Sensor Networks: MAC Protocols

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Abstract. Sensor networks are autonomous networks that consist of up to thousands of nodes performing some specific task such as sensing environmental events. The devices are highly constrained: The devices have for example poor computing capabilities and battery resources. The nodes need to communicate with other nodes to convey the sensed information to a device collecting the data. When designing MAC protocols for sensor networks, the constraints of sensor networks need to be taken into account. In this paper, short description of sensor networks is presented followed by descriptions of some MAC protocols.

1 Introduction

Usually, sensor networks are known as networks consisting of autonomous wireless nodes. The nodes are equipped to do some specific task, such as monitoring surrounding conditions, such as temperature, wind, air pressure and so on. Usually, the devices are highly constrained: The nodes do not have continuous power supply and their computational capacities are usually quite small.

The sensor networks may consist from just a few nodes to hundreds or even thousand nodes. The sensor networks may form some kind of clustered networks, where each cluster observe some area they are located and transmit their observations to more capable devices attached into a network. Thus the nodes may communicate with each other or with a base station. The communication with the base station may occur directly or through other nodes of the sensor network. In any case, the nodes are distributed randomly without any kind of an infrastructure even if the nodes communicate with some base station. Because of this, every operations need to be distributed between the nodes of the network.

The formed sensor networks are highly robust and reliable, as all nodes are able to communicate with multiple nearby nodes. This also leads to highly correlated traffic: As all nearby nodes notice the same environmental events, they all start to transmit this information simultaneously. This leads to high probability of collisions in the networks.

In designing MAC-protocols for sensor networks, the limitations of the nodes need to be taken into account. Probably the most important constraint is the limited power supply: The devices need to be turned off whenever it is possible to save as much energy as possible. Another difficulty with MAC-protocols is the lack of infrastructure. In contrast to for example infrastructure-based cellular networks, global synchronization in sensor networks is difficult. This needs to be taken into account while designing MAC-protocols.

The nodes in sensor networks consist of three subsystems. These are

1. Sensor subsystem
2. Processing subsystem
3. Communication subsystem

The sensor subsystem is responsible of sensing the environment and producing data to be transmitted. The processing subsystem takes care of some initial processing of the gathered data, or just relies the data forward to other device. The communication subsystem, or radio subsystem, takes care of communication with other nodes. The communication subsystem is the system consuming most energy.

In this paper, some aspects of MAC-protocols and examples of such protocols are discussed. The paper is based on a book by Murthy and Manoj [MM04], and papers by Shih, et. al. [SCI+01], Sohrabi, et. al [SGAP00], and Woo and Culler [WC01].

The MAC-protocols can be divided into three categories, which are fixed allocation, demand-based or contention based. In fixed allocation, each node is assigned a slot for transmission. This kind of allocation suits well, when the traffic is deterministic and equally distributed between the nodes. Fixed allocation protocols may lead to inefficient usage of transmission channel, if some nodes do not need to transmit data whereas some others would. In demand-based protocols, the channel is allocated based on demand. The protocols can be efficiently used if the data rate varies. As a downside, the protocols require extra overhead to reserve the channel. Finally, in contention based protocols the channel is reserved based on a randomized contention. Such protocols suit well if the traffic is bursty, but collisions might occur quite frequently.

The rest of the paper is organized as follows. In Section 2 a protocol called Self-Organizing MAC for Sensor Networks is described. In Section 3 a hybrid TDMA/FDMA protocol is described followed by CSMA-based MAC-protocols in Section 4. In Section 5 some conclusions are drawn. This paper follows the order in which the protocols are described in [MM04].

2 Self-Organizing MAC for Sensor Networks

In [SGAP00] a method for self-organization of wireless sensor network is described. The protocol uses fixed allocation: each pair of nodes are allocated a time slot when they are allowed to communicate. These time slots defines the communication channel, or a link, between the nodes The protocol assumes that the nodes are able to turn their radios on and off to save the battery. In addition, the authors assume, that the devices are able to operate on different frequencies. According to the paper, this is reasonable assumption, and it is said that the devices may have about 2600 different frequency bands to select the used one.

This feature is used to allocate different frequency bands to each pair of devices that are communicating together.

The basic procedure of Self-Organizing MAC for Sensor Networks (SMACS) is described in Figure 1. Nodes A and D wake up on some random time, and start a process to discover nearby devices. During the discovery phase the devices find each other and negotiate the used time slots and frequencies to be used for the communication between the devices. The device negotiate two time slots, which are used to transmit to one direction. That is, node A transmits to node D during the first time slot, and node D transmit to node A during the second, for example.

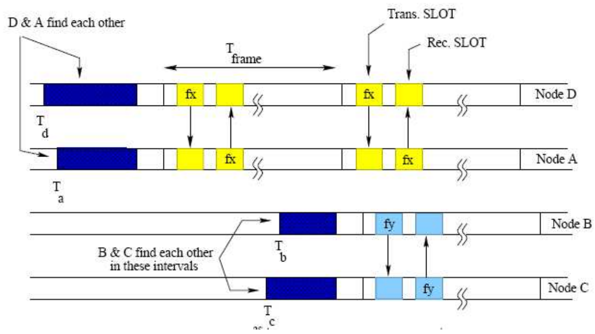


Fig. 1. SMACS Communication Schedule [SGAP00]

The different frequency bands are used to allow multiple pairs of devices to use the same time slots for transmission. This way, when new devices later create a link between themselves, they don't need to take into account the time slots the other pairs are using. In Figure 1, nodes B and C are able to use colliding time slots for communication, as they are using different frequency bands. When new links are formed, the devices do not know the frequency bands the other links are using. Thus it is possible for the devices to start using the same band as some nearby device with the time slots. According to the authors, the probability for such collisions where two links are formed with same time slots and same frequencies is quite small, as it is also needed for the devices to all hear each other before the transmission start to get corrupted. This probability is small as the frequencies are chosen at random from a large pool of possible frequencies.

After the devices have agreed on the used frequency and time slot, the devices start using these for communication. The transmission occurs every T_{frame} seconds, which is a property of a system and is constant for each node of the network. Now, the devices are able to turn off their transceivers when they do not need to transmit or receive, and turn back on for the new round of transmissions.

The initial node discovery phase is depicted in Figure 2, which takes into deeper consideration what happens between nodes B and C of Figure 1 and some other non-visible node G. Again, the nodes wake up at random times. After waking up, the nodes listen to some predetermined frequency channel for a random time. If during this initial listening time the node doesn't hear any invitations from other nodes, it initializes and sends an invitation message itself, as happens with node C in Figure 2. This message is called *TYPE1* message. The message includes node's id and the number of neighbors the node is attached to already. After node C has sent the message, nodes B and G are still in the initial listening phase, so both of these devices hear the invitation. Both, G and B then decide to respond to the invitation by broadcasting a message called *TYPE2* destined to node C. In this message, the nodes include their addresses and their attached state. In case the *TYPE2* messages sent by nodes G and B do not collide (note that they are now sent using the same frequency), node C will receive both of these messages. In Figure 2 node C will select the message sent by B, as it is received first. This is just one possibility to select the node. Other means may be for example to select the one with the strongest signal strength.

At this point, node C will indicate which node it will be attached to. The node creates a message called *TYPE3* message, which includes the information on which node was selected (in the case of Figure 2, node B). In addition, the message includes information on the inviter's schedule and frame epoch. Now, as node G receives this message, it notices that it was not chosen, shuts of its radio to go to hibernating state. After some random period of time, node G wakes up and initiates the procedure again.

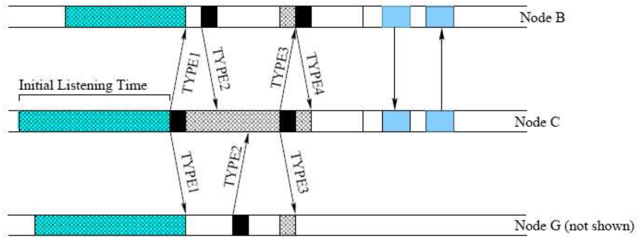
As node B receives the *TYPE3* message, it compares its own transmission schedule with the inviter's schedule received in the *TYPE3* message, and selects the two time slots to be used for transmitting and receiving. In addition, the node randomly selects the frequency band to be used and send this information in *TYPE4* message to the inviting node B. After this message the nodes send a pair of short test messages to test and finalize the channel establishment.

Using this kind of procedure, the nodes start forming small connected groups of nodes, called sub-nets in the paper. A sub-net is a connected network of nodes, where the number of nodes is at least 2. These sub-nets keep growing as more nodes are attached to them using the method described here. At some point eventually the nodes start to discover nodes from other sub-nets, these sub-nets get connected and finally the whole network is connected and able to perform whatever tasks it is assigned to do.

3 Hybrid TDMA/FDMA

A hybrid TDMA/FDMA scheme is described by Shih, et. al, in [SCI$^+$01]. The basic idea of the scheme is to utilize the strengths of both time division multiple access and frequency division multiple access to save energy in sensor networks. The scheme is centrally controlled, that is, the nodes communicate directly to a nearby base station.

In TDMA, each node (or a pair of nodes) is assigned a certain time slot to use for transmission. This time slot then repeated periodically. This way



(c) Details of node discovery phase

Fig. 2. SMACS Node Discovery [SGAP00]

the node is able to turn off the transceiver when it is not needed. This way, TDMA minimizes the time that nodes need to be kept on and utilizes maximum bandwidth for transmission. On the other hand, with TDMA the total transmit on-time is minimized. In FDMA, the nodes are assigned a certain frequency band for communication. In such a scheme, the channel is allocated all the time for the node, independent of whether the node has something to transmit or not. This way FDMA allots the minimum required bandwidth and maximises the transmit on-time.

In hybrid TDMA/FDMA the idea is to use optimal number of channels to minimize energy consumption. This is done based on the ratio of power consumption of transmitter to receiver. If transmitter consumes more power, TDMA is favored as the node is then able to turn off while not transmitting. If the receiver consumes more power, FDMA is used to avoid power consumption to time synchronization of the receiving node.

4 CSMA-based MAC-protocols

Woo and Culler discuss CSMA-based MAC protocols in [WC01]. The basic idea of carrier sensing multiple access protocols is for the devices to listen to the communication channel and transmit if it is free. If the channel is reserved, a backoff mechanism is used to try transmission again on later time. The approach is effective when all nodes are able to hear each other. On the other hand, the method needs for the devices to sense the channel and thus it is required for the transceiver to be on and consuming power.

In case the channel is reserved, a backoff mechanism is used. In case of sensor networks and correlated traffic, the backoff mechanism needs to break the synchronization of devices: if all devices try to transmit at some point, go to sleep, wake up simultaneously and transmit again, the transmission never succeeds.

To allocate the transmission channel, the paper discusses two schemes, which are RTS/CTS control scheme and rate control mechanism.

RTS/CTS scheme uses request messages and acknowledgement messages to reserve the channel. When a node wishes to transmit, it send an RTS message (request to send) to its parent node. The nodes are supposed to form a tree like structure, where the root of the tree is some base station. If node receives a CTS message (clear to send), it is free to transmit. If CTS message is not received during timeout period, a node enters a backoff state with exponentially increasing backoff window. If a node receives a CTS message destined to some other node, it goes to backoff mode also. It should be noted, that in case of sensor networks this kind of operation increases the overhead of control messages quite significantly. In case of computer networks, the packet sizes are quite large and thus some small control messages do not affect the overall communication. In contrast, in sensor networks where packet sizes are quite small, the overhead grows. It is said in the paper, that with their platform, the RTS-CTS-DATA-ACK handshakes may constitute up to 40% overhead.

Another protocol described by Woo and Culler is called rate control mechanism. The mechanism monitors the throughput of messages, and in case of successful transmission increase the transmission speed linearly. If the transmission fails, the transmission speed is decreased. A transmission is considered successful, if a node's parent node forwards the packet upward in the communication structure. If a transmission fails five times, the transmission is dropped.

The transmission speed is controlled as follows. If the maximum transmission speed is S, the original transmission speed is $S = p * S$, where $p \in [0, 1]$. When a transmission succeeds, p is incremented by a constant α. If transmission fails, p is decreased by multiplying it by a factor $\beta, 0 < \beta < 1$. In the scheme, dropping packets to be routed (that is, intermediate nodes dropping packets) is thought as waste of resources. To adjust this, the penalty for dropping route-thru packets is 50% less. The intermediate nodes are also required to give fair proportion of its bandwidth for routing packets. This way, the system does not favor the nodes closer to the base station.

5 Conclusions

In this paper, some MAC-layer protocols have been discussed. The discussion is based on a book by Murthy and Manoj [MM04]. First, some properties of sensor networks were discussed followed by descriptions of few medium access control protocols.

The main goal for MAC protocols for sensor networks is to provide suitable solutions for the specific properties of the networks. The main goal for the protocols is to maintain fairness and energy efficiency of the communications. The different protocols treat these properties differently, and it is left for the implementations to actually select the protocol that suits best the specific application.

References

[MM04] C. Siva Ram Murthy and B. S. Manoj. *Ad Hoc Wireless Networks: Architectures and Protocols.* Prentice Hall, 2004.

[SCI+01] Eugene Shih, Seong-Hwan Cho, Nathan Ickes, Rex Min, Amit Sinha, Alice Wang, and Anantha Chandrakasan. Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks. In *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 272–287, New York, NY, USA, 2001. ACM Press.

[SGAP00] Katayoun Sohrabi, Jay Gao, Vishal Ailawadhi, and Gregory J. Pottie. Protocols for self-organization of a wireless sensor network. *Personal Communications, IEEE*, 7:16–27, 2000.

[WC01] Alec Woo and David E. Culler. A transmission control scheme for media access in sensor networks. In *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 221–235, New York, NY, USA, 2001. ACM Press.