Wireless Integrated Network Sensors (WINS): The Web gets Physical

Gregory J. Pottie

Electrical Engineering Department
University of California, Los Angeles
pottie@ee.ucla.edu

1. INTRODUCTION

Wireless Integrated Network Sensors (WINS) provide distributed network and Internet access to sensors, controls, and processors embedded in equipment, facilities, and the environment. WINS combine sensor technology, signal processing, computation, and wireless networking capability in an integrated system. Integrated circuit technology now enables construction of sensors, radios, and processors at low cost and with low power consumption, enabling mass production of sophisticated but compact systems that will link the physical world to networks [1-4]. Scales will range from local to global, with applications including medicine, security, factory automation, environmental monitoring, and condition-based maintenance. Compact geometry and low cost allows WINS to be embedded and distributed at a small fraction of the cost of conventional wireline sensor and actuator systems. This can enable hundreds or thousands of sensors per user, resulting in many new network design challenges.

Centralized methods for sensor networking present impractical demands on cable installation and network bandwidth. However, by processing at source and conveying decisions rather than raw data, the burden on communication system components, networks, and human resources are drastically reduced. This same observation holds true whenever there are relatively thin communications pipes between a source and the end network, or when dealing with large numbers of devices. The physical world can generate an unlimited quantity of data to be observed, monitored, and controlled, but there are finite resources that can be put into wireless telecommunications infrastructure. Thus even as mobile broadband services are rolled out there will be a need for processing at source and careful control of communications access.

In this paper we consider two scenarios illustrating different aspects of the design tradeoffs. In the first, an autonomous network of sensors is used to monitor events in the physical world, for the benefit of a remote user connected via the web. In the second, we consider the problem of how to get sensor information from an automobile for use in maintenance applications. A general architecture is depicted in Figure 1, for now neglecting the details of how services will actually be supported by Internet-connected devices. For supplying some service, two different clusters of nodes are connected through their respective gateways to the Internet. The nodes are assumed to be addressable either through an IP address or some attribute (location, type, etc.), and are distinguished from pure networking elements in that they contain some combination of sensors and/or actuators. That is, they interact with the physical world. The gateway may itself be a sensor node similar to other nodes in its cluster, or it may be

1 The author is also with Sensoria Corporation, www.sensoria.com.
entirely different, performing for example extra signal processing and communications tasks and having no sensors. In the cluster in the top left portion of Figure 1, nodes are connected by a multi-hop network, with redundant pathways to the gateway. In the bottom cluster, nodes may be connected to the gateway through multi-hop wireless networks or through other means such as a wired LAN. The nodes in the different clusters may all be of one type, or they may be different within or across clusters. In a remote monitoring situation, there may be part of the target region with no infrastructure, and thus the multi-hop network must self-organize, while in other parts of the region there may already be assets in place that are accessible through a pre-existing LAN. There is no requirement that these assets be either small or wired; the point is to make use of all available devices for providing the desired service.

![Figure 1: WINS Network Architecture](image)

The remainder of this paper is organized as follows. In section 2, we briefly describe some design heuristics. In section 3, we discuss a number of different research efforts to deploy large networks in areas without infrastructure support. In section 4 we discuss how sensor networks within vehicles can be linked with the Internet for a variety of new applications. In section 5, we present our conclusions.

### 2. DESIGN HEURISTICS

A description of some of the fundamental physical constraints for sensing, detection, communication, and signal processing cost are given in [5]. The basic design constraints that emerge are:

1. There are many situations in which reliable detection demands sensors in close proximity to a physical event, causing numbers to scale (e.g., physical obstructions to cameras). With large numbers of sensors, the type of information obtained is qualitatively different than that obtained with remote arrays.
2. Sensors, radios, and signal processing can all ride the integrated circuit technology curve down in cost, but batteries and other energy sources improve in cost only slowly with time.
3. Communications energy cost per bit is in many instances many orders of magnitude larger than the energy required for making decisions at source, and communications is limited in its
efficiency by fundamental limits, whereas processing cost is to first order limited only by current technology.

4. Human labor does not scale; networks must be self-organizing to be economical.
5. Scaling with physical responsiveness demands hierarchy, with distributed operation at lower layers and increased centralized control at higher layers.

Note that hierarchy does not necessarily imply heterogeneous devices. If one considers human organizations, the processing abilities are roughly equal at all levels. What differs most in progressing up the chain is that different information is processed, that is, at different levels of abstraction/aggregation. Moreover, commands progressing down the chain also differ in their level of abstraction, from policies down to work directives, with varying scope for interpretation. This flexibility enables lower levels to deal with local changes in the work situation much faster than if a central controller needed to be consulted for each action, while enabling global goals to be pursued. With machines of course we have the possibility of providing highly differentiated abilities to the devices at different levels of the hierarchy. These can bring important advantages, for example, a backbone long-range high-speed communications pipe can greatly reduce latency compared to relying only on multi-hop links. Thus, while logical rather than physical hierarchy is arguably much more important in enabling scalability, it behooves the designer of large-scale systems to consider both rather than being seduced by the siren song of homogeneity. Homogeneity is any case impractical in long-lived systems composed of integrated circuit components; as for the Internet, the architecture must accommodate the addition of successive generations of more powerful components.

3. REMOTE MONITORING

To make the discussion more concrete, we now consider an application requiring identification of particular classes of targets passing through a remote region. These targets may be military vehicles, species of animals, pollutants, seismic events on Mars, or on a smaller scale, enzyme levels in the bloodstream. In any case, we assume there is no local power grid or wired communications infrastructure, but long range communications means exist for getting information to and from a remote user. Then, in laying out a network such as the one depicted in Figure 1, both energy and communications bandwidth can be critical constraints. As noted above, when the network must scale in the number of elements, this effectively means that much of the signal processing must be performed locally. For example, in studying the behavior of animals in the wild, a dense network of acoustic sensors may be employed. The nodes contain templates for the identification of the species emitting the call. Nodes which make a tentative identification can then alert their immediate neighbors so that the location of the animal can be roughly determined by triangulation. Infrared and seismic sensors may also be used in these initial identification and location processes. Then finally other nodes may be activated to take a picture of the target location so that a positive identification can be made. This hierarchy of signal processing and communications can be orders of magnitude more efficient in terms and energy and bandwidth than sending images of the entire region to the gateway. Further, the interaction of diverse types of nodes can more simply lead to automation of most of the monitoring work, with humans only brought into the loop for the difficult final visual pattern recognition on pre-selected images. On positive identification, the audio and infrared files corresponding to the image can be added to a database, which may subsequently be mined to produce better identification templates. Note that the long-range communications link (via the gateway) potentially enables the full uses of web-
accessible utilities, so that the end user need not be present in the remote location, and databases, computing resources, and the like may all be brought to bear on interpreting the (processed) data.

There is a tension between experimental apparatus for initially exploring an application domain and what will actually be needed for large-scale deployment. Because networked sensors have hitherto been very expensive, there is relatively little array data available for most identification purposes, and sensors have typically been placed much farther from potential targets than will be possible with WINS. This means paradoxically that initially fairly powerful nodes need to be constructed to conduct large-scale experiments to collect raw data, so that suitable identification algorithms can be developed using the resulting database. Likewise, in experimenting with different networking algorithms, it is desirable from the point of view of software development to initially provide a platform with considerable flexibility. In the DARPA SensIT program [6] development platforms have been produced to support such experimentation, while in parallel other researchers have pursued specialization of function and miniaturization of components to demonstrate that indeed large networks of small nodes can be produced. For example Sensoria Corporation’s WINS NG 2.0 nodes include ports for four sensors, a real-time DSP, memory, a main processor running Linux, a battery and port for external power, GPS, Ethernet, an RS-232 port and two radios to enable convenient synthesis of multi-hop networks. Software interfaces have been created to enable programmers to remotely control a large number of physical attributes of nodes, and to permit remote download of new applications. This enables a diverse user community to produce algorithms for networking, target identification, and distributed database management. On another track, researchers at UC Berkeley are engaged in producing very small nodes with limited sensing and communications abilities to demonstrate the ability to have sensing, signal processing, and communications all in one miniature package.

4. AUTOMOTIVE APPLICATIONS

All recently produced automobiles include many processors and sensors, and a variety of networks for sensing, control, and entertainment systems. Hundreds of sensor parameters are for example accessible through the On-Board Diagnostic (OBD) port. However, there is no connection between the various networks and external communications systems such as cellular phones. The objective of the Automotive Multimedia Interface Collaboration (AMI-C) standards process is to connect these networks and provide for standardized buses in automobiles that will allow the installation of a wide range of consumer electronics to essentially an automotive intranet, that could then be conveniently accessed via the Internet [7]. Ports on this bus could include any of a number of radios, enabling wireless devices within the vehicle to become part of the intranet, or enabling short-range high-speed communications between a vehicle and a residence or service station.

A key component of any such architecture as envisioned in the AMI-C standard is a gateway that separates proprietary and safety-sensitive systems in the automobile from after-market consumer electronics. The gateway contains ports to interface with legacy networks, as well as ports to interface to the consumer buses. The gateway also hosts software for managing the various services envisioned for internet-connected vehicles. These include for example maintenance information. This would allow manufacturers to see how their vehicles are actually used, or allow consumers to evaluate the need for repairs, and the effectiveness of repairs by comparing data before and after. Uploading of entertainment information, and determination of retail stores, restaurants or service stations near the present location are other potential uses. A vital function of the gateway in making such services economical is
management of the communications links. Presently, using cell phones results in very high cost per bit delivered compared to other communications means. However, if the automobile also possesses a short-range broadband link such as IEEE 802.11b, then information might be processed and stored, and uploaded to a home computer when the car is parked near the residence. Likewise entertainment information or software upgrades could be downloaded overnight. Alternatively, while refueling the car could be communicating over high-speed links at a gas station and receiving updated information or completing a purchase of MP3 audio files. On the other hand, for very high-priority services such as emergency assistance the cell-phone would be used, rather than waiting until a high-speed port comes into range. Through knowledge of the vehicle operator's preferences, the gateway can choose the appropriate mix of local processing, storage, and communications strategy to provide services at the desired costs.

Notice that the architecture depicted in Figure 1 also applies to vehicle networks, although the devices are quite different than in the previous scenario set. The gateway may have some devices responsive to the physical world directly connected to it, or they may be accessible through local area networks within the vehicle. Some of these devices and/or the gateway must perform local processing because the link to the Internet may be thin or costly. Thus for example rather than sending a continuous record of engine temperature, detailed reports might be stored only for events when temperatures cross some critical threshold, or when the temperature is high and the output of another sensor is indicating possible problems. Further processing might even be conducted to actually perform a first pass at diagnosis, and only then might a query to an expert system located on the web be made. In this way, the vehicle does not have to host the complete diagnostics system. Remote monitoring and control remain attractive for other reasons also. The vehicle owner will not want to program user preferences within the vehicle, and any sensible regulatory regime would discourage further driver distractions. Scaling also remains a large concern. Providing services to millions of vehicles presents enormous challenges, both in the volume of data that can be generated by the vehicles and in the quantity of entertainment information that may need to be transported to them. With a gateway and backend web-server network that enables remote download of software, many different companies can compete for providing information services to automobile owners. Taking this together, the high-level requirements for the design of the gateway are surprisingly similar to what is needed for the development nodes described previously for conducting large-scale data collection experiments: real time components, general purpose processors, wired and wireless network communication interfaces, APIs that permit construction of software by third parties, and remote controllability via the web.

5. CONCLUSION

The close intertwining of processing of networking is a central feature of systems that connect the physical and virtual worlds. Research is now proceeding both in the design of small, specialized nodes that could potentially be deployed in very large numbers, and in the creation of dense networks of larger nodes that can be used to learn more about the types of networking, sensing, and signal processing that will be needed in future systems. It was shown how constrained communications leads to similar design considerations for scalable networks even when data rates and processing capabilities are larger. Thus for a very broad range of systems that interface to the physical world it is necessary to consider signal processing and communications together.

6. REFERENCES


7. www.ami-c.org/home.htm