Virtual Sensor Networks - A Resource Efficient Approach for Concurrent Applications

Anura P. Jayasumana
Dept. of Electrical and Computer Engineering
Colorado State University
Anura.Jayasumana@colostate.edu

Qi Han
Dept. of Math and Computer Sciences
Colorado School of Mines
qhan@mines.edu

Tissa H. Illangasekare
Division of Environmental Science and Engineering
Colorado School of Mines
tissa@mines.edu

Abstract

Current focus of sensor networks is on systems dedicated for a specific application. Wide variety of circumstances point to the need for sensor network deployments capable of sharing the physical network resources. We introduce the concept of Virtual Sensor Networks (VSN) to provide protocol support for the formation, usage, adaptation and maintenance of subsets of sensors collaborating on specific tasks. VSN concept also promises to enhance applications that involve dynamically varying subsets of sensor nodes collaborating tightly to achieve the desired outcomes, while relying on the remaining nodes to achieve connectivity and overcome the deployment and resource constraints. This article explores the concept, mechanisms, and benefits of using VSN. Examples of VSN support functionality include support for nodes to join and leave VSNs, broadcast within a VSN, and merging of VSNs. VSNs will simplify application deployment, enhance performance and scalability, facilitate resource sharing, and provide a degree of physical topology independence in wireless sensor networks. Deployment of overlapping sensor networks aimed at different tasks, especially in harsh environments, will also significantly benefit when organized as VSNs over a shared infrastructure

1. Motivation

Continuing advances in the computational power, radio components, and reduction in the cost of high- performance processing and memory elements has led to the proliferation of portable devices (e.g., intelligent sensors, actuators, and sensory prosthetics) with substantial processing capabilities. Such devices are rapidly permeating a variety of applications domains such as avionics, environmental monitoring, structural sensing, telemedicine, space exploration, and command and control. Perhaps the single largest catalyst has been the emergence of micro-sensor nodes (e.g., Mica motes from Crossbow, Tmote Sky from Moteiv, the MKII nodes from UCLA, SunSpot from Sun, etc.) that integrate computation, networking, and sensing capabilities into a single device [6]. By providing the ability to monitor phenomena in close proximity with multihop wireless communication (enabled by on-board radios) such devices have created the possibility to build reactive systems that have the ability to monitor and react to physical events/phenomena. Given the importance and potential of the impact of sensor technologies, over the past decade, significant progress has been made on techniques to architect and program large-scale sensor systems. Important developments include design of light-weight operating systems for sensor devices, powerful programming frameworks that isolate application logic from the complexities of optimizing the computation over sensor networks, techniques for in-network processing that exploit computational resources at the sensors to reduce communication and preserve energy.

While substantial progress has been made, current research has primarily considered dedicated sensor networks each supporting one specific application. Such systems are being developed for a vast array of applications ranging from monitoring environmental phenomena, monitoring animals, location and tracking of targets, and emergency rescue [2, 8]. Reasons for using dedicated sensor networks include the limited sensing, processing, and communication abilities of the nodes, severe power constraints, and most of all, the lack of algorithms, protocols, and techniques for deploying complex sensor networks. Dedicated sensor networks are also considered to be simpler to implement as all the system resources and implementation effort can be focussed on the specific application. Research into and deployment of these dedicated sensor networks have provided a knowledge base, covering areas such as distributed algorithms - for detection, estimation, optimization and learning [9] power control strategies, and networking protocols [1], laying a solid foundation on which to realize the full potential of wireless sensor networks.

Independent sensor networks each dedicated to a specific task, however, may not be the best, most cost efficient, or the most practical deployment technique under a wide variety of conditions, e.g, for deployment of large-scale networks having thousands of nodes or covering large geographical areas or even crowded urban areas or difficult terrains. This paper describes the concept of virtual sensor networks (VSN), an approach for efficient resource sharing in sensor networks under such conditions. VSNs are in fact useful for implementing certain dedicated applications as well and we discuss two such application in detail in Section 2 and present several possible strategies to implement a VSN in Section 3. The subset of functions required to support VSNs is outlined in Section 4.

2. Virtual Sensor Networks (VSN)

A Virtual Sensor Network (VSN) is formed by a subset of sensor nodes of a wireless sensor network (WSN), with the subset dedicated to a certain task or an application at a given time. In traditional dedicated sensor networks, all the nodes in the network collaborate more or less as equal partners to achieve the end result. In contrast, the subset of nodes belonging to the VSN in the subset collaborate to carry out a given application.Thus VSN depends on the remaining nodes providing VSN support functionality to create, maintain and operate VSNs. With the proposed approach, multiple VSNs may exist simultaneously on a physical wireless sensor network, and the membership of a VSN may change over time. As the nodes in a VSN may be distributed over the physical network, they may not be able to communicate directly with each other. Figure 1 is an example of two Virtual Sensor Networks over a physical sensor network infrastructure. We next use two examples to present the concept of VSN and explain the VSN support functionality needed for their realization.

Example 1: Geographically overlapped sensing applications

Consider two sensor-network based systems, one for warning of rock slides and the other for warning of presence of wildlife, both to be deployed on a section of road passing through a mountainous terrain. With the traditional approach, these functions would be carried out by two sep-

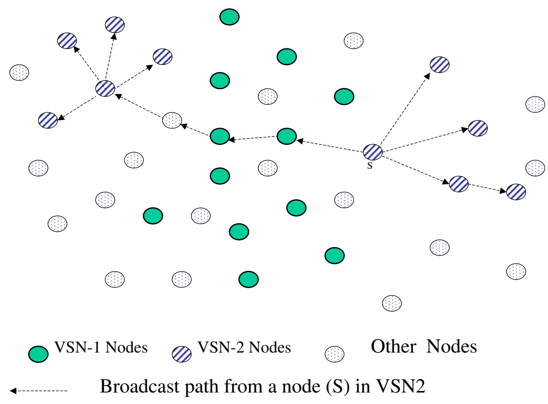

Figure 1: An example of two VSNs over the same physical sensor network infrastructure.

arate sensor networks. Resource sharing between these two systems can result in significant efficiencies. By resource sharing, we do not mean that each node implement both the functionalities as that would effectively mean a dedicated sensor network with its functional specifications redefined to include both warning functions. Instead what we refer to here is the existence of two sensor networks in a symbiotic relationship providing one's resources to the other and using the resources of the other in such a way as to benefit both the systems.

Consider as an example routing of messages in a sensor network. Sensor networks typically use multi-hop transmissions due to constraints on transmit power; it results in significant power savings and is often the only way to cover a large area. With two independent networks, the nodes in each network have to be deployed at a certain density; the nodes detecting rock-slides will have to be placed even in places where there are no rocks, and in fact power constraints may dictate where the nodes should be placed instead of application constraints. There are other reasons as well, such as fault tolerance, for these two networks that overlap partially in physical space to share resources to a limited degree, resulting in efficient resource usage and better performance attributes. However, this symbiotic relationship has to be achieved without sacrificing the advantages of individual dedicated sensor networks, especially the relative ease of development of an application running over a dedicated set of nodes. With a VSN based implementation, certain nodes will be engaged in tracking wild life, others tracking rock slides, and yet others providing communication support. The VSNs membership of nodes may change with time and external events. If a third set of VSN capable sensor nodes for rainfall measurements is deployed in the same area, for example, these nodes become a part of the existing physical network, and use its resources for implementing the rainfall measurement related functionality while supporting other nodes in providing VSN support functions.

Example 2: Underground contaminant plume tracking

Next we describe a sensor network dedicated to one application, yet one that benefits by the use of VSN concept. A chemical plume can be considered as a 3-D transient phenomenon that is spatially and temporally distributed, and which evolves in its intensity and extent. Hence, it is different from a phenomenon that is time varying in a fixed region (such as temperature/humidity changes in a room), or a phenomenon that varies in locations but not extents (such as a mobile object). For instance, plumes can change their configuration/shapes as a result of not only migration but also remedial treatment. In other words, two plumes can merge into one, and one plume can also be separated into two. As a result of this, a sensor node should adapt to plume dynamics and change its functionality to either active sensing (when they are embedded in plumes) or passive listening (when they are emerged out of plumes). This further implies that the sensor nodes should self-organize themselves to ensure that the right set of nodes collaborate at the right time for sensing and tracking a given plume, and the collected data can be delivered to the appropriate nodes, or perhaps even a remote server, for processing in an energy efficient manner. When two plumes merge, the corresponding VSNs will also merge to form one VSN tracking the newly formed plume. Similarly, breakup of a large plume into different plumes should result in the partition of VSN into multiple VSNs.

The sensor network for the three-dimensional transient plume is based on a two-tier sensor network consisting of a set of surface sensor nodes (S-nodes) and strings of sensors (W-nodes) placed within each well in a vertical array as shown in Figure 2. Each string array consists of sensors (W-nodes) placed at different depths measuring different variables (pressure, concentration, temperature, etc.). The node on the surface (S-node) at each well, in addition to monitoring, serves as a computation and communication node on behalf of the corresponding W-nodes. The S nodes form a self-configuring wireless network. Each node is at a fixed location, and the knowledge of its geographical location information is available for the application. W-nodes affected by a transient plume detect levels of concentration and pressure.

As Figure 2 indicates, the sensor nodes monitoring a plume are not necessarily adjacent in terms of connectivity. This subgroup and any other sensors of interest for tracking this plume (for example downstream nodes) are to be considered as a virtual sensor network. The shape and concentration profile of the plume as well as its migration path dictates the membership of the VSN. As the plume migrates,

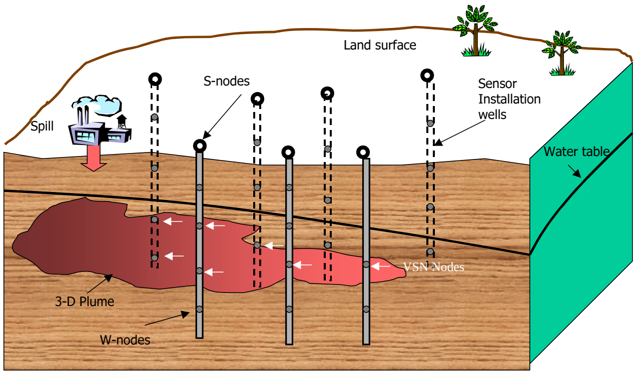

Figure 2: Physical Sensor Network Deployment for 3D transient plumes monitoring. The W-nodes within and on the boundary of the plume form a virtual sensor network (VSN). The remaining nodes provide VSN support services, such as routing among nodes in the VSN. The VSN will change with and in anticipation of plume movement.

the membership of VSN changes. The sensor network, by itself or based on prediction of models, alerts additional sensor nodes in the predicted and possible paths. The plume monitoring task thus will be based on the concept of Virtual Sensor Networks (VSNs), where multiple VSNs exist on a physical sensor network. While some of the nodes in a VSN may be able to communicate directly with each other, the VSN may consist of multiple zones, where communication between zones have to rely on nodes that are not members of the VSN. Thus providing communication support for maintaining the VSN is a key support function that is necessary.

The membership in VSN is dynamic, and the communications among VSN nodes frequently rely on other nodes. Functionality expected of a node will be dependent on whether or not it is currently a member of a VSN. Those that are not in the VSN need to support the maintenance of VSNs, while those within the VSN need to carry out tasks such as profile detection, pattern recognition, and tracking.

3. Implementations of VSN

In this section, we address challenges raised by the need to deploy large networks, e.g., to cover a large area, subject to various deployment constraints such as those on network topology, in an efficient and a scalable manner. By making available the functionality that would allow a subset of nodes in a wireless sensor network (WSN) to behave as if they were on their own independent sensor network, even though the communication among these nodes occurs via nodes not belonging to the subset, implementation of sensor network applications will be significantly simplified.

We are currently developing a set of algorithms, protocols and software that would provide the functionality necessary to support groups of nodes forming such Virtual Sensor Networks (VSN). The subset of nodes in a particular VSN will collaborate tightly to carry out the application specific functionality. This subset of nodes need not form a directly communicating subset of nodes, as the remaining nodes are expected to provide communication functionality necessary to maintain this subset.

A main reason for the current research focus on dedicated sensor networks is due to the hardware limitations, e.g., memory, processing, communication and sensing capabilities. While this will remain true for many sensor network deployments, not all the sensor networking applications and deployments have to be constrained so as to not to be able to carry out broader functionality. Hardware platforms with significant capabilities have appeared during the past few years. iBadge platform [4] for example, has sensors capable of sensing acceleration, magnetic field, pressure, humidity, light and sound on a single platform. Stargate from Crossbow is another example of a sensor platform with significant computation and storage capability. Certain platforms also provide interfaces that can be used to expand its computation and storage capabilities. Such versatile nodes could be members of different VSNs at different times. Many future sensor network deployments are likely to consist of heterogeneous nodes. Not all the nodes in a network have to be power constrained to the same extent. If certain nodes are less power limited than others, for example due to the use of solar or some other harnessing scheme, it is possible to make such nodes participate in the VSN and assume a greater computation and communication load, thus reducing the load on nodes with more limited capabilities.

To support multiple applications on the same physical sensor network, there are several different approaches. One technique is to mimic TDMA and enforce different parts of the network to be active for different applications at different times. While this is easy to implement, the scheduling of multiple applications makes this approach artificial, inefficient and sometimes impractical. Another approach is to use different radio channels for different applications. The limitation of this approach is its reliance of the hardware of sensor nodes; in addition, the number of concurrent applications is bounded by the number of existing radio channels. Most of the current platforms as well as the emerging IEEE 802.15.4 standard for sensor networking [7] can support both these approaches. However, the use of separate time slots or frequency channels imply that each network operating in a separate slot/channel has to work independent of other channels, i.e., they appear as a set of logically separate networks. This results in duplicated efforts for functions such as routing, thus resulting in inefficient use of resources. Furthermore, due to the fact that the members of a VSN may not be within the transmission range of others in the VSN, it may not always be possible to provide the node connectivity necessary with these approaches. The third approach is to rely on a shared communication channel (in time and frequency) for all the nodes as in the traditional dedicated sensor networks, yet provide VSN support using appropriate algorithms and protocols.

Other key issues involved in the implementation of VSN include:

- how to dynamically determine which node should join which VSN?
- how to maintain and support constant changes in the membership of VSN?
- how to ensure energy efficient communication between disjoint VSN segments?

We next elaborate on the different functions to be provided by our VSN design.

4. VSN Support Functions

The major functions of VSN can be divided into two categories: VSN maintenance and membership maintenance. The membership in VSN is dynamic, and the communications among VSN nodes frequently rely on other nodes. Functionality expected of a node will be dependent on whether or not it is currently a member of a VSN. Those that are not in the VSN need to support the maintenance of VSNs, while those within the VSN need to carry out tasks such as profile detection, pattern recognition, and tracking. The VSN maintenance functions include:

- adding and deleting nodes (decision made by nodes other than that being added/deleted),
- nodes entering and leaving VSN (decision made by node itself),
- broadcast within VSN,
- join two VSNs (ex. when two plumes merge),
- splitting VSNs (ex. plume broken into parts), and
- deriving contours of boundaries.

The supporting nodes (i.e., nodes that do not belong to the VSN at present) need to provide efficient message exchanges among the sensor nodes for implementation of those functions. These functions have to be implemented with minimal overhead, while taking other limiting factors in wireless sensor networks into account.

In addition, efficiently managing the membership changes in the VSN is critical for energy conservation. Sensors have different role assignments in the context of plume monitoring. For instance, sensors within the VSN actively participate in sensing for profile detection, pattern recognition and tracking; sensors outside the VSN may help relay data from VSN members to the server, or simply remain asleep, depending on whether or not they are on the path to the server. Different roles may impose different burdens on nodes. For example, nodes within the VSN consume more energy due to sensing and communicating its own readings to the server. These different sensor roles must be taken into account in supporting real-time plume monitoring, since nodes with certain critical roles may affect application level quality to a high degree while overburdened nodes might be more liable to energy starvation. Moreover, these roles need not be statically assigned to nodes in the system, since sensor roles will be changed when the VSN membership changes. Existing research has shown that optimal sensor network lifetime can be achieved by assuming an optimal sequence of feasible role assignments for each node, where the roles are sensing, relay and aggregator [3]. Instead of maximizing sensor network lifetime, we aim to achieve the best monitoring quality while minimizing energy consumption. We plan to use plume monitoring as a driving application to determine optimal sensor role assignment strategy. This strategy can be realized by using the generic framework for assigning roles in sensor networks [5]. Furthermore, the application-aware role assignments provide a guideline for sensor state transitions (i.e., switching among different power saving states), which can further be used to drive MAC layer protocols. We expect that the integrated application driven network self-organization, sensor role assignments and sensor state management will ultimately meet the requirements from plume monitoring while minimizing sensor energy consumption.

5. Conclusion

The concept of virtual sensor networks over wireless sensor networks will result in sensor networking protocols and data processing algorithms that would have wide applicability, especially in environments where multiple geographically overlapping sensor networks are deployed. In this case, the concept of VSN allows the different sensor networks in the area to operate as VSNs, but make use of nodes (e.g., those that are not power limited) from other sensor networks in the neighborhood. VSN support will simplify application deployment, enhance performance and scalability, facilitate resource sharing, and provide a degree of physical topology independence in wireless sensor networks. The protocols and algorithms for VSN will provide for formation of VSNs, communication functions such as broadcast and anycast among nodes, and adding and dropping nodes from VSN. Efficient implementation of this functionality is key to the success of the proposed approach. New application deployment will be simplified, for example, due to the fact that nodes implementing new application-specific processing can be intermixed with existing nodes. Performance and scalability enhancements can be expected due to the fact that the distributed data processing algorithms can run in the appropriate subset of nodes. We anticipate VSNs to play a key role in emerging sensor based infrastructure.

Acknowledgements

This research is supported in part by a grant from Environmental Sciences Division, Army Research Office (AMSRD-ARL-RO-EV).

References

[1] Al-Karaki J.N. and Kamal A.E., “Routing Techniques in Wireless Sensor Networks,” IEEE Wireless Communications, Dec. 2004.

[2] Akyildiz, I. F., Su, W., Sankarasubramaniam, Y. and Cayirci, E., ”Wireless Sensor Networks: A Survey,” Computer Networks, Vol. 38, 2002.

[3] Bhardwaj M. and Chandrakasan A.,“Bounding the Lifetime of Sensor Networks via Optimal Role Assignments”, Proceedings of IEEE Infocom, 2002

[4] Chen, A., Muntz, R.R., Yuen, S., Locher, I., Sung, S.I., and Srivastava, M.B., ”A Support Inftrastructure for the Smart Kindergarten,” IEEE Pervasive Computing, Vol. 1, No. 2, April-June 2002.

[5] Frank C. and Romer K., “Algorithms for Generic Role Assignment in Wireless Sensor Networks”, Proceedings of ACM SenSys, 2005

[6] Hill, J., Horton, M., Kling, R., Krishnamurthy, L., “The Platforms Enabling Wireless Sensor Networks,” Communications of the ACM, Vol. 47, No. 6, June 2004.

[7] IEEE, ”IEEE 802.15.4 Standard Specification for Low-Rate Wireless Personal Area Networks (LR-WPANs),” 2003.

[8] Romer K., Mattern, F. and Zurich E., “Design Space of WSNs,” IEEE Wireless Communications, Dec. 2004

[9] Sayeed, A., Estrin D., Pottie, G., Ranchandran, K., and Pursley M.B., “Self-Organizing Distributed Collaborative Sensor Networks,” IEEE J. Selected Areas in Communications, Vol. 23, No. 4, April 2005.