# s-net® - Energy Optimized Communication for Wireless Sensor Networks

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## Abstract
A wireless sensor network is a system of distributed sensor nodes that interact with each other and - depending on the application - even interact with the environment in order to acquire, process, transfer, and provide information extracted from the physical world and to respond to those stimuli by influencing the physical world.
Application requirements call for certain quality of service aspects or a certain system lifetime that needs to be met. The biggest contributor to quality of service aspects and power consumption aspects in a wireless sensor network is the communication protocol.
s-net® is a wireless networking protocol developed by the Fraunhofer Institute for Integrated Circuits IIS in Germany that is focusing on energy-efficient and secure data communication in wireless sensor networks (http://www.s-net-info.de).
Key element is the patented medium access control protocol SlottedMAC. It combines the advantages of time division multiple access systems (TDMA) – namely efficient use of the medium and efficient use of energy - with the scalability and flexibility advantages of contention-based protocols. The nodes synchronize themselves in a virtual tree structure rooted at the master node. This dynamic formation and self-organization of the network topology ensures low configuration effort, low maintenance and a high level of robustness. s-net® allows a multi-hop communication for data transmission via intermediary nodes with a scalable range of the multi-hop data communication for fast data transport through the network.
Time division multiplexing and time synchronization of nodes leads to ultra-low-power communication because of short send and receive activity cycles. The network layer TriNwk allows address based forwarding of packets within and outside the network.
Contrary to other protocols s-net® addresses the need for node mobility and enables nodes to roam freely inside an s-net® network.

## Introduction
A wireless sensor network is a system composed of spatially distributed sensor nodes which independently interact with one another and – depending on the application – also with the existing infrastructure by radio. This serves the purpose of acquiring, processing, forwarding and provisioning of information from the physical world. Sensor networks may vary for example in the type of networking, the topology and the direction of the data flow.

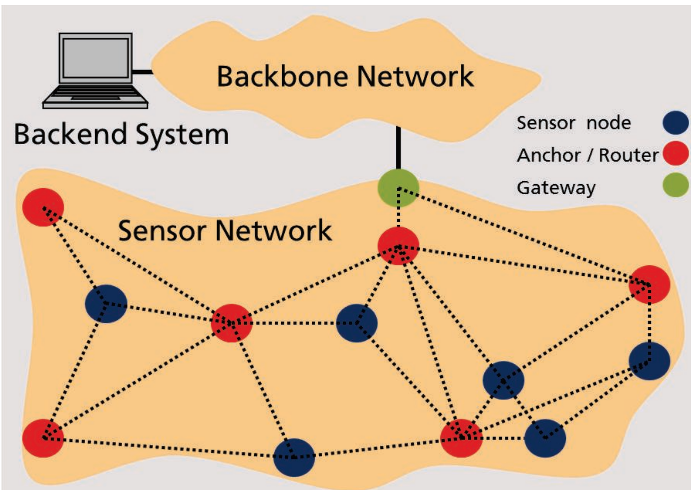


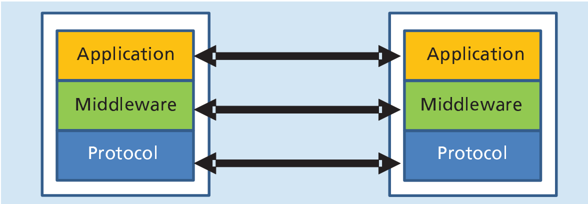

Figure 1: A wireless sensor network reference model

The sensor nodes in a sensor network interact with one another and are connected via a "backbone network" to a computer system that offers additional processing ("back-end system").

The participating nodes carry out different roles in a sensor network:
- The transfer from a sensor network to a back-end-system – e.g. an IP network – is carried out by a gateway node.
- Often, stationary nodes transfer the data (router nodes) or form the stationary basis for the localization (anchor nodes).
- Furthermore, there are (mobile) sensor nodes which, depending on the application requirement, are equipped with different sensors or actuators.

Communication takes place on different logical levels. Application components on the sensor nodes communicate with the corresponding components in the back-end system.

Figure 2: Reference model for communication in and with a sensor network




Middleware components provide basic services or more complex functionalities to the applications (e.g. localization) for this they also communicate with each other.
The transfer of messages in the network is controlled by the network communication protocol.

## Challenges

Application requirements call for certain quality of service aspects or a certain system lifetime that needs to be met. The biggest contributor to quality of service aspects and power consumption aspects in a wireless sensor network is the communication protocol.
For the design of an optimized communication protocol some fundamental requirements – amongst others - have to be defined:
- Energy: How long does the system have to be operational with a single battery charge?
- Latency: How long should it take for messages to be processed or delivered?
- Scalability: How many participants should the network support and how are the nodes distributed inside the network? A network with mobile sensor nodes may support node mobility within the network and from one network to another.
- Throughput: What volume of data traffic should be transferred over the network per time unit?
- Topology: Who needs to communicate with whom? Sensor networks can have a fixed static configuration or may adapt dynamically to the addition or removal of sensor nodes or changes of the radio connections.

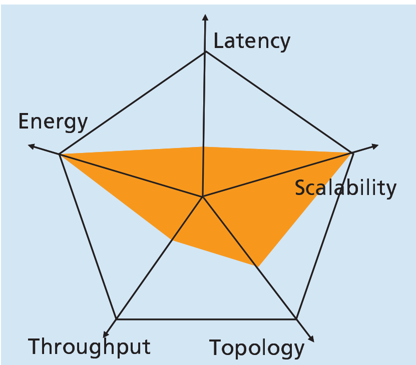



Figure 3: Wireless sensor network protocol requirements

As these requirements influence each other, the protocol designer is faced with a conflict of goals if he wants to develop an energy efficient protocol.

In a network communication protocol energy consumption is mainly caused by receive and transmit activities. For high efficiency these activities have to be coordinated. There are four main reasons which reduce power efficiency which means that they waste energy [Ye1]:

- Idle Listening: This occurs whenever a node is in receive mode and listening for possible traffic, that is not sent. Idle listening is often the major cause of energy waste so many protocols try to reduce the receive duty cycle.
- Collisions: Packets simultaneously transmitted by two or more senders may collide at the receiver. They become corrupted and have to be discarded. The necessary retransmission increases energy consumption and also latency.
- Overhearing: This occurs when a node receives a packet which is actually intended for other nodes.
- Protocol Overhead: Coordination of a network needs additional protocol control information. Sending and receiving the control information needs additional time and energy.

## s-net®

The s-net® protocol stack tries to cover all of the above mentioned causes of energy waste while keeping flexibility and scalability.

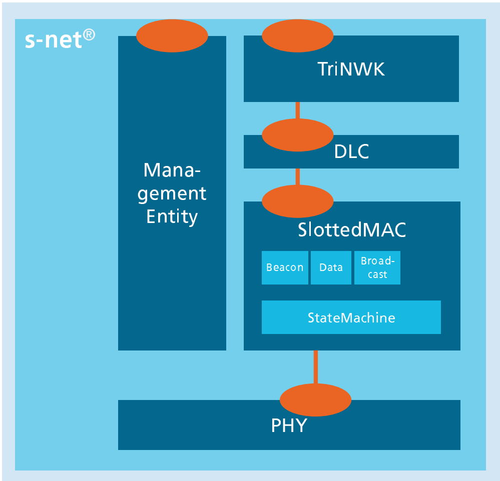



Figure 4: Overview of the s-net® communication protocol

The coordination of receive and transmit activities is done by the medium access protocol layer (MAC). The media access protocol SlottedMAC as part of the s-net® protocol stack combines the efficiency advantages of a time division multiplex system (time division multiple access - TDMA) with the scalability and flexibility of contention based protocols.
SlottedMAC introduces a frame structure for time synchronization of the network. Through synchronization, very low activity cycles can be achieved for the transmission and reception processes. As transmission and reception cause the highest power consumption in the system, a lot of energy is saved through the short activity cycles. The time-synchronization originates from the so-called master. For this, the master transmits protocol control packets on which the surrounding nodes synchronize themselves upon reception. Nodes which directly receive the signal from the master form the first layer group. Every node in layer group 1 in turn transmits synchronization packets on which all nodes in layer group 2 synchronize, etc. This results in a temporally ordered networked tree structure.
The end of a branch is reached at an end node. This type of node does not emit a beacon.

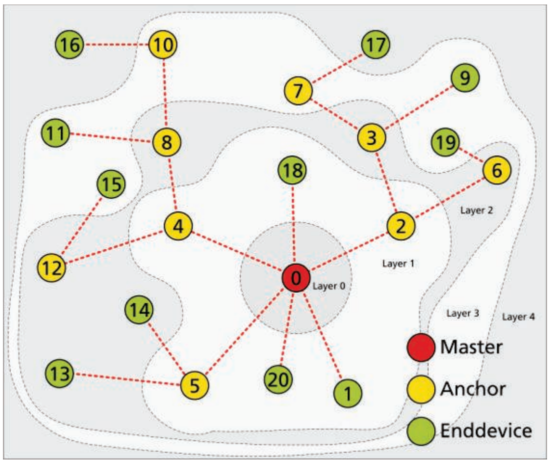



Figure 5: Net synchronization through SlottedMAC

The quality of the networking is constantly monitored and the network topology is dynamically adjusted if required. In this case, a node chooses another predecessor for reception of the synchronization packet. The data communication takes place bidirectionally between nodes. Here, the same communication pathways are preferentially used as those that arise through synchronization, which is a tree structure.

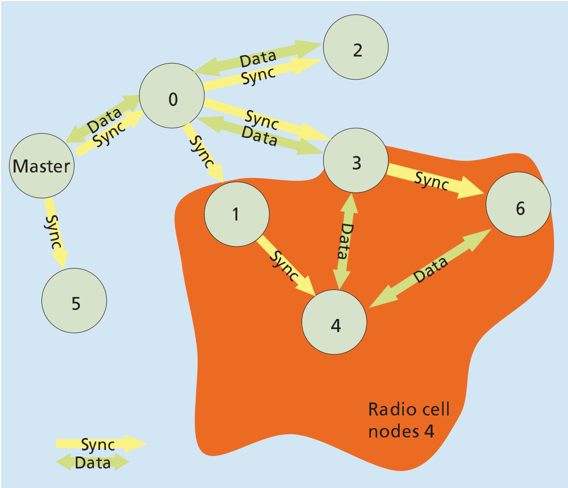



Figure 6: Time synchronization and data communication

Furthermore, data may be exchanged between all nodes in radio range of a node. This meshed data transfer is independent of the synchronization topology and the layer group. It is also used by the SlottedMAC itself for acquiring information from the surrounding environment. This is how every node collects information about its radio neighbors.
For the time-synchronization, all nodes follow a periodical frame. A frame consists of several active areas, the so-called domains. Each domain is responsible for a typical task. There are usually three domains in the s-net® protocol:

- Beacon domain: Time domain for receiving and emitting of the synchronization packets and for data communication in the direction of the end nodes. The beacon area serves as time synchronization of the nodes on the exact start of the frame which is initiated by the master and begins at the same time for all nodes.
- Data domain: Time domain for transmitting and receiving of data packets in the direction of the master.
- Meshed data domain: Time domain for receiving and transmitting of data within the node's radio cell and for acquiring information from the surrounding environment.

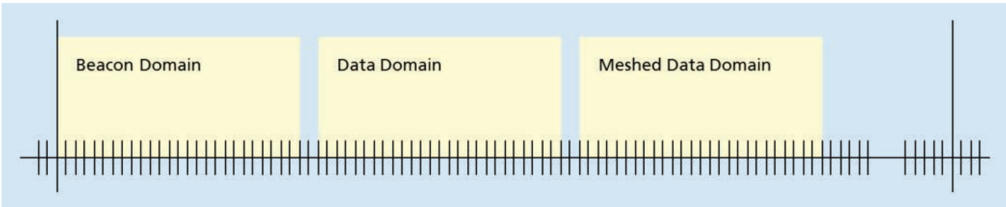



Figure 7: Arrangement of domains in a frame

The duration of a frame can be configured between 1 and 240 seconds.
A domain is divided further into time areas for layer groups. In this way, the individual layers are temporally ordered to work without collisions. Every layer is divided into several RX/TX slots respectively.
The following figure shows a possible beacon domain as an example:
Here, 3 layer groups are defined, each with 4 RX/TX slots. The master chooses an unassigned RX/TX slot in layer group 0 for transmitting its synchronization packet. A subsequent node receives this packet and in turn sends a synchronization packet in a subsequent layer group slot. The slots are allocated by self-organization.

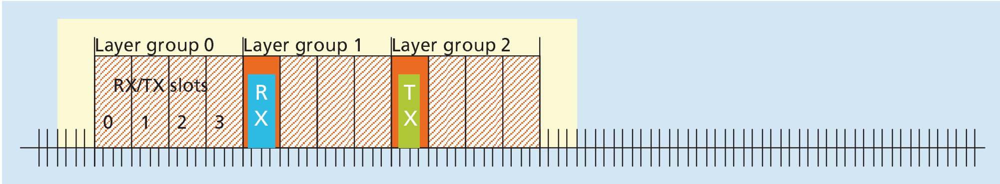


Figure 8: Beacon domain example

The duration of a frame and the number of layer groups and RX/TX slots can be configured according to the application requirement.

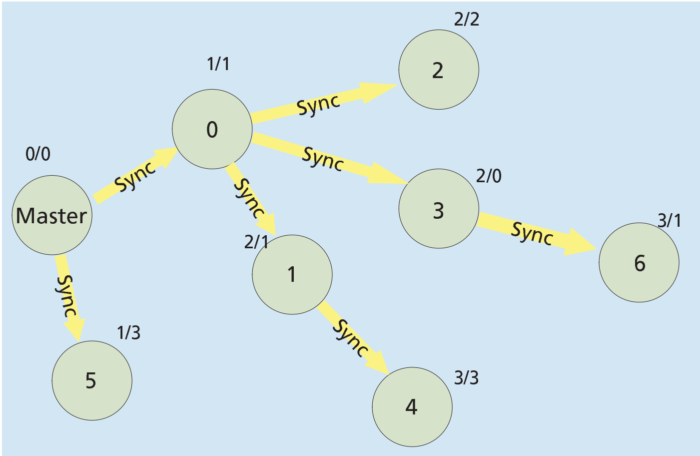


Figure 9: Exemplary allocation of the layer groups and RX/TX slots through the beacon domain

## Energy consumption

There are very low activity times for the transceiver due to the time division multiplex principle used and the high potential for configuration of the protocol stack. Extremely low power consumption can thus be achieved.
The following figures presume an interference-free environment and the following protocol stack characteristics:

- CC1101: 0 dBm transmission power, 190,4 kBit/s transfer rate
- Operation as end nodes, i.e. no transmission of beacon or broadcast packets and no reception of data packets from child nodes
- One data packet per frame

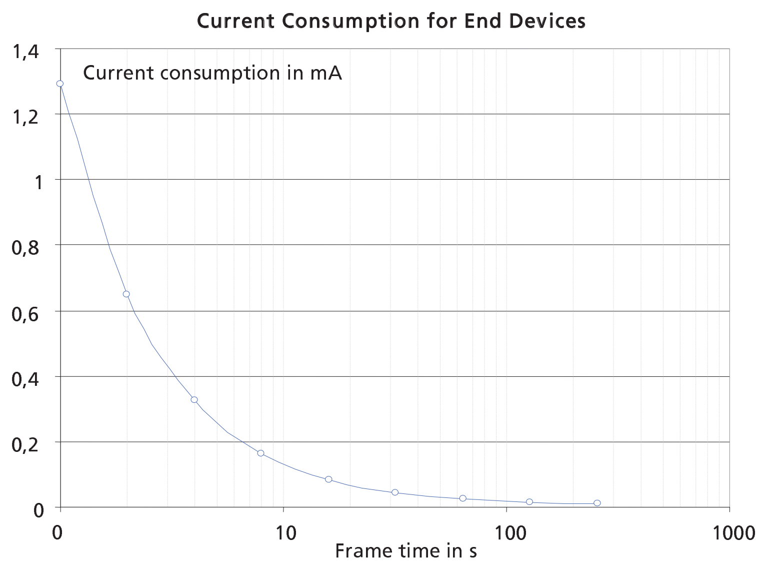


Figure 10: Typical current consumption depending on the frame duration

In the government funded project OPAL Health the proposed s-net® protocol was used to realize an asset management system in a concrete application scenario. A so called smart object is placed at medical devices. It detects its own position and sends position information periodically every 5 minutes via the s-net® wireless sensor network protocol. The s-net® frame duration in this example is configured to 8 seconds.

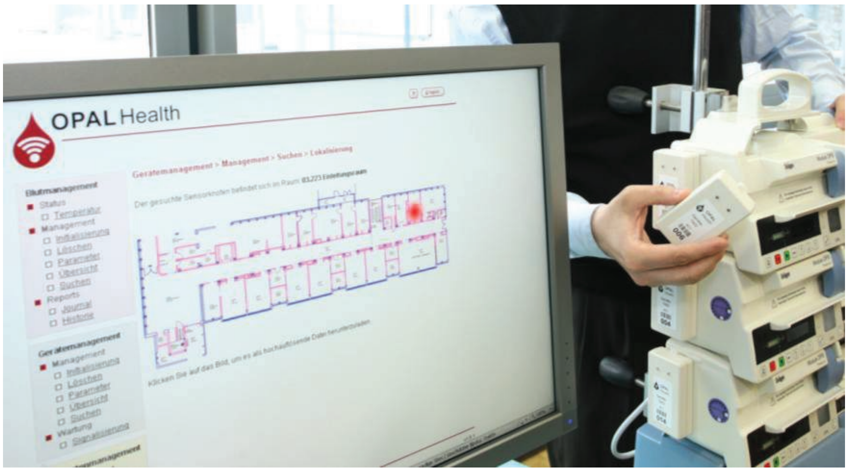



Figure 11: s-net® based asset management system in hospitals

In this case a smart object needs a mean current of only 60 µA which results in a lifetime of more than 2 years equipped with a 1200 mAh battery.

## Other features

Based on this SlottedMAC layer principles s-net® provides more features:

- Dynamic formation and self-organization of the network topology for marginal configuration effort, low maintenance and a high level of robustness. Nodes synchronize and organize themselves along a tree structure.
- Multi-hop communication for data transmission via intermediary nodes. Scalable range of the multi-hop data communication for fast data transport through the network.
- 16 bit s-net® short addresses to identify individual nodes, multicast addresses e.g. to address all child nodes, all neighbour nodes, group of nodes etc.
- Flexible parameterization of the protocol attributes for various application areas. Through this, the protocol can be adapted to various node densities, networking depths, data throughput requirements, etc..
- Scalable frame length from 1 s to 4 min for a flexible adjustment of energy consumption or latency to application requirements.
- Option for localization of mobile nodes.

## Summary

The design of an energy efficient wireless sensor network protocol has to balance the fundamental requirements data throughput, latency, scalability and topology as they all have effects on the power consumption. With s-net® a wireless sensor network protocol was presented, that introduces a time synchronization over the whole network. It introduces time slots for each participating node.
With s-net® protocol large spatially distributed energy efficient wireless sensor networks can be realized. s-net® has shown its capabilities in an asset management system which was installed in a hospital.

## References

[Ye1] Wei Ye, John Heidemann, and Deborah Estrin. An Energy-Efficient MAC protocol for Wireless Sensor Networks. In Proceedings of the IEEE Infocom, pp. 1567-1576. New York, NY, USA, USC/Information Sciences Institute, IEEE. June, 2002.