Integrating Wireless Sensor Networks with the Grid

Integrating wireless sensor networks with the traditional wired grid poses several challenges. The technical challenges center on the development of sensors and sensor network infrastructure, including the need to comply with emerging APIs for grid and Web services. Process-driven challenges, which center on the development and adoption of new business models and applications, are driving this technology. This article describes two widely different sensor network applications — emergency medical services and supply chain management — and describes how these applications fit into a new data collection network based on the Hourglass publish–subscribe paradigm.

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Today's grid architecture[1] encompasses a far greater breadth of applications than the traditional grid, which focused on distributed applications processing large amounts of data. Newer grid applications are more data-centric and more focused on distributed services. In this article, we discuss emerging grid standards that support these applications, while complying with the Open Grid Services Architecture (OSGA). Much of the data for these newer applications are collected by a new class of small, self-contained, intelligent devices that combine limited sensing and computation capabilities with wireless communications. Aggregating these tiny wireless devices into sensor networks[2] will allow the physical environment to be measured at high resolution. This, in turn, will lead to a vast increase in the quantity and quality of data available to an expanding array of grid applications, some of which will monitor our buildings, bridges and environment, while others will track perishable foods, fragile goods, people, and medical patients.

The emerging domain of wireless sensor networks has yielded a wide variety of devices with very different computation, communication, and sensing capabilities. These range from relatively powerful systems with PC-class processors and high-bandwidth wireless interfaces (IEEE 802.11), to much smaller, low-power nodes (often called motes, or smartdust)[2] that consist of simple embedded microcontrollers and low-bandwidth radios operating in the 433 or 916 MHz industrial, scientific, and medical (ISM) bands. Other wireless technologies, such as IEEE 802.15.4 and Zigbee—(a set of proposed standards for these wireless sensors), Bluetooth, and long-distance cellular can also support sensor networks. This article examines two novel sensor-network application domains: patient monitoring and supply-chain management. We look at the technical problems of integrating sensor data into the grid architecture, and then propose a solution based on the Harvard inspired Hourglass publish–subscribe data-collection network.

Medical

Researchers have proposed a variety of vital-sign sensor network architectures. These range from intelligent, wireless sensors linked by personal area networks (PANs)[3] to tightly integrated sensors on a single-mote platform.[4] The latter appears to be the most flexible and a better choice for short- and long-term patient monitoring due to the simplicity of attaching a single, lightweight device to a patient or person. Another attribute is the potential for edge-based data management. By aggregating and processing sensor data at the very edge of the network, there is the potential to filter and simplify the type and amount of data that is transmitted both locally and centrally.

The device platform should accommodate a range of sensors, depending on need, expendability, and cost. The simplest device would consist of a mote, a small battery, and a pulse-oximetry module (Figure 1 illustrates our prototype) that monitors a patient's heart rate and level of oxygen saturation in the blood. Such a device could be used in many types of healthcare and homecare settings to monitor a wide variety of conditions, including congestive heart failure, chronic obstructive pulmonary disease, asthma, and sleep apnea. Programmable sensor algorithms would filter and store the sensor data on the mote, but also wirelessly transmit the data to a PDA, smart phone, or wearable computer. These more-powerful, Internet-connected devices would act as intermediaries between individual patient sensor nodes and large applications. They would provide an alarm function and permit the sensor data to be viewed locally, stored, or sent via the Internet to an off-site base station for data processing and continuous, real-time monitoring.

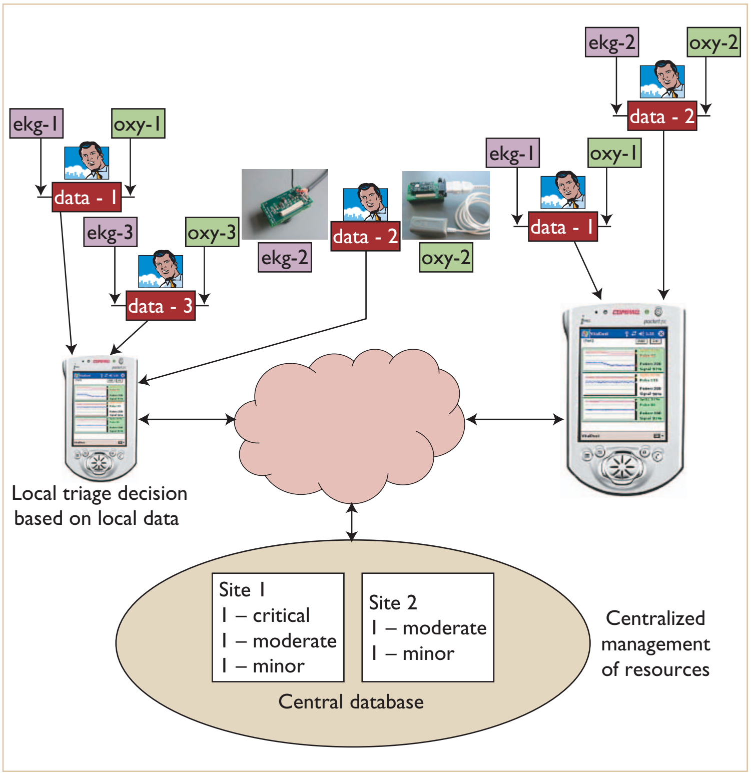

Figure 1. Multilevel triage system architecture. At each site, each EMT has vital sign data (such as EKG, blood oxygen level, and pulse) for each patient. Edge based control with central management of global resources.

Patient Care

Smart sensors would be useful in several different types of patient-care settings, especially those in which wired monitors are cumbersome, where data collection is important for diagnostic and research purposes, or if a large number of patients must be monitored and triaged to local hospitals, based on available resources. A good example is the pre-hospital phase of patient care: here, wireless sensors could simplify patient transport while providing a constant stream of vital-sign information to a mobile computer on which a paramedic or emergency medical technician (EMT) could capture additional patient information. The integrated vital sign and patient care data could then be relayed to a hospital ahead of the patient, so that physicians and nurses could better anticipate the patient's needs.

Ad Hoc Medical Sensor Networks

Mass casualty incidents (MCIs) are unexpected situations in which large numbers of casualties are gen-

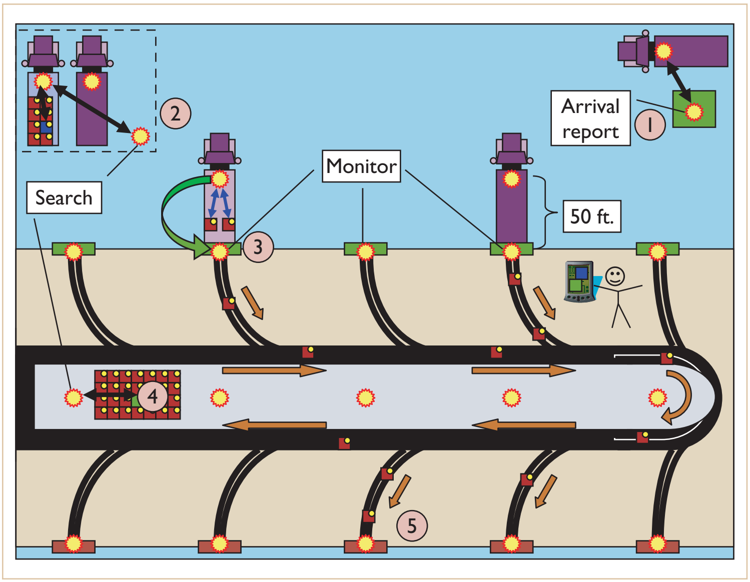

Figure 2. Supply chain management with smart sensor networks. Trucks are either stacked up waiting to be unloaded (2) or sent to an unloading dock (3). As the truck is unloaded, each item can be sensed as it moves into the warehouse (3) on the central conveyer belt. Items can be located within the warehouse (4), and as they are shipped out (5) to stores or customers.

erated over a short period. In most cases, only about 10 to 15 percent of survivors are severely injured; however, quickly identifying and stratifying these patients from among the less severely injured survivors poses a unique set of challenges. Deployment of small, wireless vital- sign sensors in a sensor network could assist first responders in monitoring and deciding which patients would benefit most from transport to a dedicated trauma center and, conversely, which patients could be safely either excluded or delayed entry into this system.

The sensors and sensor network architecture would allow aggregate patient information to be transmitted to a centralized, decision support system, so that a global view of any mass casualty situation could be gained and a greater semblance of order could be established (Figure 1). Triage in the field and triage at the hospital gates would therefore become interactive, allowing better coordination of the out-of-hospital caseload with critical, hospital-based trauma facilities and resources.

Supply Chain

There are many applications of wireless sensors in traditional operational aspects of business such as building a smart supply chain. In the Leading in the Dynamic Economy (BUILDE) program, Sears Canada and Boston University are exploring the potential business value of using motes for local data management and asset tracking in Sears' supply chain. Our early tests have shown that user-defined data can be reliably written to and read from nonvolatile memory on motes. This capability will let warehouse personnel directly attach location and supply-chain data to products.

Motivation for developing this capability was twofold. First, it will optimize Sears' customer service by more efficiently handling customized orders. For example, current systems have difficulty tracking whether individual pieces that should be shipped together (such as a living room furniture set) have all arrived and are ready to be shipped out as a unit. Second, Sears wishes to place sensing capabilities on expensive and fragile products, such as plasma screen TVs, and high-end appliances with advanced electronics; this will not only help detect whether an item has been dropped (and if so, where, when, and how serious the impact was) but also help identify and correct problems in the supply chain.

Figure 2 illustrates a simple prototype of the smart warehouse application we are researching. Arriving trucks pass an entry gate equipped with a monitor that senses items or pallets of items embedded with smart sensors as these items arrive at the warehouse. Depending on the number of trucks unloading, these trucks are either stacked up waiting to be unloaded (as shown in Figure 2's upper left hand corner) or sent to an unloading dock. If stacked up, warehouse workers searching for particular items needed in stores or by a customer might search the trucks. As the truck is unloaded, each item can be sensed as it moves into the warehouse on the central conveyer belt. Items can be located within the warehouse, and as they are shipped out to stores or customers. Figure 2 illustrates events as items arrive at the warehouse, however, our prototype design involves suppliers and shippers to track items from first contact to final arrival to a customer. This use of smart sensors enables more dynamic supply-chain management.

For our field test of this application at Sears, we tagged pieces of merchandise with motes and then followed these items through a large distribution center as they went through the receiving, staging, and shipping processes. We log various pieces of product and shipping information to the motes. This logged data includes information such as the product description, manufacturer, the date and time the manufacturer shipped it, customer name, and so on. The application performed reliably in the warehouse setting we worked in, and transmission range proved to be more than adequate — we could reliably read and write at a 50-foot distance. Our future efforts will focus on ways to reduce the amount of manual data that must be entered and sent to the motes.

Integrating Sensors into the Grid

The two applications we've described earlier (triage and the smart supply chain) are built using non-standard protocols, which make implementation difficult. For widespread adoption of wireless sensor technology applications, developers must have access to sensors with APIs that their development environments support.

Standard Grid API

The OSGA standards are the emerging API for grid applications. These standards are based on Web services (XML and SOAP), and most major vendors currently support them in products such as Microsoft's .Net, Sun's J2EE, IBM's Dynamic e-Business initiative, as well as open-source Web services development environments such as Axis in the Apache framework. These development environments promote easy access to grid services, which are usable by any client, on any host, with any operating system, as long as they are in compliance with OSGA standards. For now, pervasive adoption of wireless sensors depends on their data being encoded in XML and packed in SOAP envelopes.

Web services standards promote consistent data encoding and data transport, but they do not address how to manage the service — that's where grid services and OGSA come in. Grid standards specify a Web service's structure with regard to the methods used to query data and manage the service. When sensor data is available in the OGSA framework, integrating this data into a grid application is similar to using any other data-centric grid service. As we discuss later, sensors do not have the power to present data in the OGSA standards' framework, but application developers need these standardized ways to access data to efficiently develop applications.

Grid standards impose structure on the Web services infrastructure and define service types and their operations. Grid services range from querying the service for data, registering a service to allow dynamic discovery, subscribing to event notification, and responding to an event, as well as a grid-service method used to build these grid services. Using the Web services description language (WSDL), OSGA using Web services terminology defines the PortType (for example, methods of the grid service) of the service and its operations. For example, the `GridService` PortType (the only required PortType) has the `FindServiceData` method, which is used to query information, the `SetTerminationTime` method, which is used to set (and get) the termination time for a grid service instance, and `Destroy` method, which is used to terminate a grid service. Optional PortTypes include a `Factory` method, which is used to create new instances of a service. Sensor services that adhere to the basic Web services and grid standards discussed earlier to define their signatures stand the best chance of rapid adoption because they fit into major vendors' strategies.

Technical Challenges

Because these small, self-contained sensors often use batteries, there are severe power constraints on applications; it follows that encoding sensor data into XML and then encasing this data in a SOAP envelope is expensive, both in terms of CPU cycles and the number of bits transmitted across the wireless link. This suggests that a main challenge with integrating these low-power sensors is converting sensor data into the Web services architecture that OGSA specifies. Included in this challenge is converting data into XML (based on a schema) within a SOAP envelope and then using standard Internet protocols (SMTP, HTTP, FTP, and so on) to transport this data to applications.

In the next section, we suggest a data-collection network approach to address many of the technical problems of integrating resource-constrained wireless sensors into traditional grid applications. This network infrastructure, called Hourglass, can provide a grid API to a heterogeneous group of sensors, which, in turn, provide fine-grained access to sensor data with OSGA standards.

The Hourglass Data-Collection Network

Integrating sensor networks with existing information systems raises new challenges in terms of routing, aggregating, and querying diverse sensor network data. Applications might wish to process data from geographically distributed sensors across a range of sensing capabilities. The sensor nodes themselves might consist of tiny, resource-constrained motes or more powerful, wired systems with significant computing power. Different types of sensor data could be integrat-

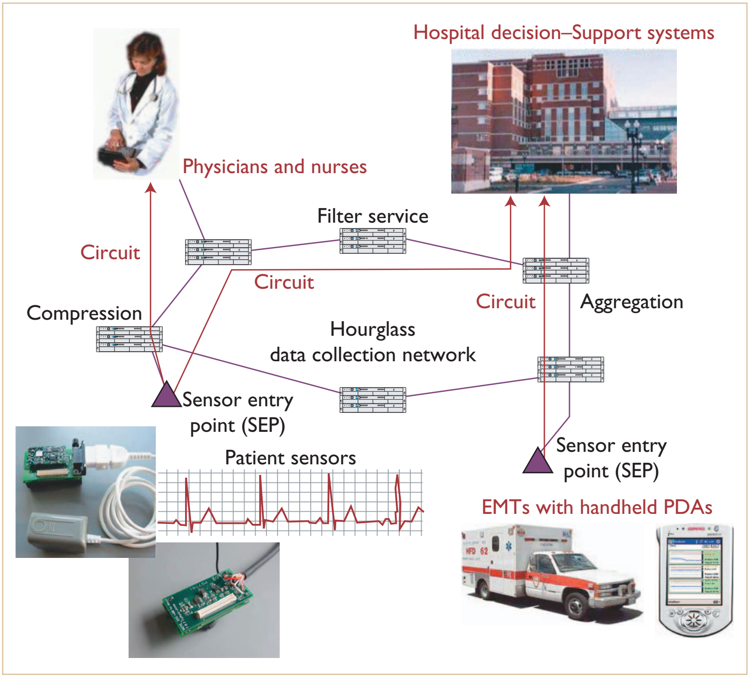

Figure 3. Hourglass: A sensor data collection network to integrate sensor data into grid applications.

ed into a single application. For example, a medical sensing network might involve patient vital-sign sensors, data culled from medical databases and laboratory results, and manual input by physicians and nurses.

To address these challenges, researchers at Harvard University, with one of the authors of this paper, are developing a robust, scalable data-collection network called Hourglass (www.eecs.harvard.edu/syrah/hourglass). Hourglass is a framework for collecting, filtering, aggregating, and storing sensor network data across several geographically diverse sensor networks. We intend it to serve as a common platform on which we can deploy multiple sensor network applications, decoupling the concerns of application data requirements from the specifics of pulling data from individual sensor networks.

Composition

As Figure 3 illustrates, Hourglass consists of three major components: the data collection network (DCN), sensor entry points (SEPs), and application entry points (AEPs). The DCN consists of a network of Internet-connected systems that discover, filter, and query multiple sensor networks. Each sensor network has one or more associated SEPs that map application data requirements onto low-level sensor network operations — by issuing a sensor-level query (as in TinyDB[5] or Cougar[6]), for example, or simply routing data from a sensor network to the DCN. AEPs are systems that provide application connectivity to the DCN, mapping application requests to DCN-based services to handle those requests.

The Hourglass DCN is based on a robust publish–subscribe network. Individual sensor networks, through the SEP, publish sensor data and metadata that describes what types of sensors the sensor network provides. An application can subscribe to one or more sensor networks and will receive a real-time data stream from each source. Apart from publish–subscribe, Hourglass supports a range of in-network services to facilitate efficient discovery, processing, and delivery of sensor network data, which include filtering, compression, aggregation, and storage of event streams in the DCN. Hourglass dynamically adapts to changing network conditions and node failures by allocating in-network services to nodes to meet performance and reliability targets. For example, to reduce bandwidth requirements, a filtering service can be instantiated near an event source to filter out noncritical or uninteresting events.

The Hourglass architecture leverages recent research in overlay networks[7] and peer-to-peer architectures[8,9] for constructing self-organizing, robust services from a collection of hosts distributed across the Internet. Our approach differs from previous work in that it focuses on real-time event delivery for sensor network applications, as well the use of in-network services permitting expressive queries across a range of sensor networks.

Goals

To support a wide range of novel applications spanning many geographically-diverse sensor networks, Hourglass has the following essential design goals.

Scalability. The system must support numerous sensor networks that act as sources of data streams, as well several applications that subscribe to sensor data. In addition, the DCN must support numerous core servers that provide event delivery, discovery, and other in-network services.

Robustness. DCN must be able to withstand failures of individual network links, core nodes, and endpoint systems. An important characteristic of sensor networks is that they might become temporarily disconnected due to wireless uplink fail-

Related Work in Data Collection Networks

The Hourglass approach draws from previous work on distributed systems, focusing on decentralized, peer-to-peer systems. The majority of work in this area has focused on the mechanics of distributed hash table (DHT) design,[1,2] distributed file systems,[1,3] and specific applications such as scalable multicast[4,5] and wide-area content distribution.[6,7] Hourglass pulls many of these ideas together into a system for distribution and filtering of real-time sensor network data. The focus on sensor data implies very different requirements in terms of traffic load, reliability, filtering, and processing than these existing systems.

Closely related to our approach are systems for querying sensor networks.[8] Systems such as TinyDB[6] and Cougar[8] allow users to express high-level queries in a dialect of SQL that collects and aggregates data within individual sensor networks. A query-processing engine runs on individual sensor nodes and is responsible for taking periodic sensor readings, combining those readings with nearby nodes, and routing results to a base station for delivery to the application. In contrast, Hourglass is focused on aggregating and querying data from across geographically diverse sensor networks. We are currently exploring the use of TinyDB as the interface between the Hourglass sensor entry point (SEP) and the sensor network itself.

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ures or channel fading caused by mobility. Hourglass must provide mechanisms for temporary buffering of data for later delivery when such a network becomes reconnected.

Security. The system must grant access only to authorized individuals, organizations, or service providers. To avoid performance or failure bottlenecks, authentication must be decentralized. In addition, different users could have differing access levels to the DCN.

Quality of service. The system must support varying degrees of quality of service (QoS) for sensor data delivery. For example, certain sensor data (such as earthquake or forest-fire detection) might require low-latency, highly reliable delivery, while other data (such as infrequent reports on environmental conditions) can tolerate certain degrees of network loss or delay. The infrastructure must be able to allocate network resources effectively to meet these QoS requirements.

Ability to innovate. The system should let researchers experiment at three layers: sensors, applications, and network infrastructure. Innovation is promoted when end users can develop new sensors and applications within a single, common network infrastructure.

Architecture

The current Hourglass prototype is based on a robust overlay network, similar to that of the Scribe[10] publish–subscribe framework. Scribe provides a robust, topic-based multicast service layered over a collection of Internet hosts implementing a distributed hash table (DHT). This model requires that applications know the fixed handle or identifier of the particular data stream from which they wish to receive information.

Obtaining stream identification keys is accomplished via the Hourglass discovery service, which allows the registration and discovery of published sensor data streams. Subscribers use an expressive query interface to discover sensor streams of interest; for example, an environmental researcher might wish to subscribe to information on all temperature sensor networks in a given geographic area. In our initial design, the discovery service provides a mapping from a sensor network metadata description (expressed in a common format such as WSDL) to a Scribe multicast address.

In-network services such as filtering, compression, aggregation, and storage run on DCN servers along the path that the publish–subscribe routing tree dictates. These services are instantiated on demand-based active subscriptions. A resource broker manages computational and network resources in the DCN core, determining the optimal placement of service components. For example, to optimize for network bandwidth, a filtering service could be instantiated on a core node near the corresponding publisher endpoint. Rather than allowing general-purpose core services, which might consume arbitrary computational resources, we constrain services to a fixed set of simple operators with bounded resource requirements.

General-purpose filters, aggregators, and compression mechanisms are straightforward to implement, and we believe that a combination of these operators will satisfy most application requirements. Any DCN core node with a modest local disk could provide storage of event streams for short periods of time (for example, maintaining a rolling log of an event stream's last several hours). On the other hand, permanent archiving of event streams requires significant storage resources. Rather than assuming every DCN node is provisioned for long-term storage, we assume that a small number of dedicated archive services will be present in the core.

The resource broker also handles differential QoS requirements for event delivery. Subscribers express their tolerances on latency and loss for each event stream; the network allocates network resources to meet these requirements. Because we anticipate running the DCN over the commercial Internet, which does not support QoS guarantees, QoS requirements must be met in an end-to-end fashion by each DCN node along the event-delivery path. This is similar to approaches such as Resilient Overlay Networks (RON)[7] that proactively select network paths to meet network QoS requirements. We assume that event streams through the DCN consume a modest amount of bandwidth (no more than tens of kilobits per second per stream) and that the number of simultaneous event flows through the core is modest (on the order of tens of thousands). Although we are concerned with reliable, real-time event delivery, we believe that the performance afforded by the commercial Internet is more than sufficient for these purposes. This is in contrast to network QoS approaches that are focused on streaming video, which has much more stringent requirements on latency and bandwidth.

We are exploring the use of Web services standards, such as OGSA, as the Hourglass infrastructure's application interface. Sensor network data streams can be described using WSDL and discovered at the application-level with WS-Inspection. Stream delivery between the DCN core and AEPs can use SOAP. We also intend to evaluate the use of WSDL, SOAP, and related protocols for coordination in the DCN core itself. Our primary concern is the network overhead imposed by these schemes and whether they are flexible enough to support the kinds of inter-node interaction the DCN requires. However, it should not be problematic for a Web services protocol to be exported to application entry points.

Conclusions

We are convinced that emerging sensor technology will support many application areas. As these small self-contained sensors become less expensive, and as better programming models become available, the breadth of applications that will use these tiny sensors will dramatically increase. A major difficulty in developing our applications has been the lack of nonstandard interfaces, and complex-programming models. We are, nevertheless, excited by the immense potential of this technology.

Integrating wireless sensors with the traditional wired grid infrastructure will allow the transfer of information about the physical world around us to a plethora of Web-based information utilities and computational services. The net result could be a network infrastructure that supports, yet pervades, everyday life in ways still unimaginable.

Acknowledgments

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