New Communication Paradigms for Very Large-Scale Sensor Networks

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I. INTRODUCTION

In this poster, we will present work in progress on two novel approaches for efficient, scalable communication in truly large scale sensor networks. This work is a follow-up on our papers in IPSN 2004 [1], [2].

Our focus is on applications in which networks of tens of thousands of sensor nodes are required, such as policing activity along a border, monitoring the presence of biological or chemical agents over large urban areas, or exploration of the surface of a planet. Not only is it difficult to scale standard multihop wireless networking protocols to such large networks, but in many such settings, one long hop is required from the cluster of sensor nodes to a remote collector node even if multihop networking among the sensor nodes is feasible. Another key difficulty in large scale networks is localization: such networks would often be randomly deployed, e.g., dropped from an aircraft or spacecraft, so that there is no a priori mapping between sensor node ID and location. Furthermore, geolocation may be unavailable due to either cost (of integrating GPS receivers into sensor nodes) or physical considerations (occlusion of GPS signals in many scenarios, and unavailability in settings such as interplanetary exploration or monitoring of wooded areas).

With the preceding context in mind, we introduce two novel concepts.

II. IMAGING SENSOR NETS

To solve the problem of scale, we draw our inspiration from conventional imaging (ranging from passive optics to active radar), interpreting the sensor nodes as pixels being imaged by a sophisticated collector node. While conventional imaging only applies to phenomena with strong enough electromagnetic signatures, imaging sensor nets utilize sensor nodes to translate arbitrary phenomena into data that can be recovered using radio frequency (RF) imaging techniques, while still allowing scaling to tens of thousands of "pixels" as in conventional imaging. Some examples are shown in Figure 1.

In IPSN 2004 [1], we had introduced a version of Imaging Sensor Nets that we termed "Virtual Radar": a moving collector flies by a sensor field, illuminating sections of it with a beacon. Sensor nodes with activity to report respond in a precisely timed fashion to the beacon when they are illuminated by it, thus creating a radar-like geometry. Modifications of synthetic aperture radar processing are then used to localize the "active" sensors. Such drastic simplification of sensor node functionality has compelling cost implications: we can use "dumb" sensor nodes without geolocation or networking capabilities, and obtain an adequate link budget with very little energy expenditure on the part of the active sensor nodes.

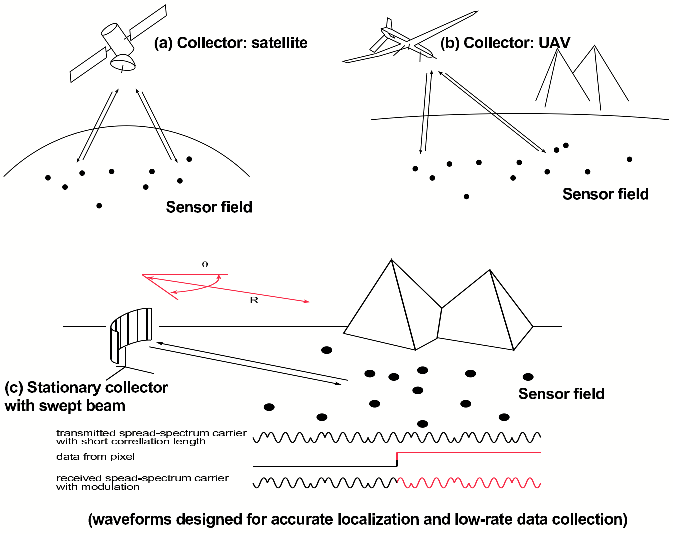

Fig. 1. Imaging Sensor Nets: three possible realizations

While our presentation last year illustrated the promise of imaging techniques for sensor net data collection, a number of practical issues must be considered before our ideas can be prototyped. For example, it is difficult for low-cost sensors to process collector's beacon and respond to it in a precisely timed fashion. Also, it is essential to allow sensors to send back more information than just 0 or 1, as in [2]. Finally, stationary collectors are easier to prototype, and are useful for many applications (e.g., border monitoring from remote sites). With this in mind, we propose the following architecture shown in Figure 2:

(a) a stationary collector scans the sensor field with a mechanically or electronically steered beam (the carrier frequency is high enough that a relatively small beamwidth can be obtained);

(b) the collector sends a beacon with a spread spectrum "location" code;

(c) sensor nodes (ultimately to be implemented as ultra low-cost CMOS ICs) electronically reflect the beacon (with or without amplification) without processing it, except for modulating it at low rate by the data they wish to send;

(d) the collector receiver (to be ultimately implemented in software after an RF front end) uses spread spectrum reception techniques to estimate the delays of the reflected components that it receives, and to demodulate the data;

(e) the outputs from (d) are fed to an imaging algorithm that processes the information from different scan angles to obtain an image

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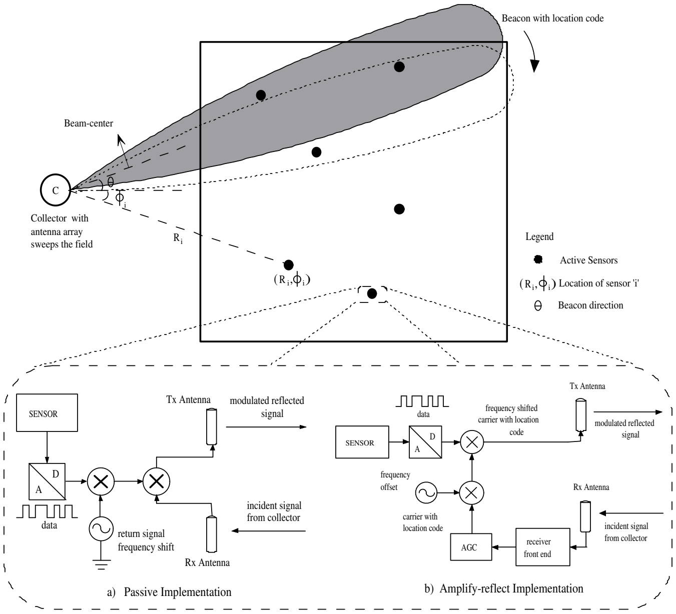
providing the locations of the sensors responding to the beacons (as well as estimates of the data associated with each sensor);
(f) the images from multiple collectors are integrated to enhance resolution, coverage and data demodulation.

Preliminary simulations based on this architecture will be presented at the conference.



a) Passive Implementation

b) Amplify-reflect Implementation

Fig. 2. Realization of Imaging Sensor Nets with Stationary Collector

III. DISTRIBUTED BEAMFORMING WITH FEEDBACK CONTROL

While imaging sensor nets do not require any collaboration across sensor nodes, local cooperation can lead to large gains in performance. We explore the concept of distributed beamforming, in which a cluster of sensor nodes agree in advance on the data to be transmitted to a collector, and then emulate an antenna array to form a beam in the direction of the collector node. If the transmit power per node is fixed, then ideal transmit beamforming leads to an increase in received power by a factor of N^2, where N is the number of cooperating nodes. This translates to a range increase of a factor of N under free space propagation, which is important when there are networks requiring long hops between node clusters, or between a node cluster and a collector node. In our IPSN 2004 paper on this subject [2], we discussed the extent to which the cooperating nodes must synchronize their transmissions. We also discussed the effect of synchronization errors in a master-slave architecture, in which a master node supplies synchronization reference to slave nodes. We showed that in order for this synchronization procedure to work, slave sensors need to have estimates of the propagation delay of their wireless channel to the master node. Errors in the estimation process, as well as errors in channel measurement cause degradation of the SNR to the receiver.

We employ distributed adaptation at the cooperating sensor nodes based on SNR feedback from the receiver (Figure 3). We illustrate our ideas using an idealized time-slotted system. Each sensor node begins by transmitting a common message signal modulated by a carrier with an unknown phase offset, and introduce a random perturbation of this phase offset in each time slot. The resulting carrier signal at the receiver is a phasor sum of the signals from the sensors, after propagating through the wireless channel. The receiver feeds back the received SNR level in each slot, by boradcasting the information to all sensors. If the SNR is better than that in the previous slot, each sensor keeps the current phase, otherwise, each sensor reverts to the phase in the earlier slot. Each sensor then repeats the process by introducing another independent random phase perturbation. We show that this procedure asymptotically achieves a phase synchronized system. Further we derive an analytical model that predicts the convergence behaviour of this procedure very accurately, and provides insights into choosing a good distribution for the phase perturbation.

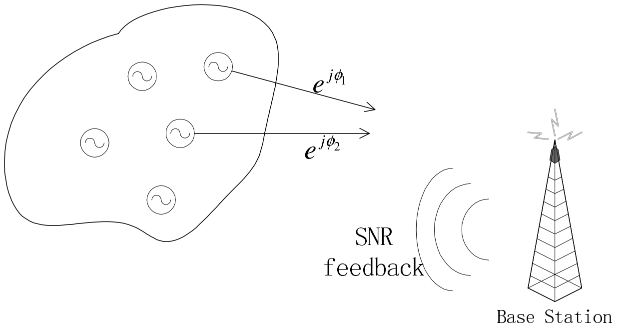


Fig. 3. Sensor network with SNR feedback

Preliminary simulation results will be provided in the poster. Implementation issues for RF and acoustic transmission will be discussed.

IV. CONCLUSIONS

While modifications of “off the shelf” multihop networking have an important role to play in the evolution of general purpose sensor networks, the focus of this poster is to illustrate that innovations at the physical layer can potentially enable alternative architectures providing fundamental advances in scaling and energy efficiency. There is much further work to be done, however, in exploring both theoretical and practical aspects of our ideas.

REFERENCES

[1] B. Ananthasubramaniam and U. Madhow, “Virtual radar imaging for sensor networks,” in *Proc. 3rd International Symposium on Information Processing in Sensor Networks (IPSN’04)*, pp. 294–300, Apr. 26–27, 2004.

[2] G. Barriac, R. Mudumbai, and U. Madhow, “Distributed beamforming for information transfer in sensor networks,” in *Proc. 3rd International Symposium on Information Processing in Sensor Networks (IPSN’04)*, pp. 81–88, Apr. 26–27, 2004.