Energy-Efficient MAC and Routing Design in Distributed Beamforming Sensor Networks

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ABSTRACT

A major task of a wireless sensor network is energy-efficient, timely, and robust dissemination of sensor readings back to the sink node. The AIDA project [1] aims to create a new sensor network architecture, that uses antenna arrays of the distributed sensor nodes to create directional radio waves that can reach order-of-magnitude farther than individual antennas of the sensor nodes. This new network architecture, based on collaborative beamforming, drastically changes many aspects of the conventional networking stack. As part of the AIDA project, we are designing new energy-efficient MAC and routing protocols for the new, distributed beamforming physical layer, which effectively involves "many-sensors-to-many-sensors" for a single data packet transmission.

1. BACKGROUND

A major task of a wireless sensor network is energy-efficient, timely, and robust dissemination of sensor readings back to a centralized host, called the sink node. While a lot of research has been done in this area, existing approaches to how individual data packets are ultimately delivered from the data sources to the sink suffer several drawbacks. The AIDA project [1] aims to *develop a new sensor network architecture, that uses antenna arrays of the distributed sensor nodes to create directional radio waves that can reach order-of-magnitude farther than individual antennas of the sensor nodes.* Such a distributed antenna array is created by aligning antennas of multiple sensor nodes and transmitting the same information simultaneously at different phases. A major thrust of the AIDA project is to address the synchronization and localization challenges required for distributed beamforming via innovative antenna, radio, and system integration designs.

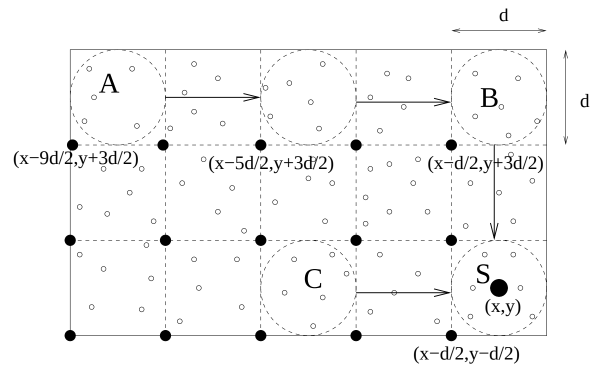

Figure 1: Grid formation and data forwarding in AIDA

As part of the AIDA project, we are designing new data dissemination protocols on top of the new physical layer based on distributed antenna array beamforming (DB). The new physical-layer model introduced by AIDA architecture, in which more than one nodes collaboratively transmit or receive the same piece of data simultaneously, combined with the directional nature of transmissions, requires drastic changes in many layers of the conventional networking stack. In the following, we examine a new addressing scheme, and propose novel MAC and routing layer protocols for the AIDA architecture.

2. ADDRESSING

Due to the "many-to-many" nature of data transmission in AIDA, we adopt a grid-based addressing scheme, instead of a conventional node-based addressing scheme. We construct a grid in the deployment field and all sensors within the same cell are assigned the same ID. Assuming that each node knows its location (through GPS or a localization scheme), a grid can be easily constructed as follows. The sink node decides on the dimension of the cell d, so that all sensor nodes within a cell are within the same broadcast domain, and it places itself at the center of its cell. It then floods a *GRID_FORMATION* packet to the whole network, which includes its own location and the cell dimension. When a sensor node receives the *GRID_FORMATION* packet, it calculates to which cell it belongs, using the information included in that packet and its own location. The address of that node is the ID of the cell it belongs to, which is equal to the coordinates of the lower left crossing point of that cell. For example, in Figure 1, the address of the sink node S with coordinates (x, y), as well as any other node in the same cell will be $(x - d/2, y - d/2)$. Similarly, the address of node A will be $(x - 9d/2, y + 3d/2)$ and the address of node B will be $(x - d/2, y + 3d/2)$. We will use the term *supernode* to denote all nodes within a cell.

3. MAC PROTOCOLS

Basic MAC The widely used 802.11 protocol cannot be used in an AIDA network, because of the directional nature of the transmissions. Although directional MAC protocols have been studied recently in the context of ad hoc networks, we propose here an alternative lightweight MAC based on the following observation: In an ad hoc network, traffic patterns usually involve data exchanging between any pair of nodes. In a statically deployed sensor network, a sensor's task is to sense events and notify the sink. Hence, the expected traffic pattern will involve much fewer transmissions and be more predictable (from each cell towards the sink cell) than in ad hoc networks.

Our proposed MAC protocol removes certain CSMA/CA capabilities. Supernodes transmit data directionally using DB. The MAC header includes the corresponding cell ID of the sender supernode. When nodes in a cell receive the data, they know the direction data came from, and they collaboratively transmit an ACK packet directionally, back to the sender's cell. Each supernode sets a timeout after each data transmission. If no ACK comes, it assumes the data packet was lost due to collision, and retries, after an exponential backoff. This MAC protocol is similar to 802.11 with RTS/CTS disabled. The difference is that 802.11 uses carrier sensing; in our case carrier sensing is limited due to directionality, but this is counterbalanced by the reduced probability of collision.

For this scheme there are two alternative approaches for the receiver supernode. In the first approach, nodes constituting the receiver supernode receive omnidirectionally. Hence, all nodes have the same data and no further data processing is required. In the second approach, nodes perform directional reception in addition to directional transmission This would further reduce collisions and it could lead to significant energy savings (for example, in Figure 1 if node S is beamformed towards node B, then reception of B's data packets will not be distorted by simultaneous transmissions from node C). However, this approach also increases the coordination overhead.

Energy-Efficient MAC In an AIDA network, there are two levels of energy-efficiency coordination: among sensor nodes within the same grid cell (*intra-cell coordination*) and among different cells (*inter-cell coordination*). For intra-cell coordination, many existing approaches can be used that put a subset of nodes into sleep mode and they change this subset over time, so that all nodes consume approximately equal amount of energy. We plan to extend the subset selection algorithm to calculate a sequence of subsets of sensor nodes which not only belabor each sensor in the cell about equal amount of time but also optimize the gain from collaborative beamforming.

Inter-cell energy-efficient coordination becomes very important in AIDA for two reasons. First, if we view all nodes within a cell as a supernode, then we have a network of supernodes, and the arguments for energy conservation in a conventional sensor network also apply here. Second, in AIDA, many more nodes will be in receive mode than in a conventional sensor network due to the long-range directional transmissions. Since an AIDA network can be seen at a macroscopic level as a network of supernodes, existing approaches for conventional sensor networks can be adapted for inter-cell coordination.

4. ROUTING PROTOCOLS

Single-Hop For small- to medium-scale sensor networks, DB can be used to directly send sensor data from data sources to the sink, as shown in Figure 1. Whenever a data source is ready to send data back to the sink, it performs two steps. First, it calculates the subset of sensor nodes within one-hop that gives the maximal gain when used for DB. It then broadcasts a $SS - START$ message which contains an incremented session Id, the subset membership and the beamforming schedule to its one-hop neighbor nodes. Finally, it starts broadcasting data packets of that session one-by-one. Each data message can be used to synchronize the subset of sensors with high precision [2]. Upon receiving each data packet, the subset of sensors perform DB to send the packet to the sink.

Multi-Hop For large-scale sensor networks, DB can be combined with clustering to perform multi-hop routing to route data packets to a significantly further away sink in the network, as shown in Figure 1, where node A is sending data to node S.

Whenever a data source is ready to send data back to the sink, it calculates the next virtual cell to which it needs to pass the data message, based on the location of the current cell it resides in, the location of the sink, and the transmission range of collaborative beamforming. DB is then invoked in a similar manner as in Single-Hop to send the data message to the next cell. In the next-hop cell, all the awake nodes receive the data message. The current clusterhead in that cell selects the next cell to forward the data message to, calculates the subset of sensor nodes that gives the maximal gain when used for distributed beamforming and broadcasts a special beacon to signal the beamforming schedule.

Acknowledgment

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5. REFERENCES

[1] AIDA. `https://engineering.purdue.edu/AIDA`.

[2] J. Elson, L. Girod, and D. Estrin. Fine-grained network time synchronization using reference broadcasts. In *5th Symposium on Operating Systems Design and Implementation OSDI 2002.*, 2002.