DISTRIBUTED SPACE-TIME COMMUNICATION FOR SENSOR NETWORKS

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ABSTRACT

A key bottleneck in the vision of large numbers of networked sensor nodes is the energy-efficient collection of data from these nodes. In this paper, we provide two complementary approaches to this problem, both of which are fundamentally different from methods currently advocated in the literature:
1. Virtual radar: In this method, complexity is moved to a collector node. The sensor nodes simply respond in precisely timed fashion to a beacon sent by the collector (e.g., an aircraft or vehicle), enabling the collector to use signal processing techniques similar to synthetic aperture radar (SAR) in order to construct an "image" of the activity in the sensor network.
2. Distributed beamforming: In this technique, local clusters of nodes agree upon the data to be sent to a remote location, and coordinate their transmissions so as to form a beam in the desired direction. It is shown that even with moderate uncertainties in the locations of the sensor nodes, it is possible to get large increases in range for the same transmitted power.

1. INTRODUCTION

Sensor networks consist of large numbers of energy-constrained nodes with communication and computation capabilities. The applications envisioned for such networks range from environmental monitoring, home and industrial automation, and security. Since transmission of data requires more energy than the processes of sensing and computation, the problem of data collection from sensor networks is key to realizing the vision of their ubiquitous deployment. Major effort is going into the development of sensor node prototypes that pack more functionality into smaller form factors [1, 2]. Complementing these are the development of protocols for sensor data dissemination and compression. Standard approaches to sensor data dissemination in the literature are based on multihop ad hoc networking, often with protocols tailored to specific applications [3, 4]. Much work is also ongoing on distributed source coding for compression of sensor data, exploiting correlation between observations at neighboring sensors [5, 6, 7].

This paper introduces techniques that are complementary to efforts currently ongoing in the literature on sensor networks. These techniques exploit the spatial distribution of sensors on the ground, and can therefore be characterized as *distributed space-time communication.* In Section 2, we describe virtual radar data collection, in which a sophisticated collector node uses radar-inspired techniques to image the activity in a network of "dumb" sensor nodes. In Section 3, we describe distributed beamforming, in which a set of more sophisticated sensor nodes act as a distributed antenna array to form beams in desired directions of transmission, thus achieving orders of magnitude gain in energy efficiency.

2. VIRTUAL RADAR DATA COLLECTION

The virtual radar approach allows sensor nodes without autolocation or networking capabilities. This is achieved by moving the complexity from the sensor nodes to a *collector node* which does know its own location at all times, and has sophisticated signal processing capabilities. One realization of this concept, pictured in Figure 1, is as follows:
(a) The sensor data collector (e.g., an aircraft, or a vehicle at the edge of the sensor field) collects multiple snapshots of activity in the sensor network. The data collection for each snapshot is initiated by the collector node sending a beacon to the sensor nodes;
(b) The sensor nodes that hear the beacon respond if they have some activity to report (e.g., a chemical having exceeded a threshold), timing their response precisely with respect to a "start transmission sequence" in the beacon. All sensor nodes may actually be identical, so that all nodes with activity to report may send the same waveform in response to the beacon;
(c) The collector node processes the net received signal received from the sensor nodes in a manner similar to synthetic aperture radar imaging, using the multiple snapshots,

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as well as possibly a receive antenna array, to resolve signals from different sensors. The waveform sent by the sensors should therefore have properties similar to that of a good radar waveform [8].

(d) The collector generates an "activity map" of the sensor field using radar signal processing techniques [8][9] [10]. Since the collector node knows its own location at the time of different snapshots, it can estimate the absolute locations of sensors with activity to report, up to the resolution of this virtual radar imaging technique.

(e) Actions based on the activity map are taken. This may be based directly on the map (e.g., dropping neutralizing agents on a chemical spill), or may involve more detailed data collection from the centers of activity.

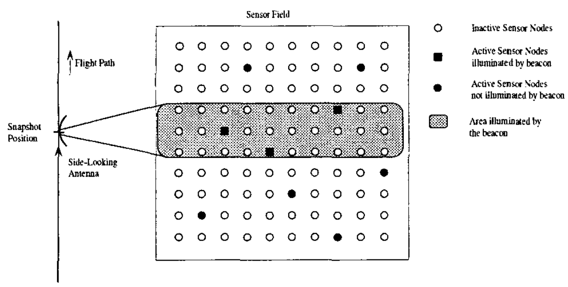

Fig. 1. A collector node obtaining multiple snapshots based on responses of active sensor nodes to its beacon.

We will omit mathematical details of virtual radar processing, restricting ourselves to the following comments. First, the analogy with true radar applies only up to a point. In particular, the local oscillator at an active sensor node transmitting back to the collector is not synchronized with that of the collector, which necessitates the application of noncoherent versions of standard SAR signal processing. Second, the fact that the active sensors are sending 1 or 0 can be used to get better location performance than true radar, in which the reflections are modeled as analog quantities. We provide the results of some numerical experiments below for provide a feel for the capabilities of this technique. Notice the poor performance of standard SAR, the improvement with the noncoherent version, and the further improvement upon exploitation of the binary information in the sensor field.

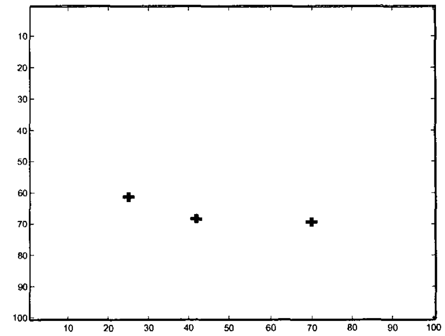

Fig. 2. Position of the active sensors in the sensor field

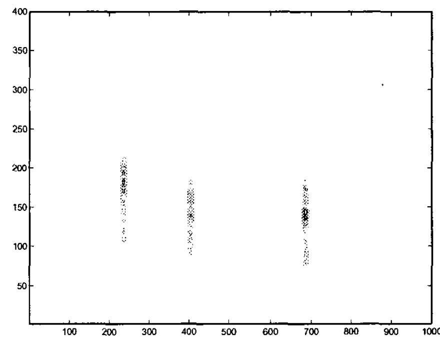

Fig. 3. Reconstructed grayscale contour image of sensor field using standard SAR techniques with no noise

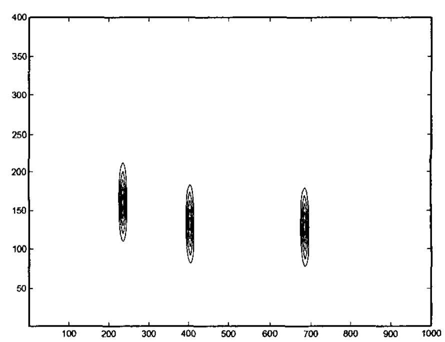

Fig. 4. Reconstructed grayscale contour image of sensor field using modified SAR techniques with no noise

3. DISTRIBUTED BEAMFORMING

Distributed beamforming involves coordination of transmissions by neighboring sensors nodes so as to form a distributed antenna array, directing a beam in the desired direction of transmission. Such beamforming can provide huge potential gains in terms of increased transmission range, or reduced transmission power, or both. If there are N nodes participating, each sending at a given power, then the total received power increases by a factor of N^2 compared to a single node's transmission. On the other hand, if the total transmitted power is kept constant as N changes (so that the transmitted power per node scales inversely as N), even

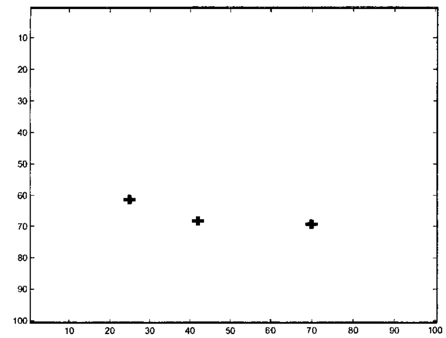

Fig. 5. Reconstructed two-level image of sensor field using modified SAR techniques with thresholding at SNR = 3 dB

then the received power increases by a factor of N compared to a single node transmitting at the same power. This latter scenario is the one considered in our analysis and numerical examples. The gains due to distributed beamforming have been mentioned in prior theoretical work [6], while implicitly assuming the synchronization between nodes required to ensure the coherent addition of the transmitted signals at the receiver. In our work, we investigate specific methods for achieving such coordination, and quantify the performance impairments due to imperfect coordination.

A little thought indicates that the key requirement for emulating a centralized antenna array using distributed elements is the synchronization of timing, carrier frequency, and carrier phase across the elements. We propose to achieve this for a a cluster of nodes by the following mechanism. A designated *master* node in the cluster broadcasts carrier and timing signals. The other *slave* nodes lock up to the carrier and timing signals sent by the master. Assuming that each slave knows its distance from the master, it can compensate for the delay with which the master signal arrives, thereby achieving frequency, phase and timing synchronization. The precision with which this synchronization is achieved depends both on the signal-to-noise ratios for the synchronization circuits employed, and on the accuracy of the estimates of the delay between the master and slave nodes. A specific scenario in which the preceding scheme becomes particularly simple is when the master and slaves are arranged in a star topology, with the master at the center. That is, the master is at approximately equal distance from each slave. This topology could be achieved either by initial placement of the nodes, or, for mobile nodes, by suitable control algorithms (along with a ranging scheme) that place the slave nodes at a desired distance from the master.

The usage mode is as follows. A remote node may broadcast a beacon asking for data. When the beacon is detected by the cluster of nodes, the slave nodes take amplitude and phase measurements (e.g., of a signal arriving from a collector node) based on a trigger signal from the master. Upon another trigger signal from the master, the complex conjugate of these measured gains is used for distributed transmit beamforming (exploiting channel reciprocity), sending data that has been previously agreed upon by the cluster. An analysis of this process reveals that the main source of error is in the phase synchronization error across the slave nodes. A further analysis indicates that the errors in the phase locked loops at the slaves (which are locked up to the master's carrier) are negligible at moderate signal-to-noise ratio, compared to the phase errors due to the uncertainty in the distances of the slaves from the master. As the number of participating nodes scales up, a central limit theorem analysis can be employed to characterize the accumulated effect of such errors. This analysis matches quite well with simulations using SIMULINK.

An overall schematic of the sensor network is illustrated in Figure 6. Figure 7 shows the communication functionality of the sensor node. The sensor data that is transmitted is just a binary pulse train of random bits. The signalling rate is chosen at about 10% of the carrier frequency (i.e. there are about 10 carrier sine wave cycles in a bit interval). The carrier is modulated by multiplying the carrier wave (obtained from the VCO output of the PLL in the sensor's synchronization circuits) with the pulse train. This is equivalent to a differentially modulated signal BPSK signal, since multiplying the pulse train is the same as a 0 degree phase shift on a "1" bit and a 180 degree phase shift on a "-1" bit.

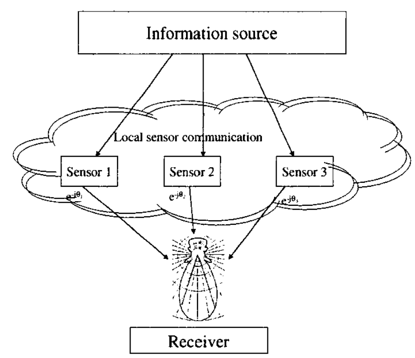

Fig. 6. Simplified model of sensor field

As an illustration of the gains that are obtainable using distributed beamforming, we plot the expected value of received power, $E(P_R)$ against the number of sensors, N in Figure 8 which also shows that a simple analytical model works quite well compared to Monte-Carlo simulation results. Figure 9 shows the variation of the ratio of beamforming gain, $\frac{E[P_R]}{N}$ to the theoretical maximum against N.

These results show the feasibility of the distributed beamforming under reasonable constraints on placement etc.

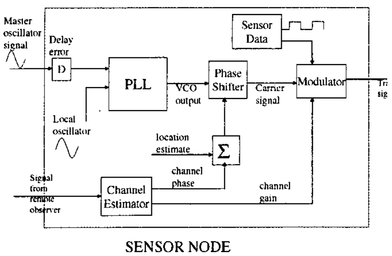

Fig. 7. Model of sensor node's communication system

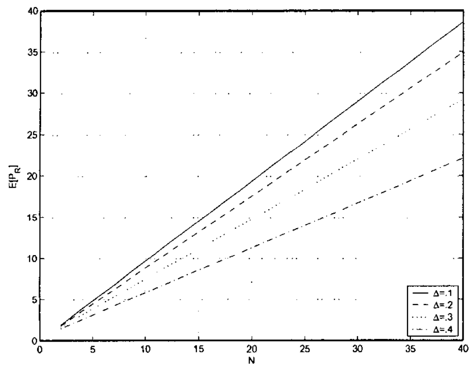

Fig. 8. The expected value of the received signal power vs. the number of sensor nodes N.

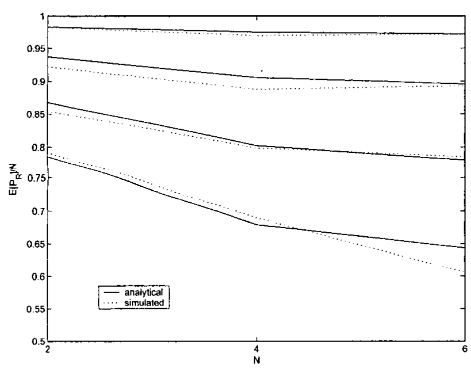

Fig. 9. $E[P_R]/N$ vs N, empirical and analytical results. The four sets of curves are for (top to bottom), $\Delta = 0.1 : 0.1 : 0.4$.

4. CONCLUSION

We have described two distinct concepts in distributed space-time communication, virtual radar and distributed beamforming, both of which exploit the spatial distribution of sensor nodes to facilitate data collection in sensor networks. Initial numerical results indicate the promise of both techniques, much further work remains in fully developing the potential of these schemes, as well as combining them with complementary concepts in multihop routing and distributed source coding.

5. REFERENCES

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