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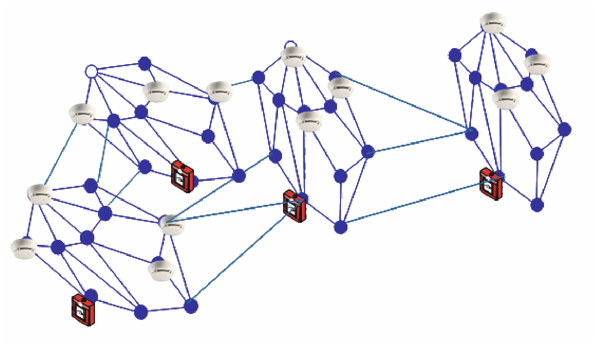
Master Thesis

Neighbor Discovery and Topology Construction of Wireless Sensor Networks



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Aldo Bazzi

Abstract

In this thesis the new procedure Mesh Construct for neighbor discovery and mesh topology construction of radio alarm systems based on multihop wireless sensor networks (WSNs) is presented.

The detectors of such a system are equipped with a radio transceiver and a pack of batteries in order to report detected dangers wirelessly over possibly multiple hops to a central node of the underlying multihop WSN. To ensure a reliable alarm message transmission several node-disjoint multi hop routing paths from each detector to the central station are required. A connectivity state is defined to determine whether the constructed mesh network fulfills this requirement.

The Mesh Construct procedure constructs a mesh network topology by initiating neighborhood discoveries on each node starting from the central station and proceeding outwards hop by hop. During the neighborhood discoveries nodes are chosen as neighbors depending on the link quality and a possible connectivity state improvement.

After the completion of the Mesh Construct procedure the operation of the radio alarm system including a topology control procedure is started. Removals of inappropriate neighbors by the topology control can cause instabilities in the connectivity state of the network and increase energy consumption.

The objective of the Mesh Construct is to discover neighbors and construct a stable mesh network topology in terms of connectivity in a fast and energy-efficient way.

The evaluation of performed Mesh Construct tests showed promising results. Compared to an existing solution with the Mesh Construct procedure the energy consumption, the duration, and the network instability could be reduced.

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Chapter 1

Introduction

A wireless sensor network (WSN) consists of a set of autonomous nodes, each equipped with one or more sensors and a radio transceiver. The sensor nodes can be deployed at distributed locations over an area in order to jointly monitor various environmental conditions. The gained informations from the sensors are processed and exchanged within the network by radio communication.

Alarm systems require sensors to detect a possible danger, e.g. a thermal or optical sensor for fire, or a motion sensor for intrusion. Detected dangers are reported to a central station in order to raise alarm. For alarm systems, often sensors are equipped with a radio transceiver and a pack of batteries to save laborious and expensive wiring of detectors. A larger region than the communication range of one single sensor can be monitored by deploying several sensors in a WSN. The monitored area of a WSN alarm system can additionally be increased with a mesh network topology. In a mesh network alarms can be forwarded over multiple sensor nodes to the central station. To ensure a reliable alarm reporting more than one multi hop routing path from a sensor node to the central station is demanded in the network.

When a WSN alarm system has been installed, the individual sensor nodes have no apriori knowledge about other existing nodes in the system. Therefore, each node has to discover nodes in the vicinity to construct the network topology. Discovered nodes are stored in a neighbor table. Through the informations in the neighbor tables the multi hop communcation paths from a sensor node to the central station can be deduced.

In this master thesis the algorithm Mesh Construct is presented. Mesh Construct is a new procedure to perform a neighbor discovery and topology construction with certain characteristics for an WSN alarm system. In the special case of a wireless fire detection sensor network the mesh topology requires at least two node-disjoint communication paths from a detector to the central station to ensure a reliable alarm reporting also in case of a detector failure.

In this report several parts have been removed due to confidentiality reasons.

1.1 Setup

The underlying systems considered in this thesis is are radio alarm systems based on a wireless sensor networks. However, the investigations in this thesis are mostly focused on a wireless fire detection sensor network but could also be generalized on an arbitrary radio alarm system.

1.1.1 Definitions

In the following some primary definitions of an radio alarm system are stated. In Figure 1.1 the mesh topology of an exemplary radio alarm system is shown.

- An *alarm system* consists of at least one *gateway* and one or more *detectors*. The detectors are equipped with sensors which can detect a danger event. In the case of a fire detection system the sensors are thermal or optical and are able to detect a fire. If a danger emerges and is detected the detectors report it to the gateway. The gateway is connected with a central unit which processes the alarm messages. The detectors and the gateway are also denoted as *nodes*.
- A *radio alarm system* is an alarm system where each node is equipped with a radio transceiver.
- For the communcation within the network each node has a table of nodes located in the vicinity, which are reachable by radio communication. The nodes listed in this table are called *neighbors*, the table is denoted as *neighbor table* (Note: Not each node in the vicinity is necessarily contained in the neighbor table!). Two nodes are *neighboring*, if both are contained in the neighbor table of each other. The radio connection between a node and one of its neighbors is denoted as *link*.

In Figure 1.1 for example node A and B are neighboring, but A and C are not. The lines between the nodes symbolize the links.

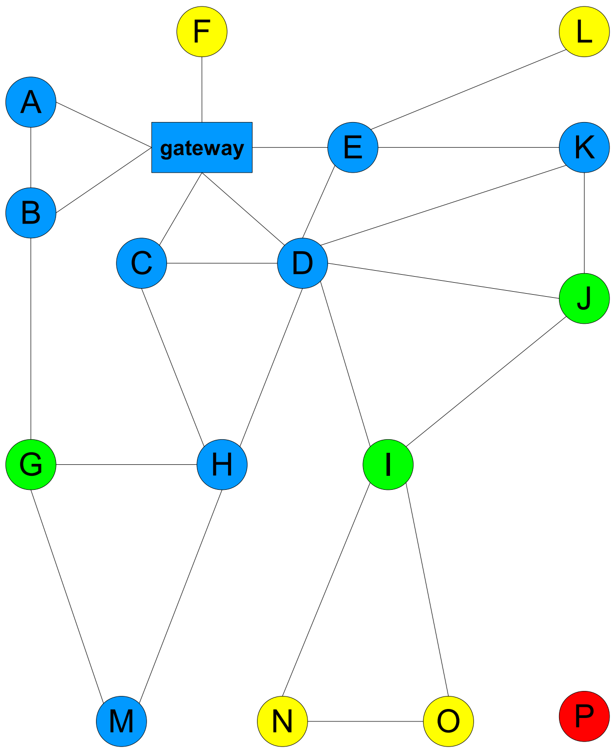


Figure 1.1: Mesh network topology of an multihop radio alarm system

- A *communication path* is a sequence of consecutive links between two nodes. For example in Figure 1.1 between the node M and the gateway there are the communication paths (M, G, B, gateway) or (M, H, C, gateway).
- A radio alarm system is denoted as *linked* if there exists a communication path between each pair of nodes. For example in Figure 1.1 the alarm system without the node P is linked.
- A *multihop radio alarm system* is a radio alarm system in which the

gateway is not a neighbor of at least one detector. In Figure 1.1 a multihop radio alarm system is shown.

In the following definitions the term ”system” is always used interchangeable with the term ”linked multihop radio alarm system”.

- The *hop count* of a specific node denotes the minimal number of links, which lie on the communication path from the node to the gateway (Note: In the case of an asymmetric neighbor relation, i.e. a node has added another node to its neighbor table but not vice versa, it is crucial to start the communication path from the node and count the links up to the gateway). In Figure 1.1 the gateway has hop count 0, the nodes A, B, C, D, E, and F have hop count 1, the nodes G, H, I, J, K, and L have hop count 2 and the nodes M, N, O, and P have hop count 3.
- The neighbors of a specific node, that have a lower hop count as the node itself, are called *parents* of this node.
- The neighbors of a specific node, that have the same hop count as the node itself, are called *peers* of this node.
- The neighbors of a specific node, that have a higher hop count as the node itself, are called *children* of this node.

  For example in Figure 1.1 the node H has the parents C and D, the peer G, and the child M.
- Two communication paths are denoted as *independent* if the communication paths between these two nodes contain no common nodes. In Figure 1.1 the communication paths (M, G, B, gateway) and (M, H, C, gateway) are independent.
- The number of *connectivity paths* of a detector denotes the number of independent communication paths between this detector and the gateway. The number of connectivity paths of the node M in Figure 1.1 is 2.

In a multihop radio alarm system, usually there is a number of connectivity paths, which is at least required in order to ensure reliable reporting of alarms, e.g. in case of broken communication paths due to detector failures or interference. The minimal required number of connectivity paths is a parameter of an alarm system (see Section 3.5) and in the following is denoted as nb_con_paths_min. To indicate the current number of connectivitiy paths of a detector a connectivity state is introduced. The state of a detector can be *red*, *yellow*, *green*, or *green+*.

- State *red*: The detector has no communication path to the gateway.

- State *yellow*: The detector has at least one communication path to the gateway.

- State *green*: The detector has at least nb_con_paths_min independent communication paths to the gateway.

- State *green+*: This is an internal system state, which indicates that the detector has at least nb_con_paths_min independent communication paths to the gateway using only parents as next hops. Such a detector may offer an additional independent communication path to the gateway to peers with less than nb_con_paths_min parents. The connectivity state of a gateway is defined as green+.

  In Figure 1.1 the parameter nb_con_paths_min is set to 2. The connectivity states of the nodes are indicated with the corresponding color, whereas nodes with a green+ connectivity state have the color blue.

Additionally, a connectivity state for the entire network can be defined analogously.

- The network connectivity state is *green*, if all detectors are at least green.

- The network connectivity state is *yellow*, if each detector is at least yellow.

- The network connectivity state is red, if at least one detector is red.

  The alarm system shown in Figure 1.1 has a red network connectivity state. A network or a node is also denoted as *connected*, if the connectivity state is at least green, and *unconnected* otherwise.

1.1.2 Multihop Wireless Fire Detection Sensor Network at Siemens BT

Siemens BT Zug and the Swiss Federal Institute of Technology Zurich are working together on a research project in the area of fire detection. The objective of this project is to investigate the potentialities and capabilities in the application of multihop wireless sensor networks for fire detection systems. The multihop wireless fire detection sensor network investigated at Siemens BT is an example of a radio alarm system.

The alarm system consists of at least one gateway and several fire detectors, which together form a mesh network and communicate by radio on the 433 MHz or 868 MHz industrial, scientific and medical (ISM) frequency bands [1].

Each gateway is connected through a wire with an alarm-processing central unit. The wired gateways have an additonal wireless interface, the detectors are all wireless. On the one hand, ommitting wires eminently facilitates the installation of the fire detection system, but on the other hand, requires the detectors to be powered by batteries. The battery supply limits the lifetime of the detectors. Since the fire detection system is designed to operate over several years, an energy consumption in the order of µW is required.

To increase the system lifetime and reduce the maintenance costs of changing batteries, the media access control is implemented through an low power listening (LPL) protocol [2]. Since the radio transceiver is the component of a node which consumes the most energy, with LPL the transceiver is switched off the most time. The nodes with a switched off transceiver are in an energy-efficient sleep mode and wake up only periodically for a short carrier sense. If a signal is detected during the carrier sense, the node stays awake and a message can possibly be received. Otherwise, the node returns to the energy-efficient sleep mode. The nodes wake up independently of each other with a periodic time interval `t_w`. The wake up times of the indiviual nodes are not synchronized to each other. In order to be sure to reach a node a long preamble with the duration of one complete sleep interval `t_w` has to be prepended to the true message.

A further enhancement in terms of energy consumption is achieved with the use of the WiseMAC [3] protocol. With WiseMAC, the wake up time schedule is enclosed in the message header and is stored in the neighbor table after each successful message reception. The knowledge of the wake up times of neighbors allows a transmitting node to use an energy-efficient short preamble and sending a message just before the destinated neighbor wakes up. Only when the wake up time of a destination node is unknown a long preamble has to be prepended to the message.

The longer the wake up period `t_w`, the less energy is consumed for carrier sense on average, but the more increased is the disbalance between messages using a short and messages using a long preamble concerning energy consumption.

For the communication between nodes of the network different message types are used (see also Section 3.3). Two different direct messages are used for the communication over the distance of one hop. A unicast message is transmitted between a pair of nodes and uses a short preamble once the wake up schedule of the destination is knwon. A broadcast message is transmitted from a node to all reachable nodes in the vincinity. The broadcast message uses always the long preamble in order to be sure that all nodes in the vicinity wake up during the transmission and receive the message. Hence, the transmission of a broadcast message causes a high energy consumption. Two different message types for the communication over the distance of one or more hops are transmitted. Dynamic source routing (DSR) messages are used for the communication between a pair of nodes over possibly several hops. Alarms are always transmitted from a detector to the gateway with delay-aware robust forwarding (DWARF) messages [4].

The network initialization and topology control of the fire detection system currently in use is accomplished by an individual protocol, which is described and analyzed in Section 2.1.

1.2 Problem Description

1.2.1 Neighbor Discovery and Topology Construction

When a multihop wireless fire detection sensor network as described in Section 1.1.2 shall be commissioned, all nodes have to be installed at distributed locations over the entire area which has to be monitored. The gateway is connected to the central unit and afterwards all detectors are sequentially mounted and switched on. However, after the physical deployment the fire detection system is not yet ready for operation because first, the network topology has to be constructed in order to be able to forward and process alarms.

When a node is powered on, the neighbor table is empty and no apriori knowledge about other installed nodes in vicinity exists. Therefore, each node has to perform a neighbor discovery in order to add nodes to the neighbor table and construct the network topology. The network connectivity state is green as soon as each installed detector is discovered and has the minimum required number of connectivity paths to the gateway. From then on, alarms can be forwarded reliably to the gateway and the operation of the fire detection system can be started.

After the switch-on of the last detector, technicians which install the system have to wait for the validation of the required green network connectivity state and the approval of the proper operation of the alarm system. Thus, the neighbor discovery and topology construction should be completed in a reasonable time to ease the installation of the system.

During the operation in each node the topology control is performed by the application described in 2.1. The application exchanges messages between neighbors in a round robin way to monitor the network connectivity state. When no more messages are received from a neighbor within a certain period (e.g. due to collisions or a detector failure), the neighbor appears to be dead and is removed from the neighbor table. Such a removed neighbor is denoted as *dead neighbor*. Besides the topology control, a *link quality manager* adapts the transmission power to save energy and removes nodes from the neighbor table with poor link quality. If as a result of removing a dead neighbor or a neighbor with poor link quality a node loses the green/green+ connectivity state, new nodes have to be discovered and added to the neighbor table. Certainly, nodes with a non-green connectivity state are unwanted during operation because important connetivity paths for alarm forwarding are missing. Additionaly, the discovering of new neighbors requires to transmit broadcast messages which consume a lot of energy.

Depending on the way which nodes are initially added to the neighbor tables, the network topology eventually has to be adapted and is unstable during the operation. In general, nodes which have a good link quality and can improve the own connectivity state are prefered as neighbors. A lot of energy wasting message retransmissions can be caused by a neighbor due to a poor link quality. Additionally, more neighbors than are required to ensure the green connectivity state are desired in the neighbor table to prevent a connectivity state change due to a single neighbor removal. Therefore, the initial choice of the neighbors is crucial for the construction of an energy-efficient and stable network topology.

The Mesh Construct algorithm introduced in this thesis is implemented as an additional protocol. The Mesh Construct shall perform neighbor discovery and topology construction which is fast, energy-efficient and achieves a connected and stable mesh network topology. After the Mesh Construct is completed the operation is started and the existing application 2.1 accomplishes the topology control.

1.2.2 Requirements and Assumptions

Several requirements for the neighbor discovery and topology construction of a fire alarm system are imposed by Siemens BT as well as by regulatory norms.

- The fire detection system shall ensure the capability of alarming also in case of a detector failure. Hence, each detector must have at least more than one independent communication path to the gateway. In particular, the paramteter nb_con_paths_min of the minimal number of required connectivity paths is set to 2. The neighbor discovery and topology construction has to be completed in a green network connectivity state. Exception is a system consisting of one gateway and only one detector [5, 4.3].
- The mesh network of the fire detection system has maximal three hops.
- The neighbor discovery and topology construction procedure has to be completed in a finite duration, at longest one hour after switching on the last installed node. Nevertheless, the duration of the commissioning shall be as short as possible to provide an easy installation of the fire alarm system.
- The memory resources of a detector are limited and are insufficient to store the informations of the entire network. Thus, the own connectivity state has to be identified by local available informations and informations from the direct, immediate neighborhood.

- The Mesh Construct procedure for neighbor discovery and topology construction shall be implemented as new protocol in the existing software.

In the scope of this thesis several assumptions are made, which are stated in the following:

- Only one gateway is contained in the wireless fire detection sensor network.
- When a node is installed and switched on, no topology and neighborhood information about other network nodes is known a priori in the node.

1.2.3 Quality Metrics and Objectives

The neighbor discovery and topology construction is a multi objective optmiziation problem. In this section the various objectives of the new procedure for the neighbor discovery and topology construction are stated. Additionally, metrics to assess the quality of the procedure are defined.

Duration

An important quality is the duration which is required to achieve a green /green+ network connectivity state. The objective is that the technicians installing the alarm system can approve the required network connectivity state as fast as possible. Therefore, the following metric is defined to assess the procedure quality concerning the duration.

- The duration `t_connected` from the last switch on of a node until all installed nodes have a green/green+ connectivity state is a metric for the tempo of the procedure. The objective is to achieve a `t_connected` as short as possible.

Connectivity

The essential property a procedure for neighbor discovery and topology construction must feature, is to initialize the alarm system for the proper operation. The requirement for the start of the operation is determined by the connectivity state. The objective of the procedure in terms of connectivity is that, all installed nodes are discovered and achieve the required connectivity state, which is at least green or green+. This ensures the reliable forwarding of raised alarms to the central unit during the operation.

The following two metrics are defined to determine if all installed nodes are discovered on the one side and on the other side have the required connectivity state.

- The number of nodes with a red connectivity state `nb_red_nds` is a metric for the discovering state of the network. The lower `nb_red_nds`, the better discovered are the installed nodes. The objetive is to achieve `nb_red_nds` = 0.

- The number of nodes with a red or yellow connectivity state `nb_red-yellow_nds` is a metric for the connectivity of the network. The lower `nb_redyellow_nds`, the more nodes have the required number of connectivity paths to the gateway. The objective is to achieve `nb_redyellow_nds` = 0.

Stability

Besides the connectivity and the duration of the procedure for neighbor discovery and topology construction, it is essential that the network remains connected during operation. The removal of dead appearing neighbors by the topology control algorithm can cause a change of the connectivity state to yellow or red. Subsequently, nodes start to broadcast and to discover new neighbors. For that reason, the network topology can change over time. Certainly, this is unwanted since the adaption of the network topology consumes additional energy to get connected again. Hence, the objective of a neighbor discovery and topology construction is to provide a network topology which is stable during the operation with enabled topology control application. The following two metrics are defined to assess the procedure quality concerning the stability.

- The number of removed dead neighbors `nb_rem_dead_nhs` is a metric for the stability. The lower the `nb_rem_dead_nhs` is, the more stable is the network topology. The objective is to achieve `nb_rem_dead_nhs` = 0.

- Additionally, the change of the node connectivity states over time is a metric for the stability (Note: Although this is a metric to assess the procedure in a rather qualitative way, it allows to make very meaningful statements for individual test results. To analyze a large number of tests a metric representing a numeric value should be defined). The objective is to achieve connectivity states which are constant over time.

The number of neighbors removed by the link quality manager is not tracked in the statistic tool used for the tests in Section 2.1.2 and Chapter 4. Therefore, the number of neighbors removed by the link quality manager is excluded from the quality metrics but is sometimes mentioned in the stability evaluation.

Energy Consumption

The energy consumption is also an essential aspect of a neighbor discovery and topology construction procedure. Since the detectors are powered by batteries, the energy budget and therefore the lifetime of the alarm system is limited. The objective is to minimize the energy consumption to increase the system lifetime and reduce the maintenance costs. The following two metrics are defined to assess the procedure quality concerning the energy consumption.

- The total current `i_total` averaged over time and the number of nodes is a metric for the energy consumption.
- Additionally, the number of transmitted broadcasts `nb_tx_bcasts` is a metric for the energy consumption. The transmission of broadcast messages contributes substantially to the energy consumption.

The gateway is excluded from the energy considerations since it is wired and not powered by batteries.

1.3 Chapters Overview

The thesis is structured in 5 chapters. In Chapter 2 the existing solution for the network initialization and topology control and related work is investigated. In Chapter 3 the conceptual design of the new procedure for neighbor discovery and topology construction is presented. Moreover, a few implementation details are indicated. In Chapter 4 the new procedure is tested and evaluated. In addition, the new procedure is compared to the existing solution described in Chapter 2 in terms of the metrics defined in Section 1.2.3. In Chapter 5 the obtained conclusions of the evaluation in Chapter 4 are stated and an outlook on possible future work is given.

Chapter 2

Background and Related Work

In the first section of this chapter the existing solution for the network initialization and the topology control of the fire detection system presented in section 1.1.2 is explained, tested, and evaluated.

In the second section related work in the area of neighbor discovery and topology construction as well as link quality estimation is outlined.

2.1 Analysis of Existing Solution - Mesh Admin

Mesh Admin is the name of the existing protocol for neighbor discovery and topology control in the wireless fire detection sensor network of Siemens BT.

The Mesh Admin is a random procedure, where each node after being switched on autonomously discovers neighbors in the vicinity through the transmission of HELLO-broadcast messages. Other nodes receiving a HELLO-broadcast message add the source to the neighbor table and periodically transmit direct hello-unicast messages to all its neighbors in a round robin way. Among other things, each message contains information about the source node, e.g. the hop count and connectivity state. Successively, information about neighboring nodes is collected through this message exchange and updated in the neighbor table. The table has up to eight entries for discovered and added neighbors. For each listed neighbor the following informations are stored as fields in the neighbor table:

Each node is able to determine its own hop count and connectivity state

Neighbor table	Neighbor table variable description
`nd_add`	Node address of the neighbor
`hop_count`	Hop count
`con_state`	Connectivity state
`check_timer_flag`	Indicates if a message from the neighbor is received within the last check timer period

Table 2.1: Mesh Admin variables for each entry of the neighbor table

through the informations provided in the neighbor table (see also Algorithm 1). The nodes communicate periodically with its neighbors and exchange informations of the neighbor table such that the nodes can update their own connectivity state. If the own connectivity state is insufficient, periodically further broadcasts are transmitted in order to discover new neighbors which can lend the desired connectivity state. Changes in the topology are only propagated through the hello-unicasts. Adjustements can take some time when several hops need to be adjusted. By this means, the whole network topology is constructed and maintained. In a node the protocol is started with the swith-on and runs infinitely long.

2.1.1 Connectivity State Update

A procedure will be presented, which allows to determine the connectivity state of a detector only with local available information in the neighbor table, that is, the hop count and the connectivity state of neighboring nodes. First, the own hop count is identified by searching for the minimal hop count in the neighbor table, then the own hop count is one higher. Through the own hop count each neighbor can be identified either as parent, peer, or child. In the following the procedure to determine the own connectivity state is indicated in Algorithm 1.

Note: The Algorithm 1 has only available local network information from the neighbor table. The procedure ensures that with a resulting green/green+ connectivity state there are at least nb_con_paths_min connectivity paths, with a resulting yellow connectivity state there is at least one connectivity path. The reverse is not necessarily true. For example for node I in Figure 1.1 the Algorithm 1 returns a yellow connectivity state although there are two connectivity paths in the network.

Important neighbors, which causes the node to achieve or maintain a green/green+ connectivity state, are locked to avoid beeing deleted if a neighbor should be added to a full neighbor table. In the following the procedure to lock important neighbors is indicated in Algorithm 2. The detailed communcation procedure among nodes is described in the next section.

2.1.2 Testing and Evaluation

The performance of the Mesh Admin algorithm is assessed through longterm tests on an experimental setup. The used testbed is described in Appendix A. Through a statistic tool and logs on the nodes various informations for an evaluation are collected during the test runtime. The number of nodes nb_nds of the testbed is 32. The test setup consists of one gateway and 31 detectors. At the beginning of the test first, the gateway is switched on and afterwards sequentially all detectors in a random order. Before a node is enabled, a time delay is inserted to simulate the installation time. The time delay between the startup of two succeding nodes is uniform random distributed in the interval [t_min, t_max]. The time delay due to the installation is set to be between one and five minutes. The test runtime t_test starts after the last switch-on and is set to twelve hours. The test parameters are listed in Table 2.2.

Test Parameters	Value
nb_nds	32
t_test	43200 s
t_min	60 s
t_max	300 s

Table 2.2: Test parameters

The set values of the Mesh Admin parameters are listed in Table 2.3.

Many longterm Mesh Admin tests have been run on the testbed. However, the number of performed tests does not claim to be statistical relevant and therefore in the following only two typical test examples thereof are shown and evaluated.

Mesh Admin Test A

Algorithm 1 Connectivity State Update

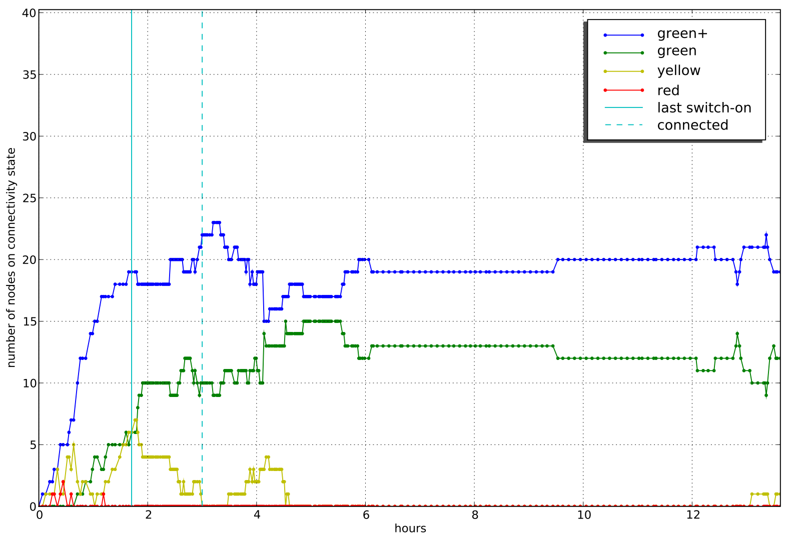
```
1: if hop_count == 1 then
2:     if number of peers $\geq$ nb_con_paths_min then
3:         own_con_state = green+
4:     else
5:         own_con_state = yellow
6:     end if
7: end if
8:
9: if hop_count > 1 then
10:    if number of green/green+ parents $\geq$ nb_con_paths_min - 1 then
11:        own_con_state = green+
12:    else
13:        if number of green/green+ parents and green+ peers $\geq$ nb_con_paths_min then
14:            own_con_state = green
15:        else
16:            if number of parents > 0 then
17:                own_con_state = yellow
18:            else
19:                own_con_state = red
20:            end if
21:        end if
22:    end if
23: end if
```

Algorithm 2 Lock Neighbors

```
1: if hop_count == 1 then
2:     lock the gateway and one arbitrary peer
3: end if
4:
5: if hop_count > 1 then
6:     lock green/green+ parents, at most nb_con_paths_min
7:     lock green+ peers at most nb_con_paths_min neighbors in total
8:     lock other parents, until a total number of locked neighbors is nb_con_paths_min neighbors
   in total
9:     if no neighbors have been locked so far, lock at leat 1 parent.
10: end if
```

Mesh Admin Parameters	Value
t_w	1.5 s
nb_con_paths_min	2
hello_timer	240 s
check_timer	$16 \cdot 240$ s = 3840 s
happpy_timer	$20 \cdot 240$ s = 4800 s

Table 2.3: Mesh Admin parameters



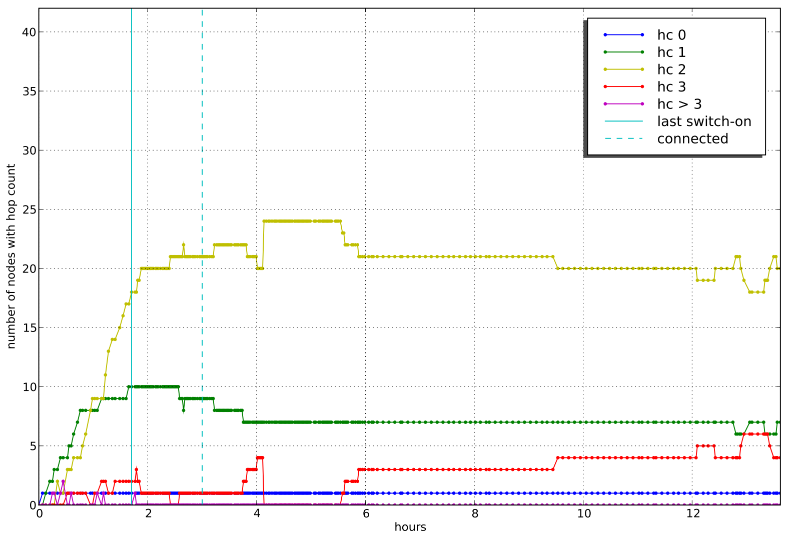


Figure 2.1: **Mesh Admin Test A**: Upper plot: Number of nodes on the corresponding connectivity states. Lower plot: Number of nodes on the corresponding hop counts.

Duration In Figure 2.1 the connectivity and hop count states of the Mesh Admin Test A are plotted over the test time. After the last switch on it takes 1 hour 17 minutes and 47 seconds until the entire network is connected. The duration `t_connected` of the Mesh Admin test A does not fulfill the requirement to be less than one hour.

Connectivity and Stability After the network is connected, `nb_red_nds` is equal to zero for the entire remaining test time. Therefore, all installed nodes are discovered.

During the operation the network does not remain connected for the entire test time. After the network is connected, three time intervals of various duration occur, wherein `nb_redyellow_nds` is unequal to zero. Hence, in each of this time intervals at least one of the installed nodes is temporary in a yellow connectivity state.

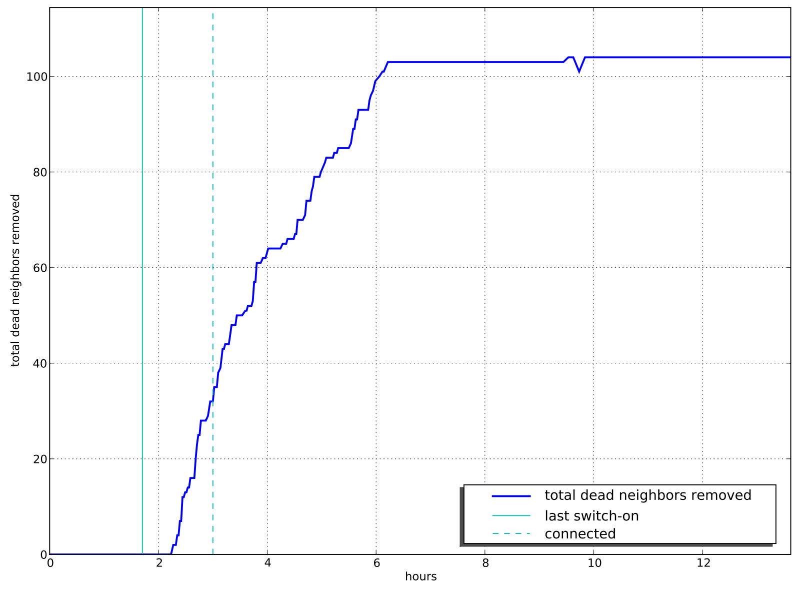


Figure 2.2: **Mesh Admin Test A**: Number of removed dead neighbors of all nodes. Note: the decrease of the curve shortly before ten hours is an artifact of the testbed caused by a failed readout of the statistics at one node

In Figure 2.2 the number of dead neighbors, which are removed during the test, is plotted over the test time. In total `nb_rem_dead_nhs` = 104 dead neighbors are removed during the test, all of them in the first six hours. Thus, the two time intervals with yellow network connectivity states towards the end of the test are caused by neighbor removals of the link quality manager. A causality between the removal of dead neighbors in the first six hours and the corresponding unstable time course of the connectivity states in Figure 2.1 can be recognized. Between the neighbor removals the network reaches an intermediate, almost stable and connected state.

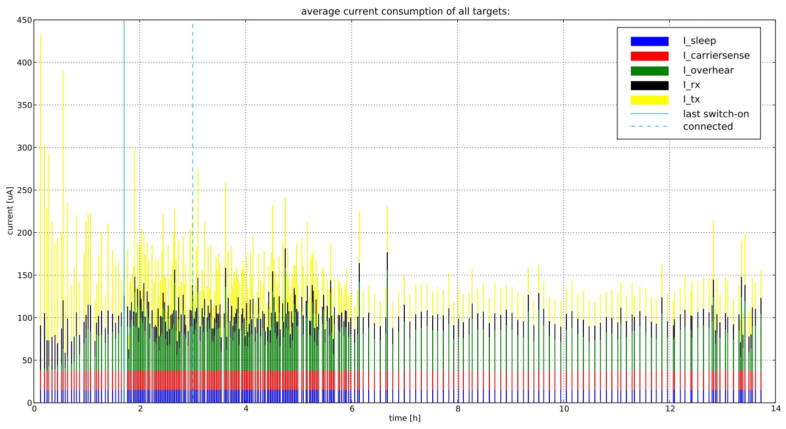


Figure 2.3: **Mesh Admin Test A**: The current consumption averaged over all targets.

Energy Consumption In Figure 2.3 the current consumtpion averaged over all targets is plotted over the test time. The total consumed current of the Mesh Admin Test A is divided into the five contributions `I_sleep`, `I_carriersense`, `I_overhear`, `I_rx`, and `I_tx`. `I_sleep` is the current consumed in the energy-efficient sleep state. `I_carriersense` is the current required for the periodic wake up and carrier sense. `I_overhear` is the current consumed for receiving messages which originally are transmitted to a different destination. `I_rx`, and `I_tx` are the currents consumed for receiving and transmitting messages.

Until the network is connected the most energy is consumed, in particular due to the transmissions of the energy expensive broadcasts. The number of transmitted broadcasts is plotted in Figure 2.4 over the testtime. The total number of transmitted broadcasts `nb_tx_bcasts` during the test is 37. Thus, several nodes had to transmit more than one broadcast. By compar-

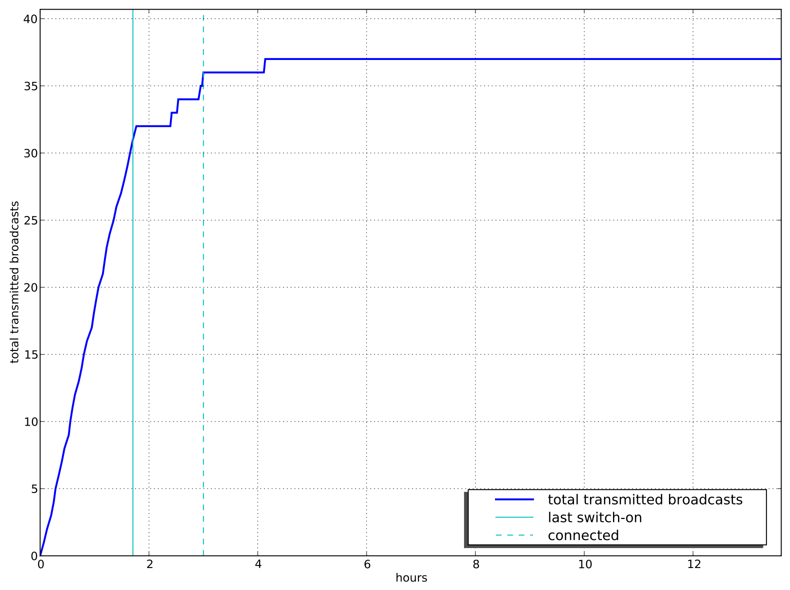


Figure 2.4: **Mesh Admin Test A**: Number of transmitted broadcasts of all nodes.

ing the time course of the current consumption with the time course of the connectivity states in Figure 2.1, a relation between the energy consumption and the stability of the connecivity states can be observed. The energy consumption in the network is higher in time intervals of unstable connectivity. In Figure 2.5 the current consumption of each individual detector averaged over the entire test time is shown. Again, the current consumption is divided into its five contributions. Although there are some nodes with a higher total current, overall the current consumption of the nodes is rather balanced. The total current consumption averaged over the time and number of nodes `i_total` is 144.090 µA.

Mesh Admin Test B

Duration In Figure 2.6 the connectivity and hop count states of the Mesh Admin Test B are plotted over the test time. In contrast to the Mesh Admin

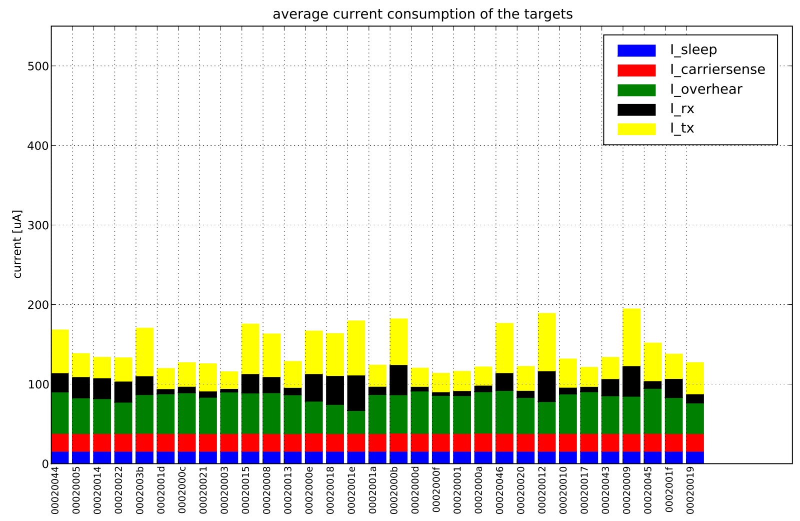


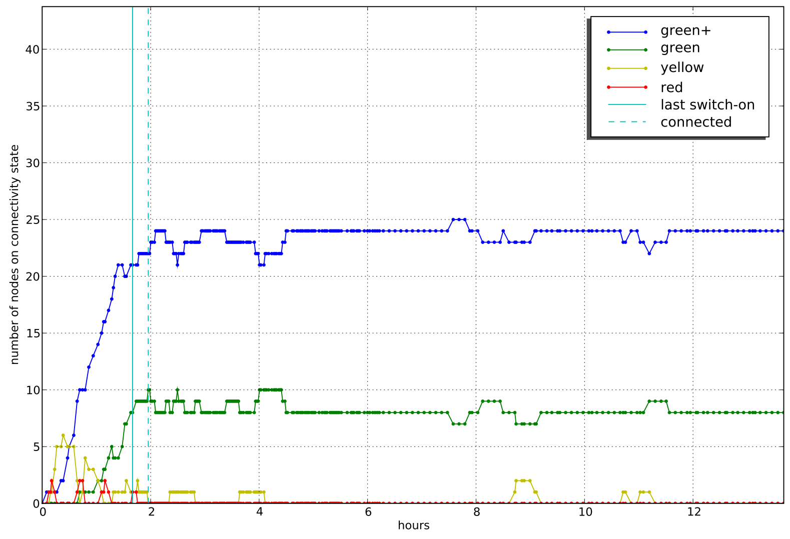
Figure 2.5: **Mesh Admin Test A**: The average current consumption of the nodes over the entire test time.

Test A, after the last switch on it takes only 17 minutes and 22 seconds until the entire network is connected. The duration `t_connected` of the Mesh Admin test B clearly fulfills the requirement to be less than one hour.

Connectivity and Stability In Figure 2.6 the connectivity and hop count states of the Mesh Admin Test B are plotted over the test time. After the network is connected, `nb_red_nds` is equal to zero for the entire remaining test time. Therefore, all installed nodes are discovered.

Like in the Mesh Admin Test A, during the operation the network does not remain connected for the entire test time. After the network is connected, five time intervals of various duration occur, wherein `nb_redyellow_nds` = 1, 2. Hence, each time one or two of the installed nodes are temporary in a yellow connectivity state.

In Figure 2.7 the number of dead neighbors, which are removed during the operation, is plotted over the test time. In total `nb_rem_dead_nhs` = 89 dead neighbors are removed during the test, all of them in the first six hours. Thus, the last three time intervals with yellow network connectivity states are caused by neighbor removals of the link quality manager. A causality between the removal of dead neighbors in the first six hours and the corresponding unstable time course of the connectivity states in Figure 2.6



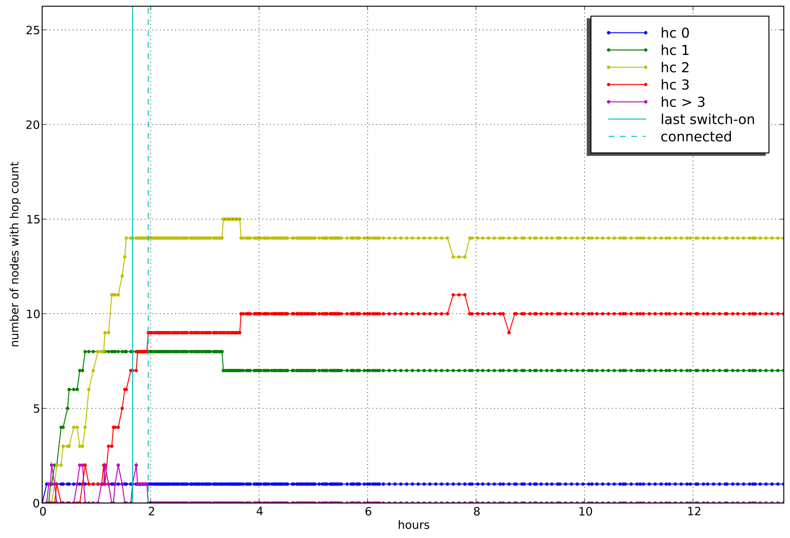


Figure 2.6: **Mesh Admin Test B**: Upper plot: Number of nodes on the corresponding connectivity states. Lower plot: Number of nodes on the corresponding hop counts.

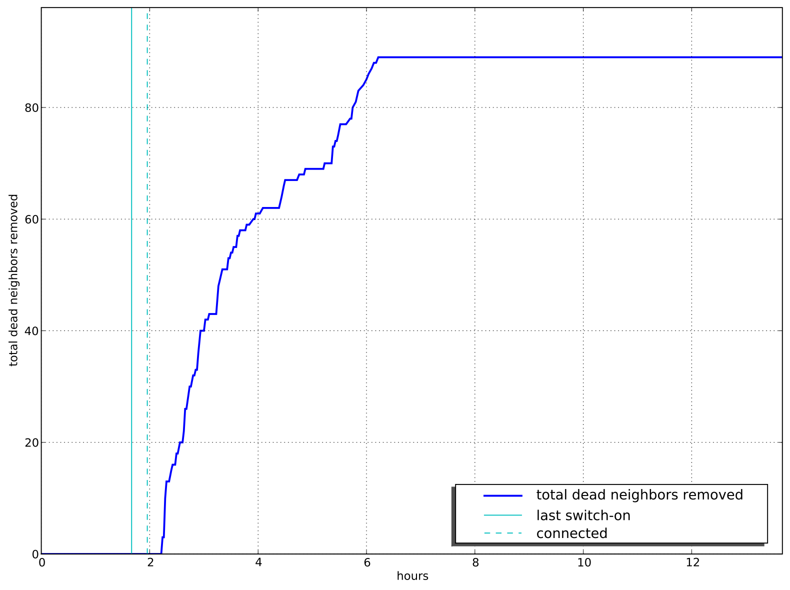


Figure 2.7: **Mesh Admin Test B**: Number of removed dead neighbors of all nodes.

can be recognized. However, not each neighbor removal necessarily causes a connectivity state change, e.g. when a child is removed from the neighbor table. Therefore, in contrast to the Mesh Admin Test A the last dead neighbor removals did not affect the connectivity state of the nodes. Between the neighbor removals the network reaches short, intermediate, almost stable and connected states.

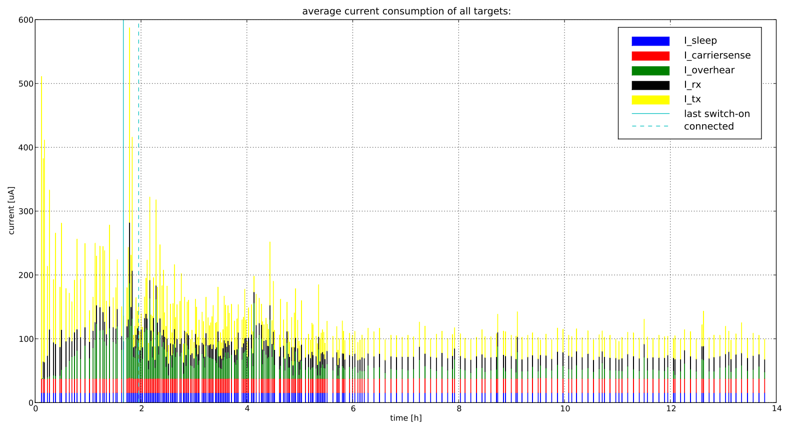


Figure 2.8: **Mesh Admin Test B**: The current consumption averaged over all targets.

Energy Consumption In Figure 2.8 the current consumtpion averaged over all targets is plotted over the test time. The total consumed current of the Mesh Admin Test B is again divided into its five contributions.

Analogous to the Mesh Admin Test A, the most energy is consumed by the transmissions of the energy expensive broadcasts during the neighbor discovery and topology control. The number of transmitted broadcasts is plotted in Figure 2.9 over the testtime. The total number of transmitted broadcasts `nb_tx_bcasts` during the test is 36. Thus, several nodes had to transmit more than one broadcast.

By comparing the time course of the current consumption with the time course of the connectivity states in Figure 2.6, again a higher energy consumption during time intervals of unstable connectivity can be observed.

In Figure 2.10 the current consumption of each individual detector averaged over the entire test time is shown. In contrast to the Mesh Admin

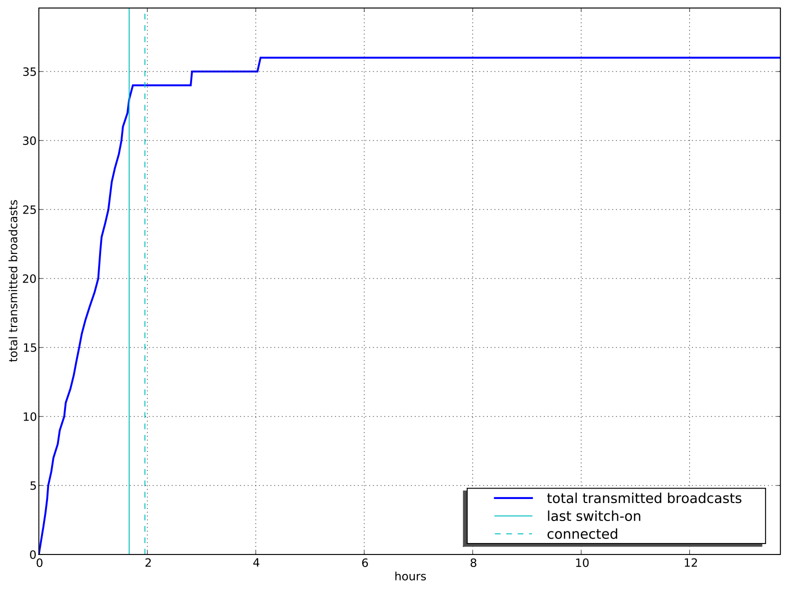


Figure 2.9: **Mesh Admin Test B**: Number of transmitted broadcasts of all nodes.

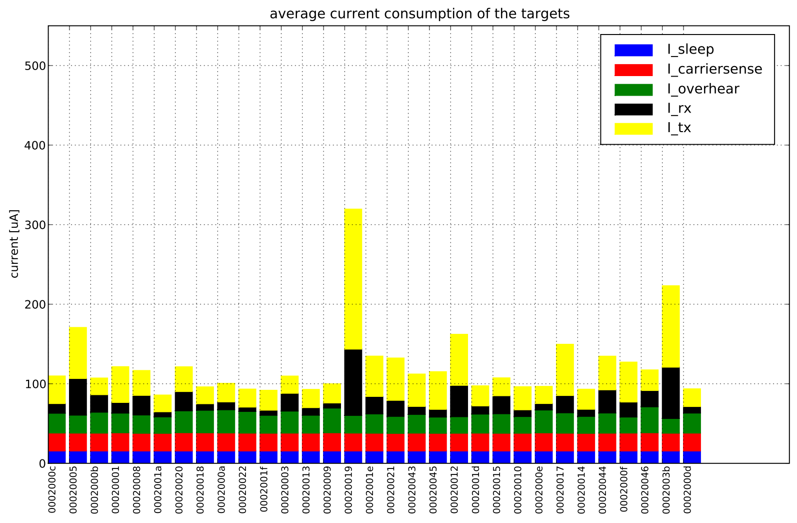


Figure 2.10: **Mesh Admin Test B**: The average current consumption of the nodes over the entire test time.

Test A, there are two nodes with a total current consumption which is about three times higher than the one of the other nodes. The operation of these detectors is eminently endangered by an early depletion of the batteries. The total current consumption averaged over the time and number of nodes `i_total` is 123.536 μA.

Conclusions

The individual Mesh Admin test results do not reveal a homogenous behaviour. The randomness of the Mesh Admin procedure is clearly recognizable in the plots. For example the duration `t_connected` is eminently variable. Additionally, there is no finite deterministic upper bound for the duration of the neighbor discovery and topology control.

The main observation of the longterm tests is the unstable time course of the connectivity and hop count states. As registered in the last sections the removal of neighbors, which ensure the required connectivity state, is responsible for the instability. The removals can consist of both, dead neighbors or neighbors with a poor link quality.

Moreover, the instability of the network connectivity state causes the unconnected nodes to transmit further messages to discover new neighbors, in particular energy expensive broadcasts. By this, the energy consumption on the battery powered detectors is additionally increased.

Therefore, the initial choice of neighbors is crucial for the stability and the energy consumption during the future operation of the alarm system.

2.2 Related Work

In this section an overview of previous work in the area of neighbor discovery and topology construction as well as link quality estimation is given.

2.2.1 NoSE: Neighbor Search and Estimation

Meier et al. in [6] and [7] propose with NoSE a time and energy-efficient initialization of a WSN. A wake up call functionality is included for switching the network from an energy-efficient sleep state through a neighbor discovery to an operational state where the topology can be set up. The wake up call can be flooded into the network by an external trigger and initiates with a timer mechanism the simultaneous start of a discovery phase with finite duration. During the discovery all nodes transmit a predefined number of discovery packets. Moreover, the nodes track the number of received packets and the corresponding RSSI to assess the link quality providing a basis for the topology set up. Energy is saved by the simultaneous discovery start and the appropiate adjusting of the wake up period of the MAC protocol for the different operational states.

2.2.2 Birthday Protocols

A popular approach for initializing WSNs is proposed in the Birthday Protocols [8] by McGlynn and Borbash. The neighbor discovery is started by an external trigger. The time is slotted and each node decides independently and randomly at the beginning of each timeslot for a sleep, listen, or transmit state. A neighbor is added when a node in the listen state receives a broadcast discovery message from another node in the transmit state. The discovery period has a finite duration after which neighbors have either been discovered or never will be.

The birthay protocols provide no information about the link quality of discovered neighbors. The size of the neighbor table is not limited, which is not given in the implementation on a practical setup. Additionally, a MAC protocol with synchronized wake ups is required to enable the slotted time.

2.2.3 XTC

Wattenhofer and Zollinger proposed XTC [9], a practical topology control algorithm for ad-hoc networks. The algorithm has three main contributions. The algorithm choses neighbors solely based on local information by communicating only twice with nodes, works for general network graphs, and does not require node position information. The algorithm orders neighbors according to the link qualities, exchanges the neighbor orders and selects topology control neighbors. If the algorithm is applied to a unit disk graph, the resulting network topology has a bounded degree of at most 6, i.e. the size of the neighbor table is limited to 6 neighbors.

Since the memory on sensor nodes usually is very scarce, the limited neighbor table property of the topology control algorithm is interesting. However, the unit disk graph assumes uniform radio propagation as in the vacuum, which is not practical.

2.2.4 A Simple Algorithm

Angelosanto et al. in [10] present a simple algorithm for neighbor discovery in wireless networks. The algorithm assumes slotted time and a neighbor discovery of limited duration. Nodes are indentified by a signature and randomly either transmit or receive during a time slot under constant probabilities. The neighbor discovery is solved by adding a neighbor if the correlation between the receive signal and the signatur of the node exceeds an discovery threshold. Collisions are avoided by using orthogonal signatures.

Analogously to the Birthday Protocols, the simple algorithm requires a MAC protocol supporting synchronized wake ups. Additionally, the nodes have to keep an apriori known list with all signatures of the network.

2.2.5 Link Quality Estimation

Meier et al. in [11] showed that the deployment of a typical multihop WSN based on low power radios results in a network with a large percentage of very poor link characteristics. A pattern based link estimation scheme is presented which allows to rate the link quality in an energy-efficient way during the initialization phase in order to construct optimal neighbor tables from the beginning.

Srinivasan and Levis in [12] showed that for new transceivers the RSSI above the sensitivity threshold is a promising link quality indicator. A RSSI above the sensitivity threshold results in a packet reception rate (PRR) of at least 85%, whereas around the sensitivity threshold the RSSI does not have a good correlation with the PRR.

Chapter 3

Conceptual Design

In this chapter the conceptual design of the Mesh Construct is presented. The first section outlines the basic idea of the Mesh Construct. In the following sections the details of the procedure concerning the different node functions, messages, timers, and parameters are explained in more depth. In the subsequent section pseudocodes of the three main components of the procedure are indicated. In the last section the maximal duration of the Mesh Construct procedure is theoretically derived.

In this chapter various variables and fields, messages, and parameters are introduced. For a better visualization `variable` and `field names` are written in typewriter font, *message names* are written as emphasized text, and parameter names are typeset as sans serif.

3.1 Basic Idea of Mesh Construct

The Mesh Construct algorithm is a deterministic procedure to construct a mesh network topology for a wireless fire detection sensor network. The Mesh Construct differs in several essential aspects from the existing solution (see Section 2.1). The existing solution is a random procedure with an infinite duration, which is running completely autonomously on each node. In contrast to that, the Mesh Construct is a deterministic procedure which is finished after a finite duration. Additionally, the procedure is no longer running completely autonomously on each node but is controlled centrally by the gateway.

In the Mesh Construct algorithm there are three different functions a network node can fullfil, either gateway, discoverer, or, just a neighboring

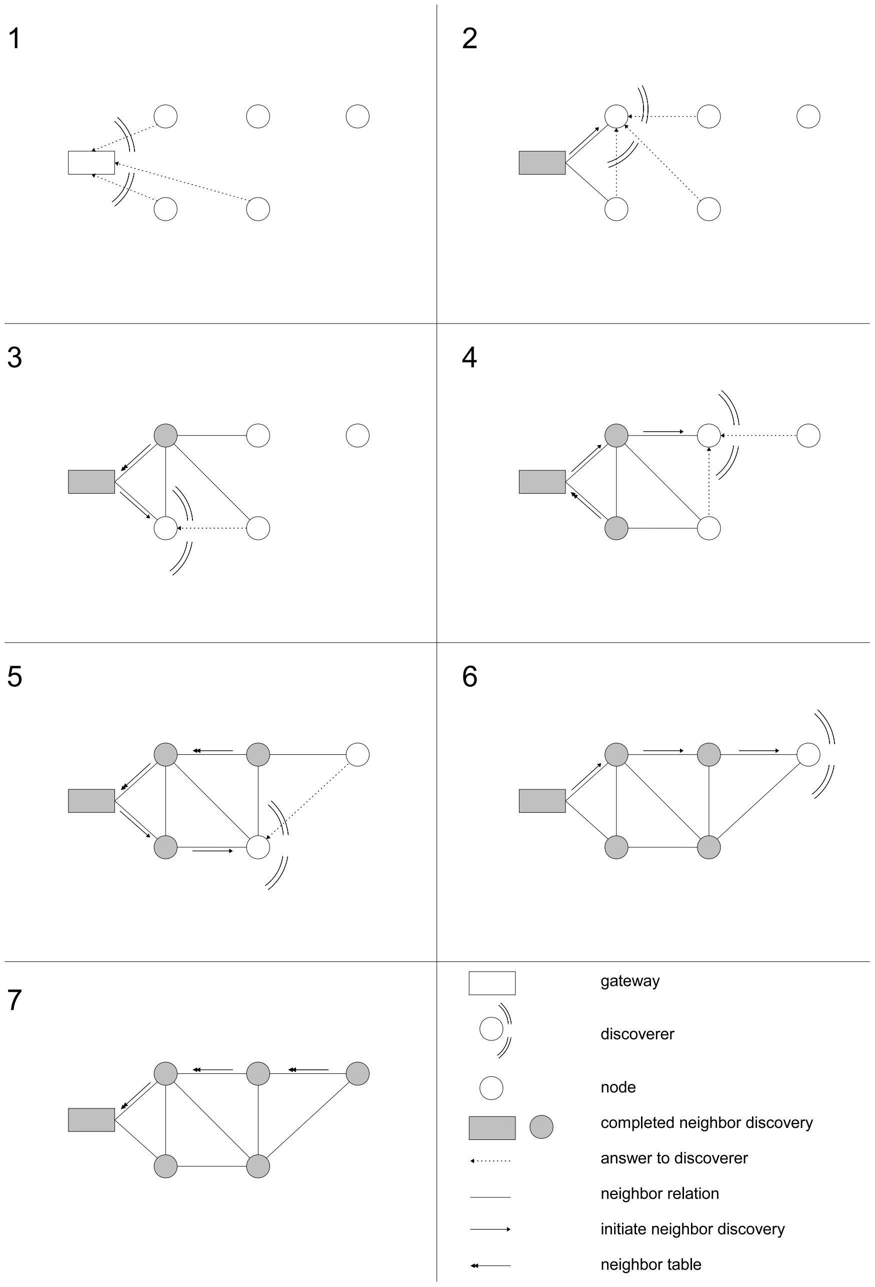


Figure 3.1: An example of the basic idea of the Mesh Construct

node. The gateway functionality is contained only in one single node in the whole network. The discoverer and node functionality is contained in each node, also in the gateway. The node with the gateway functionality acts like a choirmaster who conducts the construction of the mesh network and arranges the time periods where the discoverers are allowed to discover potential neighbors. A node in the discoverer function performs a neighborhood discovery in order to find other nodes in mutual radio range. The discoverer chooses the most suitable nodes for the purpose of the network as neighbors and transmits its choice in form of a neighbor table message to the gateway. The gateway successiveley stores and maintains the received neighbor tables to gain information about the whole mesh network topology. The functionality of a neighboring node denotes a node interacting with a discoverer. The three different node functions are described in Section 3.2. The different messages used for the communication between the nodes are described in Section 3.3.

An easy example of the Mesh Construct procedure for a small number of nodes is illustrated in Figure 3.1. The underlying idea of the Mesh Construct is to start from the network center at the gateway and construct the mesh network through neighborhood discoveries by proceeding outwards hop by hop. First, the gateway self performs a neighborhood discovery as a discoverer to find neighbors with hop count 1 (number 1 in Figure 3.1). Not all discovered nodes are necessarily chosen as neighbors. Next, further neighborhood discoveries are sequentially initiated by the gateway on each node with hop count 1 (number 2 and 3 in Figure 3.1). After the completion of these neighborhood discoveries a network consisting of nodes with hop count 1 and 2 is constructed. Through the received neighbor tables of nodes with hop count 1 the gateway has obtained informations about the children of the nodes with hop count 1, which are nodes with hop count 2. In this manner the gateway succesively continues to sequentially arrange neighborhood discoveries on the next hop to find new nodes and construct the mesh network (number 4, 5 and 6 in Figure 3.1). The Mesh Construct algorithm stops if the neighbor tables of all installed nodes are received or the maximal number of allowed hops is attained (number 7 in Figure 3.1). After the Mesh Construct is completed the installed nodes are part of a constructed mesh network and the primary scheduled operation (e.g. fire detection) with network topology control can be started.

The whole Mesh Construct procedure is described more detailed in Section 3.1.1. The neighborhood discovery is an component of the Mesh Construct algorithm and is described in Section 3.1.2. The choice of the neighbor nodes is a component of the neighborhood discovery algorithm and is described in Section 3.1.3.

3.1.1 Mesh Construct

The Mesh Construct is the basic procedure and can be started by a trigger mechanism at the gateway after the last detector of a wireless fire detection sensor network is physically installed. The communication scheme of the gateway and an arbitrary discoverer during the Mesh Construct is shown in the Figure 3.2. The Mesh Construct procedure is also described in the pseudocode of algorithm 3 in Section 3.6. All message types exchanged between the gateway and the discoverer are described in Section 3.3.

Due to the fact that the transmission medium is wireless, it can always be assumed that a message is not received at the destination because of a collision or any type of interference. Therefore, the whole procedure must be able to cope with missing messages at any time. Timers and retry mechanisms with thresholds for the number of retries are introduced to prevent the algorithm from stopping. The different applied timers are described more detailed in Section 3.4.

Once the Mesh Construct is started by the trigger, the gateway performs a complete neighborhood discovery. Afterwards, the gateway stores its added neighbors with hop count 1 as future discoverers in a discoverer table `discoverer_tbl`. All variables and fields of the Mesh Construct procedure are defined in Section 3.2. In the following the gateway sequentially initiates the procedure shown in the Figure 3.2 on each discoverer in the discoverer table in order to allow temporal non-overlapping neighborhood discoveries. The hop count of the discoverer performing the current neighborhood discovery is denoted as the Mesh Construct state `mc_state`.

The gateway transmits a *start_discovery* message to the first discoverer in `discoverer_tbl` and starts the two timers `t_rx_ack_start` and `t_rx_nhtbl` simultaneously. As a reaction on receiving a *start_discovery* the first discoverer starts the neighborhood discovery procedure and transmits an *ack_start-_discovery* back to the gateway. If an *ack_start_discovery* is received at the gateway, the timer `t_rx_ack_start` is stopped. When `t_rx_ack_start` ex-

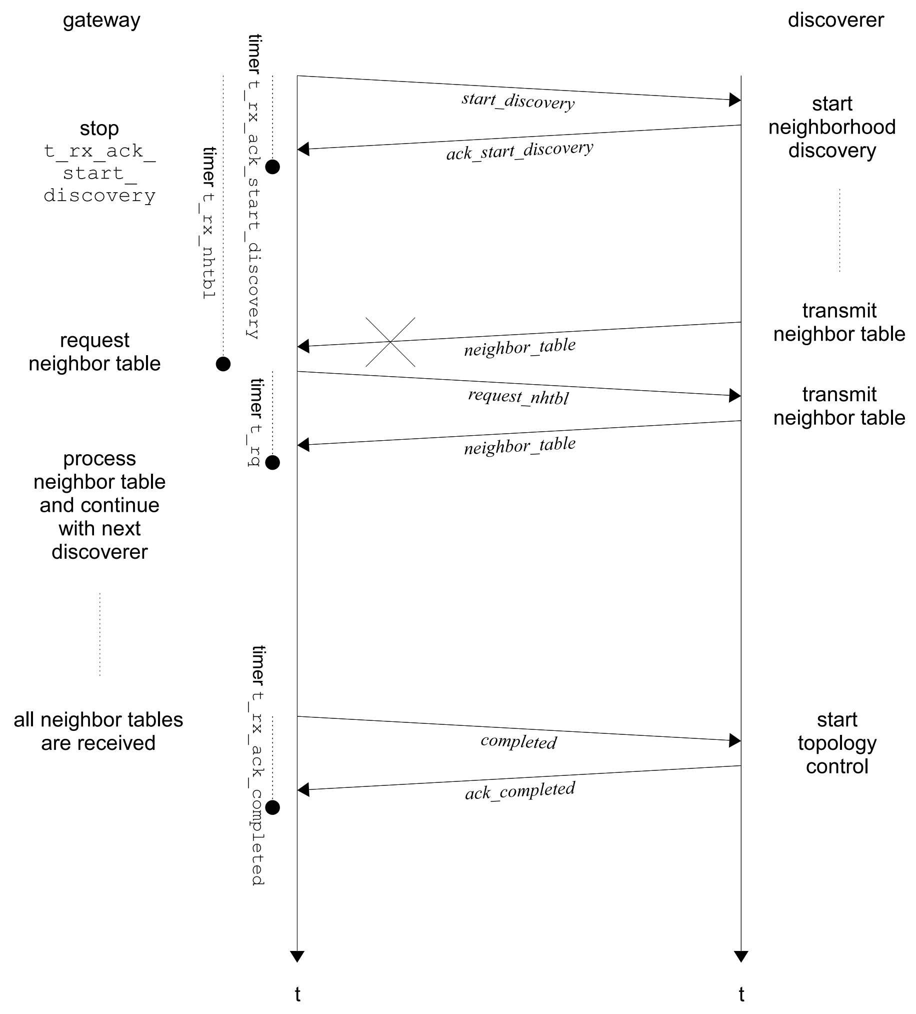


Figure 3.2: Mesh Construct: Communication scheme of the gateway and an arbitrary other discoverer

pires and the number of retries `rtr_start` has not already exceeded the threshold rtr_start_max, another *start_discovery* is transmitted and the two timers are restarted. Otherwise the start of the neighborhood discovery failed, and the procedure continues with the next discoverer.

As soon as a neighborhood discovery is completed, the discoverer node transmits its `neighbor_tbl` in a *neighbor_table* message to the gateway. If the timer `t_rx_nhtbl` at the gateway expires without having received the expected neighbor table and the number of retries `rtr_request` has not exceeded the threshold rtr_request_max, then a *request_nhtbl* message is transmitted to the discoverer. When the timer `t_rx_nhtbl` expires, it implies that the timer `t_rx_ack_start` has been stopped and an *ack_start* is already received. Therefore, the neighborhood discovery should already be completed and an other, shorter timer `t_rq` is started for the requesting of the neighbor table. When the timer `t_rq` expires another *request_nhtbl* is transmitted if the retries have not exceeded the threshold rtr_request_max, otherwise the transmission of the neighbor table failed and the procedure continues with the next discoverer.

When a neighbor table is received at the gateway, the timers `t_rx_nhtbl` and `t_rq` are stopped. Additionally, the gateway processes the information of the neighbor table. In particular, neighbors of the discoverer which have a hop count that is one higher than the current `mc_state` are stored in the `discoverer_tbl`. By this means, with each received neighbor table the gateway successively adds new discoverer on the next hop to the discoverer table. When all neighbor tables of the current `mc_state` are received at the gateway, the Mesh Construct procedure continues on the next `mc_state`.

The Mesh Construct procedure terminates if all nodes in the discoverer table have performed their neighborhood discovery and the following transmission of the neighbor table or otherwise no more nodes with a hop count less or equal than the maximal number of allowed hops nb_hops_max are in the `discovery_tbl`.

After the Mesh Construct procedure is completed, the operation of the alarm system including the topology control is started by the sequential transmission of *completed* messages to each discoverer in `discovery_tbl`. A discoverer receiving a *completed* starts the operation and transmits an *ack_completed* back to the gateway. The timer `t_rx_ack_completed` waiting for the reception of the *ack_completed* is started at each transmission of a *completed* and ensures with a retry mechanism that each discoverer starts the operation. As last node the gateway starts the operation.

3.1.2 Neighborhood Discovery

The neighborhood discovery is a component of the Mesh Construct algorithm. During the Mesh Construct each node in the network performs at least one neighborhood discovery. The objective of the neighborhood discovery is to collect as much information as possible about other nodes in the vicinity in order to provide a good basis of decisionmaking for choosing neighbors (see Section 3.1.3 and algorithm 5). For that reason, messages of different types have to be exchanged between the discoverer and neighboring nodes to transmit informations and to notify the chosen neighbors. Finally, the neighborhood discovery ends with the construction of a neighbor table. The communication scheme of a neighborhood discovery ist illustrated in the Figure 3.3. The neighborhood discovery is also described in the pseudocode of algorithm 4 in Section 3.6.2.

At the beginning of the neighborhood discovery the discoverer transmits a sequence of `nb_tx_bcast` numbered *broadcast* messages. The different messages are described in Section 3.3. All paramteters of the Mesh Construct are listed in Section 3.5. All variables and fields are defined in Section 3.2. The transmit power `tx_power` of each *broadcast* is linear increasing and proportional to the broadcast sequence number `bcast_nb`. Among others, this feature is used to assess the link quality to discovered nodes and is described in Section 3.1.3.

When a neighboring node receives the first *broadcast* from a discoverer, the sequence number `bcast_nb` is stored as `first_rx_bcast` and the timer `t_rx_bcasts` depending on `first_rx_bcast` is started. The different timers are described in Section 3.4. While this timer is running the node waits for the reception of the remaining *broadcasts* from the discoverer. At the expiration of `t_rx_bcasts` the node transmits a *broadcast_received* message back to the discoverer. The *broadcast_received* contains several informations about the discovered node, in particular the field `first_rx_bcast`.

By this manner the discoverer collects informations about nodes in mutual radio range and stores it into a node table `node_tbl`. By the time the discoverer transmits the first *broadcast*, a timer `t_rx_bcast_rx` is started simultaneously. While the timer is running, the gateway waits for *broad-*

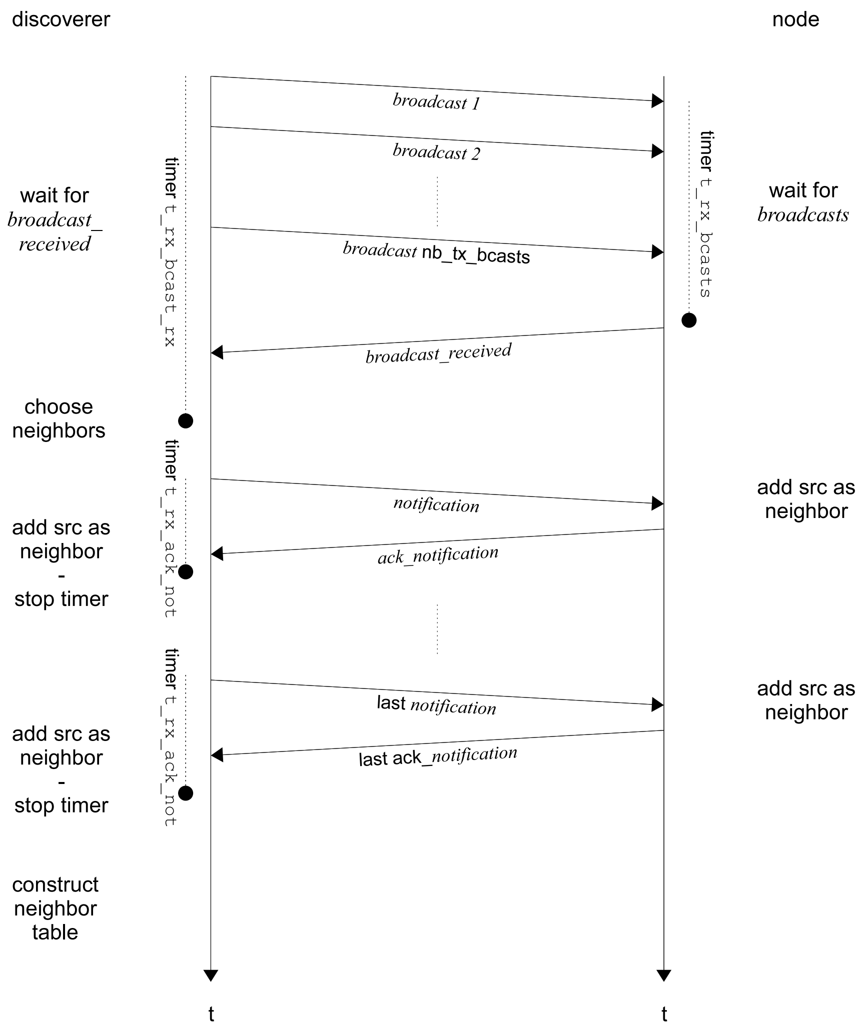


Figure 3.3: Neighborhood discovery of a single node: Communication scheme of the discoverer and an arbitrary other node

cast_received messages. When the timer `t_rx_bcast_rx` expires, the discoverer chooses the best nodes from the `node_tbl` according to the choose neighbors algorithm 5. The output of the algorithm is a list of chosen nodes. Subsequently, the discoverer transmits a *notification* message to the the first chosen node. Simultaneously, a timer `t_rx_ack_not` is started at the discoverer. A node receiving a *notification* adds the source as neighbor to the `neighbor_tbl` and transmits an *ack_notification* back to the discoverer. As reaction on receiving an *ack_notification* the discoverer adds the source as neighbor as well, restarts `t_rx_ack_not` and transmits a *notification* to the next chosen node. Upon having received all *ack_notifications*, the discoverer constructs a neighbor table and thus the neighborhood discovery is completed.

Like in the Mesh Construct procedure timers and retry mechanisms with thresholds for the number of retries are introduced to prevent the algorithm from stopping in case of a lost message. E.g. while the timer `t_rx_bcast_rx` is running the discoverer waits for receiving *broadcast_received* messages. When `t_rx_bcast_rx` expires and not a single *broadcast_received* is received, the discoverer transmits again a sequence of *broadcasts* if the number of retries `rtr_bcast` has not already exceeded the threshold rtr_bcast_max. If so, no neighbors could be found with the neighborhood discovery. Analogously, while the timer `t_rx_ack_not` is running the discoverer waits for a particular *ack_notification*. When `t_rx_ack_not` expires the discoverer retransmits the *notification* if the number of retries `rtr_not` for this node has not already exeeded the threshold rtr_not_max. If so, new nodes are chosen if the number of retries `rtr_choose` has not already exceeded the threshold rtr_choose_max, otherwise no additional neighbors could be found.

The neighborhood discovery is completed with the construction of the neighbor table, whether it could be filled up with neighbors or remains empty.

3.1.3 Choose Neighbors

The choose neighbors procedure is a component of the neighborhood discovery. The procedure chooses neighbors among all nodes which are discovered during the neighborhood discovery. The objective of the choose neighbors procedure is to make the best choice for the purpose of the whole wireless sensor network. The choose neighbors procedure is also described in the pseudocode 5 in Section 3.1.3.

In a wireless fire detection sensor network two aspects are cruicial for the choice of the neighbors. On the one hand, neighbors with a good link quality are important. If messages to or from a neighbor are received only rarely and require many retransmissions because of a bad link quality, a lot of energy of the batteries is wasted and the reliability of the network function is decreased. Thus, it is energy-efficient and more reliable for the network function to choose the nodes with the best link quality as neighbors. On the other hand, a node needs a certain number of independent communication paths to the gateway to ensure the desired connectivity state. Therefore, it is important to choose parents and peers with the best connectivity state in order to achieve the own required connectivity state. Since the purpose of a wireless fire detection sensor network is to forward alarms to the gateway, the existence of the required number of independent communication paths is weighted as more important than the quality of the links.

To evaluate the quality of a wireless link two quantities are used. The link quality from the discoverer to the node is assessed through the sequence number of the first received *broadcast* `first_rx_bcast`. The transmit power `tx_power` of each *broadcast* is linear increasing and proportional to the broadcast sequence number `bcast_nb`. The first *broadcast* is transmitted with tx_power_min and the last broadcast with tx_power_max. The linear dependence of `tx_power` and `bcast_nb` is shown on figure 3.4 and calculated in the Equation 3.1 and the following equations.

$$\texttt{tx\_power} = m \cdot \texttt{bcast\_nb} + b \tag{3.1}$$

By setting in the known pair of variates in the Equation 3.1

$$\begin{aligned} \mathsf{tx\_power\_min} &= m \cdot 1 + b && (3.2) \\ \mathsf{tx\_power\_max} &= m \cdot \mathsf{nb\_tx\_bcasts} + b && (3.3) \end{aligned}$$

for the slope and the intercept results a dependency only on parameters

$$\begin{aligned} m &= \frac{\mathsf{tx\_power\_max} - \mathsf{tx\_power\_max}}{\mathsf{nb\_tx\_bcasts} - 1} && (3.4) \\ b &= \frac{\mathsf{tx\_power\_min} \cdot \mathsf{nb\_tx\_bcasts} - \mathsf{tx\_power\_max}}{\mathsf{nb\_tx\_bcasts} - 1} && (3.5) \end{aligned}$$

A small `first_rx_bcast` number implies the reception of the *broadcast* already with a low transmit power. Hence, the lower the broadcast sequence

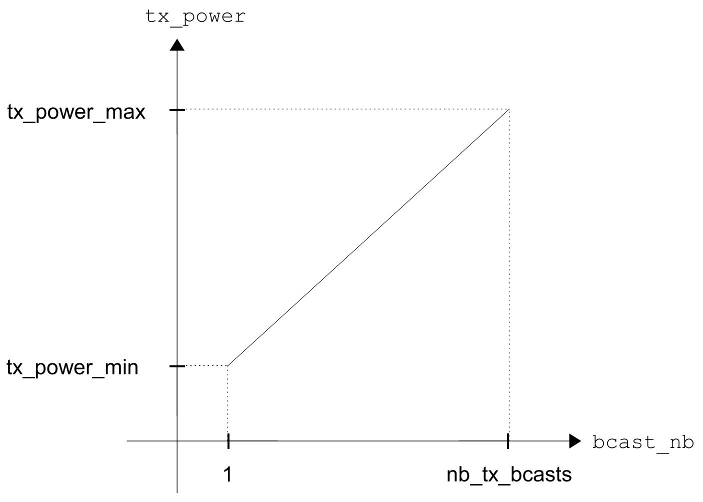


Figure 3.4: linear increasing txpower

number the better is the link quality. To assess the link quality from the node to the discoverer the received signal strength is measured and stored in the variable `rssi`. By considering the link quality in both directions, the choice of neighbors with an unsymmetric link quality shall be prevented. The `first_rx_bcast` and `rssi` are message fields of the *broadcast_received* and are stored for each discovered node in the node table.

To make the best choice concerning the connectivity state the following items from the node table are required for each node: number of peers `nb_pe`, connectivity state `con_state`, hop count `hop_count`, number of neighbors `nb_nhs`, and number of retries to transmit a *notification* `rtr_not`. Additionaly, for the discoverer the following fields are required: own hop count `own_hop_count`, own number of parents `own_nb_pa`, own number of peers `own_nb_pe`, and own number of children `own_nb_ch`.

The choose neighbor procedure starts with a check of the node table. Nodes which have already exceeded the threshold for the notification retries (`rtr_not` $\geq$ rtr_not_max) or have already a full neighbor table (`nb_nhs` $\geq$ nb_nhs_max) are removed from the node table. Subsequently all nodes are sorted for the minimal first_rx_bcast and the maximal rssi. Thereby, always the node with the better link quality is chosen, when two nodes have the same ranking concerning the connectivity state. The discoverer always tries to meet the requirements of the parameters concerning the minimal number of parents, peers, or children on the corresponding hop counts (pe_hc1_min, pa_hc2_min, ...). Moreover, the discoverer always checks and only chooses a node if the own number of parents own_nb_pa, the own number of peers own_nb_pe, and the own number of children own_nb_ch does not already meet the requirements. In the following the choose neighbor procedure distinguishs 4 different cases:

- own_hop_count = 0:
  There is no connectivity state information at disposal of the gateway at the start. The gateway choses the first nb_nhs_max nodes with the best link quality from the node table.

- own_hop_count = 1:
  The discoverer chooses the first pe_hc1_min peers with minimal nb_pe to prevent that each discoverer with hop count 1 chooses the same peers. Additionally, the required connectivity state is ensured. Then, ch_hc1_min children with a minimal con_state are chosen in order to add new nodes to the network and improve their connectivity state.

- own_hop_count = 2:
  The discoverer chooses the first pa_hc2_min parents with maximal con_state to ensure the own required connectivity state. If not enough parents can be chosen, additonal peers to the pe_hc2_min with a maximal con_state are chosen instead to ensure the own required connectivity state. Then, ch_hc2_min children with a minimal con_state are chosen in order to add new nodes to the network and improve their connectivity state.

- own_hop_count = 3:
  The discoverer chooses the first pa_hc3_min parents with maximal con_state to ensure the own required connectivity state. If not enough parents can be chosen, additonal peers to the pe_hc3_min with a maximal con_state are chosen instead to ensure the own required connectivity state. If not already chosen, pe_hc3_min children with a minimal con_state are chosen in order to improve their connectivity state.

At the end of the procedure the list of the chosen nodes is truncated to the number of neighbors which can maximally be added. For that reason, only the first (`nb_nhs_max - own_nb_nhs`) nodes are returned as the list of chosen neighbors.

3.2 Node Functions and Fields

In this section the three different node functions and their corresponding fields are described in more detail. The three different node types are denoted as gateway, discoverer, and node functionality.

3.2.1 Gateway

It is assumed that only one node with the gateway functionality exists in the entire network. More gateways in one single network are conceivable but in the scope of this thesis only networks with one gateway are investigated. However, the gateway implements also the discoverer and node functionality.

The gateway controls and monitors the whole Mesh Construct procedure. In particular, the start, the proceeding temporal non-overlapping neighborhood discoveries, and the termination i. e. the start of the topology control are initiated by the gateway. Besides, the gateway constructs and maintains a discoverer table, wherein informations about each node in the network are stored. For that reason, several additional variables and fields are required in the gateway and listed in the Table 3.1 and Table 3.2.

The discoverer table `discoverer_tbl` contains the node address `nd_add` and the connectivity state `con_state`. The node address indentifies the different discoverers and the connectivity state is required to track the connectivity state of the entire network. Besides, `nd_add` and `con_state` in the discoverer table for each discoverer the `hop_count` and a `trace` are stored. For example these informations are required to initiate a neighborhood discovery. In a `trace` the addresses of the nodes on the communication path between the gateway and the discoverer are stored. The combination of the `trace` and the `hop_count` allows to transmit a DSR message from the gateway to the discoverer over more than one hop. The DSR messages are described more detailed in Section 3.3.3.

The discoverer index `discoverer_ind` indicates the discoverer in the `discoverer_tbl`, which is currently performing a neighborhood discovery.

Gateway	Gateway variable description
`discoverer_tbl`	Discoverer table with informations of all discoverer nodes (see Table 3.2)
`discoverer_ind`	Indicates the current discoverer node
`mc_state`	The Mesh Construct state indicates on which hop count the current discoverer is performing the neighborhood discovery
`nb_nds_on_hc`	Number of discovered nodes on the current `mc_state`
`nb_rx_nhtbl`	Number of received neighbor tables on the current `mc_state` (see Table 3.6)
`rtr_start`	Number of retries for transmitting a *start_discovery* to the current discoverer
`rtr_request`	Number of retries for transmitting a *request_neighbor_table* to the current discoverer
`rtr_completed`	Number of retries for transmitting a *completed* to the current discoverer

Table 3.1: Variables of the gateway

`discoverer_tbl`	`discoverer_tbl` variable description
`nd_add`	Node address of the discoverer
`con_state`	Connectivity state of the discoverer
`hop_count`	Hopcount of the discoverer
`trace`	The list of node addresses of one communication path from the gateway to the discoverer

Table 3.2: Variables for each discoverer entry of the discvoerer table

The Mesh Construct state `mc_state` indicates the hop count of the current discoverer `discoverer_ind`. The number of nodes `nb_nds_on_hc` on the current Mesh Construct state is set each time the `mc_state` is incremented according the hop count informations in the discoverer table. The number of received neighbor tables `nb_rx_nhtbl` is incremented if the expected neighbor table is received. The variables `rtr_start` and `rtr_request` are required to count the corresponding retries.

3.2.2 Discoverer

The discoverer functionality is contained in each node of the network, since each node has to perform at least one neighborhood discovery. The task of a discoverer consists of discovering and choosing neighbors. The chosen neighbors are notified and subsequently added to the neighbor table in case an *ack_notification* is received. The neighbor table is transmitted to the gateway to deliver the information about the mesh network topology. The variables and fields required in the discoverer are listed in the Table 3.3 and Table 3.4.

For deciding which neighboring nodes to choose as neighbors the discoverer for each discovered node stores information contained in the *broadcast_received* messages in a node table `node_tbl`. How a discoverer chooses nodes depending on the values of the fields in the node table is described in Section 3.1.3.

The number of received *broadcast_received* messages `nb_rx_bcast_rx` is incremented at the reception of a *broadcast_received* and is required to determine if no nodes at all are beeing discovered. After neighbors have been chosen the number of notifications to transmit `nb_tx_notifications` is set in order to be able to decide wether all expected *ack_notifications* are received. The variables `rtr_bcast` and `rtr_choose` are required to count the corresponding retries.

3.2.3 Node

The node functionality is the basic functionality contained in each node of the mesh network. A node is only reacting on certain events: *broadcasts* are answered with *broadcast_received*, *notifications* are answered with *notifications*, and DSR messages are forwarded if required. Nodes are passive as

Discoverer	Discoverer variable description
`node_tbl`	Table of collected informations about nodes in the neighborhood (see table 3.4)
`nb_rx_bcast_rx`	Number of received *broadcast_received* from discovered nodes
`nb_tx_notifications`	Number of transmitted *notifications* to chosen neighbors
`rtr_bcast`	Current number of retries for transmitting nb_tx_bcasts *broadcasts*
`rtr_choose`	Current number of retries for choose neighbors

Table 3.3: Variables of a discoverer

`node_tbl`	`node_tbl` variable description
`nd_add`	Address of the node
`nb_nhs`	Number of neighbors of the node
`nb_pes`	Number of peers of the node
`con_state`	Connectivity state of the node
`hop_count`	Hop count of the node
`first_rx_bcast`	Number of first received *broadcast* of the node
`rssi`	RSSI value of the received *broadcast_received* from the node
`rtr_not`	Number of retries for transmitted *notifications* to the node

Table 3.4: Variables for each node entry of the node table

long as none of these events occur. The variables and fields required in a node are listed in the Table 3.5 and Table 3.6.

Each node has an operation state variable `op_state`, which can be in the *sleep*, *Mesh Construct*, or *topology control* state. When a node is physically installed and switched on, the operation state is initialized as sleep state. Upon receiving the first *broadcast* the operation state is set to Mesh Construct. When a *completed* message is received the state is changed to topology control.

Additionally, when the first *broadcast* is received, the `bcast_nb` of the message is stored as first received *broadcast* to `first_rx_bcast` and the `gw_address` of the message is stored. If more mesh netork exists, the `gw_address` is included in direct messages to indicate whether a node is in the network with the same gateway.

When a node receives a *notification* the source node is added as neighbor in the neighbor table `neighbor_tbl`. Each node entry in the neighbor table will in future be used to communicate within the mesh network.

Node	Node variable description
`neighbor_tbl`	Table containing information of chosen neighbors (see Table 3.6)
`op_state`	sleeping, mesh construct, operation
`gw_address`	Address of the gateway
`first_rx_bcast`	Number of first received *broadcast*
`nb_pa`	Number of parents in `neighbor_tbl`
`nb_pe`	Number of peers in `neighbor_tbl`
`nb_ch`	Number of children in `neighbor_tbl`
`hop_count`	Hop count
`con_state`	Connectivity state
`txpower`	The current transmit power

Table 3.5: Variables of a node

3.3 Message Types

In this section the different messages and message types used for the communication within the mesh network are described. There are three different message types, the direct, DWARF, or DSR message. For each single

`neighbor_tbl`	`neighbor_tbl` variable description
`nd_add`	Node address of the neighbor
`con_state`	Connectivity state of the neighbor
`hop_count`	Hop count of the neighbor

Table 3.6: Variables for each neighbor entry of the neighbor table

message it is indicated between which node types it is transmitted, which information is contained, in which situations the message is sent, and which actions are performed when the message is received. Each message contains the message type, the destination address, and the source address as message fields.

3.3.1 Direct Messages

Direct messages are exchanged over a distance of one hop. There are unicast messages from one node to another or a broadcast message from one node to all nodes in communcation range.

broadcast

A *broadcast* is transmitted from a discoverer to all nodes in communication range. The information fields contained in a *broadcast* are listed in the Table 3.7.

broadcast	*broadcast* field description
`msg_type`	Identifier indicating the message type *broadcast*
`dest_bcast`	Destination address
`src_bcast`	Source address
`bcast_nb`	Sequence number of the *broadcast*
`gw_address`	Gateway address

Table 3.7: Message fields of a *broadcast*

The *broadcast* message is transmitted `nb_tx_bcast` times with linear increasing transmit power at the beginning of a neighborhood discovery. The broadcast sequence number is incremented after each transmission.

When a node receives the first *broadcast* from a discoverer, the broadcast sequence number `bcast_nb` is stored to `first_rx_bcast` and the timer `t_rx_bcasts` depending on `first_rx_bcast` is started. Additionally, the address of the gateway `gw_address` is stored if it is not known yet at the node.

broadcast_received

The *broadcast_received* message is transmitted as answer from a node to a discoverer from whom a *broadcast* has been received. The information fields contained in a *broadcast_received* are listed in the Table 3.8.

broadcast_received	*broadcast_received* field description
`msg_type`	Identifier indicating the message type *broadcast_received*
`dest_bcast_rx`	Destination address
`src_bcast_rx`	Source address
`gw_address`	Gateway address
`bcast_nb`	Sequence number of first received *broadcast*
`con_state`	Connectivity state of the source
`hop_count`	Hop count of the source
`nb_nhs`	Number of neighbors of the source
`nb_pes`	Number of peers of the source
`rssi`	RSSI at the destination

Table 3.8: Message fields of a *broadcast_received*

The *broadcast_received* message is transmitted to the source of a received *broadcast* `src_bcast` when the timer `t_rx_bcasts` expires.

When a discoverer receives a *broadcast_received* the message fields are stored in the node table `node_tbl`. The message field `rssi` denotes the received signal strength indication (RSSI) measured at the discoverer and actually, is only a virtual message field.

notification

The *notification* message is transmitted from a discoverer to a node in order to notify the node that it is chosen as neighbor. The information fields contained in a *notification* are listed in the Table 3.9.

Discoverers transmit *notification* messages at the end of the neighborhood discovery after nodes are chosen as neighbors from the node table.

notification	*notification* field description
`msg_type`	Identifier indicating the message type *notification*
`dest_not`	Destination address
`src_not`	Source address
`gw_address`	Gateway address
`con_state`	Connectivity state of the source
`hop_count`	Hop count of the source

Table 3.9: Message fields of a *notification*

When a node receives a *notification* from a discoverer the node adds the discoverer to its neighbor table `neighbor_tbl`. Additionally, the own connectivity state is updated from the neighbor table. As an answer an *ack_notification* is transmitted to the source of *notification* `src_not`.

ack_notification

The *ack_notification* message is transmitted to the source of a received *notification* `src_not`. The information fields contained in a *ack_notification* are listed in the Table 3.10.

Variable	Variable description
`msg_type`	Identifier indicating the message type *ack_notification*
`dest_ack_not`	Destination address
`src_ack_not`	Source address
`gw_address`	Gateway address
`con_state`	Connectivity state of the source
`hop_count`	Hop count of the source

Table 3.10: Message fields of a *ack_notification*

The *ack_notification* message is transmitted to the source of a received *notification* `src_bcast` as a direct reaction on receiving a *notification*.

When a discoverer receives an *ack_notification* from a node the source is added to the neighbor table `neighbor_tbl`. Additionally, the own connectivity state is updated from the actualized neighbor table.

3.3.2 DWARF Messages

In this thesis all DWARF messages are transmitted from any discoverer to the gateway. A DWARF message can be forwarded over several communication paths with several hops to the gateway. In addition, the communication paths from the discoverer to the gateway are not determined a priori. More informations about the DWARF message mechanism are given in (reference dwarf paper).

neighbor_table

The information fields contained in a *neighbor_table* message are listed in the Table 3.11.

neighbor_table	*neighbor_table* field description
`msg_type`	Identifier indicating the message type *neighbor_table*
`dest_nhtbl`	Destination address equal to `gw_address`
`src_nhtbl`	Source address
`neighbor_tbl`	Table containing information of chosen neighbors

Table 3.11: Message fields of a *neighbor_table*

A *neighbor_table* message is transmitted to the gateway when a discoverer has completed its neighbor discovery. The whole `neighbor_tbl` of the discoverer is added to the message.

When the gateway receives a *neighbor_table* the timers `t_rx_nhtbl` or `t_rq` are stopped and the informations of the neighbor table contained in the message are stored in the `discoverer_tbl`. Furthermore, the node addresses of one communication path from the discoverer to the gateway are stored in a `trace` in the discoverer table.

ack_start_discovery

The information fields contained in a *ack_start_discovery* message are listed in the Table 3.12.

An *ack_start_discovery* is transmitted from a discoverer to the gateway in response to a received *start_discovery* message.

When an *ack_start_discovery* is received at the gateway, the timer `t_rx-_ack_start` is stopped.

Variable	Variable description
`msg_type`	Identifier indicating the message type *ack_start_discovery*
`dest_ack_start`	Destination address equal to `gw_address`
`src_ack_start`	Source address

Table 3.12: Message fields of a *ack_start_discovery*

ack_completed

The information fields contained in a *ack_completed* message are listed in the Table 3.13.

Variable	Variable description
`msg_type`	Identifier indicating the message type *ack_completed*
`dest_ack_comp`	Destination address equal to `gw_address`
`src_ack_comp`	Source address

Table 3.13: Message fields of a *ack_completed*

An *ack_completed* is transmitted from a discoverer to the gateway in response to a received *completed* message.

No action is executed, when an *ack_completed* is received at the gateway.

3.3.3 DSR Messages

DSR messages are transmitted from the gateway to any node in the mesh network. A DSR message can be forwarded over several hops to the destination node. Therefore, the requirement to transmit a DSR message is a known trace stored in the discoverer table of the gateway. A trace is a list of node addresses of the communication path from the gateway to the destination node. A trace is stored each time a neighbor table is received from a discoverer at the gateway for each child of the discoverer. The discoverer address is appended to the own trace of the discoverer and stored as trace for each child of the discoverer. The trace of a discoverer with hop count 1 is an empty list. If a node receives a DSR message, the message will be forwarded to the next node of the trace unless the receiving node is the final destination.

start_discovery

The information fields contained in a *start_discovery* message are listed in the Table 3.14.

Variable	Variable description
`msg_type`	Identifier indicating the message type *start_discovery*
`dest_start`	Destination address equal to `gw_address`
`trace`	Node addresses to the destination node
`src_start`	Source address

Table 3.14: Message fields of a *start_discovery*

A *start_discovery* message is transmitted from the gateway to a discoverer to initiate the start of a neighborhood discovery.

When a *start_discovery* message is received at a discoverer, an *ack_start-_discovery* message is transmitted to the gateway to confirm the reception. Subsequently, the neighborhood discovery procedure is started.

request_neighbor_table

The information fields contained in a *request_neighbor_table* message are listed in the Table 3.15.

Variable	Variable description
`msg_type`	Identifier indicating the message type *request_neighbor_table*
`dest_rq_nhtbl`	Destination address equal to `gw_address`
`trace`	Node addresses to the destination node
`src_rq_nhtl`	Source address

Table 3.15: Message fields of a *request_neighbor_table*

A *request_neighbor_table* message is transmitted from the gateway to a discover when the timer `t_rx_nhtbl` or `t_rq` is expired before a neighbor table is received from the discoverer at the gateway.

In response of receiving a *request_neighbor_table* a discoverer transmits the requested *neighbor_table* message to the gateway.

completed

The information fields contained in a *completed* message are listed in the Table 3.16.

Variable	Variable description
`msg_type`	Identifier indicating the message type *completed*
`dest_comp`	Destination address equal to `gw_address`
`trace`	Node addresses to the destination node
`src_comp`	Source address

Table 3.16: Message fields of a *completed*

A *completed* message is transmitted from the gateway to each node of the network, when the Mesh Construct procedure is completed.

A node receiving a *completed* message, sets the `op_state` to topology control, starts the topology control application and transmits an *ack_completed* message back to the gateway. To speed up the operation state change, a node only forwarding the *completed* changes the operation state as well, but does not transmit an *ack_completed* .

3.4 Timers

Timers with corresponding retry mechanisms are introduced to prevent the Mesh Construct Algorithm from running infinitely. The set timers are used to limit the waiting time for a certain event to a finite duration. There are two different types of timers applied in the Mesh Construct. The first type of timers waits for an unknown amount of events and hence is designed to expire in any case before further actions are performed (e.g. the timers in Sections 3.4.1 and 3.4.2). The second type of timers waits for one certain event and is stopped immediately if the expected event occurs (e.g. the timers in Sections 3.4.3, 3.4.4, 3.4.5, and 3.4.6).

To design the Mesh Construct algorithm as stable as possible, the duration of the timers is always chosen in a conservative way. Therefore, the duration of a timer is theoretically calculated as the time period required for the event to occur in a worst case scenario.

Since the WiseMAC protocol is implemented in the wireless fire detection sensor network, each node can only receive messages at every periodic wake up point. The constant time period between these wake up points is denoted as the wake up period `t_w`. Thus, the duration of each timer is determined by a number of time slots `t_w`. For further informations about the WiseMAC protocol see (ref wisemac).

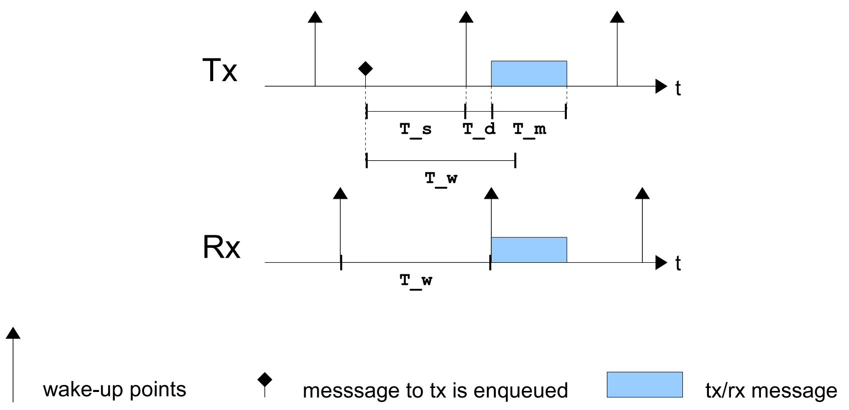


Figure 3.5: Scheme for transmitting a direct message

To determine the duration of certain timers, the duration for the transmission of one direct message is required. The possible worst case situation of a direct transmission is illustrated in the Figure 3.5. A message is enqueued in a node for transmission an infinitesimal time after the wake up point of the destination node. The transmitting node has to wait the remaining time for its own wake up point `t_s` plus the time difference between the wake up patterns of both nodes `t_d` until the transmission of the message can be started. Depending on the length of the message `t_m` the total duration `t_total` from the point where the message is enqueued for transmission until it is entirely received at the destination node is possibly longer than one wake up period `t_w`.

$$\texttt{t\_total} = \texttt{t\_s} + \texttt{t\_d} + \texttt{t\_m} > \texttt{t\_w} \tag{3.6}$$

Therefore, the assumed time duration for transmitting a direct message is rounded up to two wake up periods.

$$\texttt{t\_direct} = 2 \cdot \texttt{t\_w} \tag{3.7}$$

As a consequence of equation 3.7 the maximal duration for the transmission of a DWARF oder DSR message is given by the maximal number of hops.

$$\begin{aligned} \texttt{t\_dwarf} &= \mathsf{nb\_hops\_max} \cdot \texttt{t\_direct} \\ &= 2 \cdot \mathsf{nb\_hops\_max} \cdot \mathsf{t\_w} \end{aligned} \tag{3.8}$$

$$\begin{aligned} \texttt{t\_dsr} &= \mathsf{nb\_hops\_max} \cdot \texttt{t\_direct} \\ &= 2 \cdot \mathsf{nb\_hops\_max} \cdot \mathsf{t\_w} \end{aligned} \tag{3.9}$$

In the following sections for each timer the derivation of the duration is described. Moreover, for each timer the starting point, the event the timer waits for, and the actions which will be performed at the timer stop or expiration are indicated.

3.4.1 Timeout receive broadcasts t_rx_bcasts

The timer t_rx_bcasts is started when the first *broadcast* of a discoverer is completely received at a node. While the timer t_rx_bcasts is running, the node waits for the reception of the remaining (nb_tx_bcasts - first_rx_bcast) *broadcasts* of the discoverer. When the timer expires the node transmits a *broadcast_received* to the discoverer.

Due to a technical restriction it is not possible to transmit *broadcasts* in consecutive time slots. A number of idle_slots has to be inserted between the transmission of two *broadcasts*. During the transmission of the *broadcast* sequence the reception of a *broadcast_received* at the discoverer is complicated or not possible. Thus, the node transmits the *broadcast_received* message only after the last *broadcast* is received. Since each node in communication range receives the last *broadcast* approximately at the same time, a simultaneous transmission of the *broadcast_received* to the gateway leads to numerous collisions at the gateway. For that reason a random number of time slots t_w is added to the timer duration in order to decrease the number of collisions. The random number is uniformly distributed over the set $\{0, \mathsf{nb\_nds}\}$. The scheme for the duration of the timer t_rx_bcasts is shown in the Figure 3.6.

$$\begin{aligned}\texttt{t\_rx\_bcast}\,(\texttt{first\_rx\_bcast}) &= [(\mathsf{nb\_tx\_bcasts} - \texttt{first\_rx\_bcast}) \\ &\quad \cdot (\mathsf{idle\_slots} + 1) \\ &\quad + \mathrm{random}\,(0, \mathsf{nb\_nds})] \cdot \mathsf{t\_w} \qquad (3.10)\end{aligned}$$

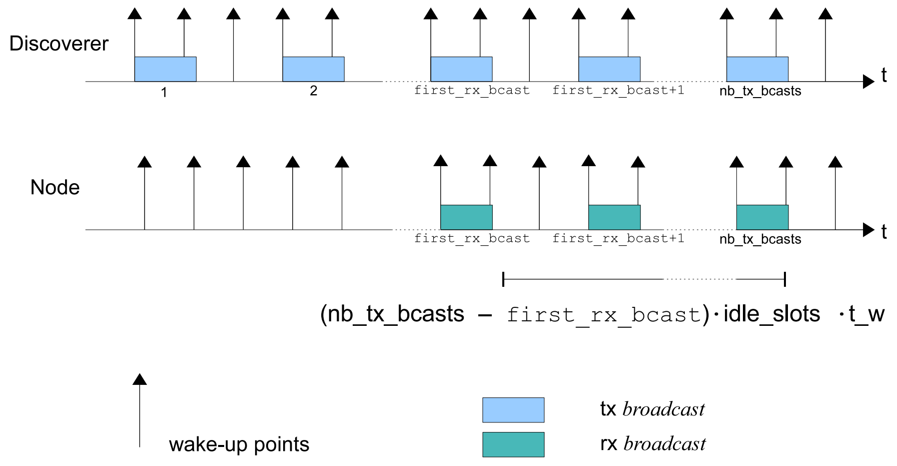


Figure 3.6: Scheme for the duration of the timer `t_rx_bcast`

3.4.2 Timeout receive broadcast-received `t_rx_bcast_rx`

The timer `t_rx_bcast_rx` is started when the discoverer starts the transmission of the first *broadcast* of the sequence. While the timer `t_rx_bcast_rx` is running, the discoverer waits for the reception of *broadcast_received* messages. When the timer expires the discoverer starts the choose neighbors algorithm.

The scheme for the duration of the timer `t_rx_bcast_rx` is shown in the Figure 3.7. The duration of the timer `t_rx_bcast_rx` is composed of the time required for transmitting the *broadcast* sequence `t_bcast_seq` and the random time waited of the nodes `t_wait` to reduce collisons. From the Figure 3.7 the duration of the `t_bcast_seq` results

$$\texttt{t\_bcast\_seq} = [1 + (\mathsf{nb\_tx\_bcasts} - 1) \cdot (\mathsf{idle\_slots} + 1)] \cdot \mathsf{t\_w} \qquad (3.11)$$

If the worst case is assumed the `t_wait` is equal to the maximal waiting time slots

$$\texttt{t\_wait} = \mathsf{nb\_nds} \cdot \mathsf{t\_w} \tag{3.12}$$

The total duration of the timer `t_rx_bcast_rx` results as

$$\begin{aligned}\texttt{t\_rx\_bcast\_rx} &= \texttt{t\_bcast\_seq} + \texttt{t\_wait} &(3.13)\\ &= [(\mathsf{nb\_tx\_bcasts} - 1) \cdot (\mathsf{idle\_slots} + 1) \\ &\quad +1 + \mathsf{nb\_nds}] \cdot \mathsf{t\_w} &(3.14)\end{aligned}$$

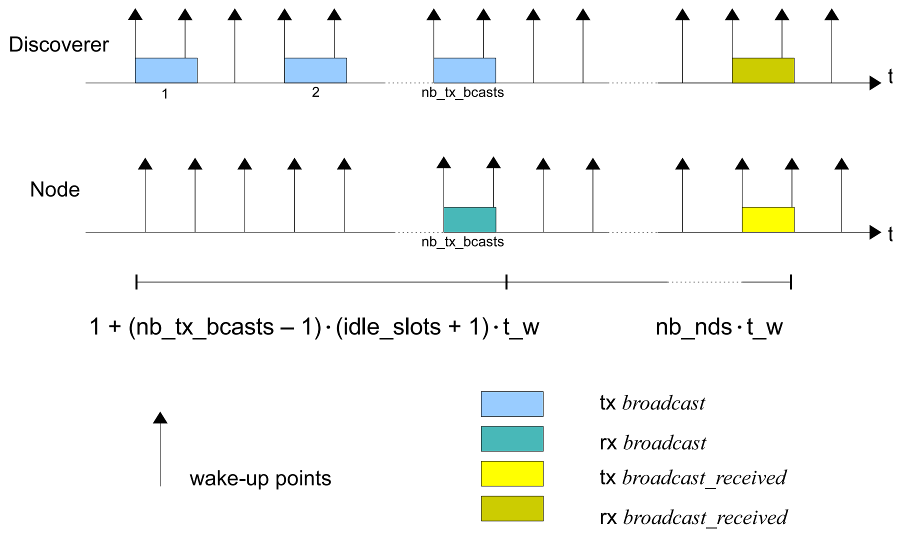


Figure 3.7: Scheme for the duration of the timer `t_rx_bcast_rx`

3.4.3 Timeout receive ack-notification `t_rx_ack_not`

The timer `t_rx_ack_not` is started when a discoverer transmits a *notification* to a chosen node. While the timer `t_rx_ack_not` is running, the discoverer waits for an *ack_notification* from the chosen node. When an *ack_notification* is received at the discoverer, the timer is stopped. If the timer expires, another *notification* is transmitted to the node unless the number of retries `rtr_not` has not exceeded the threshold rtr_not_max. If the threshold is exceeded, new neighbors are chosen an notified with a *notification*.

Since *notifications* and *ack_notifications* are transmitted only over one hop, the duration of the timer `t_rx_ack_not` is equal to the time required to transmit two direct messages.

$$\begin{aligned}\texttt{t\_rx\_ack\_not} &= 2 \cdot \texttt{t\_direct} & (3.15)\\ &= 4 \cdot \mathsf{t\_w} & (3.16)\end{aligned}$$

3.4.4 Timeout receive ack-start-discovery `t_rx_ack_start`

The timer `t_rx_ack_start` is started when the gateway transmits a *start-_discovery* to a discoverer. While the timer `t_rx_ack_not` is running, the gateway waits for an *ack_start* message from the discoverer. When an *ack_start* is received at the gateway, the timer is stopped. If the timer expires, another *start_discovery* is transmitted to the discoverer unless the number of retries `rtr_start` has not exceeded the threshold rtr_start_max. If the threshold is exceeded, the start of the discovery failed and a *start_discovery* is transmitted to the next discoverer.

Start_discovery and *ack_start* messages are transmitted over several hops. The *start_discovery* is a DSR message and the *ack_start* is a DWARF message. Therefore, the duration of the timer `t_rx_ack_start` is equal to the time required to transmit a DSR and a DWARF message.

$$\begin{aligned}\texttt{t\_rx\_ack\_start} &= \texttt{t\_dsr} + \texttt{t\_dwarf} & (3.17)\\ &= 2 \cdot \mathsf{nb\_hops\_max} \cdot \texttt{t\_direct} & (3.18)\\ &= 4 \cdot \mathsf{nb\_hops\_max} \cdot \mathsf{t\_w} & (3.19)\end{aligned}$$

3.4.5 Timeout receive neighbor-table `t_rx_nhtbl`

The timer `t_rx_nhtbl` is started when the gateway transmits a *start_discovery* to a discoverer. While the timer `t_rx_nhtbl` is running, the gateway waits for a *neighbor_table* message from the discoverer. When a *neighbor_table* is received at the gateway, the timer is stopped. If the timer expires, a *request_nhtbl* is transmitted to the discoverer unless the number of retries `rtr_request` has not exceeded the threshold rtr_request_max. If the threshold is exceeded, the reception of the neighbor table failed and a *start_discovery* is transmitted to the next discoverer.

For the calculation of the duration of the timer `t_rx_nhtbl` it is assumed, that each event occurs with the last retry and an infinitesimal time before the corresponding timer would expire. First, one plus the maximal number of retries for transmitting the *broadcast* sequence times the timer `t_rx_bcast_rx` is awaited. It is assumed, that only on the last retry from each node an *broadcast_received* is received and from the previous transmitted *broadcast* sequences no *broadcast_receiced* messages are received at the discoverer. Second, the maximal number of neighbors plus the maximal number of retries for choosing a new neighbor times the time required for notify a neighbor, assumed that the maximal number of retries for a notification is needed, is awaited. Finally, a DWARF message with the neighbor table is transmitted to the gateway.

$$\begin{aligned}\texttt{t\_rx\_nhtbl} &= \texttt{t\_rx\_bcast\_rx} \cdot (1 + \mathsf{rtr\_bcast\_max}) \\ &\quad + \texttt{t\_rx\_ack\_not} \cdot (1 + \mathsf{rtr\_not\_max}) \\ &\quad \cdot (\mathsf{nb\_nhs\_max} + \mathsf{rtr\_choose\_max}) \\ &\quad + \texttt{t\_dwarf} \qquad (3.20)\end{aligned}$$

3.4.6 Timeout receive requested-neighbor-table `t_rq_nhtbl`

The timer `t_rq` is started when the gateway transmits a *request_nhtbl* to a discoverer which already has performed a neighbor hood discovery. While the timer `t_rq` is running, the gateway waits for a *neighbor_table* message from the discoverer. When a *neighbor_table* is received at the gateway, the timer is stopped. If the timer expires, another *request_nhtbl* is transmitted to the discoverer unless the number of retries `rtr_request` has not exceeded the threshold rtr_request_max. If the threshold is exceeded, the reception of the neighbor table failed and a *start_discovery* is transmitted to the next discoverer.The duration of the timer `t_rq` can be calculated analoguous to the timer `t_rx_ack_start`, since also a DSR and a DWARF message are transmitted.

$$\begin{aligned}\texttt{t\_rq\_nhtbl} &= \texttt{t\_dsr} + \texttt{t\_dwarf} && (3.21)\\ &= 2 \cdot \mathsf{nb\_hops\_max} \cdot \texttt{t\_direct} && (3.22)\\ &= 4 \cdot \mathsf{nb\_hops\_max} \cdot \mathsf{t\_w} && (3.23)\end{aligned}$$

3.5 Parameters

Paramter	Parameter description
nb_nds	Total number of nodes
nb_nhs_max	Maximal number of neighbors per node
nb_hops_max	Maximal number of hops in the network
nb_con_paths_min	Minimal number of independent communication paths from a detector to the gateway
nb_tx_bcasts	Number of *broadcasts* a discoverer transmits
t_w	Wake up period of the Wisemac
idle_slots	Technical required idle time between transmitting a message
tx_power_min	Minimal transmit power
tx_power_max	Maximal transmit power
rtr_bcast_max	Maximal number of retries for transmitting nb_tx_bcasts broadcasts
rtr_choose_max	Maximal number of retries for choose neighbors
rtr_not_max	Maximal number of retries for transmitting a *notification* to a particular node
rtr_start_max	Maximal number of retries for transmitting a *start*
rtr_request_max	Maximal number for transmitting an *request_neighbor_table*
pe_hc1_min	Minimal number of peers on hopcount 1
ch_hc1_min	Minimal number of children on hopcount 1
pa_hc2_min	Minimal number of parents on hopcount 2
pe_hc2_min	Minimal number of peers on hopcount 2
ch_hc2_min	Minimal number of children on hopcount 2
pa_hc3_min	Minimal number of parents on hopcount 3
pe_hc3_min	Minimal number of peers on hopcount 3

Table 3.17: Parameters of Mesh Construct

3.6 Pseudocodes

3.6.1 Mesh Construct

Algorithm 3 Mesh Construct

```
GATEWAY:
init
    mc_state = 0
    discoverer_ind = 0
    discoverer_tbl = { }
    rtr_completed = 0
    run Discover Neighborhood
    store neighbor_tbl in discoverer_tbl
    continue on next hopcount

continue on next hopcount
    mc_state++
    if mc_state > nb_hops_max then
        Mesh Construct completed
    else
        set nb_nds_on_hc on mc_state
        nb_rx_nbtbl = 0
        continue on next node
    end if

continue on next node
    discoverer_ind++
    rtr_request = 0
    rtr_start = 0
    initiate discovery

initiate discovery
    tx start_discovery to discoverer_ind
    set timer t_rx_ack_start
    set timer t_rx_nhtbl

Mesh Construct completed
    tx completed to discoverer_ind
    set t_rx_ack_completed

upon rx ack_start_discovery:
    stop timer t_rx_ack_start

upon rx neighbor_tbl:
    stop timer t_rx_nhtbl
    nb_rx_nhtbl++
    store neighbor_tbl in discoverer_tbl
    if nb_rx_nhtbl ≤ nb_nds_on_hc then
        continue on next node
    else
        continue on next hopcount
    end if

upon rx ack_completed:
    stop timer t_rx_ack_completed
    if discoverer_ind > 0 then
        discoverer_ind−
        tx completed to discoverer_ind
        set t_rx_ack_completed
    else
        start the operation with topology control
    end if


upon timer t_rx_ack_start expires:
    stop timer t_rx_nhtbl
    rtr_start++
    if rtr_start ≤ rtr_start_max then
        initiate discovery
    else
        if nb_rx_nhtbl+1 ≥ nb_nds_on_hb then
            continue on next hopcount
        else
            continue on next node
        end if
    end if

upon timer t_rx_nhtbl or t_rq expires:
    rtr_request++
    if rtr_request ≤ rtr_request_max then
        tx request_neighbor_tbl to discoverer_ind
        set timer t_rq
    else
        if nb_rx_nhtbl+1 ≥ nb_nds_on_hc then
            continue on next hopcount
        else
            continue on next node
        end if
    end if

upon timer t_rx_ack_completed expires:
    rtr_completed++
    if rtr_completed ≤ rtr_completed_max then
        tx completed to discoverer_ind
        set t_rx_ack_completed
    else
        if discoverer_ind > 0 then
            rtr_completed = 0
            discoverer_ind−
            tx completed to discoverer_ind
            set t_rx_ack_completed
        else
            start the operation with topology control
        end if
    end if

DISCOVERER:
init
    discovery_started = false

upon rx start_discovery:
    tx ack_start_discovery to gw
    if discovery_started == false then
        discovery_started = true
        run Discover Neighborhood
        tx neighbor_tbl to gw
    end if

upon rx request_neighbor_tbl:
    tx neighbor_tbl to gw

upon rx completed:
    start the operation with topology control
    tx ack_completed to the gateway

```

3.6.2 Neighborhood Discovery

Algorithm 4 Neighborhood Discovery

```
DISCOVERER:
init
    nb_rx_bcast_rx = 0
    node_tbl = {}
    NbRxAckNot = 0
    rtr_bcast = 0
    rtr_choose = 0
    start

start
    set timer t_rx_bcast_rx
    for bcastnb = 1 to nb_tx_bcast do
        txpower = $m \cdot$ bcastnb + b
        tx broadcast(txpower,bcastnb)
        wait idle_slots
    end for

upon rx broadcast_received:
    nb_rx_bcast_rx++
    add src_bcast_rx to node_tbl

upon rx ack_notification:
    add src_ack_not to neighbor_tbl
    stop timer t_rx_ack_not
    NbRxAckNot++
    if NbRxAckNot $\geq$ nb_tx_notifications then
        //neighborhood discovery completed
        return neighbor_tbl
    else
        chosen_node++
        tx notification
    end if

upon timer t_rx_bcast_rx expires:
    if nb_rx_bcast_rx == 0 then
        rtr_bcast++
        if rtr_bcast $\leq$ rtr_bcast_max then
            //restart discovery
            go to start
        else
            //No neighbors found
            return neighbor_tbl
        end if
    else
        run Choose Neighbors
        set nb_tx_notifications
        tx notification
    end if

upon timer t_rx_ack_not expires:
    chosen_node.rtr_not++
    if chosen_node.rtr_not $\leq$ rtr_not_max then
        tx notification
    else
        rtr_choose++
        if rtr_choose $\leq$ rtr_choose_max then
            run Choose Neighbors
            NbRxAckNot = 0
            set nb_tx_notifications
            if nb_tx_notifications == 0 then
                //No neighbors are chosen
                return neighbor_tbl
            else
                tx notification
            end if
        else
            //No additional neighbors found
            return neighbor_tbl
        end if
    end if

tx notification
    tx notification to chosen_node
    set timer t_rx_ack_not

NODE:
init
    first_rx_bcast = 0
    neighbor_tbl ={}

upon rx broadcast(bcast_nb):
    if first_rx_bcast == 0 then
        first_rx_bcast = bcast_nb
        discoverer_add = src_bcast
        set timer t_rx_bcast(first_rx_bcast)
    end if

upon rx notification:
    add src_not to neighbor_tbl
    tx ack_notification to src_not

upon timer t_rx_bcast expires:
    tx broadcast_received(first_rx_bcast) to discoverer_add
    first_rx_bcast = 0
```

3.6.3 Choose Neighbors

Algorithm 5 Choose Neighbors

```
1: input
2:     discoverer fields: own_nb_nbs, own_nb_pas, own_nb_pes, own_nb_ch, own_hop_count
3:     node_tbl fields for each node: nb_pes, con_state, hop_count, first_rx_bcast, rssi, nb_nhs, rtr_not
4:
5: start
6:     chosen_nodes = {}
7:     remove nodes with (nb_nhs $\geq$ nb_nhs_max) or (rtr_not $\geq$ rtr_not_max) from node_tbl
8:     Sort nodes of node_tbl descending for maximal rssi and minimal first_rx_bcast
9:
10: if own_hop_count == 0: then
11:     append the first nb_nhs_max nodes to chosen_nodes
12: end if
13:
14: if own_hop_count == 1: then
15:     if pe_hc1_min - own_nb_pes > 0 then
16:         nb_missing_peers = pe_hc1_min - own_nb_pes
17:         append the first nb_missing_peers nodes with hop_count = 1 and minimal nb_pes to chosen_nodes
18:     end if
19:     if ch_hc1_min - own_nb_ch > 0 then
20:         nb_missing_children = ch_hc1_min - own_nb_ch
21:         append the first nb_missing_children nodes with hop_count = 2 and minimal con_state to chosen_nodes
22:     end if
23: end if
24:
25: if own_hop_count == 2: then
26:     if pa_hc2_min - own_nb_pas > 0 then
27:         nb_missing_parents = pa_hc2_min - own_nb_pas
28:         append the first nb_missing_parents nodes with hop_count = 1 and maximal con_state to chosen_nodes
29:     end if
30:     nb_chosen_pas = len(chosen_nodes)
31:     if pe_hc2_min - own_nb_pes + (pa_hc2_min - nb_chosen_pas) > 0 then
32:         nb_missing_peers = pe_hc2_min - own_nb_pes + (pa_hc2_min - nb_chosen_pas)
33:         append the first nb_missing_peers nodes with hop_count = 2 and maximal con_state to chosen_nodes
34:     end if
35:     if ch_hc2_min - own_nb_ch > 0 then
36:         nb_missing_children = ch_hc2_min - own_nb_ch
37:         append the first nb_missing_children nodes with hop_count = 3 and minimal con_state to chosen_nodes
38:     end if
39: end if
40:
41: if own_hop_count == 3: then
42:     if pa_hc3_min - own_nb_pas > 0 then
43:         nb_missing_parents = pa_hc3_min - own_nb_pas
44:         append the first nb_missing_parents nodes with hop_count = 2 and maximal con_state to chosen_nodes
45:     end if
46:     nb_chosen_pas = len(chosen_nodes)
47:     if  pe_hc3_min - own_nb_pes + (pa_hc3_min - nb_chosen_pas) > 0 then
48:         nb_missing_peers = pe_hc3_min - own_nb_pes + (pa_hc3_min - nb_chosen_pas)
49:         append the first nb_missing_peers nodes with hop_count = 3 and maximal con_state to chosen_nodes
50:     end if
51:     if pe_hc3_min - own_nb_ch > 0 then
52:         nb_missing_peers = pe_hc3_min - own_nb_ch
53:         append the first nb_missing_peers nodes with hop_count = 3 and minimal con_state to chosen_nodes
54:     end if
55: end if
56:
57: if len(chosen_nodes) > nb_nhs_max - own_nb_nhs then
58:     remove the last len(chosen_nodes) - (nb_nhs_max - nb_nhs) entries of chosen_nodes
59: end if
60: return chosen_nodes
```

3.6.4 Implementation

In this section a few remarks concerning the implementation of the Mesh Construct procedure in an embedded system are stated.

Control Functions

The Mesh Construct Algorithm 3 and the Neighborhood Discovery Algorithm 4 are implemented slightly different than presented in the pseudocodes of the last section. The algorithms are implemented as control functions, which are invoked each time a corresponding event occurs or a timer expires. A decision tree determines the actions which have to be executed in the current state of the procedure. For that reason, a few addional variables are introduced.

RAM Optimization

The memory on the microprocessor applied in the nodes of the used testbed (see also Appendix A) is very scarce. The available random access memory (RAM) is only 4 kilobytes. The required RAM for the variables presented in the last sections is much higher than the RAM provided in the microprocessor. Therefore, the variables of the Mesh Construct procedure have to be optimized to reduce the required RAM. Several optimizations have been realized and listed in the following.

- The addresses of the nodes are 32 bit MAC addresses. Because they appear very often in the variables of the Mesh Construct, a look-up table is introduced. The nodes store each unknown MAC address in the look-up table and use only the corresponding index for the intern storage of the neighbor and node table (in the gateway also the discoverer table).

- Timers require 64 bits RAM. To reduce RAM usage different timers, which never can overlap due to the conceptual design, are summarized to one timer.

- Various boolean variables are unified to bit fields (flags) of a 8 bit unsinged integer variable.

3.7 Theoretical Upper Bound for the Duration of the Mesh Construct

The maximal duration of the Mesh Construct $\texttt{t\_mc\_max}$ is composed of different contributions. First the maximal time to initiate a neighborhood discovery in each detector $\texttt{t\_init\_disc}$ is derived. There are ($\textsf{nb\_nds}$ - 1) detectors which can require ($\textsf{rtr\_start\_max} + 1$) attempts to transmit a *start_discovery* message to. Therefore, for $\texttt{t\_init\_disc}$ results

$$\begin{aligned}\texttt{t\_init\_disc} &= (\textsf{nb\_nds} - 1) \cdot (\textsf{rtr\_start\_max} + 1) \\ &\quad \cdot \texttt{t\_rx\_ack\_start}\end{aligned} \tag{3.24}$$

The maximal time required for each node (including the gateway) to perform the neighborhood discovery $\texttt{t\_disc}$ is given by

$$\texttt{t\_idisc} = \textsf{nb\_nds} \cdot \texttt{t\_rx\_nhtbl} \tag{3.25}$$

The maximal time required to receive the *neighbor_table* message from each detector $\texttt{t\_rx\_neighbor\_table}$ is given by the maximal retries for requesting the neighbor table and the timer duration $\texttt{t\_rq\_nhtbl}$

$$\begin{aligned}\texttt{t\_rx\_neighbor\_table} &= (\textsf{nb\_nds} - 1) \cdot \textsf{rtr\_request\_max} \\ &\quad \cdot \texttt{t\_rx\_rq\_nhtbl}\end{aligned} \tag{3.26}$$

Finally the DSR message *completed* has to be transmitted to each node to start the topology control

$$\texttt{t\_tx\_completed} = (\textsf{nb\_nds} - 1) \cdot \texttt{t\_dsr} \tag{3.27}$$

By combining all these equations for the maximal duration of the Mesh Construct procedure results

$$\begin{aligned}
\texttt{t\_mc\_max} &= \texttt{t\_init\_disc} + \texttt{t\_idisc} \\
&\quad + \texttt{t\_rx\_neighbor\_table} + \texttt{t\_tx\_completed} \qquad (3.28) \\
&= (\mathsf{nb\_nds} - 1) \cdot \\
&\quad [(\mathsf{rtr\_start\_max} + 1) \cdot \texttt{t\_rx\_ack\_start} + \texttt{t\_rx\_nhtbl} \\
&\quad + \mathsf{rtr\_request\_max} \cdot \texttt{t\_rx\_rq\_nhtbl} + \texttt{t\_dsr}] \\
&\quad + \texttt{t\_rx\_nhtbl} \qquad (3.29)
\end{aligned}$$

Chapter 4

Testing and Evaluation

In this chapter the Mesh Construct procedure is tested and evaluated. In the first section the test setup and the test parameters are described. In the second section the values of the the Mesh Construct parameters described in Section 3.5 are set. In the third section a timing analysis of the timers introduced in Section 3.4 is carried out. In Section 4.4 the Mesh Construct procedure is assessed by the quality metrics defined in Section 1.2.3. In the last section of this chapter the Mesh Construct procedure is compared to the existing solution described in Section 2.1.

Although many Mesh Construct tests have been run on the testbed, the number of performed tests does not claim to be statistical relevant and therefore in this chapter only three examples thereof are shown and evaluated. However, the evaluation of the Mesh Construct exhibits some promising results.

4.1 Test Setup

The performance of the Mesh Construct procedure is assessed through tests on an experimental setup analogously to Section 2.1.2. The used testbed is described more detailed in Appendix A. The number of nodes $\mathsf{nb\_nds}$ of the testbed is 32. The test setup consists of one gateway and 31 detectors. At the beginning of the test first, the gateway is switched on and afterwards sequentially all detectors in a random order. Before a node is enabled, a time delay is inserted to simulate the installation time. The time delay between the startup of two succeding nodes is uniform random distributed in the interval $[\mathsf{t\_min}, \mathsf{t\_max}]$. The time delay due to the installation is set to be between one and five minutes. The test runtime t_test starts after the last switch-on and is set to twelve hours. The test parameters are listed in Table 2.2.

Test Parameters	Value
nb_nds	32
t_test	43200 s
t_min	60 s
t_max	300 s

Table 4.1: Test setup

4.2 Parameters

In Table 4.2 the set parameters of the Mesh Construct tests are listed. The parameters nb_nds, idle_slots, tx_power_min, tx_power_max are determined by the testbed. The paramteter nb_nhs_max is set to be one smaller than in the alarm system described in Section 1.1.2, where the last entry of the neighbor table is used as an overwrite slot for the MAC layer. The parameters nb_hops_max and nb_con_paths_min are determined by the requirements given in Section 1.2.2. The parameter t_w is adopted also from the alarm system described in 1.1.2. However, for the evaluation of the network initialization also tests with a wake up period of 0.5 s are run. The retry parameters are determined empirically.

The parameters used in the choose neighbor algorithm are set with the objective to construct a mesh network with redundancy concerning the connectivity states. Each node tries to choose two parents and an additional peer with maximal connectivity states as neighbors in order to have three connectivity paths to the gateway (Except nodes with hop count 1, which instead choose two additional peers, because these nodes have with the gateway only one possible parent). Nodes with hop count 1 or 2 additionally try to add two children with minimal connectivity state. By this, new nodes are added to mesh network, and the connectivity state of the added nodes can be improved. Finally, two of the maximal seven neighbor table entries are not filled with neighbors in order to give nodes with a higher hop count the possibility to add a second parent during its neighbor discovery.

Depending on the purpose and the requirements of the alarm system, mesh network topologies with different characterictics can be constructed with appropriate choices of the parameters of the choose neighbor algorithm.

Paramter	Value
nb_nds	32
nb_nhs_max	7
nb_hops_max	3
nb_con_paths_min	2
nb_tx_bcasts	3
t_w	1.5 s (Mesh Construct test A and B) 0.5 s (Mesh Construct test C)
idle_slots	2
tx_power_min	-16 dBm
tx_power_max	+13 dBm
rtr_bcast_max	1
rtr_choose_max	3
rtr_not_max	2
rtr_start_max	5
rtr_request_max	5
pe_hc1_min	2
ch_hc1_min	2
pa_hc2_min	2
pe_hc2_min	1
ch_hc2_min	2
pa_hc3_min	2
pe_hc3_min	1

Table 4.2: Parameters of the Mesh Construct tests

4.3 Timing Analysis

In this section the Mesh Construct timers introduced in Section 3.4 are investigated. For each timer the duration is calculated with the paramteres set in Section 4.2 and plots are generated to visualize the temporal behavior of the relevant occuring events. In the following sections several examples thereof are shown.

4.3.1 Timeout receive broadcasts `t_rx_bcasts`

The duration of the timer `t_rx_bcasts` is not deterministic. However, if the parameters of Table 4.2 are set into Equation 3.10, the following durations result.

$$\begin{aligned} \texttt{t\_rx\_bcast}\,(1) &= [(3-1)\cdot(2+1)+\text{random}\,(0,32)]\cdot 1.5\text{ s} \quad (4.1)\\ &= 9\text{ s}+\text{random}\,(0,32)\cdot 1.5\text{ s} \quad (4.2)\end{aligned}$$

$$\begin{aligned} \texttt{t\_rx\_bcast}\,(2) &= [(3-2)\cdot(2+1)+\text{random}\,(0,32)]\cdot 1.5\text{ s} \quad (4.3)\\ &= 4.5\text{ s}+\text{random}\,(0,32)\cdot 1.5\text{ s} \quad (4.4)\end{aligned}$$

$$\begin{aligned} \texttt{t\_rx\_bcast}\,(3) &= [(3-3)\cdot(2+1)+\text{random}\,(0,32)]\cdot 1.5\text{ s} \quad (4.5)\\ &= \text{random}\,(0,32)\cdot 1.5\text{ s} \quad (4.6)\end{aligned}$$

In Figure 4.1 the occuring events for the discoverer 0002000D concerning the timer `t_rx_bcasts` are plotted over the test time. The timer is started with the reception of the first *broadcast*. All nodes, except of three, received already the *broadcast* with sequence number 1, which is transmitted with minimal power. When the timer expires the *broadcast_received* is transmitted. The random duration of the timer `t_rx_bcasts` scatters the transmission of the *broadcast_received* messages in time. The necessity of randomness to decrease collisions at the discoverer unfortunately extends the average idle time between the reception of the first *broadcast* and the transmission of the *broadcast_received*, which in this example is 22.671 s.

4.3.2 Timeout receive broadcast-received `t_rx_bcast_rx`

By setting the parameters of Table 4.2 into Equation 3.14 for the duration of the timer `t_rx_bcast_rx` results

$$\begin{aligned} \texttt{t\_rx\_bcast\_rx} &= [(3-1)\cdot(2+1)+1+32]\cdot 1.5\text{ s} \quad (4.7)\\ &= 58.5\text{ s} \quad (4.8)\end{aligned}$$

In Figure 4.2 the occuring events for the discoverer 0002000D concerning the timer `t_rx_bcast_rx` are plotted over the test time. The timer is

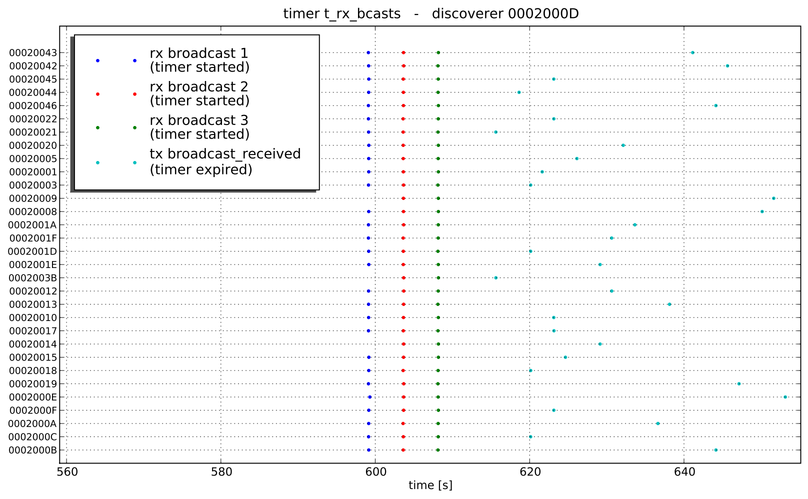


Figure 4.1: **Mesh Construct Test B:** Timer `t_rx_bcasts`, discoverer 0002000D

started with the transmission of the first *broadcast* and expires after 58.5 s. When the timer expires, the choose neighbor algorithm is started and the chosen nodes are notified. The expiration of the timer, is indicated in the figure by a red vertical line. In this example only one *broadcast_received* is received after the timer expired and is not considered for the subsequent choice of neighbors. During the whole Mesh Construct test B only 26 (4.3%) of the *broadcast_received* are received after the timer expiration, i.e. less than one *broadcast_received* per discoverer is not considered. These omissions are minor and therefore the duration of the timer `t_rx_bcast_rx` can be considered as appropriate. A shortening of the timer duration could probably lead to collisions at the discoverer between *broadcast_received* messages received after timer expiration and received answers to already transmitted *notifications*.

4.3.3 Timeout receive ack-notification `t_rx_ack_not`

By setting the parameters of Table 4.2 into Equation 3.16 for the duration of the timer `t_rx_ack_not` results

$$\texttt{t\_rx\_ack\_not} = 4 \cdot 1.5 \text{ s} \tag{4.9}$$

$$= 6 \text{ s} \tag{4.10}$$

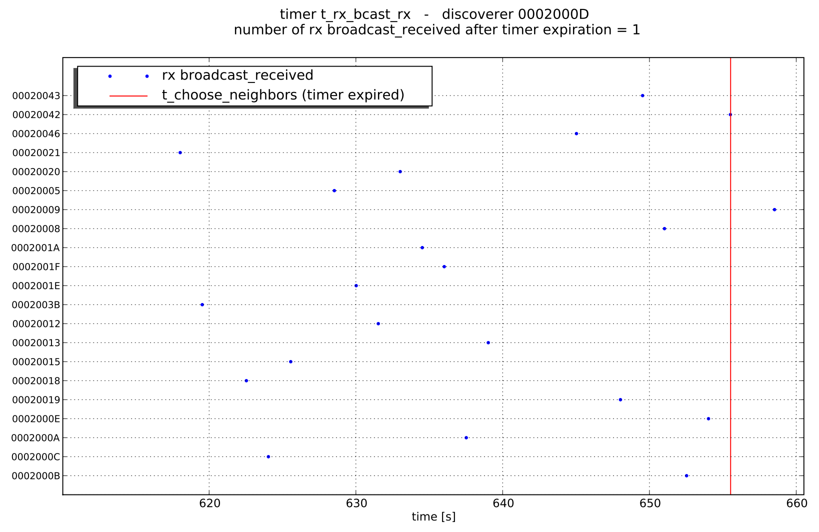


Figure 4.2: **Mesh Construct Test B:** Timer `t_rx_bcast_rx`, discoverer 0002000D

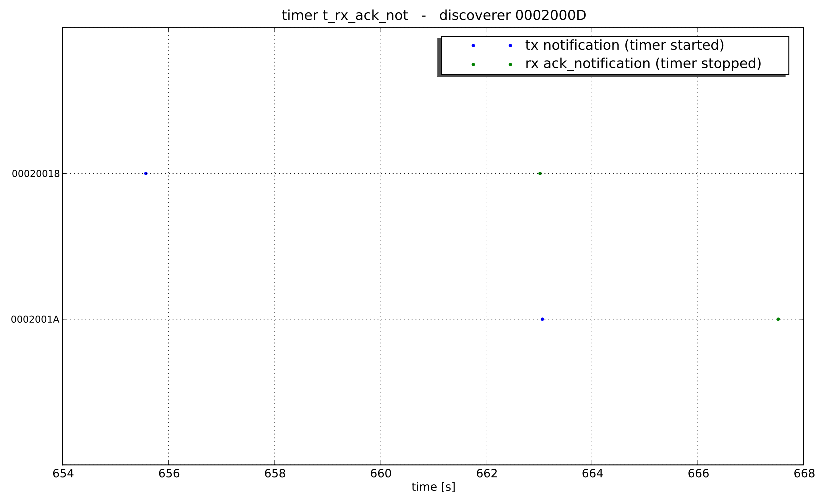


Figure 4.3: **Mesh Construct Test B:** Timer `t_rxack_not`, discoverer 0002000D

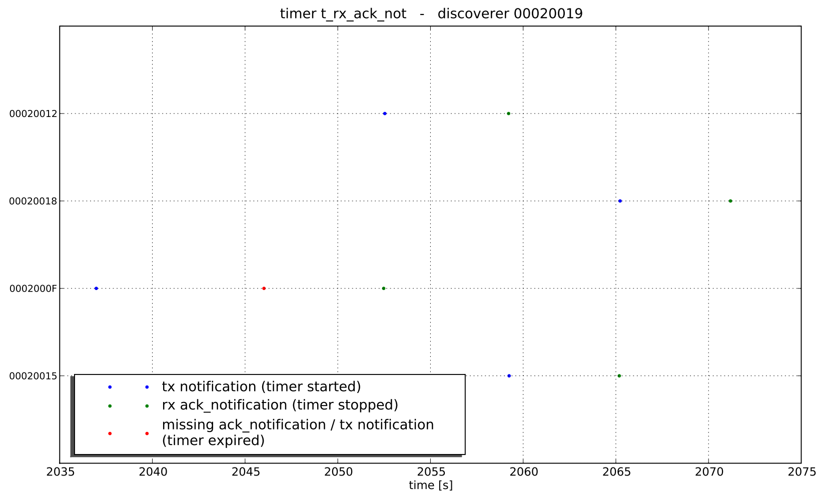


Figure 4.4: **Mesh Construct Test B:** Timer `t_rxack_not`, discoverer 00020019

In Figure 4.3 and 4.4 the occuring events for the discoverer 0002000D and 00020019 concerning the timer `t_rx_ack_not` are plotted over the test time. The timer is started with the transmission of a *notification* and is stopped with the reception of an *ack_notification*. Only 4 (3.8%) of the timers `t_rx_ack_not` expired and a further *notification* had to be transmitted, one such example is shown in Figure 4.4.

4.3.4 Timeout receive ack-start-discovery `t_rx_ack_start`

By setting the parameters of Table 4.2 into Equation 3.19 for the duration of the timer `t_rx_ack_start` results

$$\texttt{t\_rx\_ack\_start} = 4 \cdot 3 \cdot 1.5 \text{ s} \quad (4.11)$$
$$= 18 \text{ s} \quad (4.12)$$

In Figure 4.5 the occuring events for all discoverers concerning the timer `t_rx_ack_start` are plotted over the time relative to the timer start. The timer `t_rx_ack_start` starts with the transmission of a *start_discovery* and stops with the reception of an *ack_start_discovery*. When the timer expires another *start_discovery* is transmitted. For example, for the discoverers 0002001D, 00020017, and 0002000E a retry is required to receive

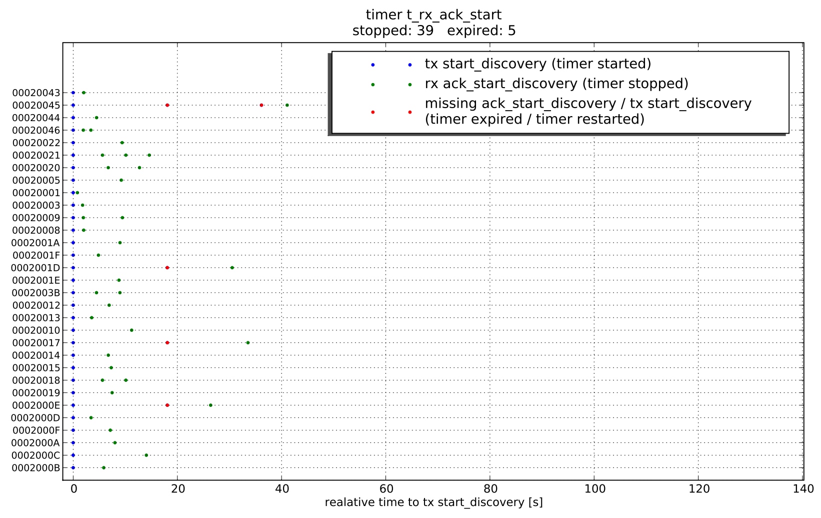


Figure 4.5: **Mesh Construct Test B:** Timer `t_rx_ack_start`

an *ack_start_discovery*. The average time which remained before expiration when the timer was stopped is 10.691 s. Hence, the duration of the timer `t_rx_ack_start` of 18 s is rather conservative, but is not reduced. In most tests the expiration of the timer `t_rx_ack_start` was caused by a lost *ack_start_discovery* message and therefore additional retransmissions would predominantly increase the energy consumption and not reduce the duration of the Mesh Construct procedure.

There are discoverer, for example 00020046, which have received several *ack_start_discovery* messages without that the timer `t_rx_ack_start` expired and caused a retransmission of a *start_discovery*. That is because the MAC layer also has an own acknowledgement and retry mechanism for direct messages. Several received *ack_start_discovery* messages can occur, if the acknowledgment of a forwarded DSR message from the destination node to the node on the second last hop is not received and the message is retransmitted.

4.3.5 Timeout receive neighbor-table `t_rx_nhtbl` and requested neighbor table `t_rq_nhtbl`

By setting the parameters of Table 4.2 into Equation 3.20 and 3.23 for the duration of the timer `t_rx_nhtbl` and `t_rq_nhtbl` results

$$\begin{aligned}\texttt{t\_rx\_nhtbl} &= 58.5\ \text{s} \cdot (1+1) + 6\ \text{s} \cdot (1+1) \cdot (7+2) + 9\ \text{s} && (4.13)\\ &= 288\ \text{s} && (4.14)\end{aligned}$$

$$\begin{aligned}\texttt{t\_rq\_nhtbl} &= 4 \cdot 3 \cdot 1.5\ \text{s} && (4.15)\\ &= 18\ \text{s} && (4.16)\end{aligned}$$

In Figure 4.6 the occuring events for all discoverers concerning the timers `t_rx_nhtbl` and `t_rq_nhtbl` are plotted over the time relative to the start of the timer `t_rx_nhtbl`. The timer `t_rx_nhtbl` starts with the transmission of a *start_discovery* and is stopped with the reception of a *neighbor_table*. When the timer `t_rx_nhtbl` expires a *request_nhtbl* is transmitted and the timer `t_rq_nhtbl` is started. When the timer `t_rq_nhtbl` expires another *request_nhtbl* is transmitted.

Most of the *neighbor_table* messages are received much earlier as the timer `t_rx_nhtbl` would expired. Therefore, to reduce the duration of the Mesh Construct procedure in case of a lost *neighbor_table* message the timer `t_rx_nhtbl` is empirically set to 120 s. By this, the idle times of the discoverers 0002001E, 0002003B, 00020018, and 0002000B are reduced about three minutes each.

4.3.6 Maximal Duration of the Mesh Construct

By setting the parameters of Table 4.2 and the duration of the timers computed in this section into Equation 3.29 for the maximal duration of the Mesh Construct procedure `t_mc_max` results

$$\begin{aligned}\texttt{t\_mc\_max} &= (32-1) \cdot \\ &\quad [(5+1) \cdot 18\ \text{s} + 120\ \text{s} \\ &\quad +5 \cdot 18\ \text{s} + 9\ \text{s}] \\ &\quad +120\ \text{s} && (4.17)\\ &= 10257\ \text{s} && (4.18)\end{aligned}$$

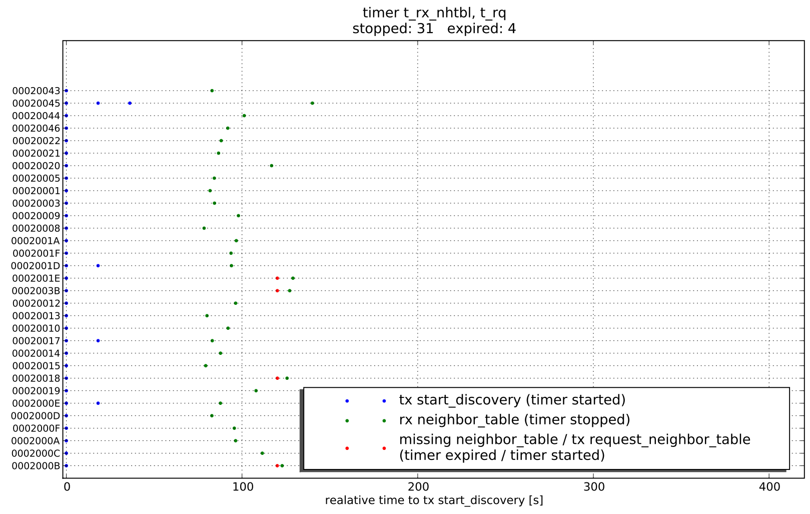


Figure 4.6: **Mesh Construct Test B:** Timers `t_rx_nhtbl` and `t_rq_nhtbl`

In the worst case with the parameters set in 4.2 the Mesh Construct procedure is completed after 2 hours 50 minutes and 57 seconds.

4.4 Test Results

In this section three examples of Mesh Construct tests are evaluated and the corresponding test results are presented. In the Mesh Construct tests A and B the wake up period `t_w` is set to 1.5 s in order to have equal test conditions as in the testing of the existing solution in Section 2.1.2. When the Mesh Construct procedure is *completed*, i.e. the neighbor table of the last discoverer is received at the gateway, the operation of the system with the toplogy control is started. The duration from the last switch-on until the procedure is completed will be denoted as `t_completed`. The phase containing the installation of the nodes and the Mesh Construct procedure in the following will also be denoted as the *non-operational phase*. In the Mesh Construct test C only the non-operational phase is investigated. To reduce the duration and the energy consumption during the neighbor discovery and topology construction the wake up period `t_w` in the Mesh Construct test C is set to 0.5 s.

4.4.1 Mesh Construct Test A

Duration

In Figure 4.7 the connectivity and hop count states of the Mesh Construct Test A are plotted over the test time. In Figure 4.8 the same is plotted over the non-operational phase containing the installation and the Mesh Construct procedure. The Mesh Construct procedure is only started when the last node is installed and powered on. After the last switch-on it takes 37 minutes and 35 seconds until the entire network is connected. The duration `t_connected` of the Mesh Construct test A clearly fulfills the requirement to be less than one hour. The Mesh Construct procedure is completed after 52 minutes and 2 seconds.

Connectivity and Stability

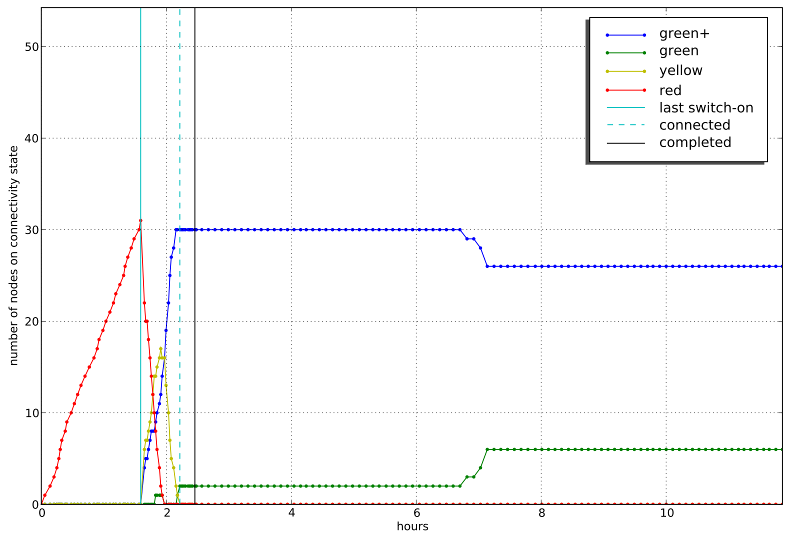
After the network is connected, `nb_red_nds` is equal to zero for the entire remaining test time. Therefore, all installed nodes are discovered.

After the network is connected and the Mesh Construct is completed the operation starts and `nb_redyellow_nds` is equal to zero for the entire remaining test time. Thus, the network remains connected during the operation.

In Figure 4.9 the number of dead neighbors, which are removed during the test, is plotted over the test time. In total `nb_rem_dead_nhs` = 1 dead neighbors are removed during the test. In Figure 4.7 it can be observed that the removal of one dead neighbor causes a connectivity state change at four nodes from green+ to green. Since the mesh network topology constructed by the Mesh Construct has a redundancy concerning the connectivity states, the removal of one dead neighbor does not evoke yellow or red connectivity states. During the test, except from a single dead neighbor removal, the connectivity states are stable over the entire operation.

Energy Consumption

In Figure 4.10 the current consumtpion averaged over all targets is plotted over the test time. The total consumed current of the Mesh Admin Test A is divided into the five contributions `I_sleep`, `I_carriersense`, `I_overhear`, `I_rx`, and `I_tx`. `I_sleep` is the current consumed in the energy-efficient sleep state. `I_carriersense` is the current required for the periodic wake up and



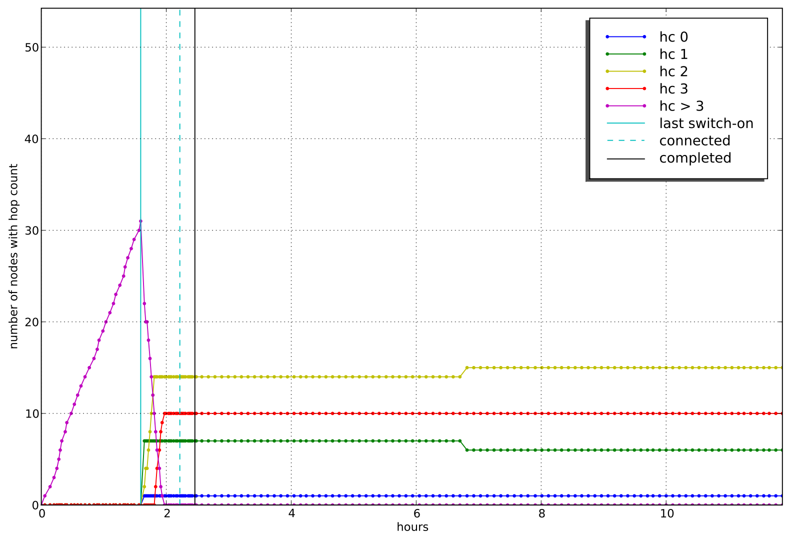
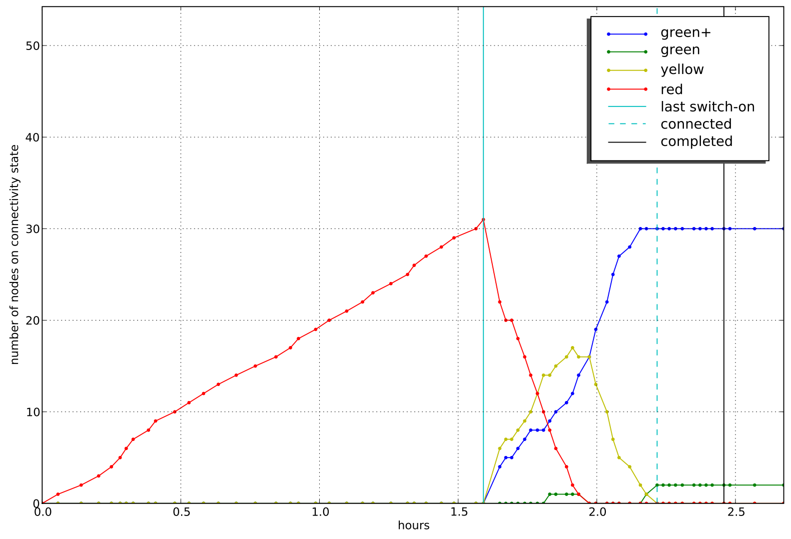


Figure 4.7: **Mesh Construct Test A**: Upper plot: Number of nodes on the corresponding connectivity states. Lower plot: Number of nodes on the corresponding hop counts.



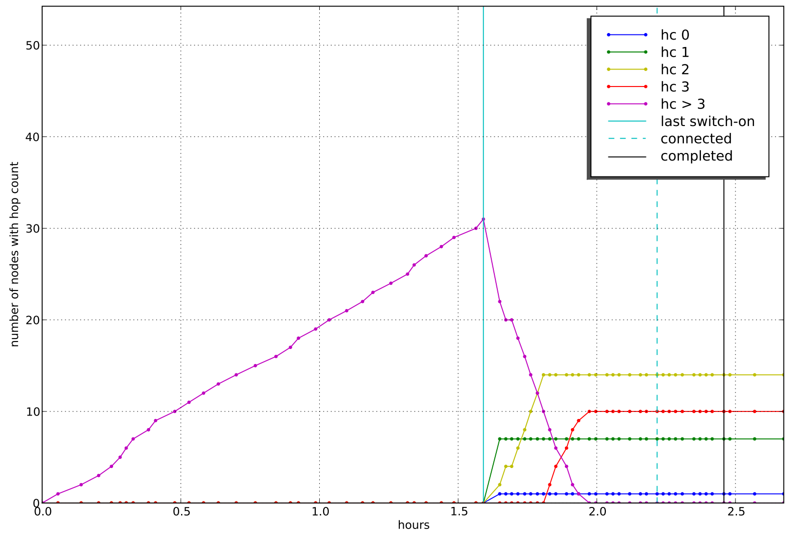


Figure 4.8: **Mesh Construct Test A**: (non-operational phase) Upper plot: Number of nodes on the corresponding connectivity states. Lower plot: Number of nodes on the corresponding hop counts.

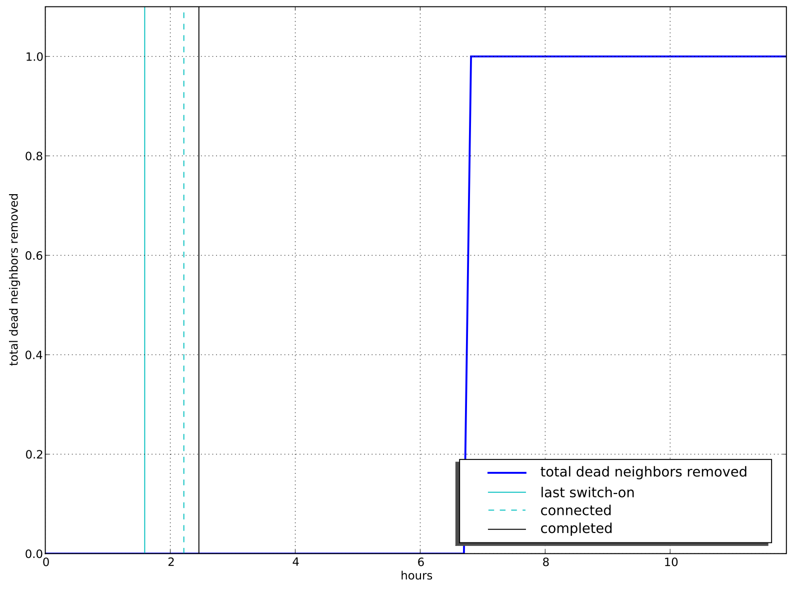


Figure 4.9: **Mesh Construct Test A**: Number of removed dead neighbors of all nodes.

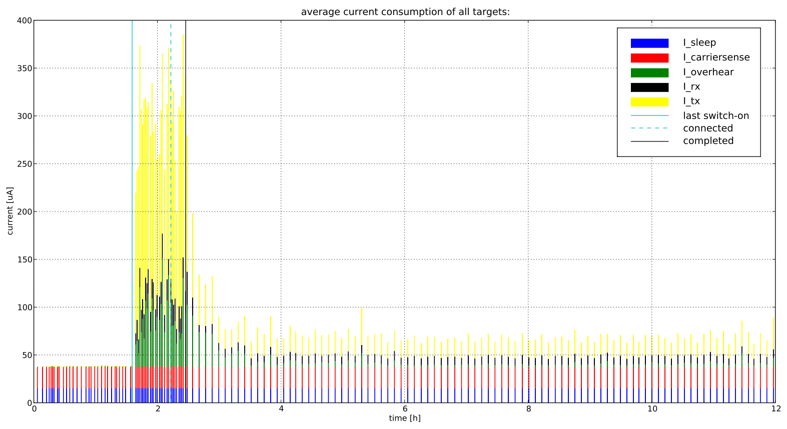


Figure 4.10: **Mesh Construct Test A**: The current consumption averaged over all targets.

carrier sense. `I_overhear` is the current consumed for receiving messages which originally are transmitted to a different destination. `I_rx`, and `I_tx` are the currents consumed for receiving and transmitting messages.

The most energy is consumed during the Mesh Construct procedure, in particular due to the transmissions of the energy expensive broadcasts. The number of transmitted broadcasts is plotted in Figure 4.11 over the test time. The total number of transmitted broadcasts `nb_tx_bcasts` during the test is 96. Thus, each of the 32 nodes exactly transmitted the 3 scheduled broadcasts during the neighborhood discovery. No broadcasts are transmitted during the operation.

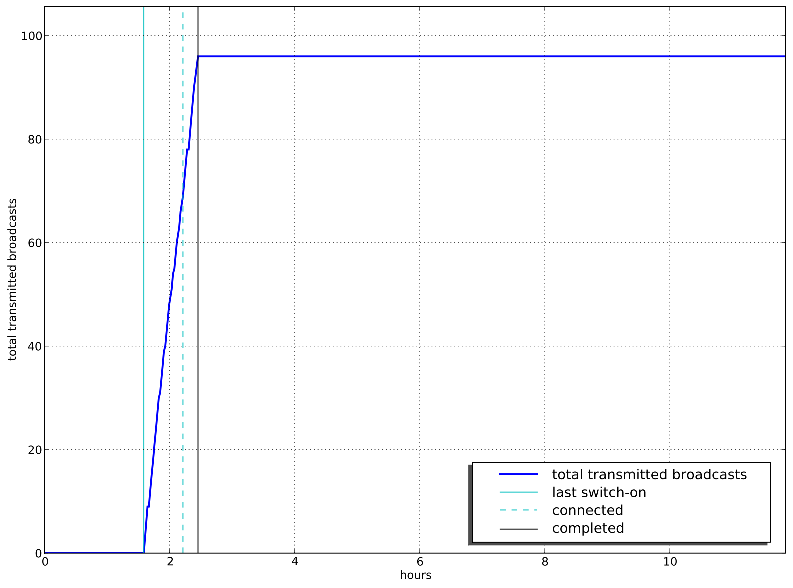


Figure 4.11: **Mesh Construct Test A**: Number of transmitted broadcasts of all nodes.

By comparing the time course of the current consumption with the time course of the connectivity states in Figure 4.7, it can be observed, that the current consumption is uniform during the operation if the network remains connected.

In Figure 4.12 the current consumption of each individual detector averaged over the entire test time is shown. Again, the current consumption is divided into its five contributions. Overall, the current consumption of the

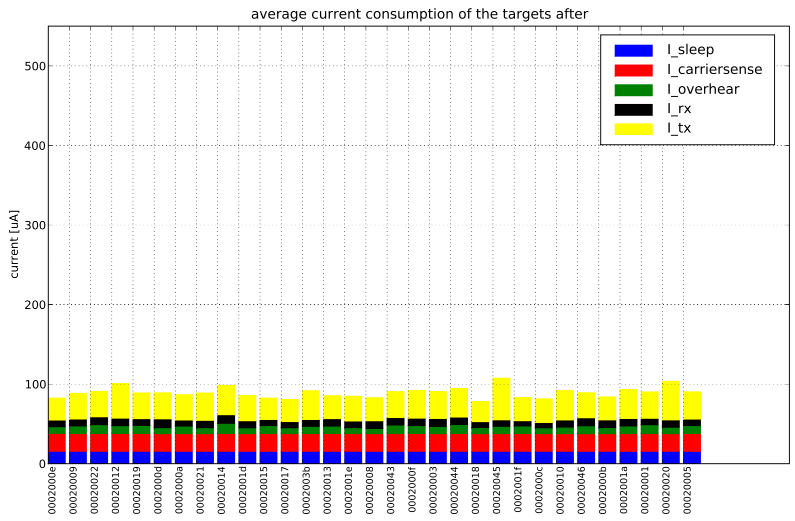


Figure 4.12: **Mesh Construct Test A**: The average current consumption of the nodes over the entire test time.

nodes is balanced. The total current consumption averaged over the time and number of nodes `i_total` is 89.328 μA.

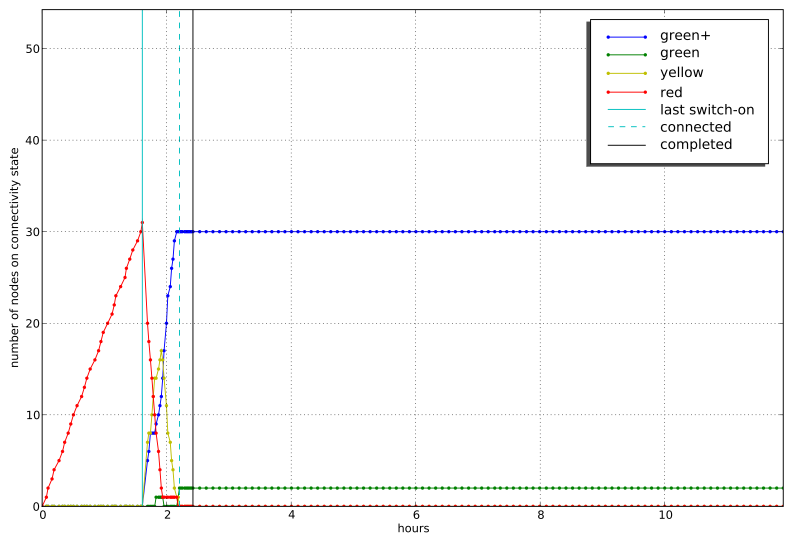
4.4.2 Mesh Construct Test B

Duration

In Figure 4.13 the connectivity and hop count states of the Mesh Construct Test B are plotted over the test time. In Figure 4.14 the same is plotted over the non-operational phase containing the installation and the Mesh Construct procedure. Again, the Mesh Construct procedure is only started when the last node is installed and powered on. After the last switch-on it takes 35 minutes and 50 seconds until the entire network is connected. The duration `t_connected` of the Mesh Construct test B clearly fulfills the requirement to be less than one hour. The Mesh Construct procedure is completed after 48 minutes and 47 seconds.

Connectivity and Stability

After the network is connected, `nb_red_nds` is equal to zero for the entire remaining test time. Therefore, all installed nodes are discovered.



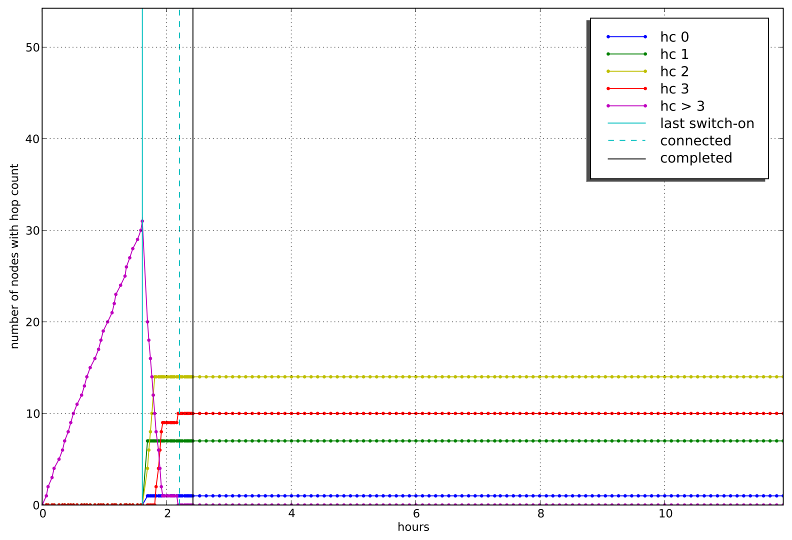
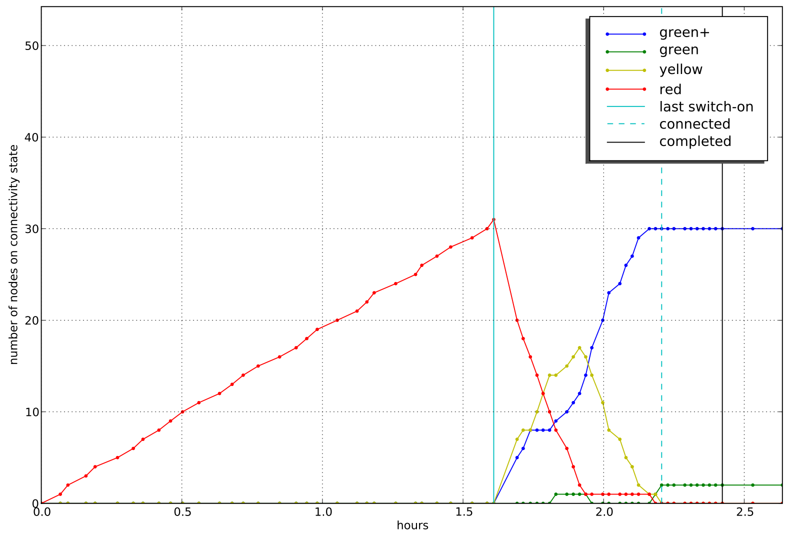


Figure 4.13: **Mesh Construct Test B**: Upper plot: Number of nodes on the corresponding connectivity states. Lower plot: Number of nodes on the corresponding hop counts.



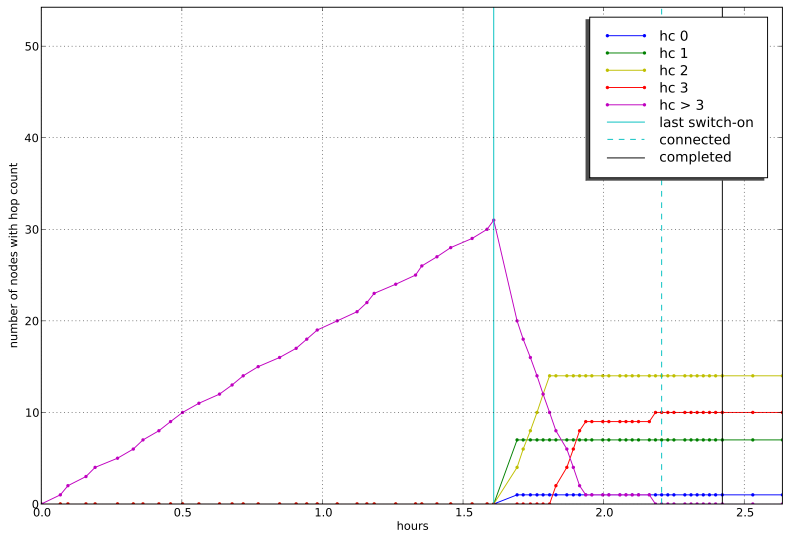


Figure 4.14: **Mesh Construct Test A**: (non-operational phase) Upper plot: Number of nodes on the corresponding connectivity states. Lower plot: Number of nodes on the corresponding hop counts.

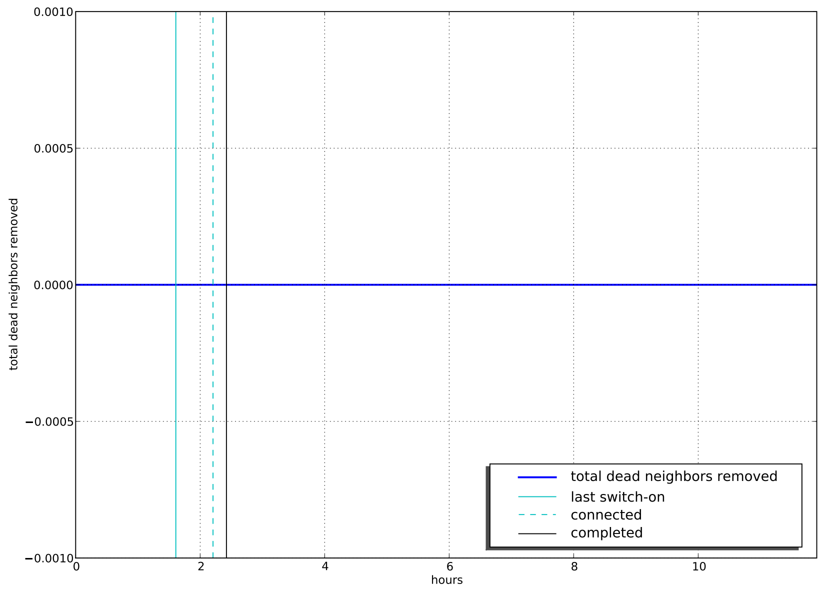


Figure 4.15: **Mesh Construct Test B**: Number of removed dead neighbors of all nodes.

After the network is connected and the Mesh Construct is completed, the operation starts and `nb_redyellow_nds` is equal to zero for the entire remaining test time. Thus, the network remains connected during the operation.

In Figure 4.15 the number of dead neighbors, which are removed during the test, is plotted over the test time. In total `nb_rem_dead_nhs` = 0 dead neighbors are removed during the test. In the Mesh Construct Test B the connectivity states are constant and stable during the operation.

Energy Consumption

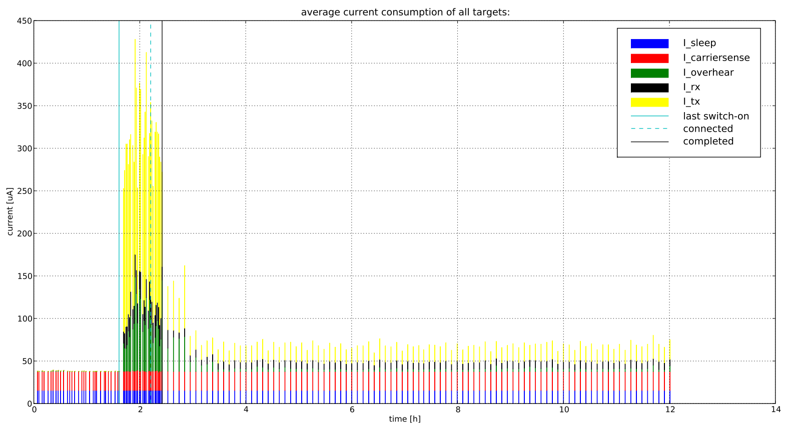


Figure 4.16: **Mesh Construct Test B**: The current consumption averaged over all targets.

In Figure 4.16 the current consumtpion averaged over all targets is plotted over the test time. Again, the total consumed current of the Mesh Construct Test B is divided into the five contributions.

During the Mesh Construct procedure the most energy is consumed, in particular due to the transmissions of the energy expensive broadcasts. The number of transmitted broadcasts is plotted in Figure 4.17 over the test time. The total number of transmitted broadcasts `nb_tx_bcasts` during the test is 96. Thus, each of the 32 nodes exactly transmitted the 3 scheduled broadcasts during neighborhood discovery. No broadcasts are transmitted during the operation.

By comparing the time course of the current consumption with the time

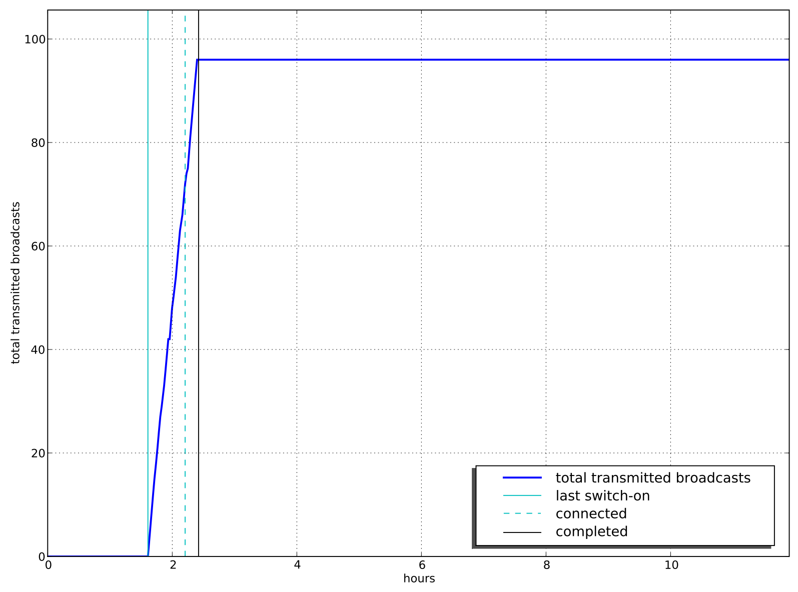


Figure 4.17: **Mesh Construct Test B**: Number of transmitted broadcasts of all nodes.

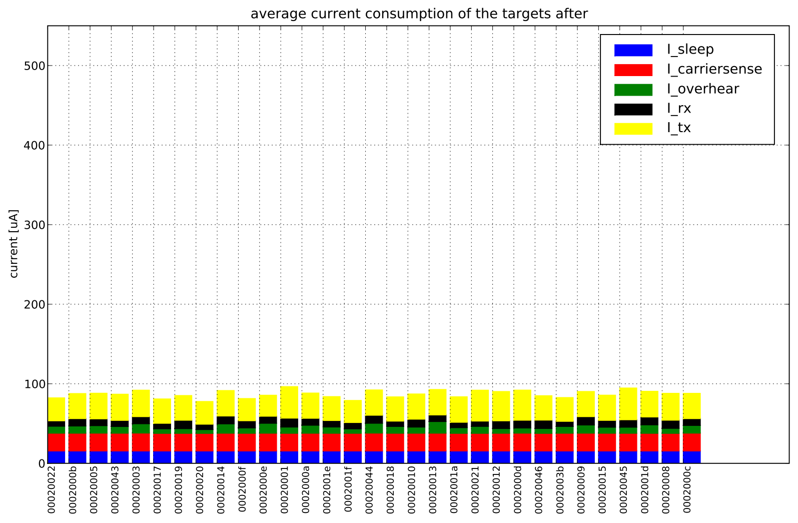


Figure 4.18: **Mesh Construct Test B**: The average current consumption of the nodes over the entire test time.

course of the connectivity states in Figure 4.7, it can be observed, that the current consumption is uniform during the operation if the network remains connected.

In Figure 4.18 the current consumption of each individual detector averaged over the entire test time is shown. Again, the current consumption is divided into its five contributions. Overall, the current consumption of the nodes is balanced. The total current consumption averaged over the time and number of nodes `i_total` is 87.245 µA.

4.4.3 Mesh Construct Test C

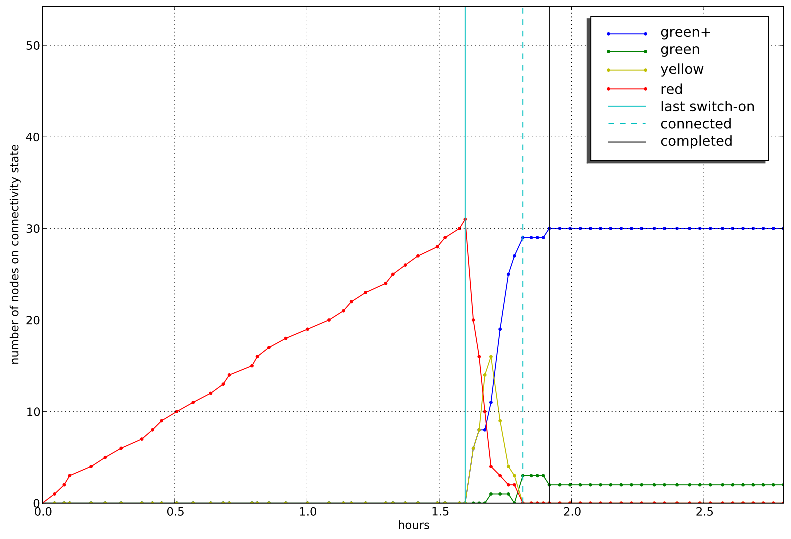
The Mesh Construct procedure is initiated by a trigger mechanism at the gateway and has a finite and determined duration after which the operation is started. Therefore, it is theoretically possible to adjust paramteters at the operation state changes, in particular when the neighbor discovery and topology construction is started (The operation state changes from sleep to discovery) and completed (The operation state changes from discovery to operation).

The use of LPL in WSNs introduces a trade-off between energy-efficiency and the latency, e.g. for transmissions of messages [13]. The shortening of the wake up period on the one hand increases the wake up frequency and hence the energy comsumption for carrier sensing but on the other hand, increases the rate at which messages can be transmitted and additionally decreases the duration and thus the energy consumption of broadcasts. Therefore, it is obvious that appropriately adapting the `t_w` during the neighbor discovery and topology control can reduce the duration and the energy consumption of the Mesh Construct procedure.

Since the change of the parameter `t_w` is not yet implemented in the software, in the Mesh Construct Test C only the start up is investigated with a `t_w` set to 0.5 s. The operation and hence the stability of the procedure are not considered.

Duration

In Figure 4.19 the connectivity and hop count states of the Mesh Construct test C are plotted over the test time. After the last switch-on it takes 13 minutes and 5 seconds until the entire network is connected. The duration `t_connected` of the Mesh Construct test B clearly fulfills the requirement to



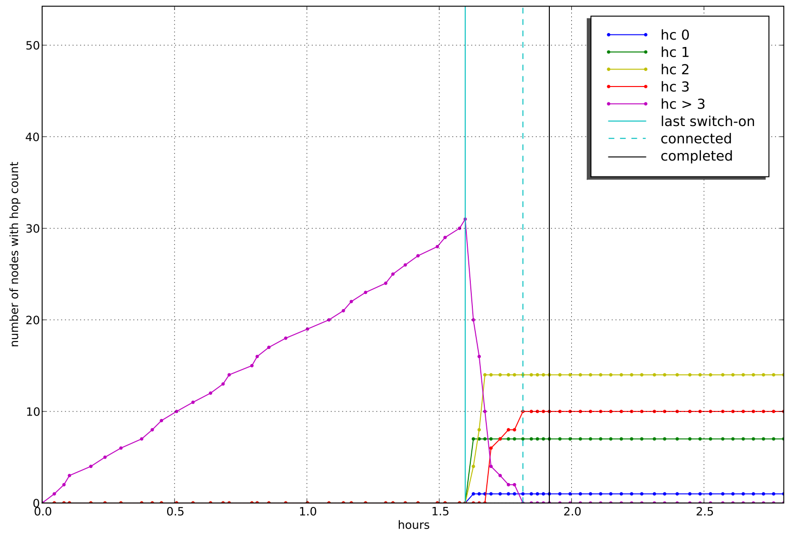


Figure 4.19: **Mesh Construct Test C**: (non-operational phase) Upper plot: Number of nodes on the corresponding connectivity states. Lower plot: Number of nodes on the corresponding hop counts.

be less than one hour and is significantly shorter than in the Mesh Construct tests A and B. The Mesh Construct procedure is completed after 19 minutes and 4 seconds.

Energy Consumption

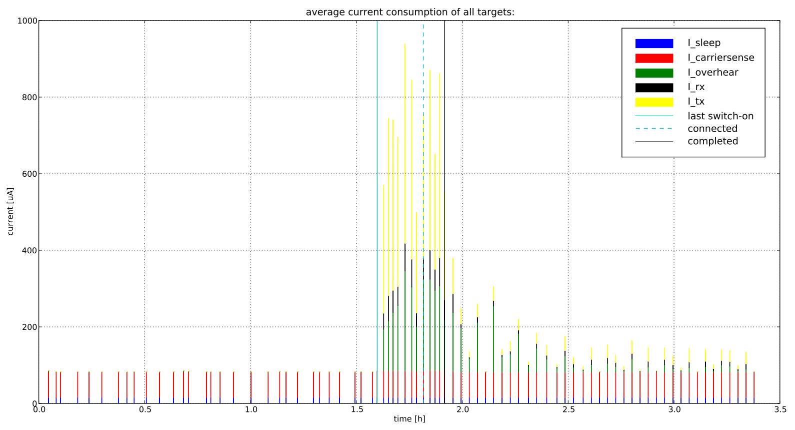


Figure 4.20: **Mesh Construct Test C**: The current consumption averaged over all targets.

In Figure 4.20 the current consumtpion averaged over all targets is plotted over the test time. Again, the total consumed current of the Mesh Construct Test C is divided into the five contributions.

The current consumption during the neighbor discovery and topology construction in the Mesh Construct test C is higher as in the tests A and B. Additionally the current `i_carriersense` is about three times higher because of the wake up period `t_w` of 0.5 s instead of 1.5 s. In Figure 4.21 the average current consumption of each individual detector during the neighbor discovery and topology construction is shown. The total current consumption during the Mesh Construct procedure averaged over all nodes `i_avg_mc` is 689.645 µA.

To compare the overall energy consumption the relevant test results are summarized and listed in Table 4.3. The energy consumption is compared by computing the average depleted battery charge of one detector `q_avg_mc` during the entire Mesh Construct procedure.

Overall, the Mesh Construct procedure in test C is completed signifi-

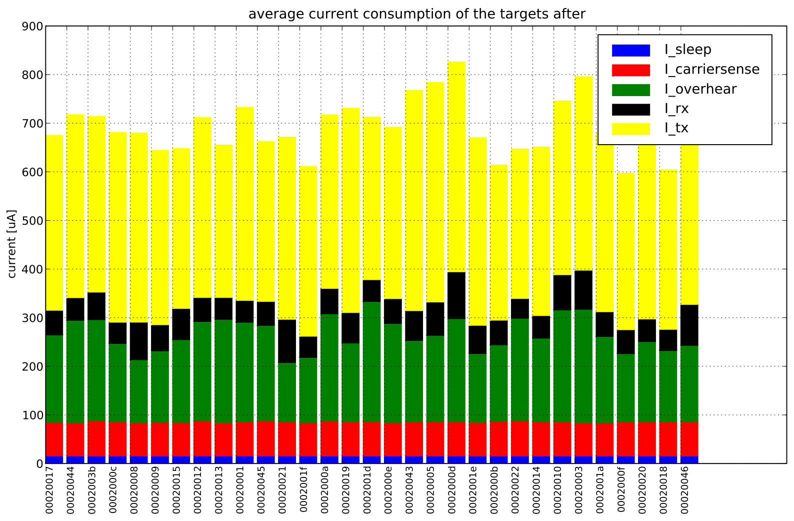


Figure 4.21: **Mesh Construct Test C**: The average current consumption of the nodes during the Mesh Construct procedure.

	Test A	Test B	Test C
`t_completed`	3122 s	2927 s	1144 s
`i_avg_mc`	295.830 µA	291.390 µA	689.645 µA
`q_avg_mc`	0.924 As	0.853 As	0.789 As

Table 4.3: Energy consumption during the Mesh Construct procedure

cantly faster than in Test A and B and less energy is consumed as assessed by the depletion of the battery charge.

4.5 Comparison with the Existing Solution

In this section the test results of the Mesh Construct tests are compared to the test results obtained with the existing solution. The values of the defined quality metrics are summarized and listed in Table 4.4.

	eS test A	eS test B	MC test A	MC test B
`t_connected`	1 h 17 min 47 s	17 min 22 s	37 min 35 s	35 min 50 s
max(`nb_red_nds`) *	0	0	0	0
max(`nb_redyellow_nds`) *	4	2	0	0
`nb_rem_dead_nhs`	104	89	1	0
`nb_tx_bcasts`	37	36	96	96
`i_total`	144.090 µA	123.536 µA	89.328 µA	87.245 µA

Table 4.4: Comparison between the existing Solution (eS) and the Mesh Construct (MC). (*: The maximal value after the network is connected the first time until the test end is considered.)

In general, the results of the Mesh Construct test are more homogeneous than the results of the existing solution, especially the duration `t_connect`. It can be assumed that, the heterogeneous nature of the results obtained with the existing solution arises from the fact that the existing solution is a random procedure, whereas the Mesh Construct is deterministic. In particular, depending on the random order of the node switch-ons a completely different network topology is constructed with the existing solution. For example this can be observed by comparing the different compositions of the hop counts in the Figures 2.1 and 2.1. In the Mesh Construct tests, independent of the random order of the switch-ons, exactly the same composition of hop counts can be observed after the network is connected.

Duration

In constrast to the existing solution, in each Mesh Construct test the duration `t_connect` is less than one hour. However, there are test examples, where the existing solution is connected faster than the Mesh Construct.

Connectivity and Stability

With both, the Mesh Construct or the existing solution all nodes are discovered. During the operation the network constructed by the existing solution attains several times a yellow network connectivity state whereas with the Mesh Construct the network remains connected. By considering the plots of the connectivity states and the number of removed dead neighbors, the Mesh Construct procedure results in a more stable network topology than the existing solution.

Energy Consumption
Although the number of transmitted broadcasts of the Mesh Construct is sharply higher, the overall average current consumption per node is lower than in the existing solution. That is because energy can be saved by a stable network topology in terms of connectivity.

Chapter 5

Conclusions

In the first section of this chapter the work presented in this thesis is summarized. The achieved contributions are indicated in the second section. In the last section an outlook on possible future work in the area of this thesis is given.

5.1 Summary

In this thesis the new procedure Mesh Construct for the neighbor discovery and topology construction of a multihop WSN is presented. The objective of the procedure is to be fast and energy-efficient. In addition, a stable and constant mesh network topology with certain characteristics for the purpose of the operational phase of the WSN shall be constructed.

A fire alarm system based on a multihop WSN is the underlying system investigated in this thesis. Due to the safety-critical function of a fire alarm system a mesh network topology with at least two node-disjoint multihop communication paths from each detector to the gateway is required to ensure reliable alarm forwarding in case of detector failures. A network connectivity state is defined in order to indicate whether the mesh network topology fulfills this requirement.

The Mesh Construct procedure is controlled by the gateway and constructs the mesh network topology through initiating sequentially neighorhood discoveries on each discovered node starting from the gateway and proceeding outwards hop by hop. Nodes performing a neighborhood discovery choose the best discovered nodes for the purpose of the network as neighbors. In case of the fire alarm system, neighbors which can improve the network connectivity state and have a good link quality are prefered. After the neighborhood discovery, the choice is stored in a neighbor table and transmitted to the gateway, which maintains and updates the network informations in order to be able to initiate the next neighborhood discoveries. The Mesh Construct is completed when the neighbor table of each discoverer is received at the gateway and the operation of the WSN including a topology control can be started.

Tests and evaluations of the existing solution for the network initialization and topology control revealed several results: First, there is no finite deterministic upper bound for the duration of the network initialization. Second, during the operation the mesh network topology is unstable and sometimes the required network connectivity state is not ensured, due to removals of inappropriate neighbors by the topology control. Third, the neighbor removals cause unconnected nodes to discover new neighbors, which significantly increases the energy consumption.

Through the insights gained from the evaluation of the existing solution the choice of the neighbors during the neighborhood discovery and the hop by hop construction of the mesh network topology are crucial elements in the conceptual design of the Mesh Construct to improve the performance of the neighbor discovery and topology construction.

Although the amount of performed Mesh Construct tests is not staticstical relevant, the examples of test evaluations show promising results. First, the duration of the Mesh Construct procedure is finite and fast enough to fulfill the requirements. Second, the appropriate choice of neighbors and the hop by hop construction reduce neighbor removals during the operation and lead to a more stable and better connected mesh network topology compared to the tests with the existing solution. Third, through the stable and connected network topology the total energy consumption during the tests is reduced compared to the tests with the existing solution.

Moreover, the triggered start and the finite duration of the procedure allow to adjust parameters at operation state changes. A Mesh Construct test with a shorter wake up time period of the WiseMAC, showed that the duration and the energy consumption can be further reduced during the neighbor discovery and topology construction.

5.2 Contributions

In the following the main achievements and contributions of this thesis are stated.

- The presented Mesh Construct is a procedure with the objective to discover neighbors and construct a stable and connected mesh network toplogy in a fast and energy-efficient way. In particular, the Mesh Construct is suited for an alarm system based on a multihop WSN.
- The Mesh Construct procedure has a triggered start and a finite duration. A deterministic upper bound for the duration can be computed. The triggered start and finite duration theoretically allow to appropriately adjust parameters for the different operation states, before, during and after the Mesh Construct prodecure.
- With appropriate parameter choices the possiblity to rate and choose neighbors depending on the link quality or the resulting connectivity state improvement is provided. For an alarm system a good choice can decrease the instability and introduce redundancy on the network connectivity state in order to prevent the network from getting unconnected in case of limited neighbor removals by the topology control during operation.
- With the informations about the network topology at the gateway, installed nodes which are not discovered can be identified and possibly placed in an more appropriate location for the network.
- The Mesh Construct applied to the fire alarm system described in Section 1.1.2 can reduce energy consumption, duration, and instability in the mesh network topology.

5.3 Outlook

In this section proposals for possible future work in the area of this thesis are indicated:

- To achieve a statistical relevance of the evaluation results more tests in series could be performed and evaluated.

- By running more tests with systematic choices of all the possible parameter constellations the performance of the Mesh Construct for a particular application could be optimized.
- The possiblity of the Mesh Construct to adapt parameters at operation state changes could be implemented in practice to improve the performance during the neighbor discovery and topology construction. For example, as showed with the Mesh Construct test C, the energy consumption and the duration of the Mesh Construct procedure can be decreased by shortening the WiseMAC wake up period `t_w`. In addition, a longer `t_w` could reduce the energy consumed for the periodic carrier sense in the operation state before the Mesh Construct actually is started.

Appendix A

Testbed

In this section of the appendix the testbed used in the tests documented in Section 2.1.2 and Chapter 4 is described. Several parts of the testbed were developed during the master's thesis of Florian Betschart [14].

The testbed consists of 32 nodes, which can be used either for the gateway or for the detectors. The radio module on the nodes is based on a MSP430 microprocessor [15] and uses an ADF7021 low power narrow-band transceiver for wireless communication in the sub-gigahertz frequency band. The MSP430 has 4 kilobytes random access memory (RAM) and 56 kilobytes read only memory (ROM).

A Deployment Support Network (DSN) [16] is applied to the nodes of the testbed. The DSN is a second network laid out above the actual WSN in order to monitor, configure and reprogram the sensor nodes using a remote procedure call protocol. The DSN applied to the testbed is based on a hybrid solution of USB-interfaced DSN nodes and an Ethernet platform. Each sensor node is attached to an adapterboard equipped with an USB-interface. The adaptorboards are connected via USB to an Ethernet gateway, which uses a TCP/IP stack to communicate with a DSN-server. The DSN-server provides an interface to access the DSN and initiate several different tasks, which can be accomplished through the DSN:

- New compiled software code can be downloaded to the microprocessor of the sensor nodes.
- Sensor nodes can be enabled and disabled.
- Tests can be started.

- Debug, warn, and error logs of the nodes can be read out.
- Collected statistics of the sensor nodes can be read out.

The read out statistics during tests are directly stored in a MySQL database [17]. Over the logs of the nodes and the MySQL database test results can be evaluated and analyzed.

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