Wireless Sensor Networks

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Abstract -- **Recent advances in commercial IC fabrication technology have made possible the integration of wireless transceivers, CMOS signal processing, and sensing in one integrated circuit package. Combination with actuation is also possible. This amounts to a low-cost means to link communications and computer networks to the physical world, and may have profound consequences in such diverse areas as security, process control, planetary exploration, and medical monitoring and diagnosis. We outline the system design issues for a distributed sensor network, in which each node has a limited energy supply and relatively low data rate link. The nodes must establish a synchronous multi-hop network, determine locations, and cooperate for such purposes as beamforming and passing messages to the outside world.**

I. INTRODUCTION

A wireless integrated network sensor (WINS) node can include MEMS components such as sensors, RF components, and actuators, and CMOS building blocks such as interface pads, data fusion circuitry, specialized and general purpose signal processing engines, and microcontrollers. The more complicated but low duty cycle applications would for example be run in the general purpose processors, while frequently invoked operations would be run on specialized circuits to save power. The individual nodes may have modest capabilities, but may achieve large scale effects through coordinated activity in a network of hundred to tens of thousands of nodes. Examples of coordinated activities are beamforming for enhanced target detection, multi-hopped communications, distribution of timing and position information, and coordinated actuation to produce macro-scale effects from micro-devices. The distribution of intelligence throughout the network greatly promotes this scalability through massive reduction of control and data traffic.

As WINS have many possible applications, to focus discussion in the succeeding sections we consider the following security scenario. Sensor nodes are to be randomly dispersed over an area so as to detect and possibly identify targets. The nodes may contain one or several types of sensors, are capable of RF communications, and contain signal processing engines both for processing the data prior to transmission and to manage the networking protocols. The nodes create a self-organizing network, and are capable of cooperative functions such as beamforming and cooperative communications. Low power operation is critical in such an application, as the nodes must operate using small batteries. The question is then what design choices need to be made to make the network scalable, with prolonged low-power operation.

II. DETECTION AND COMMUNICATIONS TRADES

Each detection device is inherently limited in range by the background noise and the attenuation of signals with distance. This is also true for the communications system. In this section we breifly outline some of the tradeoffs in designing a distributed system to provide both sensing and communications coverage.

Consider seismic detection. The Earth has a low-pass characteristic and additionally generates broadband seismic noise. Consequently, the seismic signature of any particular object gets distorted with range, and the SNR declines as the signal becomes attenuated. If the set of objects to be identified have well-defined seismic characteristics, it is possible to perform an adaptive deconvolution operation to remove the low-pass distortion based on each hypothesis, and then perform threshold tests to determine which hypothesis is most likely. Nevertheless, the higher frequencies will be less reliable, and clearly the closer sensors are to the source the more likely a reliable identification can be made. Thus, a distributed network of sensors will collect significantly different information than a system relying on a small number of highly sensitive elements at large range.

It is also possible to coordinate a distributed network of sensors for such purposes as beamforming for higher SNR identification and location-finding. This is particularly effective for objects that lie within the interior region of the network, but can also be done for exterior objects, with the usual penalties for SNR and distortion with range. This can be accomplished whether the sensors are regularly or randomly distributed. The network can form beams using ad hoc collections of sensors, i.e., those that have reasonable SNR for the event in question. Data is collected at one of these nodes according to the beamforming protocol (with time stamps) and then synthesized. Thus, low cost sensor networks provide not only the opportunity of placing detectors close to sources, but can also provide high-resolution beamforming.

Low-power RF communications is an exercise in using more rather than less signal processing. The fundamental constraint is that circuits operating at high (RF) frequencies burn more power than those operating at low (baseband) frequencies. Therefore, techniques which can reduce the volume of data to be transmitted or the power at which it must be transmitted lead to large overall savings, even if some additional processing at baseband is required. Data reduction can be accomplished with local decision making. This can lead to orders of magnitude greater reductions in the network load than simply relying upon data compression. Secondly, diversity techniques must be exploited to reduce the average transmission power. With low cost nodes, a dense deployment will enable multiple transmission routes. The dense deployment together with multi-hopped communciations will help to counteract the third or fourth power attenuation with distance typical of ground to ground communications, and closed loop power control can reduce transmission power to the minimum required for reliable transmission. Even considering the down-

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and up-conversion costs of a transceiver relaying messages, this will usually lead to a net power savings. Even more importantly, this will enable routing around obstacles such as ridges or hills. In cluttered environments, frequency diversity can also be of benefit. In the presence of fading, diversity techniques allow orders of magnitude reduction in power levels. Thus, a more sophisticated radio will use dramatically less power than a radio which has few degrees of control freedom.

At the expense of data rate, it is also possible for the nodes to coordinate their communications to overcome gaps in the network. Coherent combining at RF among scattered nodes is not practical due to the tight synchronization requirements (alternatively, exacting requirements on the clocks), but noncoherent combining for transmission and reception are both feasible.

III. NETWORK POWER MANAGEMENT

In single processor systems with multiple sensor or communications ports, all elements have access to a common timing base, with all data paths fabricated with the same technology, enabling matching. Use of centralized processing implies no communications cost. However, for a distributed sensor network timing, position, routing, processing scheduling, and communications must all be coordinated by passing control messages among nodes which cost power and which are subject to degradations due to node failure and jamming.

The solution lies in an integrated approach with aggressive power management at all levels: i) spread spectrum communications with interference avoidance for jam resistance, ii) adaptive power control in communications to use minimal power, iii) link rate adjustment to extend range in adverse conditions, iv) multi-hop routing to minimize total power consumption, v) varying node alertness level to conserve power for essential tasks, vi) cooperative algorithms designed for shared processing with close neighbors, vii) distribution of data only to those nodes that need to know, viii) distributed synchronization to limit message collisions and preserve code lock, ix) distribution of resource maps to conserve power in critical nodes and x) hardware optimized for low power operation. It is the choice of protocols rather than the optimization of the hardware that leads to the largest power savings. With the proper choice of protocols, nodes may be in dormant states with high probability, executing tasks only when absolutely essential. Relatively high false alarm rates are tolerated in the low-power but frequently invoked operations; operations which lower the false alarm probability to the target level are costlier, but far less frequent. With these techniques, the cost of communicating can be reduced, enabling the nodes to engage in reliable cooperative detection and communication tasks.

IV. NETWORK ARCHITECTURES

For low-cost installation, it is desirable that the sensor nodes form self-organizing networks. A variety of approaches are possible, but to enable power down modes the end result in many applications should be a synchronous network. To enable scalability, the nodes should over the whole region begin by forming subnetworks, in which internal communications will be coordinated by a master (e.g., the first node to wake up). These subnetworks may include mechanisms to slow down growth once a certain size has been reached, to move into a phase of connecting with other clusters of nodes (absorbing or being absorbed). This merging process will include alignment of clocks and exchange of routing and resource information.

An interesting issue which includes trades among cost, functionality, and reliability is whether the network should be constructred from homogeneous or heterogeneous elements. From the reliability and manufacturing cost standpoint it is desirable for the nodes to at least be very similar. However, there are certain functions such as GPS or long range communications which, while vital to the network as a whole, need not be implemented in every element. Indeed, it is possible to distribute position and timing information within the network when only a small fraction of the nodes possess an absolute position/timing reference, provided transducers are available at each node to provide sounding signals detectable by neighbors. Longer range radios may be needed for communciations back to a basestation, but relying upon only one such radio per network can lead to obvious reliability problems, as well as excessive power loading for the nodes in proximity to the radio.

Another important question is what hierarchy of signal processing functionality should be imposed on the network in the interests of scalability to tens of thousands of nodes. It is clear that individual nodes must possess considerable signal processing ability in order to limit costly communications. However, other functions such as aggregation of messages to form summary reports may also be needed in order to avoid information overload on links near the terminal destination. Should every node have to support this function, or should special nodes be designated to do so? Likewise, certain nodes which have aggregated information may also have responsibility for requesting further data, so that final decisions can be made, thereby reducing the amount of traffic that must be passed upstream over congested links. The obvious problem with requiring every node to be capable of these functions is an increased signal processing hardware cost per node, but interestingly, there may be a savings in overall network power consumption by doing so, in that routing can be made more flexible, and indeed dynamic. Whether the cost of the nodes is therefore materially increased depends on what other functions they must perform and the architecture of the signal processing engine. Clearly there is also a reliability benefit from having a flat hierarchy, with functions taken up by nodes as needed. The high cost of communications as compared to signal processing leads to a different regime of tradeoffs than might ordinarily be considered in designing networks.

V. CONCLUSION

WINS technology can provide a low-cost linkage between the physical world and information networks. We have outlined the design considerations for one such application, but it is only the beginning in an exciting new area of multidisciplinary research.

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