Integration of Wireless Sensor Networks, Wireless Local Area Networks and the Internet

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Abstract - *Future wireless networks are envisioned to be pervasive and ubiquitous. The integration of wireless sensor networks with wireless local area networks and the Internet is an important issue of future wireless networks. This paper has identified three challenges in the integration of wireless sensor networks with wireless local area networks and the Internet: (i) reliable communication issue among sensors, actuators, and applications under the energy-conservation constraints, (ii) time-synchronization issue, and (iii) system architecture issue. Solutions for those challenges are presented and a resulting integrated system has been illustrated.*

Keywords: Sensor networks, wireless local area networks, the Internet, system integration.

1 Introduction

Future wireless networks are envisioned to be pervasive and ubiquitous considering recent development of small-size, low-cost, highly-sensitive sensors and low-power inexpensive wireless communication radios to enable wireless sensor networks [1]. Sensors or sensor nodes, in general, have sensing, data processing, and communication functionality. A wireless sensor network is a self-organizing cooperative ad hoc network that is composed of a set of planed or randomly deployed sensors, which are sensitive to the variation of their surrounding environment and capable of communicating with each other through their wireless channels [2].

Wireless sensor network research has been undergoing a quite revolution, promising to have significant impact on a broad range of applications relating to safety and security, health care, environment, energy, food quality, and manufacturing [3]. The coming years will likely see a growing reliance on and need for more powerful sensor systems, with increased performance and functionality [4-5]. In this paper, an advanced medical home powered by wireless sensor networks is used as an illustrative application scenario.

A medical home tries to monitor its residents' health conditions and report the data to local or remote healthcare specialists and/or physicians if necessary. An advanced medical home will be composed of (*i*) typical sensors, such as temperature sensors, thermometers, microphones, and video cameras; (*ii*) advanced sensors, such as body temperature sensors, pulse oximeters, body position monitors, electrocardiogram (ECG) sensors, and blood pressure sensors; and (*iii*) actuators, such as medical devices, speakers, and video displays. The computational units within the sensors and actuators run applications that take the sensor data as input and produce data for the actuators and/or other applications, e.g., a heart monitoring application. Because of the mobility of the resident, wireless sensors are essential components in the medical home system. Also wireless local area networks are becoming more and more popular in home networking infrastructure. Thus there is an increasing possibility that the wireless local area networks will act as backbones in the advanced medical home scenario to connect the body and environment sensor networks to the Internet so that physicians and medical systems can remotely monitor and diagnose the health conditions of the local residents in the medical home. Figure 1 extends it to advanced home networking.

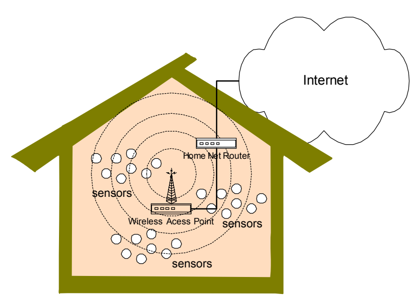

Figure 1. Advanced home networking scenario

Besides the advanced medical homes, there are a lot of applications, not only in the civilian scenarios mentioned above but also military ones, which need the integration of wireless sensor networks, wireless ad hoc [6-8] or local area networks, and the Internet.

2 Challenges

Based on the medical home example and other application scenarios in which we are conducting research, e.g., networked earthquake engineering simulations and large infrastructure monitoring, three major challenges have been identified in the integration of wireless sensor networks with wireless local area networks and the Internet: (*i*) reliable communication issue among sensors, actuators, and applications under the energy-conservation constraints [9], (*ii*) time-synchronization issue [10], and (*iii*) system architecture issue [11-12].

2.1 Energy-conserving reliable communication

The communication of the integrated system of wireless sensor networks, wireless local area networks, and the Internet includes data-collection/task-dissemination from/to the wireless sensor networks. The reliability of the communication includes the robust data collection under severe node conditions and destination-reachable command dissemination under limited energy constraints, considering the sensor node mobility and/or harsh working environment.

The advantage of small-size, low-power characteristics of sensor nodes brings the resource-limitation constraints when we design protocols and applications based on the wireless sensor networks. The constraints include relatively small wireless bandwidth, low CPU processing power, small amount of memory, and limited battery lifetime. Some of those limitations are disappearing due to technology improvements. For example, the CPU speed has increased almost 400 times during the past decade [13]. However, the limitation of the battery lifetime will be long-time factors contributing to the resource-limitation constraints. Therefore energy-conservation issue is critical.

2.2 Time synchronization

Time synchronization is also a critical issue in the integration because of the following reasons [14-16].

- The application scenarios of the integrated system are real-time. For example, in an earthquake simulation or in-situ environment, the critical phenomena observation time only lasts for a period of seconds. It is desirable to record data from different sensors with timestamps in an accuracy of milli-second, if not micro-second, and analyze the data in an integrated way. Therefore real-time data collection requires time-synchronization function at each sensor node.

- Data fusion [17] as a basic function of wireless sensor network also requires time synchronization. In a lot of cases, sensors are deployed in a dense fashion so that when an event happens multiple sensor report the observed phenomena at the same time. By using time-synchronization, redundant messages can be recognized and suppressed to reduce the unnecessary data traffic across the sensor networks to save energy.

- Time-synchronization can be used to realize synchronized sleep periods. To conserve battery energy of wireless sensor nodes, it is desirable to put the sensor nodes into sleeping mode and wake them up only to exchange information when necessary. Synchronization is needed here to wake up the sensor nodes at the same time.

- The list of the above-mentioned reasons is not a complete one. There are other reasons such as using accurate timestamp for some encryption algorithms to provide security services in the wireless sensor networks and synchronizing time for collaborative tasks across the integrated networks.

2.3 System architecture

Another important issue is the system architecture issue in the integration, including software architecture and hardware architecture. Once there are pieces of functionality realized by various components, such as time synchronization protocol and routing protocols in the wireless sensor networks, the next issue is how to integrate them together to make the integrated system compatible with the software and hardware architecture of the existing wireless local area networks and the Internet.

The future wireless networks are envisioned to have extensive communication and collaboration among laptops, handheld devices, and the wireless sensors across the integrated networks. Thus an obvious system architecture requirement is to have the system flexibility to support heterogeneous devices, such as Palms. Also protocol flexibility is important to enable the integrated system to take advantage of salient features of different protocols targeting different application scenarios. In other words, the protocol flexibility will be helpful for the system's compatibility, extensibility and performance.

Note that the domain of the first challenge is mostly within the wireless sensor networks, and the second and the third ones are across the whole integrated networks. For example, there is a multi-level time synchronization mechanism, called Network Time Protocol (NTP), in the Internet, and corresponding research on time synchronization in the mobile ad hoc networks. How to integrate those protocols to make them interact seamlessly is an important issue across the integrated networks.

3 Solutions

In our research, energy-efficient reliable routing approaches are designed for the robust data-collection/task-dissemination from/to the wireless sensor networks; a lightweight protocol is devised to realize global time synchronization in the wireless sensor networks considering the limitations of existing protocols in the Internet and wireless sensor networks; and a prototype system for the integration has been implemented based on heterogeneous collaborative architecture.

3.1 Energy-efficient reliable routings

There already exist many routing protocols designed for the application context of wireless sensor networks [18-22]. Some of them are revisions from protocols that have already gained success in wireless or wire-line networks. Others are developed from the ground up to fit the new communication scenarios. They have salient features, e.g., decentralized architecture that requires no central control node to handle the global network establishment, management, and maintenance and optimization tasks. Other features include resource-awareness and data-centric properties.

However, there are two implicit assumptions used in the previous routing protocol design, which is NOT appropriate for future wireless network integration. One assumption is that there is a relatively reliable sensor node condition. In a lot of application scenarios, such as earthquake observation, interested events may come together with destruction to the sensor nodes. Therefore it is important that the routing protocol remains its good performance under high node failure ratio condition. The other is that the network can provide sufficient throughput during most of the interested period of time. However, in some applications, the network traffic generated by the events generally behaves in a bursty manner. During the interested period of time, huge amount of data from a small area may need to be reported and go far beyond the system transmission capacity. This raises the problem of data buffering. The question is: whether to buffer data at individual nodes then take the risk of losing packets at bottleneck nodes in routing, or distribute packets in a wider area within the network and take advantage of the network capacity.

Considering these concerns about reliable routing, two protocols have been developed to handle the one-to-many communications, e.g., interest distribution or task assignment, and one-to-one communications, e.g., sensor data reporting.

3.1.1 Flossiping

The first protocol is called flossiping [23], which is a controllable combination of flooding and gossiping. In flooding, a new piece of information will be broadcasted by a node to all its neighbors and relayed by the neighbors. This will guarantee the shortest path to the destination, and thus the optimal delay characteristic. However, it produces overlap and explosion problems, thus wastes significant amount of power. In gossiping, only a randomly selected neighbor will relay the piece of information to reduce the power consumption at the cost of delay because of the increased average number of hops to the destination.

The idea behind flossiping is combining the flooding and gossiping to create a simple and flexible protocol in delay-power tradeoff. Specifically we use a single branch gossiping and a controllable low-probability random selective relaying and let each sensor node decide its own activity in the routing procedure to achieve a resource-aware routing. The relaying branch is controlled by time-to-live (TTL) such that the overall power consumption can be constrained. The gossiping branch is not controlled by TTL and the gossiping process will not stop until the packet reaches its destination, which guarantees the reliable packet delivery.

Analyses and simulations have justified that: flossiping can provide a reliable solution for information delivery and flexible delay-power tradeoff capabilities. For example, Figure 2 shows that there are optimal values of the probability for the relaying branch to achieve optimal delay-power tradeoff by adjusting THrsr that is a threshold value assigned by the source to control the procedure of low-probability random selective relaying of the gossiping branch.

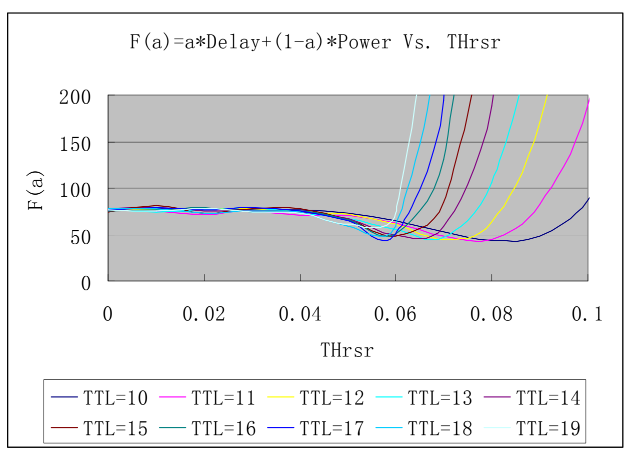

Figure 2. Delay-power combined performance functions vs. a control parameter THrsr of Flossiping

3.1.2 Self-nominating

The second protocol is called self-nominating [24], which is used for a sensor node to report data to a sink. It leaves the routing decision to each node of a sender's neighborhood, which is within the coverage of the sender's wireless communication signal. The sender just broadcasts the data packet to its neighbors, and passively listens to any feedback to make sure that the packet is properly handled.

If a neighbor receives the packet from the sender, it will determine a random number based on its characteristics, such as its distance to the data sink and its remaining battery power. The shorter the distance, the smaller the random number will be. And the lower the power, the larger the random number will be. This random number is used to control a timer. When the timer expires, which means that the received packet has not been relayed by other neighbor node yet (as explained below), it will trigger the receiver to relay the packet.

Once the sender receives the relay of the current packet, by broadcasting it will notify all its neighbors about the relay event to stop their timers to avoid packet duplication. Thus the self-nominating gives the relaying responsibility to the first responding neighbor and guarantees that the most promising next-hop neighbor will have the largest possibility to relay the packet.

Figure 3 shows the simulation results of the robustness of the self-nominating protocol. The *x* axis represents the single node failure ratio and the *y* axis represents the average number of hops to the sink. Each curve shows a different case with different total number of nodes in the wireless sensor networks. It can be concluded that the more backup nodes the more robust the network will be. Note that the self-nominating still maintains small delay routes even when 50 percent nodes get failed, which shows its reliability and robustness.

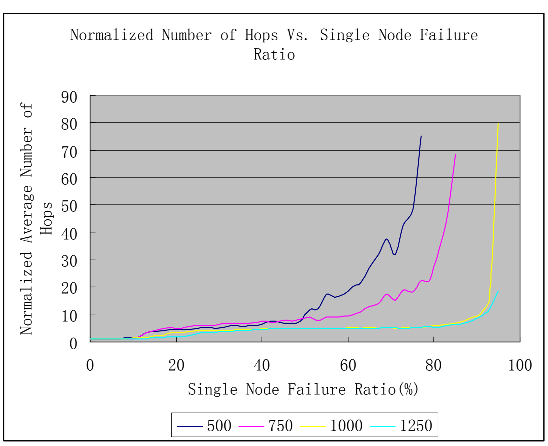

Figure 3. The reliability/robustness of the self-nominating

3.2 Time synchronization

Existing approaches for time synchronization in wireless sensor networks include Post-facto sync [14], RBS [15], Tiny-sync and mini-sync [16], and etc. There is a common problem observed as follows. In wireless sensor networks, the ad hoc network topology implies referenced synchronization that requires considerations of a *PADR* component in reducing the time synchronization error, include the *P* part as processing time, the *A* part as access time, the *D* part as the delay time, and the *R* part as receiving time. In post-facto sync, the *D* part has been assumed to be zero and no consideration about the *P*, *A*, and *R* parts in the synchronization. In RBS, the *P* and *A* parts have been eliminated by using a reference packet and the *D* and *R* parts are assumed to be zero. In tiny- and mini-sync schemes, the *D* part has been removed by round-trip time and the *P*, *A*, and *R* parts have not been taken into account.

Considering the limitations of the previous approach on the *PADR* estimation, we have designed a lightweight time synchronization protocol to achieve global time synchronization in the wireless sensor networks. Specifically, we have used a level discovery mechanism [25] to enable the global time synchronization and introduced an adjuster-based scheme to decrease the effect of *PADR* on the synchronization error. Please refer to details in [26] due to the space limitation.

3.3 System architecture

To the best of our knowledge, there is no existing system that is suitable to be compared to in terms of system architecture solution for the integration issue and we build the system from the ground up. Figure 4 and the following descriptions sketch general system architecture of the integrated networks.

– The sensor network is a self-organizing cooperative one since a certain task assigned and triggered by the manager node may involves multiple nodes in the network by routing protocols such as the flossiping.

– Each sensor node is capable of sensing phenomena, collect and process data, and report/route the data back to the data sink by routing protocols such as the self-nominating.

– The data sink is a laptop with both RF and LAN interfaces relaying the data to the manager node through wireless/local area network, or the Internet.

– The manager node stores the collected sensor data in a data repository for the integrated data analysis with the data from other systems.

Based on the integrated wireless networks and Habanero™ collaborative framework [27], we have developed a heterogeneous collaborative system for users using heterogeneous computing devices to monitor and study data collected from wireless sensor networks for some collaborative tasks, such as fire-fighting and examples mentioned in Section 1 and Section 2. Habanero™ provides a generic server and a set of APIs for development of collaborative applications. We have enabled the display of the data collected by sensors and the collaboration between multiple users on various types of devices, such as PDAs and other kinds of mobile wireless devices that support Java™. Figure 5 shows an integrated snapshot of the user interfaces on both a Palm and a laptop with sensor data being collaboratively monitored. An arrow has been draw by the Palm user who wants to discuss that specific temperature data with a remote user using the laptop.

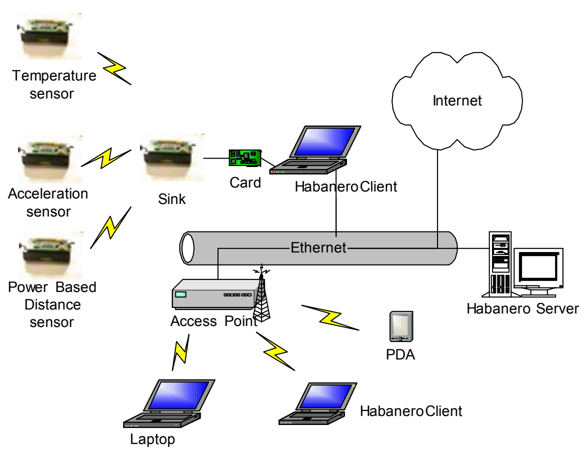

Figure 4. Architecture of the integrated network systems

Figure 5. User interfaces of the integrated system with sensor data being collaboratively monitored

4 Conclusions

The integration of wireless sensor networks with wireless local area networks and the Internet is an important issue of future wireless networks. This paper has identified three challenges for the integration: (*i*) reliable communication issue among sensors, actuators, and applications under the energy-conservation constraints, (*ii*) time-synchronization issue, and (*iii*) system architecture issue. Solutions for those challenges are presented and a resulting integrated system has been illustrated.

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References

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Communications Magazine*, Vol. 40, No. 8, pp. 102-116, August 2002.

[2] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister, “System architecture directions for networked sensors,” in the Prococeedings of the International Conference on Architectual Support for Programming Languages and Operating Systems, pp. 93-104, 2002.

[3] D. Estrin, J. Heidemann, R. Govindan and S. Kumar, “Next century challenges: scalable coordination in sensor networks”, in the Proceedings of the Fifth Annual International Conference on Mobile Computing and Networks (MobiCOM'99), Seattle, Washington, pp. 263-270, August 1999.

[4] K. Römer, O. Kasten, and F. Mattern, “Middleware challenges for wireless sensor networks,” *ACM Mobile Computing and Communication Review*, Vol. 6 No. 4, pp. 59-61, October 2002.

[5] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar. “Scalable coordination in sensor networks,” in the Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom’99), pp. 263-270, N.Y., August 15-20, 1999.

[6] C. E. Perkins and P. Bhagwat, “Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers,” in the Proceedings of the ACM

SIGCOMM'94 Conference on Communications Architectures, Protocols and Applications, London, UK, August 1994, pp. 234-244.

[7] D. B. Johnson and D. A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," *Mobile Computing*, edited by T. Imielinski and H. Korth, Kluwer Academic Publishers, Chapter 5, pp. 153-181.

[8] C. E. Perkins and E. M. Royer, "Ad-hoc On-Demand Distance Vector Routing," in the Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications (WMCSA'99), New Orleans, LA, USA, pp. 90-100, February 1999.

[9] R. K. Min, *Energy and Quality Scalable Wireless Communication*, Ph.D. Dissertation, EECS Department, MIT, May 21 2003.

[10] J. Elson and K. Romer, "Wireless Sensor Networks: A New Regime for Time Synchronization," in the Proceedings of the Workshop on Hot Topics in Networks (Hotnets-I), Princeton, USA, October 2002.

[11] W. Heinzelman, *Application-Specific Protocol Architectures for Wireless Networks*, Ph.D. Dissertation, Massachusetts Institute of Technology, June 2000.

[12] P. Gupta and P.R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, Vol. 46, pp. 139-157, January 1999.

[13] T. Starner, "Thick Clients for Personal Wireless Devices," *IEEE Computer*, Vol. 35, No. 1, pp. 133-135, January 2002.

[14] J. Elson and D. Estrin, "Time synchronization for wireless sensor networks," in the Proceedings of the 2001 International Parallel and Distributed Processing Symposium (IPDPS'01), Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing, San Francisco, CA, USA, pp. 1965-1970, April 2001.

[15] J. Elson, L. Girod, and D. Estrin, "Fine-grained network time synchronization using reference broadcasts," in the Proceedings of the Fifth Symposium on Operating Systems Design and Implementation (OSDI'2002), Boston, MA, December 2002.

[16] M. L. Sichitiu and C. Veerarittiphan, "Simple accurate time synchronization for wireless sensor networks," in the Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'2003), New Orleans, LA, March 2003.

[17] S. I. Roumeliotis and G. A. Bekey, "An extended Kalman filter for frequent local and infrequent global sensor data fusion," in the Proceedings of the SPIE (Sensor Fusion and Decentralized Control in Autonomous Robotic Systems, Pittsburgh, PA, USA, Oct. 14-15, pp. 11-22, 1997.

[18] D. Ganesan, R. Govindan, S. Shenker and D. Estrin, "Highly Resilient, Energy Efficient Multipath Routing in Wireless Sensor Networks," *Mobile Computing and Communications Review* (*MC^2R*), Vol. 1, No. 2, 2002.

[19] C. Karlof and D. Wagner, "Secure Routing in Wireless Sensor Networks: Attacks and Countermeasures," *AdHoc Networks*, *Special Issue on Sensor Network Applications and Protocols*, Vol. 1, Issues 2-3, pages 293-315, September 2003.

[20] B. Krishnamachari, D. Estrin, S. Wicker, "Modelling Data-Centric Routing in Wireless Sensor Networks," in the Proceedings of IEEE Infocom, 2002.

[21] C. Intanagonwiwat, R. Govindan, D. Estrin, J. Heidemann, and F. Silva, "Directed diffusion for wireless sensor networking," *IEEE/ACM Transactions on Networking*, Vol. 11, No. 1, pp. 2-16, February 2003.

[22] I. Rubin and A. Behzad, "Cross-layer Routing and Multiple-Access Protocol for Power-Controlled Wireless Access Nets," IEEE CAS Workshop, Sep. 5-6, 2002.

[23] Y. Zhang and L. Cheng, "Flossiping: A New Routing Protocol for Wireless Sensor Networks," accepted by 2004 IEEE International Conference on Networking, Sensing and Control (ICNSC2004), Taipei, Taiwan, China, March 21-24, 2004.

[24] Y. Zhang and L. Cheng, "Self-nominating: a robust affordable routing in wireless sensor networks," VTC 2003 - Wireless Ad hoc, Sensor, and Wearable Networks, Orlando, Florida, USA, October 6-9, 2003.

[25] Saurabh Ganeriwal, Ram Kumar, Mani Srivastava, "Timing Sync Protocol for Sensor Networks," in the Proceedings of ACM SenSys, Los Angeles, CA, 2003.

[26] L. Cheng, T. Lin, Y. Zhang, and Q. Ye, "Monitoring wireless sensor networks by heterogeneous collaborative groupware," ISA/IEEE Sensors for Industry Conference (Sicon'04), New Orleans, LA, USA, January 27-29, 2004.

[27] A. Chabert, E. Grossman, L. S. Jackson, S. R. Pietrowicz, and C. Seguin, "Java object-sharing in Habanero," *Communications of the ACM*, Vol. 41, Issue 6, pp. 69-76, 1998.