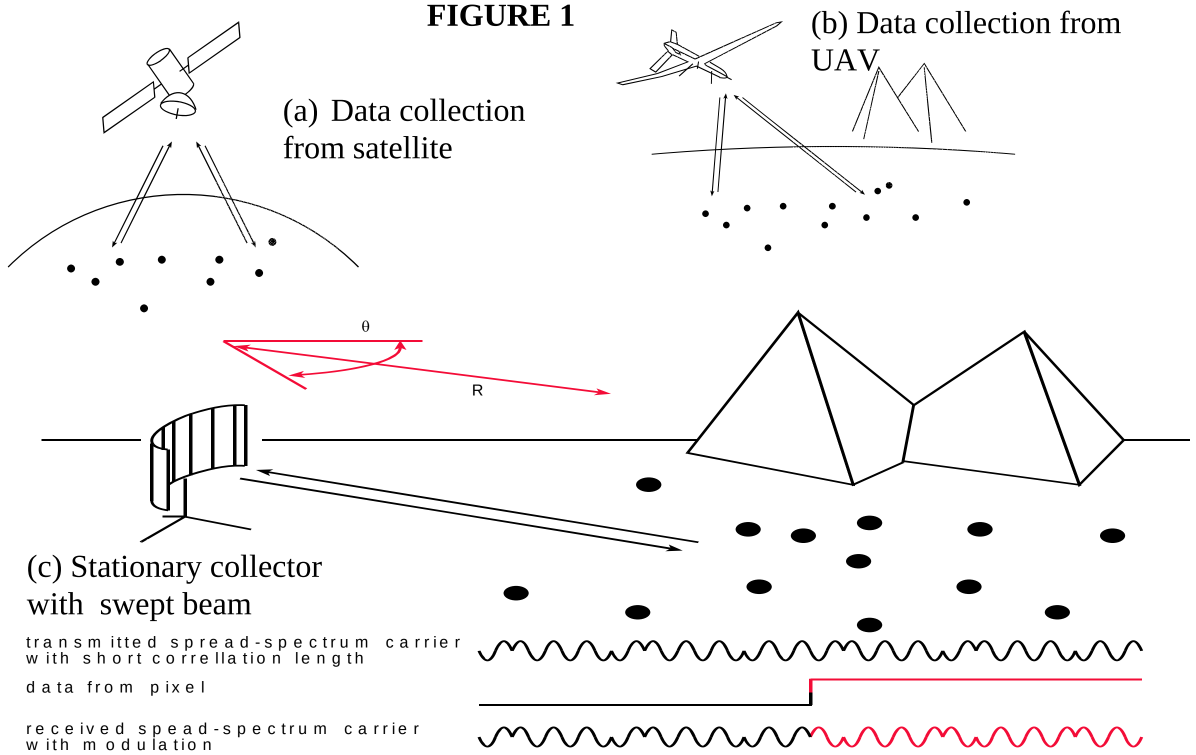
Imaging Sensor Nets: An RFID-inspired Framework for Million Node Sensor Networks

U. Madhow, M. J. W. Rodwell, B. Ananthasubramaniam, M. K. Seo, P. Park
ECE Department, University of California, Santa Barbara, CA 93106, USA

Sensor networks consist of devices that can sense various aspects of their operating environment, and efficiently communicate the sensed information. The heightened ``awareness" provided by these networks have a host of applications, including intelligent automation in homes and factories, environmental monitoring, border security, and information gathering on the battlefield. In terms of prototyping and experimentation, most efforts in sensor networks today employ nodes that are some version of the Berkeley wireless motes (e.g., these are now commercially available from Crossbow, www.xbow.com). These motes have short-range wireless capability and can form an *ad hoc*, multihop wireless network. Sensors and data acquisition cards can be interfaced to the mote's radio. Applications run on top of a lightweight operation system called TinyOS. Mote-based sensor networks can scale to tens or hundreds of nodes, and are suitable for many small-scale applications, such as home or building automation. However, there are many applications that demand truly large-scale sensor networks with tens of thousands of nodes or more, such as border security, battlefield information gathering, and even interplanetary exploration. Current networking technology simply does not scale up to such large numbers of nodes.

Introducing Imaging Sensor Nets: We propose an architecture for truly large-scale sensor networks which is based on interpreting sensor nodes as "pixels'" forming an Imaging Sensor Net, some potential realizations of which are depicted in the figure below.

FIGURE 1



The nodes are capable of sensing any given phenomenon of interest, and we employ an imaging approach to data collection. A sophisticated, location-aware, collector node scans the sensor field systematically using a radio frequency (RF) beacon. Sensor nodes being scanned ``reflect" the beacon (possibly also modulating it with low rate data) either actively or passively. The collector processes the content and timing of the responses from the sensor nodes using an appropriate blend of radar, imaging, and data demodulation techniques. This yields an image of the activity in the sensor field, in which the sensors are localized as pixels whose values correspond to the data they have sent back. By moving the complexity to the collector node, we do not require either geolocation or networking capabilities on the part of the sensor nodes. Indeed, the component sensor nodes need not even have a unique identity, since the association of their measurement with their location is performed by the collector. The elimination of network overhead implies that the data transmitted by the sensors can be drastically reduced, thus yielding link budgets that can sustain ranges of 10s or 100s of kilometers. This in turn enables an architecture in which one or more collectors directly communicate with sensors, bypassing the scaling problems associated with multihop transmission between sensors.

Prototyping Project: We have started building a prototype Imaging Sensor Net with funding from the National Science Foundation. The objective is to develop the theory and practice of Imaging Sensor Nets to a point that a path for technology transfer becomes evident. We address two key technical challenges. The first is to demonstrate that electronic reflection of the collector's beacon (and low data rate transmission) can be accomplished with ultra low cost sensor transceivers realized as CMOS ICs, while attaining ranges of 10-100 km. The second is to demonstrate accurate sensor localization at large ranges. Our planned demonstration scenario is as in Figure 1(c), where a stationary collector sweeps a sensor field with a beam. The collector's beacon contains a location code which is a direct sequence spread spectrum waveform with good autocorrelation, and hence localization,properties. Sensors which fall in the beam electronically reflect the collector's beacon either actively or passively, along with frequency translation to avoid backscatter, and low rate data modulation. We employ ``millimeter wave" carrier frequencies that are an order of magnitude higher than those used in current RF communication systems, in order to increase image resolution using highly directional transmission and reception (much more feasible at small wavelengths) at the collector node, and to reduce the sensor node form factor (millimeter wave antennas can be realized as patterns of metal printed on the circuit board).

Sample Link Budgets: We do link budget calculations for 60 GHz, ignoring atmospheric attenuation for convenience. We would avoid this oxygen absorption band when we wish to operate at truly large ranges such as 100 km, using instead comparable frequencies such as 24 GHz or 70 GHz. Using the standard free space propagation range equation with active transmission from the sensor nodes as a benchmark, $\frac{P_{received}}{P_{transmitted}} = \frac{D_{transmit} D_{receive} \lambda^2}{16\pi^2 R^2}$ (where $D_{transmit}$, ,$D_{receive}$ are the transmit and receive antenna directivities, respectively, R is the range, and λ is the wavelength), we obtain that a bit rate of 100 Kb/s (using QPSK at a bit error rate of 10^{-9}) can be attained at a range of 100 km using 5 mW sensor power, assuming that the collector employs an antenna of diameter 1 m. This huge range allows important applications in planetary and earth remote sensing. The preceding link budget is reduced by 3 dB (and the range by a factor of 1.4) for our preferred implementation of amplifying and reflecting the collector’s beacon, since the collector’s receiver now sees noise from both the sensor and collector RF circuitry. For a ``passive" reflector (which consumes power, but does not employ millimeter wave circuit elements), feasible range is governed by the radar range equation, which is analogous to the free space propagation equation with R^{-2} replaced by R^{-4}. In this case, a collector node with a 1 meter diameter antenna and 10 W radiated power can communicate with sensors at 1 km range with 100 kb/s data rate.

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