DATA LINK LAYER DESIGN FOR WIRELESS SENSOR NETWORKS

Lizhi Charlie Zhong, Jan Rabaey, Chunlong Guo, Rahul Shah

Berkeley Wireless Research Center
Department of EECS
University of California at Berkeley

ABSTRACT

This paper presents the architecture of data link layer for wireless sensor networks. Requirements are specified and functional description is given. Relationship between different subsystems is also discussed. The designed data link layer has ultra-low power consumption. It is distributed, simple and robust. Additionally, it requires no synchronization.

INTRODUCTION

A node in a wireless sensor network is just like a human being, intelligent, wireless and has some knowledge about his local environment. Human beings team up to do things they are not capable of individually. Similarly, nodes in a wireless sensor network organize themselves into a network and use the network to do cooperative processing.

Other wireless networks include cellular network, wireless LAN (802.11a and b) and home area network (Bluetooth). Packet switched network will be introduced to support wireless internet, but voice is and will still be the dominant application in cellular network. Cellular network is targeted at users with high mobility. The data rate for mobility at this level is very limited due to the Doppler shift. Wireless LAN, on the other hand, is pushing for very high data rate, but the mobility it can support is low. It is targeted at enterprises. Bluetooth and Home RF are targeted at home. The required data rate there is much lower and the radio range much shorter. The mobility is low, too.

Wireless sensor network is very different from the above networks. It has a large number of nodes. The distance between neighboring nodes is shorter than any of the above networks. Due to the sheer number of nodes, the cost for each node has to be less. The power consumption must be much lower because replacing the battery of every node even once a month would be a maintenance nightmare. The data rate and mobility in wireless sensor network are lower as well. What is more, there is inherent redundancy in sensor data.

Wireless sensor network is targeted at both office and home. One key application is to use sensor network to carefully control the lighting and air conditioning inside a building to minimize the energy consumption without sacrificing comfort. This application is becoming increasingly important in light of the current energy crisis. On the other front, as new communications algorithms demand more and more computation power, a single microprocessor cannot deliver the performance within a reasonable power budget. High power consumption not only reduces battery life, but also requires very complicated cooling technologies to deal with heat dissipation. This opens the door for distributive computing, where intelligence is distributed and cooperation is needed to accomplish a task. Wireless sensor network fits right in there.

SENSOR NETWORKS IN MILLITARY APPLICATIONS

Currently, information that can be exchanged between soldiers in the battlefield is very limited. Soldiers mainly rely on voice for local communications. Long-range communications is typically point-to-point and requires high transmission power, with the danger of being eavesdropped. The system has a single point of failure. With sensor network, every soldier will be a “sensor”, since he has information about his local settings based on what he sees and listens himself and what the equipments he carries measure. Soldiers can communicate with his neighbors wirelessly, and organize themselves into a network based on military operations. Rich information can be exchanged over such a network either locally or over a long range. This results in much better cooperation between soldiers in a wide geographic range. The short range of each transmission minimizes the possibility of being eavesdropped.

Sensor networks in military applications must be optimized for low power consumption. In addition, they must not require global synchronization among all network nodes. The control must not be centralized as well. Low power consumption ensures the radio every soldier carries is small, lightweight and can be operated for a very long time. On the other hand, if global synchronization is not required, a network can be setup on the fly anywhere in the battlefield, and the operation of the network is robust even when nodes come in and out of the network. The network also has no single point of failure, since there is no single control point. Sensor network's inherent redundancy further increases the reliability of the communications. All these attribute to a very robust network military applications would like to see.

PROBLEM STATEMENT

It is clear from above that a wireless sensor network needs have very low power consumption. It has to be robust. The setup of the network should be easy. So the data link layer of such a network must be designed correspondingly. First, the data link layer must also be optimized for power. It should be reactive. Power is used only if there is an event. When there is no event, the entire system including data link layer should hibernate. The data link layer should use distributed methods. A distributed network is more scalable and more robust because it has no infrastructure. Global synchronization must not be required in the data link layer. Finally, the data link layer design needs to be simple and robust.

ACCESS PROTOCOLS FROM LITERATURE

The Media Access Control (MAC) is an important functionality supported in the data link layer. MAC protocols [1]-[8] in the literature can be classified into different categories based on different principles. Some are centralized, with the base station or group leader doing the access control; some are distributed. Some use a single channel; some use multiple channels. Some use various versions of random access, some use reservation and scheduling. They are also optimized for different things: power, delay, throughput, fairness, Quality of Service (Qos) or support for multiple services.

We have proposed an ultra-low power access control scheme in [9]. Several power saving techniques are used in the scheme. It trades bandwidth for higher power efficiency. It also exploits the redundancy in sensor networks to further improve the power efficiency. The algorithm is fully distributed and requires no synchronization.

The rest of the data link layer, however, needs to be designed with MAC jointly to bring down the power consumption aggressively.

PICO-RADIO PROJECT

Pico-radio network is designed by Berkeley Wireless Research Center (BWRC) to be an ultra-low power, wireless ad-hoc network [10]. The projected power consumption for each node is 100µW. A node costs less than 50 cents. The size of it is about 1 cm^3. The power consumption is minimized vertically across different layers and horizontally through the entire network. That is, the power is not only optimized for a particular layer, but also for all layers. The power is not only optimized for a particular node, but also for the entire network.

All nodes in the network have the same protocol stack. All layers of the stack are designed to be reactive to save energy. The application layer can be configured based on application requirements. For example, in an office building environment control application, a node can be configured to have any of the four functionalities: control node, sensor node, actuator node and interface node. A control node requests data from sensor nodes. Based on the information received, it commands actuator nodes to take corresponding actions. An interface node is used to monitor the status of the network. It can also be used as a gateway to other networks, such as internet. The mapping from functionality to physical nodes is not necessarily one to one. For example, a control node and a sensor node may be the same physical node. No matter what configuration, actions happen only if there is an event.

The network layer uses a multi-hop routing scheme based on probabilistic forwarding. Multiple paths from source to destination are obtained during route discovery, but the probability of taking any path is inversely proportional to the energy metric of that path. This means that the minimum energy path has very high probability of being used, while other paths are also used sometimes, so if some new nodes come up which can offer a better path, it can be also be used. Thus the scheme uses the optimal path "most" of the time, but has alternative routes ready in case of node failure. It is also responsive to new nodes coming up which can offer lower-energy paths. This design is reactive in the sense that periodic flooding is not used. Flooding is triggered only when there is a change in network topology. This flooding is also directional. Only nodes impacted by the topology change will be included in the flooding.

The data link layer has all the intelligence needed to handle everything within one hop. The details of it will be explained in the following sections. The Unified Modeling Language (UML) is used to specify the requirements for

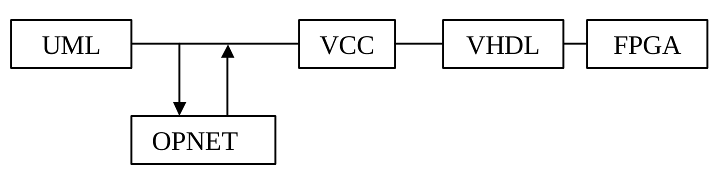

Figure 1 From Requirements to Implementation

the layer, from which algorithms are developed. OPNET and MATLAB are used to do the simulations. After the algorithms have been evaluated, UML is used again to describe the functionalities. Each functionality is then mapped to a behavior model in Virtual Component Co-Design (VCC). Functional simulation with other layers (e.g. network, application) can be performed. Verification can be obtained. VCC can also create the Verilog Hardware Description Language (HDL) code for the models to be implemented in Field Programmable Gate Array (FPGA).

The RF uses a sub-sampling receiver with passive front end. An array of high-Q on chip filters (e.g. FBAR filters) is used to provide the diversity. The received energy can be reduced by 1 to 2 orders of magnitude. By biasing Low Noise Amplifier (LNA), the radio can be turned off when there are no incoming messages.

DESIGN ASSUMPTIONS

The average data rate is assumed to be low. So the duty cycle of the radio can be very low. Unlicensed band will be used and bandwidth is assumed not to be a limiting factor. The density of nodes is high. The distance between neighboring nodes is less than 10m. Most of nodes in the network are static. Even the mobile nodes have low mobility (walking speed). Sensor data is highly correlated in time and in space. Furthermore, applications have high delay toleration.

DATA LINK LAYER FUNCTIONAL DESCRIPTION

Pico radio data link layer supports a set of functionalities. They and their relationship to one another are shown in the UML class diagram below:

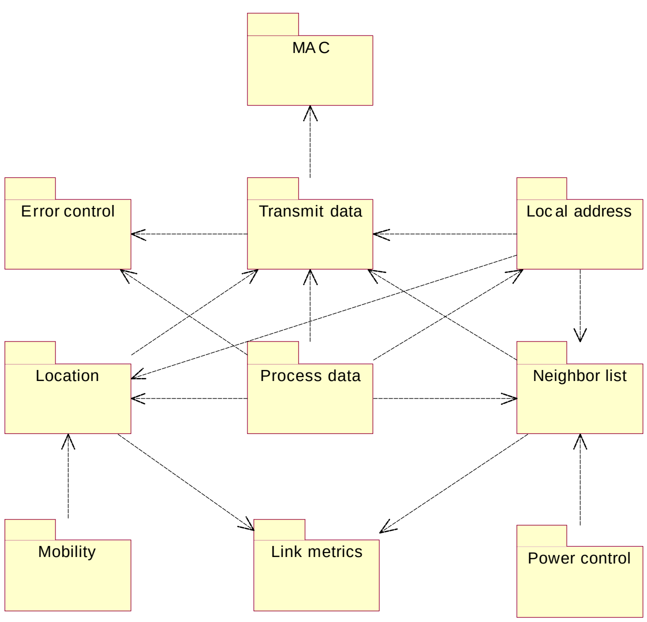

Figure 2 Data Link Layer Architecture

Each block/subsystem in the diagram represents a functionality supported and the arrows indicate the direction of the dependency between subsystems. For example, transmit data subsystem depends on MAC subsystem to know when to transmit and what channel to use.

Starting from top, from left to right, a brief description of every subsystem is given below. More in-depth discussion of them is given in a separate section to help readers get the big picture first. As mentioned earlier, the MAC subsystem does access control. It specifies the time a node can transmit and the channel to use for transmission.

Error control subsystem encodes or decodes data based on a specific error detection or correction code.

Transmit data subsystem transmits data to the physical layer.

Local address subsystem is responsible for assigning a locally unique address to a node.

Location subsystem computes or refines a node’s location based on its own location (or its assumed location), its neighbors’ (assumed) locations and the distances between its neighbors and itself [11].

Process data subsystem processes the data from the physical layer.

Neighbor list subsystem creates and maintains the neighbor list. The neighbor list has the following information about every neighbor: location, local address and link metric.

Mobility subsystem supports mobile nodes.

Link metric subsystem provides a metric for every link. The network layer uses the metric to compute the probability of taking a path. The subsystem also stores channel status (needed by MAC subsystem) and Received Signal Strength (RSSI) measurements (needed by location subsystem).

Power control subsystem specifies the transmission power level.

DATA LINK LAYER USE CASES

The subsystems described above work together to accomplish the tasks in the data link layer. The UML system level use case diagram clearly shows how other layers use the data link layer. The stick men in the diagram are actors, which interface with the data link layer. For example, the network layer will use the data link layer to transmit data to the physical layer and receive data from it. It also searches the neighbor list in the data link layer for a particular neighbor's information.

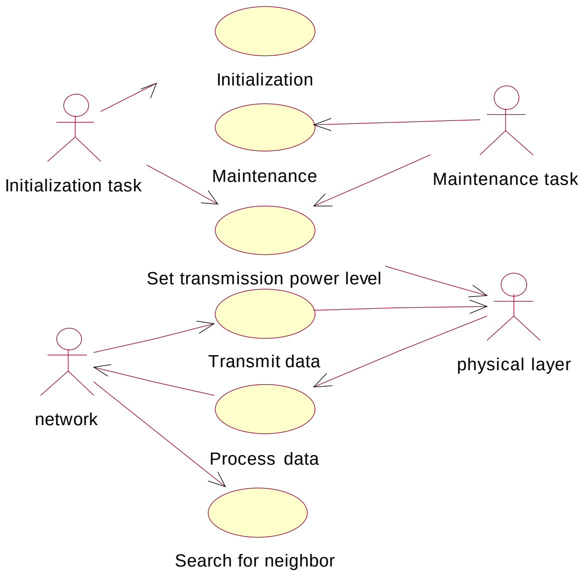

Figure 3 Data Link Layer System Level Use Case Diagram

SUBSYSTEM DESIGN REQUIREMENTS

For every subsystem, there can be multiple ways to design it. How to quantify the requirements and break them down to every subsystem is still under investigation. The availability of design metrics will provide the basis for comparison.

Error control codes are known to have higher power efficiency even with all the redundant bits added. This is of course at the cost of bandwidth. But bandwidth is not a serious concern for sensor networks. The tradeoff is really between the complexity of the encoder and decoder (computational power consumption) and transmission power efficiency. Because the distance between neighboring nodes is short, computational power can be comparable to transmission power.

Transmit data subsystem add data link layer control information to the payload and uses error control subsystem to encode the entire packet. It also implements retransmission mechanism. For unicast data from the network layer, it also maintains a queue for every neighbor. Multiple packets for the same neighbor are combined into a longer one to reduce the ratio of overhead.

The use of locally unique address not only reduces the number of bits needed to represent an address, but also makes the network scalable. Local address subsystem maintains an address list for a node. This list records the availability of every possible address. If an address is not available, the list also has information on how many times it has been used in the node's two-hop neighborhood. "Locally unique" not only means a node's address must be different from any of its neighbors, but also implies that any two neighbors of the same node must have different addresses even if they are not neighbors to each other. A systematic way to ensure the second condition is to let a node's address to be different from its neighbors' neighbors' addresses. As a result, a node needs to mark all the addresses used in its two-hop neighborhood as unavailable. When it needs to assign itself an address, it randomly picks an available one from the list. If a node's neighbor has moved out of the node's neighborhood, the address will be made available only if no other neighbors in the node's two-hop neighborhood are using the same address. If any, the number of times that address is being used is decremented by one.

To construct the address list, a set of handshakes needs to be performed when a node enters the network for the first time. It sends a request to all neighbors. Every neighbor responds with its address and its neighbors' addresses. The node then updates its address list based on the information received. After some time, thinking all neighbors have responded, the node will assign itself an address based on its address list. Complete neighborhood information is necessary to guarantee that the assigned address is locally unique. The nature of wireless communications and the fact there may be new nodes coming to the network often cause some nodes not having the complete information about their neighborhood. Therefore further handshakes are needed to resolve potential address conflictions. But this process converges once the network topology stays unchanged.

The local address assignment algorithm doesn't work well with mobile nodes, which keep on moving from one neighborhood to another. So the address assignment for mobile nodes will be different from that for static nodes. A separate address cluster is allocated to mobile nodes to reduce the handshakes. Another difference between the two types of nodes is that batteries of mobile nodes can be replaced more easily than those of static nodes. Some static nodes, for example, are inside a wall. Mobility subsystem will exploit this difference to put more load on mobile nodes.

The metric provided by link metric subsystem is currently the energy spent on a link. As a result, the optimal path chosen by the network layer is the path with minimum energy. Since power needs to be optimized for an entire network, not just for a particular node, network life is a better metric. Network life measures how long a network with minimum connectivity can survive for given battery supplies and a fixed rate of power regenerating. Path should be selected such that maximum network life is obtained. How to quantify network life is still an open question. Using the minimum energy path certainly increases network life. But routes need also be selected such that a particular node will not be in too many paths. Otherwise the battery of this node will run out quickly and all the paths going through it will be impacted. Network life is also related to the connectivity of the network. If a network has many redundant paths, alterative paths can be used when a node goes down. In summary, network life is related to the energy profile of the paths, the balance of the load and the topology of the network. Link metric subsystem will provide a metric enabling maximum network life.

The power level specified by power control subsystem can be for a node, a link or on packet-by-packet basis, depending on how fine the control should be. The power level is adjusted based on connectivity, interference and power consumption. Simply using the minimum transmission power may minimize the power consumption for a hop. But using higher transmission power improves connectivity and this may results in lower overall power consumption, especially in the case of flooding. Also, minimum connectivity needs to be guaranteed to keep the network alive, so the transmission power needs to be adjusted after the number of neighbors has been changed.

From the above discussion, it is clear that different subsystem not only have to work together to complete a task, their design optimizations are also interrelated. They needs to be co-designed to achieve overall optimal performance.

CONCLUSIONS

Wireless sensor networks have tons of applications, including many military applications. A data link layer especially designed for wireless sensor networks is described in this paper. Future work includes defining a link metric that maximizes network life and identifying design metrics to quantify network behavior.

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