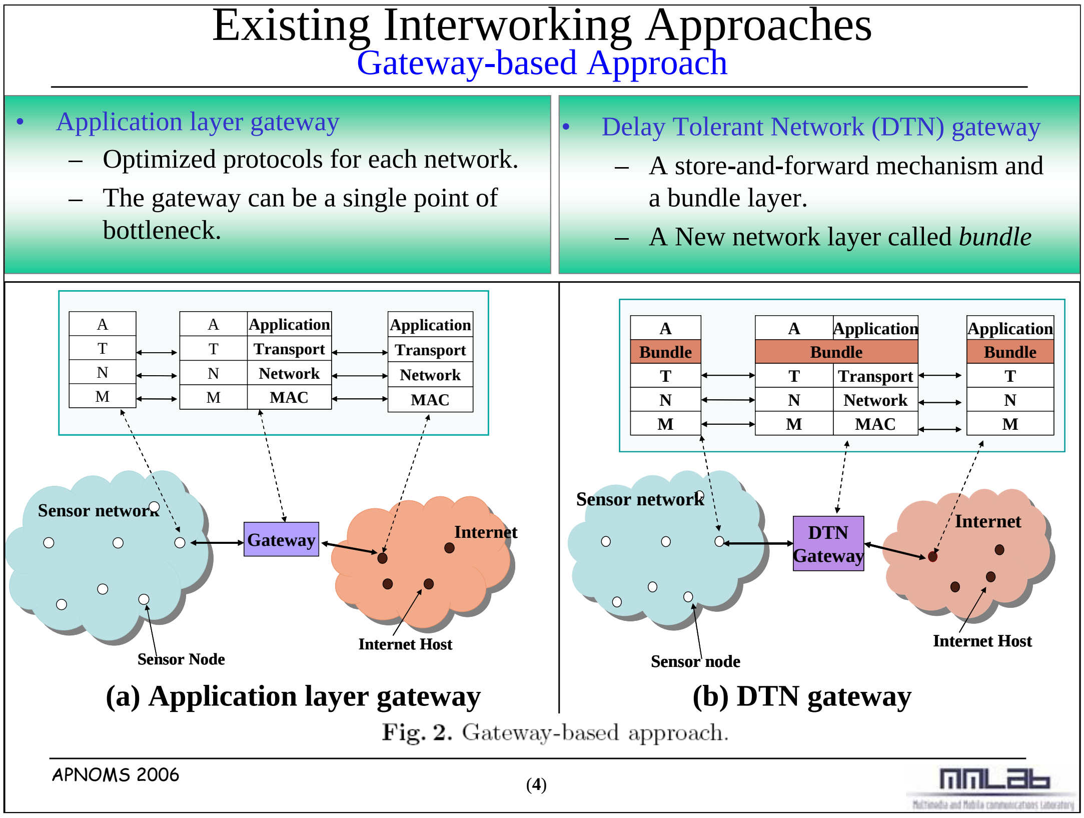
– Scalability: In WSNs, many sensor nodes are deployed to perform a specific role. Also, there exist many Internet hosts that try to get information from WSNs. Accordingly, the interworking architecture should be able to accommodate a large number of sensor nodes and Internet hosts.

– Extensibility: Many new WSN applications are continuously emerging and much more applications will appear in the future. Therefore, the Inter-working architecture should be designed in an extensible manner.

– Distributed: If the interworking architecture is dependent on a central node, the central node can be a single point of failure. To overcome this problem, distributed mechanisms are preferable.

– Efficiency: The interworking architecture should be efficient in terms of query resolution delay, energy consumption, and protocol overhead, and these criteria for efficiency are determined by applications under consideration.

– Reliability: Even though several techniques (e.g., caching, estimation, and aggregation) are employed for efficient operations, these techniques should not prevent correct operations. In other words, the interworking architecture should be sufficiently reliable and failure-resilient.



3 Existing Interworking Approaches

So far, several studies have been conducted for WSN-Internet interworking [8–11]. These works can be divided into two categories: gateway-based and overlay-based approaches.

3.1 Gateway-based Approach

Different protocols can be used for WSNs and Internet and therefore a gateway is an essential element to connect a WSN with the Internet, which performs several tasks such as protocol conversion and message relay.

A simple gateway-based approach is to use an application layer gateway (see Figure 2(a)). The application layer gateway receives query messages from one side (typically Internet) and translates the received message into a new one that can be interpreted on the other side (typically WSNs). Typically, the application layer gateway is designed only for a specific application. In this approach, all interworking processes are performed only at the application layer gateway. Therefore, it does not incur high initial deployment costs. Also, WSNs and the Internet can be fully separated by the application layer gateway, so that optimized protocols for each network can be individually applied. However, the gateway can be a single point of bottleneck. Even though multiple gateways can be deployed, other issues such as synchronization between gateways and load distribution can be raised in this case. In addition, as the application layer gateway is tailored for a specific application, it is not extensible.

Another gateway-based approach is to utilize a delay tolerant network (DTN) gateway [8]. The DTN is a new network designed to address several challenging issues, e.g., long and variable delay, asymmetric data rates, and high error rates [11]. The DTN adopts a store-and-forward mechanism and a bundle layer on the top of region-specific network protocols to support interoperability of heterogeneous regions. A common bundle layer protocol is used across all regions. On the other hand, the layers below the bundle layer are chosen for its specific environment of each region. Figure 2(b) illustrates an example of DTN gateway-based approach. In the DTN architecture, when the DTN gateway receives a packet from the Internet, the DTN gateway transforms the lower layer messages of the bundle layer into those of WSNs, and then delivers the packet to WSNs. If the link of WSNs is broken due to high error rate in wireless links, the packet is not transmitted and stored at the bundle layer for future forwarding. Different from the application layer gateway approach, the DTN gateway can be used for various types of applications and thus the DTN gateway-based approach provides higher extensibility.

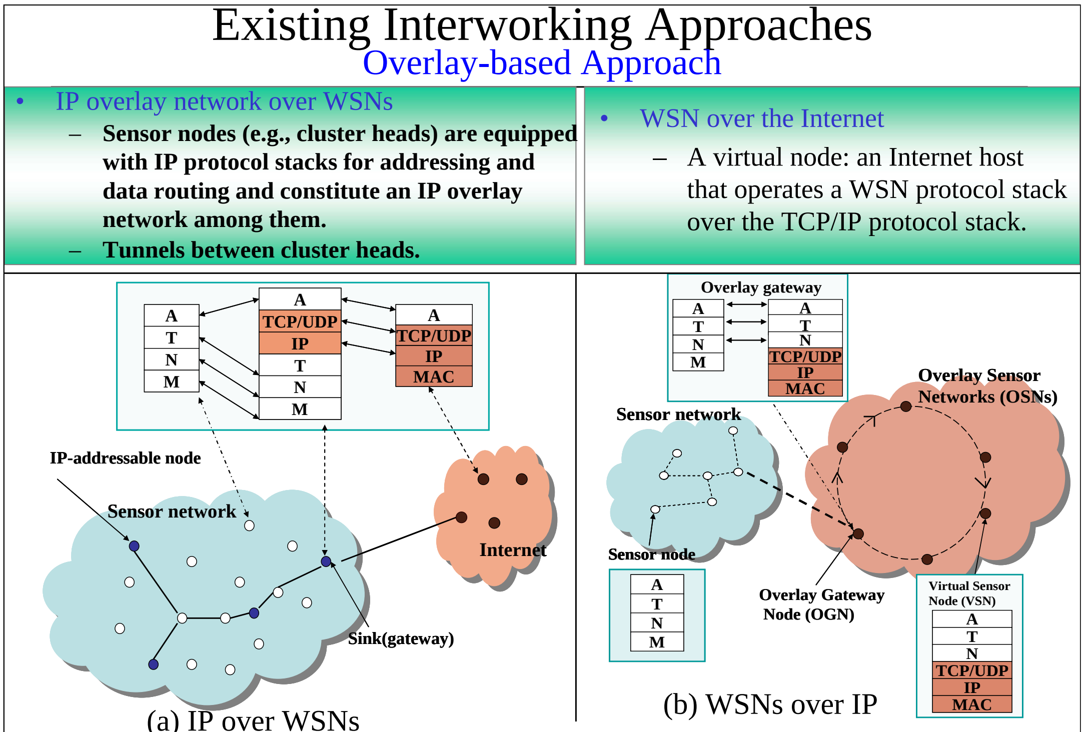
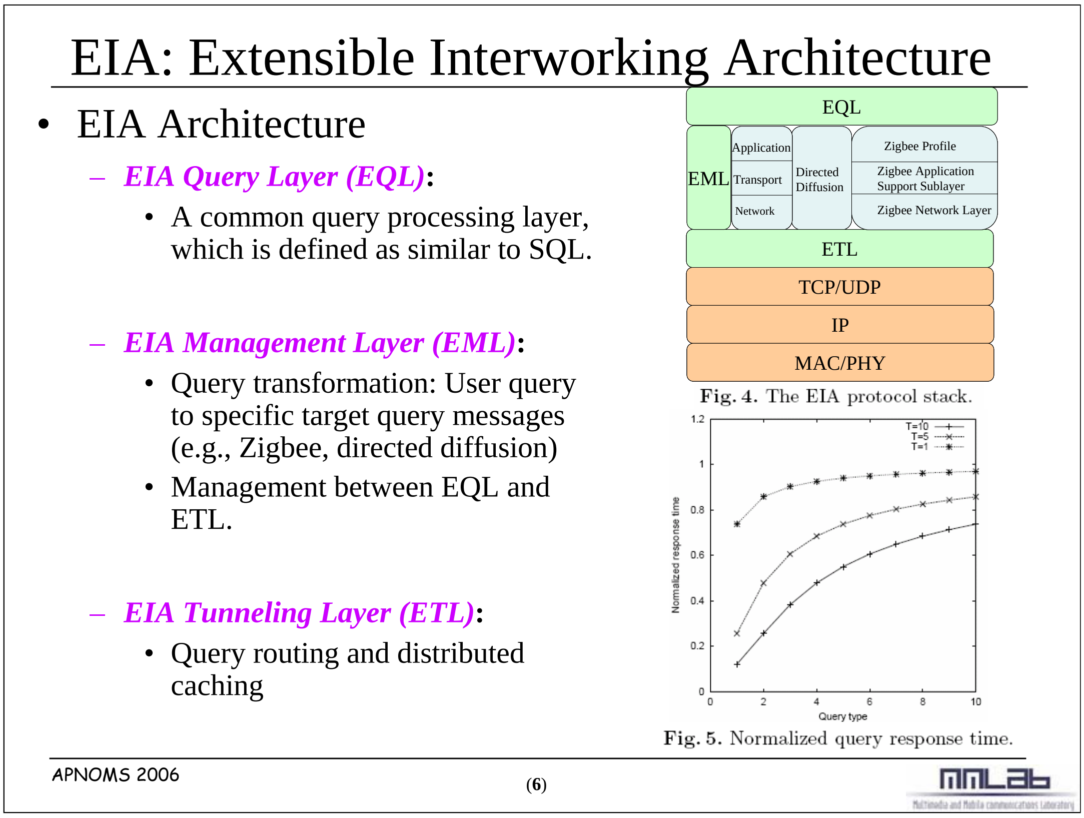


Fig. 3. Overlay-based approach.

3.2 Overlay-based Approach

The first overlay-based approach is to implement an IP overlay network over WSNs [8], i.e., IP over WSNs. Namely, sensor nodes are equipped with IP protocol stacks for addressing and data routing. Typically, it is quite difficult to assign IP addresses to all wireless sensor nodes. Therefore, only a few nodes, e.g., cluster heads, configure their IP addresses and constitute an IP overlay network among cluster heads (see Figure 3(a)). A key issue of this approach is how to interwork address-centric routing protocols in the Internet with date-centric routing protocols in WSNs. For this problem, a tunnel is established between cluster heads and a data-centric routing protocol can be implemented over this tunnel. The main advantage of this approach is that it does not need any flooding of messages and an Internet host can directly send massage to IP-addressable nodes. This functionality enables to build wireless sensor/actuator systems efficiently. Let us take an example of a lighting system in a large building. When a sensor detects that there is no one in the office, the detected data is delivered to the Internet server and the system administrator then sends an instruction to an actuator to turn off the light. In this situation, if the actuator has a specific IP address, this operation can be implemented more efficiently, without any flooding in data-centric routing protocols.

The second approach is to construct an overlay WSN over the Internet [9], i.e., WSNs over IP. The approach extends the data-centric routing protocol in WSNs into the Internet via overlay networking in the application layer. When the packets originated from WSNs arrive at the gateway, they are encapsulated within a typical TCP/IP packets and then delivered to a specific destination IP host. Figure 3(b) shows an overlay WSNs over the Internet. The major components are virtual nodes running over the Internet and overlay gateways. A virtual node is an Internet host that operates a WSN protocol stack over the TCP/IP protocol stack. The virtual nodes then form a virtual sensor network over the Internet. The virtual node can interpret WSN packets because it has the WSN protocol stack. On the other hand, the overlay gateway has two protocol stacks for the Internet and WSNs. It performs the packet transformation, which is more simple than those of application layer and DTN gateway approaches. This is because the overlay gateway simply encapsulates the received packer into a typical TCP/IP packet, without any interpretation at the gateway level. Since virtual sensor nodes handle both the TCP/IP protocol stack and sensor network protocol stack, a high overhead may be incurred in this approach. However, since Internet hosts have a sufficient computing power, we believe that this overhead is not significant. On the other hand, virtual sensor nodes can be implemented by software, so that it has an advantage of easy deployment. Also, it is possible to integrate large size WSNs in remote areas via the Internet.



4 EIA: Extensible Interworking Architecture

EIA follows an open network architecture to build an efficient end-to-end data gathering system integrating WSNs with the Internet. EIA enables to integrate a variety of heterogeneous WSN applications deployed in a large-scale area. A recent work called IrisNet (Internet-scale Resource-Intensive Sensor Network Services) introduces a novel management framework for widely distributed and heterogeneous sensors attached Internet hosts [12]. Even though IrisNet and EIA have a similar design motivation, EIA has two distinct features. First, EIA assumes wide-area WSNs while IrisNet focuses on wired sensor networks. Hence, EIA tries to optimize the query processing to be performed in wireless networks through distributed caching. Second, EIA provides self-organization property, which is essential for fault-tolerant services, via peer-to-peer (P2P) overlay networking.

4.1 EIA Architecture

The EIA architecture specifies a wireless sensor network (WSN) and a overlay sensor network (OSN). The WSN is a typical wireless sensor network consisting of wireless sensor nodes with radio interfaces. On the other hand, the OSN is an overlay network, which emulates a WSN over Internet. There are two types of nodes in OSNs: overlay gateway node (OGN) and virtual sensor node (VSN). EIA is designed for WSNs deployed in a large-scale area, so that multiple OGNs and VSNs are assumed. The OGN provides an interface between WSNs and OSNs, while the VSN deals with routing query and response messages. The VSN implements protocols for WSNs over TCP/IP protocol stack. On the other hand, the OGN has a dual protocol stack for interworking between WSNs and OSNs. All of these nodes are designed based on the concept of open system architecture. Therefore, a new WSN application can easily be added without any changes in OGNs and VSNs.

EIA defines three layers: EIA Query Layer (EQL), EIA Management Layer (EML), and EIA Tunneling Layer (ETL). Figure 4 shows the EIA protocol stack supporting directed diffusion [5] and Zigbee [13], which are representative sensor network protocols. When a new WSN application needs to be supported, EIA can be easily extended by defining interfaces between three layers. The main functions of three layers are as follows.

–EQL: To support a variety of WSNs and applications, EIA provides a common query processing layer, which is defined as similar to SQL.

–EML: In EIA, a user initiates its query through the EIA user interface (i.e., Web interface). The query is transformed into a specific target query message (e.g., Zigbee, directed diffusion), and the target query message is delivered to neighbor VSNs or OGNs. The EML handles these procedures between EQL and ETL.

– ETL: EIA supports a distributed caching algorithm, so that an additional header is added for distributed caching at the ETL. Also, query routing is performed at the ETL.

EIA: Extensible Interworking Architecture

- **Application Layer Graph (ALG)**
  - To support data centric routing in OSNs,
  - The data dissemination graph is constructed when the query is propagated or an event of interest occurs.
  - The proactive ALG construction gives more advantages in terms of OSN maintenance overhead
  - ALG should be scalable and self-organizable.
- **Distributed Caching**
  - To extend lifetime of wireless sensor nodes
  - VSNs can cache the information obtained by relaying query results.
  - The average query response time in EIA

$$R = T_{OSN} \times P_{OSN} + (T_{OSN} + T_{WSN}) \times (1 - P_{OSN})$$

4.2 Application Layer Graph (ALG)

The goal of data gathering system is to collect some interesting information from physical worlds. To this end, data centric routing protocols such as directed diffusion [5]) are widely accepted in WSNs. To support data centric routing in OSNs, each VSN constructs an ALG. For WSNs, the data dissemination graph is constructed when the query is propagated or an event of interest occurs. Namely, the reactive method is widely used because of dynamics in wireless networks. On the contrary, since OSNs are built over the wired Internet, dynamics are not serious constraints. Therefore, the proactive ALG construction gives more advantages in terms of OSN maintenance overhead. In addition, the ALG should be scalable and self-organizable. Since EIA can be deployed in an incremental manner, the ALG should be re-organized with minimal overhead when a new VSN is added or removed. To meet these requirements, P2P overlay networking [14] can be utilized.

4.3 Distributed Caching

In WSNs, prolonging the lifetime of wireless sensor nodes is one of the critical issues. Unlike wireless sensor nodes, VSNs have sufficient computation power and memory capacity. Therefore, VSNs can cache the information obtained by relaying querying results. This information is stored in the local cache of VSNs and can be used for resolving another query requesting the same information. This cache management scheme is similar to that of ACQUIRE [15]. Consequently, the distributed caching can prolong lifetime of wireless sensor networks.

Depending on the sensor applications, the out-of-date data may be useless. There-fore, each sensor application has a mechanism to specify the valid timing requirement. To investigate the effectiveness of the distributed caching, we formulate the query response time in EIA as

$$R = T_{OSN} \times P_{OSN} + (T_{OSN} + T_{WSN}) \times (1 - P_{OSN})$$

where T_{OSN} and T_{WSN} represent the query response time in the OSN and WSN, respectively. P_{OSN} denotes the probability that a query is resolved by the cached information within the OSN. We assume that the frequency process for each query type follows a Zipf distribution and the query arrival process follows a Poisson distribution. If the total query arrival rate is normalized to 1.0, P_{OSN} can be computed as $1 - e^{-P_i T}$, where P_i is the access probability of type *i* query and T is the cache lifetime. Figure 5 indicates the normalized query response time when $T_{OSN} + T_{WSN}$ is normalized to unity. Since the frequency of query 1 is the highest, the query can be resolved by the distributed caching more frequently and therefore its response time is the smallest. Also, as the cache lifetime increases, EIA can reduce the query response time more significantly.

Conclusion & Future Work

- Wireless sensor network technologies are being advanced continuously and will be integrated with the Internet to build end-to-end systems.
- Extensible Interworking Architecture (EIA)
  - A new interworking architecture
  - Application layer graph (ALG): data centric routing in the Internet
  - Distributing caching: prolong WSN lifetime
- EIA testbed:
  - Sensor nodes: Nano Qplus (OS) + Nano 24 board + IEEE 802.15.4
  - User interface: JavaServer Pages (JSP)

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5 Conclusion

In real applications, wireless sensor networks (WSNs) will be integrated with the Internet to build end-to-end systems. In this paper, we first reviewed the state of the art on the interworking of WSNs and the Internet. Also, we presented several design issues for efficient interworking. Based on these design issues, we proposed a new interworking architecture: extensible interworking architecture (EIA). For the purpose of efficient interworking, EIA supports data centric routing based on the application layer graph (ALG) and distributing caching. Currently, we are implementing the EIA testbed, where we will conduct extensive measurements focusing on the scalability and heterogeneous issues in WSNs/Internet interworking.

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