Sensors **2002**, *2,* 286-293

sensors
ISSN 1424-8220

http://www.mdpi.net/sensors

Invited Paper

The Development of Localized Algorithms in Wireless Sensor Networks

Hairong Qi*, Phani Teja Kuruganti and Yingyue Xu

Electrical and Computer Engineering Department, University of Tennessee, Knoxville, TN 37996

* Author to whom correspondence should be addressed. E-mail: hqi@utk.edu

Received: 13 July 2002 / Accepted: 17 July 2002 / Published: 22 July 2002

Abstract: Advances in sensor technology and wireless communications have made networked microsensors possible, where each sensor individually senses the environment but collaboratively achieves complex information gathering and dissemination tasks. These networked sensors, however, possess several characteristics that have challenged many aspects of traditional computer network design, such as the scalability issue caused by the sheer amount of sensor nodes, the infrastructureless network, and the stringent resource on-board the sensors. These new features call for a re-design of overall structure of applications and services. It has been widely accepted that practical localized algorithms is probably the best solution to wireless sensor networks. In this article, we discuss recent research results on localized algorithms design in supporting services and applications in sensor networks.

Key words: Localized algorithm, Wireless sensor networks, Energy-efficient communication, Collaborative signal and information processing

---

Introduction

Advances in MEMS, wireless communications, and digital electronics have made it possible to produce large amount of small-size, low-cost sensors which integrate sensing, processing, and communication capabilities together and form an autonomous entity. Large amount of these sensors can be quickly deployed in the field, where each sensor independently senses the environment but collaboratively achieves complex information gathering and dissemination tasks like intrusion detection, target tracking, environmental monitoring, remote sensing, global surveillance, etc. In an interesting article written by Kris Pister [15], he described his vision of sensor networks in 2010, "... *In 2010 your house and office will be aware of your presence, and even orientation, in a given room.*

Lighting, heating, and other comforts will be adjusted accordingly. ... In 2010 a speck of dust on each of your fingernails will continuously transmit fingertip motion to your computer. Your computer will understand when you type, point, click, gesture, sculpt, or play air guitar...". Although reads like a science fiction, researchers are starting to make progresses in making this come true. For example, the SmartDust project [16] at Berkeley pushes the size limit of sensors to an extreme - a cubic millimeter, such that these sensors can float in the air like dust; the WINS (Wireless Integrated Wireless Sensors) project at UCLA [17] and the WSN (Wireless Sensing Network) project at Rockwell Science Center [22] integrate multi-modality sensing devices and low-level signal processor on the microsensor, making it more intelligent and powerful; the Odyssey developed by the MIT SeaGrant Office is a low cost autonomous underwater vehicle (AUV) with a length less than two meters. It has been used for underwater surveillance and not requiring any special handling equipment for launch and recovery [1]. All these progresses in microsensor research have made it one step closer toward anytime, anywhere sensing which will eventually revolutionize the way we think and live.

Despite the exciting potentials presented by sensor networks, their unique characteristics have challenged many aspects of traditional computer networking design. Here, we summarize the advantages of sensor networks as well as the challenges from three points of view: scalability, dynamics, and stringent resource.

- Scalability issue and the distributed solution

As the cost of sensors becomes extremely low, it can be afforded to deploy large number of sensors in the field, e.g. hundreds or thousands. The sheer amount of sensor node causes scalability problem. A centralized approach sends data from each sensor to a fusion center (or processing center) where data processing and fusion are carried out. This approach works fine when the number of sensor nodes is relatively small and the data file needs to be transferred is not large. However, when the amount of sensor nodes goes to hundreds or thousands, the centralized approach will not scale. A natural solution to this problem is the distributed approach. Distributed sensor network (DSN) has been studied extensively since early 80s. Wesson et al [24] were among the first to propose the design of DSNs. Since then, several efficient DSN architectures have been presented in the literature, including the hierarchical and committee organization [24], the flat tree network [10, 18], the deBruijn based network [9], and the multi-agent fusion network [11]. All these approaches try to design a network structure such that it facilitates distributed data dissemination.

- Dynamics issue and the self-organization solution

Although DSN research can deal with the scalability issue, it is based on the assumption that the network structure will remain stable since it is constructed. The second unique feature of wireless sensor networks is that it is infrastructureless. Sensors, can be either static or mobile, are usually deployed in large amount which makes it very difficult, if not impossible, to have a pre-designed network structure. Furthermore, because of the limited power supply on each sensor node and the dynamically changing environment, existing sensors may die out, new sensors may be deployed. All of these factors make the sensor network a very dynamic environment. Previous research results from DSN which tend to design efficient network structures to help improve distributed data dissemination could not handle this kind of dynamics. The sensor network has to be self-organizable.

- Stringent resource issue and the localized algorithm solution

Sensor nodes usually compose of four basic units [2]: a sensing unit, a processing unit, a transceiver unit, and a power unit. The power unit supports all the activities on a sensor node, including communication, local data processing, sensing, etc. The lifetime of a sensor node is mainly determined by the power supply since battery replacement is not an option in sensor networks. The longer the lifetime of a sensor, the more stable the network. In order to save power, redundant activities should be reduced if not eliminated. For example, implosion problem should be avoided which is caused by using flooding protocols where multiple copies of the data might be transmitted to the same destination from different intermediate sources; communications should be constrained since it has been shown [14, 15, 21] to be the most power-consuming process. Efficient and intelligent usage of battery becomes a most challenging problem. In order to reduce redundancy and thus save power, localized algorithms seem attracting since only a subset of nodes in the network are invoked for a specific task. Localized algorithm is a special kind of distributed algorithm. How to choose the subset of sensor nodes to participate in a specific task is, however, a non-trivial problem.

The stringent resource issue also indicates low bandwidth supply and unreliable wireless links. How to achieve complex data dissemination tasks within the limit of the wireless communication networks is also a challenging problem.

In this article, the development of localized algorithms in sensor networks is discussed, including the localized networking services and the collaborative information processing applications. In order to develop efficient localized networking services, they have to be tightly coupled with the application. In another word, the network routing protocol design is moving toward application layer.

Localized Networking Service

Most localized networking algorithms have their origin from ants colony. Study [5] shows that although ants usually have only limited individual capacity for orientation, they are able to select with great reliability the shortest route between nest and food by interacting with each other through their trail pheromone. We discuss two representative localized algorithms specifically designed for sensor networks.

Directed Diffusion

Directed diffusion [4, 8] developed at ISI/USC and UCLA is a novel network protocol built for information retrieval and data dissemination. It is task specific and provides good support for event-driven applications like wireless sensor networks. One of its novel ideas is that it is “data-centric”, meaning routing is based on data contained in the sensor nodes rather than traditional IP theme where end-to-end delivery method is used based on unique identifications. In directed diffusion, data generated by sensor nodes are identified by their attributes. Sinks or nodes that request data send out *interests* into the network. If the attributes of the data generated by source nodes match these interests, a *gradient* is setup within the network and data will be *pulled* toward the sinks. Therefore, it is essentially a *receiver-initiated* routing protocol. Intermediate nodes are capable of caching and transforming data. Take target tracking as an example, when there is a target moving through the network, the sensor nodes could publish the signal energy and geographical information of the sensor as an attribute to the network, thus facilitating other nodes to know about the existence of the target in a certain geographical area.

Directed diffusion also facilitates the design of energy-efficient distributed sensing applications [8]. It provides Geographic and Energy Aware Routing Protocol (GEAR) which helps define a closed geographic region for propagating *interests* that improves performance by avoiding the *interest* messages to flood the entire network [23].

Sensor Protocols for Information via Negotiation (SPIN)

SPIN is developed at MIT [7, 12]. It is a protocol designed for wireless sensor networks and has several similarities with directed diffusion. SPIN names its data using high-level data descriptors, the *meta-data*, compared to the *interest attributes* used in directed diffusion. The meta-data and the raw data have a one-to-one mapping relation. The format of meta-data is application-specific. SPIN uses meta-data negotiations to eliminate redundant data transmissions over the network. Its two key innovations are *negotiation* and *resource-adaptation*.

In the SPIN protocol, the initiating node which has new data *advertises* the data to the neighboring nodes in the network using meta-data. When the neighboring node wants this kind of data, it sends a *request* to the initiator node for the data. The initiator node responds and *sends* data to the sinks. Therefore, SPIN is essentially a *sender-initiated* routing protocol.

Each node has its own resource manager to keep track of the usage of energy resource. Before data transmission, each node polls its resources to make a decision whether it should participate in the activity or cut it back. SPIN is essentially a flooding protocol, however, the use of meta-data for negotiation and the adaptation to resource available on the sensor nodes help it eliminate most of the redundant data transfer, making it more prudent in forwarding third-party data.

Comparison and Discussion

SPIN and directed diffusion are both application-specific and subject-based communication protocols for wireless sensor networks. Application-specific is the trend of networking service design in sensor networks. Resource management and energy-efficient routing has to be done tightly-coupled with application in order to achieve energy-efficient communication.

Both protocols, in contrast to the traditional routing protocols, are data-centric which means all communications are based on the named data. In directed diffusion the data is named or identified by the attributes and in SPIN the data is named by metadata.

Both protocols are designed to be a reliable communication medium. The SPIN protocol is developed to overcome the classic flooding by negotiating between the nodes before the actual data is transmitted. Thus SPIN is sender initiated data communication protocol.

In the case of directed diffusion, the receiver and sender diffuse interests onto the network and if the interest matches, then the sender publishes the data and the data is drawn down toward the receiving node. Therefore, in the directed diffusion protocol, the data communication is receiver-initiated.

Both protocols are energy-aware. In SPIN, the nodes poll the available resources and SPIN nodes can make decisions adaptive to the resource available. Similarly in directed diffusion, the Geographic and Energy Aware Routing (GEAR) helps in propagating interest messages to a specified geographical location defined by latitude and longitude, localizing the flooding in the network and helping to be more application specific. In a sense, both the protocols are flooding-based but vary from the classic-flooding due to the implementation of different mechanisms to control the unwanted flooding in the network.

Collaborative Information Processing Development

The March 2002 issue of IEEE Signal Processing Magazine [13] is specifically dedicated to collaborative signal and information processing (CSIP) in microsensor networks. CSIP is, first of all, a localized algorithm. Local sensors which will most likely contribute to the problem solving are selected. The selection process leverages resource constraint of the sensor node. The local processing of raw data over a few selected sensors presents a new challenge to information processing community. Researchers are working vigorously to try to answer questions like how to predict (select) sensor nodes with just local information, how to distribute the processing over the selected sensor nodes, how to achieve fault tolerance, etc. In this section, we discuss a few methods developed recently in this field. We assume that the CSIP algorithm will be developed on top of the localized networking services discussed in Sec. 2.

The Information-Driven Approach

PARC has developed an information-driven dynamic sensor collaboration for target tracking application [3, 25]. In order to achieve energy-efficient computing, it selects the next node which most likely improves the tracking accuracy based on both the information constraints and constraints on cost and resource consumptions. This application is built on directed diffusion as the communication medium.

Specifically, the approach formulates the tracking problem as a sequential Bayesian estimation problem. In order to estimate an unknown, each new sensor measurement is combined with the current estimate to improve the estimation accuracy. Therefore, the problem of selecting the next sensor can be formulated as an optimization problem. The sensor selection is based on the amount of information so as to maximize the information that the selected sensor would obtain. There can be only one sensor active at any given time doing the sensing, which proves to be very energy efficient on the sensor network.

The challenge is that in order to avoid communicating redundant or less useful information, the next node selection has to be done without explicit knowledge of the measurement. The decision has to be made solely based on the sensor characteristics of the current node and the *predicted* contribution of other sensors.

Mobile Agent Approach

The usage of mobile-agent-based computing paradigm in sensor networks is proposed in [19, 20]. Mobile agent is a special kind of software which can execute autonomously. Once dispatched, it can migrate from node to node performing data processing autonomously, while software can typically only execute when being called upon by other routines. In the context of sensor networks, the mobile agent is defined as an entity of four attributes: *identification*, *itinerary*, *data space*, and *method*, where identification is used to uniquely identify the mobile agent, data space is the agent's data buffer which carries the partially integrated results (this result should provide progressive accuracy as the agent migrates from node to node), itinerary is the route of migration, and method is the processing task (or execution code) carried with the agent.

In the mobile agent computing model, data stay at the local site, while the processing task is moved to the data sites. By transmitting the computation engine instead of data, the mobile agent model offers several important benefits: 1) Network bandwidth requirement is reduced. Instead of passing large amounts of raw data over the network, only the agent of small size is sent. This is especially important for real-time applications and where the communication is through low-bandwidth wireless connections; 2) Better network scalability can be achieved. The performance of the network is not affected when the number of sensor is increased. Agent architecture can support adaptive network load balancing automatically; 3) Extensibility is supported. Mobile agents can be programmed to carry task-adaptive processes which extends the capability of the system; and 4) Stability. Mobile agents can be sent when the network connection is alive and return results when the connection is re-established. Therefore, the performance of the system is not much affected by the reliability of the network.

Mobile-agent-based approach is similar to information-driven approach in the sense that it calculates its next hop on-the-fly based on information provided by neighbors at that moment. The calculation is based on the signal energy sensed at the sensor, the geographical local of the surrounding nodes, and the power status. It migrates to a node with more remaining power, stronger signal energy, and closer location. The mobile agent approach provides more stable performance and better fault tolerance than the information-driven approach, however, with the cost of more communication burden.

The Relation-Based Approach

A relation-based approach views the problem of sensing, tracking from a new angle. Instead of sensing the environment through extensive and detailed low-level data and solving the problem based on low-level signal processing, Guibas proposes to sense *relation* [6]. Relation-based approaches sense the environment based on high-level description of the task and then *command* selective sensor nodes to sense and communicate. The selection process results in minimizing the computational, communication, and sensing resources.

Relation-based approach provides us a new angle to solve collaborative information processing problems. If the information-driven and the mobile-agent approaches use a bottom-up approach for developing the tracking, then relation-based approach uses top-down solution, which might be more attractive since it is closer to how human thinks and behaves.

Summary

Because of the distributed, dynamic, ad-hoc, and energy-constraint nature of the sensor network, localized algorithms need to be developed for their scalability, robustness and energy-effectiveness advantages. Localized algorithms intelligently select necessary nodes for sensing, tracking, and reasoning to avoid flooding the network with useless or redundant data, and thus extend the lifetime of the sensor network. The selection of participating nodes can be most efficiently done if both the network services and the applications consider it.

References

1. Odyssey. MIT Sea Grant's AUV Lab, http://auvlab.mit.edu/
2. Akyildiz, F.; Su, W.; Sankarasubramaniam, Y.; Cayirci, E. Wireless sensor networks: a survey. *Computer Networks* **2002**, *38*, 393-422.
3. Chu, M.; Haussecker, H.; Zhao, F. Scalable information-driven sensor querying and routing for ad hoc heterogeneous sensor networks. *International Journal of High Performance Computing Applications* **2002**.
4. Estrin, D.; Govindan, R.; Heidemann, J.; Kumar, S. Next century challenges: scalable coordination in sensor networks. *Intl. Conf. on Mobile Computing and Networking (MobiCom)* **1999**, 263-270.
5. Goss, S.; Aron, S.; Deneubourg, J. L.; Pasteels, J. M. Self-organized shortcuts in the Argentine ant. *Naturwissenschaften* **1989**, *76*, 579-581.
6. Guibas, L. J. Sensing, tracking, and reasoning with relations. *IEEE Signal Processing Magazine* **2002**, 73-85.
7. Heinzelman, W. R.; Kulik, J.; Balakrishnan, H. Adaptive protocols for information dissemination in wireless sensor networks. *MobiCom* **1999**.
8. Intanagonwiwat, C.; Govindan, R.; Estrin, D. Directed diffusion: a scalable and robust communication paradigm for sensor networks. *MobiCom* **2000**.
9. Iyengar, S. S.; Jayasimha, D. N.; Nadig, D. A versatile architecture for the distributed sensor integration problem. *IEEE Trans. Comput.* **1994**, *43(2)*, 175-185.
10. Jayasimha, D. N.; Iyengar, S. S.; Kashyap, R. L. Information integration and synchronization in distributed sensor networks. *IEEE Trans. Syst., Man, Cybern.* **1991**, *SMC-21*, 1032-1043.
11. Knoll, A.; Meinkoehn, J. Data fusion using large multi-agent networks: an analysis of network structure and performance. *Proceedings of the International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI)* **1994**, 113-120.
12. Kulik, J.; Heinzelman, R. B.; Balakrishnan, H. Negotiation-based protocols for disseminating information in wireless sensor networks. Submitted to *ACM Wireless Networks* **2000**.
13. Kumar, S.; Zhao, F.; Shepherd, D. Collaborative signal and information processing in microsensor networks. *IEEE Signal Processing Magazine* **2002**, 13-14.
14. Meguerdichian, S; Slijepcevic, S; Karayan, V; Potkonjak, M. Localized algorithms in wireless ad-hoc networks: location discovery and sensor exposure. *MOBIHOC* **2001**.

15. Pister, K.; My view of sensor networks in 2010. http://www.eecs.berkeley.edu/~pister/SmartDust/in2010
16. Pister, K. Smart Dust: Autonomous Sensing and Communication in a Cubic Millimeter, http://robotics.eecs.berkeley.edu/~pister/SmartDust/
17. Pottie, G. J.; Kaiser, W. J. Wireless integrated network sensors. *Communications of the ACM* **2000**, *43(5)*, 51-58.
18. Prasad, L.; Iyengar, S. S.; Kashyap, R. L.; Madan, R. N.; Functional characterization of sensor integration in distributed sensor networks. *IEEE Trans. Syst., Man, Cybern.* **1991**, *SMC-21*, 1082-1087.
19. Qi, H.; Iyengar, S. S.; Chakrabarty, K. Multi-resolution data integration using mobile agents in distributed sensor networks. *IEEE Trans. Syst., Man, Cybern. C* **2001**, *31(3)*, 383-391.
20. Qi, H.; Wang, X.; Iyengar, S. S.; Chakrabarty, K. High performance sensor integration in distributed sensor networks using mobile agents. *International Journal of High Performance Computing Applications* **2002**.
21. Raghunathan, V.; Schurgers, C.; Park, S.; Srivastava, M. Energy-aware wireless microsensor networks. *IEEE Signal Processing Magazine*, **2002**, 40-50.
22. Rockwell. Wireless Sensing Network (WSN), http://wins.rsc.rockwell.com/
23. Silva, F.; Heidemann, J.; Govindan, R. Network Routing Application Programmer's Interface (API) and Walk Through 9.0.
24. Wesson, R.; Hayes-Roth, F.; Burge, J. W.; Stasz, C; Sunshine, C. A. Network structures for distributed situation assessment. *IEEE Trans. Syst., Man, Cybern.* **1981**, *SMC-11(1)*, 5-23.
25. Zhao, F.; Shin, J.; Reich, J. Information-driven dynamic sensor collaboration for tracking applications. *IEEE Signal Processing Magazine* March **2002**.

Sample Availability: Available from the author.