A Spatial-Temporal Access Network for Area Event Monitoring

Jussi Haapola
Centre for Wireless Communications
jhaapola@ee.oulu.fi
21st June 2004

1 Introduction

The course work will describe a sensor network that communicates using a spatial and temporal division access method. An illustration of the network is depicted in Fig. 1. First, we define a ‘sensing area’ that consists of a set of sensors spatially in close proximity that are likely to sense a similar event at any given time. The sensing area may be a number of devices in a circle as in Fig. 1 or a whole partial layer marked in green or red. The sink node has spatial antennas, so that multiple sensor node messages can be received simultaneously if they are from different parts of the network. The directional antennas also enable a rough sensing area location with adequate precision. The measurement sensor nodes have omnidirectional antennas and lower transmission ranges. The transmission range is just enough to get a message from one coloured section to the next same coloured section towards the sink with adequate received SNR.

In addition, the course work will look at issues of data processing and forwarding in sensor networks, especially applied for use with this MAC technique. Data prevention can be applied globally so that nodes don’t need to send unnecessary data. Neighbor data processing is done, for instance by overhearing packets, to combine and reduce the amount of data sent. And finally, data aggregation can be performed while forwarding data.

In the work, we will concentrate on two layers; the data link layer (DLL) and the application layer (APL). The addressed components are

- Sensing area classification / joining,
- neighbour / sensing area node discovery,
- next-hop-to-sink discovery,
- spatio-temporal MAC, and
- data prevention, neighbour data processing \( H(Y) \rightarrow H(X|Y) \) and forwarding.

The last item can be considered to belong mainly to the APL while the rest lie in the DLL domain. There are a number of parameters that need to be defined and taken into account when designing the network.

- Sink range: how far can the sensor nodes receive the signal of a sink with enough SNR to successfully decode the messages? The sink obviously possesses a greater
transmission range and more power for transmission than a sensor node, but there is a limit to ensure that the life time of a sink is at least as much as the life time of a sensor node. The sink can also take advantage of the directional antennas it has.

- Sensor density vs. sink density: because the distribution of both sensor and sink nodes can be random (e.g. artillery munitions based distribution) we can only compare the relative densities of sensor nodes and sink nodes to get an estimation of sufficient sink node coverage. The densities also influence the needed transmission ranges for sink nodes. With a very high relative sink density there is not much need for multi-hop communications whereas with low relative sink density the network might be disconnected due to too long transmission requirements or too many hop communication.

- Spatio-temporal areas and SNR: How to separate spatio-temporal areas is a problem of paramount importance. Probably the simplest and still adequate solution is to use predetermined received SNR thresholds for the sensor nodes to classify themselves into different areas. There is a misplacement problem however, when a sensor node’s reception of sink node beacons is attenuated by terrain or damaged antennas. With a large number of sensor nodes, the sink nodes can probably notice this inconsistency.
and cope with the effects.

- Sensor node range: the optimal transmission range also defines the number of hops needed from the furthest sensing area to the sink. On the other hand decreasing the transmission power of nodes closer to the sink will decrease the energy consumption of the closer sensor nodes and would mitigate their increased energy consumption because of forwarding.

- Sensing area: Can an optimal sensing area be predefined and what is the optimal number of nodes needed in a sensing area? The further one is from the sink the larger the spatio-temporal areas are and the probability of having radically different measurement results within a spatio-temporal area increases. A clear set of rules on how to classify oneself in a correct sensing area is needed.

- Data processing and prevention: How effectively can the application layer data prevention and aggregation techniques work together with the MAC algorithm as a whole and in practice? Does it really save that much power to be worth it?

Figure 2: Spatio-temporal network with multiple sinks.
2 Components from DLL

These components are a part of the data link layer and especially the medium access control sublayer. Even the next-hop-to-sink discovery and maintenance is done in the DLL. The purpose of these components is to enable the network to function as well as trying to optimise the usage of the communications channel while carefully considering node energy usage for communication.

2.1 Spatio-Temporal MAC

As depicted in Fig. 1, the base assumption is that the sink node has much better capabilities for communication than a sensor node. Those capabilities include longer transmission range, sectored antenna with 4 sectors, network synchronisation functionality, extended battery life time, more processing power, and guaranteed channel access times.

The idea behind spatio-temporal access is to divide each of the sectored antenna areas into $N$ areas. These $N$ areas are pieces of the sector from one end to the other end of the sector and some width. The sectors are numbered starting from 0 being the area closest to the sink up to $N$. The sink periodically transmits a beacon frame to all sensor nodes. After the beacon there is a predetermined period in which the sensor nodes can communicate freely using some MAC protocol, for example nonpersistent CSMA. However, the free communication is limited to only paired or odd (0 belonging to paired) numbered areas at a time. The communications permission the alternates after every beacon form paired to odd and vice versa.

Adjacent sectors operate in different phases: when one sector's paired areas are free to communicate, the sectors adjacent to it must have the odd areas free for communication. Also if sensor nodes receive frames from an adjacent sector sensor node, they will discard the message without further processing.

The communications flow is directed always towards the sink for the sensor nodes and the sink can directly transmit to any node in its area of influence.

The sink node periodically sends out a beacon signal to the nodes. The frequency of the beacon is dependent on the data rate used as well as the size of the transmittable frames. The beacon interval should be some integer number of transmittable frames and the average contention times associated with those frames. Acknowledgement frames have to be taken into account as well.

The beacon consists of

- beacon number,
- antenna sector ID,
- sink ID,
- beacon transmission power,
- next beacon time, and
- an optional packet of data for control or expected data values.

The beacon number is a continuously running 8 bit counter that resets itself after reaching the highest value of 0xFF. The counter is 8 bits long to make sure that no data frame sent at a certain beacon number exists in the network after the counter has reached the same beacon
number the next time. The LSB indicates whether paired or odd numbered areas are free to communicate.

Antenna sector ID is needed to make certain a transmitted frame reaches the sink through the sector antenna in which sector the sensor node that originally transmitted frame is. This requirement is essential in area localisation.

Sink ID is necessary because several sinks might be reachable by a single sensor node. The sensor node must synchronise with only one sink at a time. Also sink ID is necessary in sink-to-sink communications.

Beacon transmitted power is needed by a sensor node for efficiently classifying oneself into a certain sector area.

Next beacon time indicates the amount of time nodes have for contention communication. The value should infrequently change because the sensor nodes might have difficulties into adjusting rapidly to new situations.

The optional packet may include anything the sink wishes to inform the sensor nodes. All sensor nodes should listen to the beacon unless they are in deep sleep mode.

2.2 Sensing Area Classification

The width of a sector area is dependent on which received SNR boundaries are defined. For example, in the beacon the sink indicates the transmission power $TX_{\text{pow}}$ (in dB) it uses for the beacon. The sensor nodes that receive a number of consecutive beacons with a power of $TX_{\text{pow}} - 10$ dB classify themselves to belong to area 0. Those sensor nodes receiving the beacon with $TX_{\text{pow}} - 25$ dB belong to area 1, while $TX_{\text{pow}} - 45$ dB and $TX_{\text{pow}} - 70$ dB received powers belong to areas 2 and 3, respectively. Other methods may also be used, but received signal strength is probably the simplest and fastest method with minimum communication.

2.3 Sensing Area Node Discovery

Once a node has classified itself to belong in a certain area it immediately begins to function as a sensor. Whenever a sensor node needs to transmit data, it also sends a frame header consisting of the following fields.

- beacon number,
- antenna sector ID,
- sink ID,
- area number that it belongs to, and
- data.

Beacon number is transmitted in order to associate an event into some known time interval when the message eventually reaches the sink.

Antenna sector ID is needed to make certain a transmitted frame reaches the sink through the sector antenna in which sector the sensor node that originally transmitted frame is. This requirement is essential in area localisation.

Sink ID is necessary because several sinks might be reachable by a single sensor node. The sensor node must synchronise with only one sink at a time and the possible forwarding nodes have to be able to pass the message to the right sink node.

Area number is an important parameter because it identifies the approximate location of a node and provides the necessary information for nodes closer to sink to know whether to
forward the data or not. It also announces the nodes presence to its neighbours and allows for data aggregation/prevention.

Data is the sensor values a node wishes to transmit.

Because of the random access MAC protocol and spatio-temporal allocation, a sensor node will receive data frames from four different sources: from a node associated to different sink, from the wrong sector, the area one hop further from the sink node, and its own area. The messages received from a node associated with another sink or a wrong sector will be discarded without any processing. The messages from the one hop further from the sink will be processed and possibly forwarded. The messages overheard from a node's own sector provide information on a device's neighbours, whether similar sensor data that a node has was just sent from the same area, and the received SNR can provide some information on the distance of the nodes.

If necessary, it is up to the APL to define individual node addresses because only the sinks need distinct IDs to communicate with each other. Both the DLL and the APL can access common queues and edit them when necessary. Messages that are received for forwarding are always passed to the APL for data aggregation/prevention.

2.4 Next-Hop-To-Sink Forwarding

The MAC protocol within the spatio-temporal framework does not have many limitations. However, it should be of random access type because of the limitation of a spatio-temporal period in time. Good candidates are CSMA, CSMA/CA, and MACAW type protocols. Collision avoidance techniques are favoured because RTS and CTS frames can be made very small, maximum 2 octets, so the collision period will be small. However, independent of the choice of the MAC protocol communication will be multicast, always. Let us consider if a light version of CSMA/CA is used. When a node in area $n$ has data to transmit it will first perform carrier sense (CS) and upon finding the channel vacant transmit an RTS frame. The destination of that RTS frame will be anyone within the area $n - 2$. The source address will be \{area $n$, sector $x$, sink $y$\}. With this information any node in area $n - 2$ of sector $x$ of a sink $y$ can respond with a CTS frame. That is in fact what is done and the nodes in area $n - 2$ who received the RTS will contend on the channel and the winner will transmit a CTS to area $n$. Now the channel is reserved for the duration of the data transmission for those two nodes and the other nodes can sleep during that period. After a successful ACK both the sender and the receiver will lower their probabilities for transmitting or receiving the next data packet by a function $f(\text{lower})$ in order to save battery energy if they have any known neighbours. If a node has not sent or received data in a period $T^{\text{raise}}$ it will increase its probability of transmitting or receiving data by a function $f(\text{raise})$.

In short, the communications method is contention-based multicast, and the winner of the contention is actually the looser in energy expenditure. Decreasing and increasing the probabilities of transmission and reception is a way of compensating for the energy loss and should even out the lifetime of nodes within an area.

It is obvious that nodes closer to a sink have to receive and transmit more data than nodes further from the sink. This is because the nodes closer to the sink have to forward more data. Therefore, it is suspected that the nodes closer to the sink will exhaust their energy first. To compensate for the energy exhaustion problem two approaches are taken: The APL does data aggregation/prevention and the sensor areas are arranged in such a way that the nodes closer to the sink need lower transmission power to reach the next hop closer to the sink than
nodes further away from the sink. The method is called progressive deepening and it can be shown that with progressive deepening the energy exhaustion time can be made almost independent of the area in which a node resides.

3 Components from APL

These components of the project are related to the application layer techniques used in the sensor network, and to the interaction between nodes in preventing or aggregating data towards the sink.

3.1 Global Aggregation

Global aggregation is a technique for tracking expected values, for instance sensor values, globally in a sink node in order to prevent unneeded data updates. For the set of values being tracked in the network, based on sensing areas, a sink will keep it’s last updated value, plus an expected value for the next sensing period based on previous values. This is then periodically broadcast to the entire sensing network. If a sensor has a value which is different enough from the expected for the same sensing area, it will send an update to the sink. Depending on the specific application, specific parameters need to be set such as the update period, the acceptable difference and sensing area size.

3.2 Neighbour Data Processing

Within one area of the spatio-temporal network, we can define one or more sensing areas. This can be done using SNR levels. Within a sensing area duplicate values may be of no use to the sink, depending on the application. For that reason, overhearing can be used to prevent unnecessary data transmissions.

When the nodes in a sensing area wake up (for the same period in this spatio-temporal MAC design), we want only the necessary sensor values to be transmitted to the sink. In order to overhear, nodes that receive packets from the same area will act in promiscuous mode, that is, they will receive all packets. These packets are sent up to the network layer. The network layer handles packets based on port numbers (as in IP or nanoIP), and will send it to the correct application. This application can then make the decision of wether it has overheard a duplicate value. If so, it does not transmit in during that period, but waits for the next. This is then application dependent, and needs minimal support from the MAC.

3.3 Forwarding

The spatio-temporal MAC handles the transmission of packets to other areas using contention-based multicasting. This is done to ensure that only one node receives (and possibly forwards) a packet. If the sink receives the packet, it has priority and will always win contention. Otherwise nodes have random (or weighted) contention values.

When a node wins contention on a packet from an area (further away from the sink) it passes this again up to the application layer. Action is then up to the application. In some cases the data can be aggregated with the node’s own data. In other cases it will simply forward the packet onwards to the sink.

This however requires that every node in the network has the same applications. Otherwise if a node receives a packet for a port it doesn’t have an application for, it would simply be dropped.