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Passive discovery schemes for opportunistic message relaying schemes based on IEEE 802.15.4

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Berlin, August 2008

TKN Technical Report TKN-08-008

TKN Technical Reports Series
Editor: Prof. Dr.-Ing. Adam Wolisz

Contents

Abstract

Body sensor networks are an important building blocks for many applications in the areas of healthcare, assisted-living and well-being. Body sensor networks move as a whole, typically together with a person carrying them. One interesting approach to exploit body sensor networks for the dissemination of data are *opportunistic message relaying approaches*, in which body sensor networks are used as relays and their mobility is exploited to carry data closer to its destination. As a first key contribution, in this paper we describe the design and implementation of CMDP, the *critical message delivery protocol*, which is designed to provide the necessary mechanisms to use mobile BSNs based on IEEE 802.15.4 as mobile relays: the discovery of other BSNs and the transfer of data between BSNs. As a second key contribution, we analyze the problem of passively discovering other BSNs in some detail, assuming that the BSNs are based on the beacon-enabled mode of the IEEE 802.15.4 standard. We provide insights into suitable listening strategies and their tradeoffs between detection probability and the average listening duration.

Chapter 1

Introduction

Body sensor networks (BSN) are expected to play a major role in future health- and wellness-related services and systems [1, 2].[1] They give people the freedom to move around while their vital functions are monitored and diagnosed. Body sensor networks have some similarities with "normal" fixed wireless sensor networks [3], but there are also important differences, including for example the comparably small number of nodes and the specific mobility pattern (group mobility). The small geographical size of body sensor networks makes personal area networking technologies like IEEE 802.15.4 a particularly attractive networking technology for body sensor networks [4].

In many of the envisioned health- and wellness-related systems BSNs are not the only system component, but are complemented by an infrastructure involving stationary sensor networks, backend servers and gateways. On the backend servers medical data is stored persistently and made accessible to medical staff. In the EU ANGEL project such a system architecture is currently developed [5], [6]. The BSNs considered in ANGEL are based on the IEEE 802.15.4 standard [7] as the underlying wireless technology. Since data traffic within a BSN is often time-critical and subject to reliability requirements [8] we assume that BSNs run in the beacon-enabled mode of IEEE 802.15.4 in order to benefit from its capabilities to support time-bounded traffic using GTS slots. The gateways designed within ANGEL are either fixed gateways (e.g. set-top boxes) or mobile gateways (e.g. an enhanced mobile phone). Typically, within a BSN no facility for wide-area communications is present, but a gateway is required to transfer data from a BSN to a backend server and from there subsequent medical actions are triggered.

Unfortunately, it cannot be guaranteed that a BSN is always in reach of a gateway or that the neighbored gateway is fully operational. When this happens in a critical medical situation (e.g. an elderly person looses consciousness at a place hidden from other, closeby persons), additional provisions are needed to transmit a corresponding message to the backend server and trigger appropriate treatment. To achieve this, in ANGEL we follow the concept of *opportunistic message relaying* [9]. More specifically, we enable a person A's BSN to discover other BSNs in the vicinity and to subsequently transfer the message to them. When the other BSN has access to a gateway it can forward the data to it, otherwise it can carry around the data for a while (exploiting mobility of its user) and transfer it to further BSNs, which behave in the same way. As an analogy, A's alarm message are replicated to other BSNs like a virus, and each replication either

[1] We gratefully acknowledge the partial support of this research activity by the European project FP6-2005-IST-5-033506 ANGEL

manages to reach a gateway, it "infects" further BSNs, or it is deleted when it is too old.

To achieve this functionality, a BSN sending or forwarding a message needs different capabilities. First, it must be able to discover the presence of other BSNs or gateways in reach, even if these operate on other carrier frequencies. We refer to this step as *BSN discovery* or *PAN discovery*. Due to mobility and small transmit power, the time window available for discovery can be small, in the order of a few (tens of) seconds. Secondly, a BSN must be able to transmit the message into a neighbored BSN or gateway. We refer to this step as *relaying*. The third part, which is not in the scope of this paper, is to control the "infection" process so as to ensure that a message quickly reaches a gateway while at the same time avoiding that too many copies of the same message circulate in forwarding BSNs, creating congestion.

As a first major contribution of this paper, we describe the design and implementation of the *critical message delivery protocol* (CMDP). This protocol provides the major functionalities for opportunistic relay message dissemination using other mobile BSNs. CMDP operates on top of a standard beacon-enabled IEEE 802.15.4 MAC and does not require any additional services or special support from the underlying MAC and PHY. A key design feature is CMDP's ability to use multiple helper nodes for discovery and relaying, thus offering the applications a tradeoff between discovery reliability and discovery times on the one hand and resource usage on the other hand. In our design we have taken great care to separate strategy and mechanism: the protocol implementation provides the major mechanisms (discovery, relaying) and furthermore provides hooks for the higher layers to make strategic decisions like the proper infection strategy.

The second major contribution of this paper is a more detailed analysis of BSN discovery schemes. Since the beacon-enabled mode of IEEE 802.15.4 prevents the usage of active inquiry methods (i.e. methods in which the searching network broadcasts specific control packets to trigger answers from surrounding BSNs), we focus on the design and modeling of suitable passive methods, in which the searching BSN snoops the medium to capture beacons coming from other BSNs. We propose a simple scanning method and provide an analytical model for its performance (the probability to detect another BSNs within a given time budget and the average detection times). This model is validated by simulations and measurements and we show amongst others that for our scanning method there is a tradeoff between the detection probability and the average detection times.

This paper is structured as follows: in Chapter 2 we provide the necessary background on IEEE 802.15.4 and the ANGEL project. In Chapter 3 we describe the design and implementation of CMDP. In Chapter 4 we investigate passive discovery of foreign BSNs by a single listener. We provide an analytical model, validate it against simulations and measurements and evaluate it. Some additional properties of the analytical model are stated in the Appendix A. In Chapter 5 we experimentally exploit the case of multiple listeners. Related work is surveyed in Chapter 6 and we offer our conclusions in Chapter 7.

Chapter 2

Background

In this chapter we provide the relevant background on the system and protocol architecture designed within the ANGEL project and the IEEE 802.15.4 standard.

2.1 IEEE 802.15.4

The IEEE 802.15.4 low-rate wireless personal area network (LR-WPAN) standard [7] was finalized in October 2003, a revised version has been published at the end of 2006. It covers the physical layer and the MAC layer.

2.1.1 Channelization and node types

An IEEE 802.15.4 node can work in one of 27 frequency channels, placed in three different frequency bands: there is one channel in the range from 868 to 868.6 MHz, ten channels in the range from 902 to 928 MHz and 16 channels in the 2.4 GHz ISM bands. An IEEE 802.15.4 network selects one of those channels at its discretion and stays on it – frequency hopping is not used. In this paper we concentrate on the 2.4 GHz PHY.

The standard defines different types of nodes in the networks which have different responsibilities: *full-function devices* (FFD) and *reduced-function devices* (RFD), with RFDs implementing only a subset of the full protocol functionality in order to allow for energy-efficient operation. A full-function device can operate in three different roles: as a *PAN coordinator* (or network coordinator), as a *coordinator* or as a *device*. In contrast, an RFD can only act in the role of a device. There is only a single PAN coordinator in a network, but there could be several coordinators (from now on, unless otherwise mentioned, when referring to a coordinator we mean to include the PAN coordinator as well). The PAN coordinator initiates the network and selects the major operational parameters, including the PAN identifier, the frequency channel and the duty cycle (see below). The coordinators can communicate in a peer-to-peer fashion in tree or mesh networks. In contrast, devices can only exchange packets with the coordinator they are associated with, thus forming a star network. Coordinators need to buffer downlink (from coordinator to device) packets for simple devices and the protocol leaves the decision on when to transmit these packets to the devices, not to the coordinator.

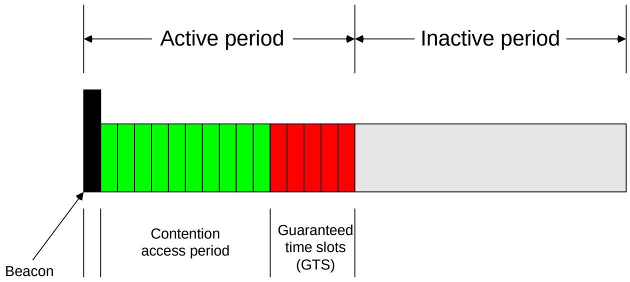

Figure 2.1: Superframe structure of IEEE 802.15.4

2.1.2 The beaconed mode

The protocol offers two different modes: the *unbeaconed mode* and the *beaconed mode*. The beaconed mode is based on a TDMA scheme: the time is subdivided into consecutive *superframes*, the structure of a superframe is shown in Figure 2.1. The superframe is subdivided into an active period and an inactive period. At the beginning of the active period the coordinator broadcasts a *beacon packet* without performing a carrier-sense operation. The length of the superframe and the relative length of the active period within a superframe (the *duty cycle*) are configurable. More specifically, the superframe length and therefore the beacon period is given by [7, Sec. 7.5.1.1]:

$$aBaseSuperframeDuration \cdot 2^{BO}$$

where $aBaseSuperframeDuration = 15.36$ ms (for the 2.4 GHz PHY) and $BO \in \{0, 1, \ldots, 14\}$ is the configurable *beacon order*. The duration of the active period is given by

$$aBaseSuperframeDuration \cdot 2^{SO}$$

where $0 \leq SO \leq BO \leq 14$ is the configurable *superframe order*. Therefore, the allowed beacon periods are restricted to a fixed set of values that are all given by a constant times a power of two.

During the inactive period all nodes, including the coordinator, can sleep. The active period is subdivided into 16 slots, the beacon packet is always transmitted at the beginning of the first slot. The beacon packet contains, among other things, the communication parameters (BO, SO) selected for this PAN. At the end of the active period a maximum of seven *guaranteed time slots* (GTS) can be allocated to nodes in an exclusive manner. In the remaining slots (called *contention access period*, CAP) the associated nodes can send uplink packets to the coordinator or they can request pending data from the coordinator. During this time they compete for the medium using a slotted CSMA-scheme. The guaranteed time slots can be used for both downlink and uplink packets.

2.1.3 Discovery support of the IEEE 802.15.4 MAC

In the following we give a short overview of IEEE 802.15.4 MAC layer services that are used by the CMDP. To discover the presence or absence of PANs the MAC management service provides a primitive `MLME-SCAN` that initiates a channel scan over a given list of channels.

Three different scanning techniques are available, the passive, the active and the energy detection scan. The energy detection scan allows to obtain the maximum detected energy in each requested channel without giving any indication about the identity or type of the radiating entity. The *active scan* transmits beacon requests on each requested channel and listens for response beacons for a given time. RFDs are not required to support the active scan. Furthermore, the active scan is restricted to the non-beaconed mode of IEEE 802.15.4 [7, Sec. 7.5.2.1.2].[1] In the *passive scan*, which must be supported by all nodes including RFDs, a device only listens for beacons on requested channels without transmitting beacon requests. In beacon-enabled PANs only the passive scan can be used. The passive and active scan report back detected beacons. Alternatively, but less common, a device can enable *promiscuous mode* in which the radio is switched to receive mode. The usual address filtering mechanism is disabled and all subsequently received frames (including packets from different networks) are signalled to the next higher layer.

On a beacon-enabled PAN a device can synchronize and track beacons through the `MLME-SYNC` primitive. The tracking of beacons is optional and can be disabled through the same primitive; however, before a device may transmit a frame to a coordinator on a beacon-enabled PAN, it must always receive the beacon that marks the beginning of the respective superframe. To join a PAN a device usually requests association with the help of the `MLME-ASSOCIATE` primitive. Association is, however, no requirement for data transfer.

2.2 The ANGEL architecture

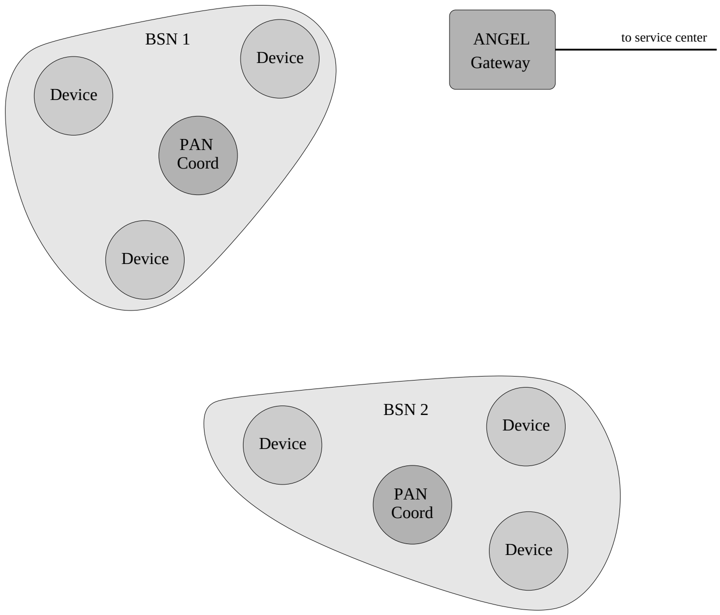

Figure 2.2: Simplified highlevel architecture of the ANGEL system.

[1] More specifically, coordinators of beacon-enabled PANs ignore the beacon request command and continue to transmit beacons periodically. Therefore, in beacon-enabled PANs the actice scan can not be used for discovery.

The ANGEL project ("Advanced Networked embedded platform as a Gateway to Enhance quality of Life") is a research project supported by the European Commission within the 6th Framework Programme. The project designed and implemented a distributed platform capable of delivering health-related services to consumers [5], [6].

A simplified view on the relevant parts of the ANGEL architecture is shown in Figure 2.2. The ANGEL service center is a backbone server on which medical data is persistently stored and made accessible to the ANGEL users (patients, doctors, nursing staff) and from which also medical actions are triggered. The ANGEL gateway can be a fixed or a mobile gateway. It possesses two different network interfaces: on the one hand it possesses an IEEE 802.15.4 interface in order to exchange data with fixed sensor networks or, more importantly, with mobile BSNs. On the other hand, a gateway has a wide-area network interface connecting it to the sercice center. This can be a GSM/GPRS interface or a fixed Internet connection. ANGEL supports two types of sensor networks. On the one hand, fixed sensor networks provide environmental data like temperature or humidity, which can have an impact on a persons well-being. On the other hand, body sensor networks are attached to persons and form autonomous networks. A BSN is in general not in the vicinity of a gateway but when it is, it exchanges medical data or configuration updates with the gateway. For the remainder of the paper we consider BSNs only.

A BSN is always an autonomous network, and to avoid taking one persons data for another persons data, BSNs are not allowed to merge with each other or with gateway networks. A BSN consists of a number of sensor nodes, and one of them assumes the role of a leader. In accordance with IEEE 802.15.4 parlance we call this node the coordinator. To simplify exposition, we assume that a BSN is a single-hop network. The operation of CMDP does not depend on whether the BSN is a single-hop or a multi-hop network. Amongst other duties, the coordinator has a list of all the BSN members and knows their capabilities. Within a BSN the IEEE 802.15.4 physical and MAC layer is used as the underlying radio technology. The following assumed characteristics of a BSN are important for the design of CMDP:

- We assume that all BSNs operate in beaconed mode, since medical applications often require periodic sampling and processing of data and furthermore a predictable quality of service for this data. The coordinator chooses the main communication parameters like the center frequency, beacon order and superframe order independently of other BSNs, i.e. there is no single parameter set that is common to all ANGEL BSNs.

- The network type (Gateway, BSN) can be recognized by specific fields in the beacon payload.

It should be noted that the ANGEL system foresees the usage of ZigBee [10] for the higher protocol layers. However, since we want our work to be independent of any higher layer protocol, ZigBee is not considered any further.[2]

ANGEL gateways can be either fixed or mobile [12]. A (mobile) gateway is not necessarily part of a BSN. In general, there is not always a gateway in reach of a BSN. A gateway contains an IEEE 802.15.4 network coordinator, which also chooses his communication parameters at his own discretion.

[2]However, a technical comment must be made. The IEEE 802.15.4 MAC lacks the concept of service access points or multiplexing of higher-layer protocols. To have the critical message delivery protocols described in this paper run in parallel to ZigBee (it cannot run on top of ZigBee, since CMDP federates among *distinct* networks, whereas ZigBee considers only the case of communication within a single network), a thin wrapper layer on top of IEEE 802.15.4 has been designed which adds, amongst others, a protocol multiplexing functionality [11].

Chapter 3

CMDP design and implementation

In this chapter we describe the design and implementation of the *critical message delivery protocol* (CMDP). The aim of CMDP is to provide the mechanisms that are needed to use mobile, IEEE 802.15.4-based BSNs as data mules, i.e. to exploit the mobility of BSNs and the (controlled) replication of messages between different BSNs for data dissemination. The whole CMDP and data mule approach in general targets the delivery of "critical" messages, i.e. messages which occur rarely and which are very important, and for which consequently the wasteful approach of message replication is warranted.

A key design concern of CMDP was to separate mechanism and strategy. The major mechanisms upon which CMDP is built are the discovery of neighbored BSNs (which from now on we will also call *foreign BSNs*) and afterwards the transfer of data. We refer to the data transfer phase also as the *relay phase*. Based on these mechanisms an application can make strategic decisions concerning the message replication process (e.g. number and identity of neighbors to which a message is replicated). This replication strategy is not in the scope of this paper, but its goal is in general to ensure that a message reaches a gateway without creating an "explosion" of replicated messages. The further data delivery from gateways to the ANGEL service center is assumed to be reliable.

A key concept of CMDP that sets it apart from the mechanisms that IEEE 802.15.4 already offers is the ability to use several helpers. The CMDP is in general initiated and controlled by the coordinator of the *home BSN*, i.e. the BSN that wants to initiate a message transfer. This home coordinator uses a dedicated signaling mechanism to instruct a number of his BSN members to help with the discovery of foreign BSNs. The home coordinator can select the helpers according to the availability of nodes in the BSN and the urgency of the message at hand. When a foreign BSN has been found, the home coordinator can instruct another set of helpers to transfer the data to the foreign BSN. By using multiple helpers in this relay phase the message transfer reliability can be increased.

3.1 Architecture

The CMDP architecture consists of three main building blocks, a core module, a discovery and relay policy module as depicted in Figure 3.1. This decomposition allows to separate the functionality of the core (i.e. the mechanisms) from the decision process

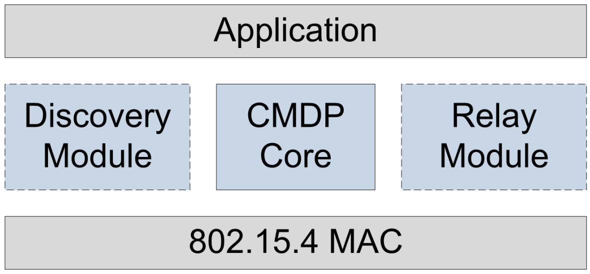

Figure 3.1: CMDP Architecture

of the policy modules for discovery and relay. Thus, policies can be easily exchanged without modification of the CMDP core. The core itself provides the functionality to perform a discovery, to exchange data with neighboring PANs and to signal corresponding instructions to helper devices and the results back from the helpers to the home coordinator. Furthermore the core keeps tables and management data related to associated devices, discovered neighbored PANs, as well as command and message handling. The discovery policy module decides which associated devices shall perform a discovery on which channels and for which durations. Similarly, the relay policy module decides which associated devices shall help with relaying a message to which neighbored BSNs.

CMDP provides different types of interfaces. The *external interface* offers the CMDP services to higher layers. This interface includes a service by which higher layers can request dissemination of data through CMDP (`CMDP-DATA.request`) and a second service indicating the arrival of a message (`CMDP-DATA.indication`). The core provides an *internal interface* through which the policy modules have read-only access to internal data structures and may instruct devices to perform discoveries or relays. In addition, the policy modules are informed about the creation, modification or removal of associated devices, messages and neighboring PANs.

The discovery and relay instructions initiated by the policy modules are transmitted in the beacon payload. The beacon payload of coordinators running the CMDP may contain the following information:

- Network type (BSN / Gateway)
- Relaying capabilities of the BSN
- Gateway connectivity
- Ongoing discovery and relay instructions

The network type allows neighbouring BSNs to identify the PAN during discoveries. The relaying capabilties provide information if the BSN has enough resources to support the relay of messages. If the PAN is a mobile BSN, the gateway connectivity describes whether or not it has been in reach of a gateway and optionally the time of the last contact. The beacon payload is kept short in normal operation (one or two bytes, depending on the gateway connectivity) to reduce energy costs. Synchronized devices tracking beacons of a coordinator always have to receive the complete beacon including the payload before the transceiver can be disabled if no data is pending. In case a helper device misses a beacon in which it is instructed to perform an action, the coordinator may request the status of the device to keep the state information consistent.

3.2 Discovery

In the 2.4 GHz band the IEEE 802.15.4 standard provides 16 frequency channels and allows individual PANs to choose from a vastly varying range of beacon periods and duty cycles. This makes BSN discovery non-trivial. Furthermore, since PANs are independent, they are not synchronized in time. The ultimate goal of PAN discovery is to detect at least one foreign PAN (alternatively, all neighbored PANs). To discover a PAN means to receive a beacon frame originating from the foreign PAN, since only after receiving a beacon all relevant communication parameters of the foreign PAN (its frequency, superframe order, beacon order and relative phase shift to the home PAN) are known. As explained in the introduction, we assume that ANGEL BSNs are operated in the beaconed mode of IEEE 802.15.4 which implies that only passive listening methods are applicable [7, Sec. 7.5.2.1.2].

In general, BSN discovery can be distinguished between direct or indirect monitoring depending on which BSN members are involved in the discovery. In case of direct monitoring the coordinator itself performs the discovery. He can do this in his inactive period (avoiding service disruptions in the home BSN) or in his active period (taking the risk of service disruptions while listening on other frequency channels). In both cases, however, there is some risk that a foreign BSN using the same channel and beacon order and being active at the same time as the home coordinator will not be discovered. With indirect monitoring the coordinator is not involved in monitoring but instead instructs associated devices (helpers) to search for other BSNs and to report their findings back to the coordinator. The home coordinator can select one or more of its BSN members to help with discovery. The selection of helpers can for example be based on their current relevance for the user applications. The indirect approach potentially has one significant advantage: the different production qualities found for the same type (vendor, brand) of hardware or the different positions of nodes on a human body might for direct discovery lead to situations where the home coordinator is shielded from the foreign PAN, for example the human body is between them [13]. By relying on multiple helpers, chances are that at least one of them has good hardware or has a direct line of sight to the foreign PAN.

The CMDP uses an indirect passive approach to detect neighbouring BSNs. Since a foreign PAN may operate on a different channels but with the same beacon order and phase as the home coordinator, it would not be possible to detect the foreign PAN with a direct approach without the home coordinator stopping own beacon transmissions for a while. Furthermore, the distribution on multiple devices allows to speed up or to increase the reliability of the discovery.

In more detail, CMDP discovery operates as follows. In the first step, the home coordinator selects a number of helper nodes, specifies for each helper the channels on which it listens and the listening scheme to be followed on these channels. The home coordinator adds corresponding instructions to its next beacon packet. After receiving the discovery instructions the devices stop tracking the beacons of the home coordinator when the time required to execute the instruction exceeds the time until the next home beacon.[1]

In order to commence with the actual discovery the devices enable the promiscuous mode and listen on the given channel list for predefined times. Depending on the

[1] This is technically achieved by issueing the `MLME-SYNC` primitive with the TrackBeacon parameter set to false. The purpose of this is to prevent the MAC from generating error messages about lost synchronizations (`MLME-SYNC-LOSS` indication primitive), which might confuse other software components on the helper node. The `MLME-SYNC-LOSS` indication would be generated by the MAC layer of a device tracking the beacons of a coordinator if *aMaxLostBeacon* = 4 consecutive beacons are not received.

discovery parameters devices record all kind of 802.15.4 frames or only beacons. If a device successfully detects a foreign BSN, the discovery process can be canceled or continued (this is subject to the listening policy).

The instructed devices always resynchronize to their home coordinator. The time in which the radio has to be enabled for the resynchronization process can be reduced by using the information about the last received beacon as well as the beacon order of the home coordinator. If a device is resynchronized, it will always report back any findings according to the discovery instructions.

Having the described CMDP discovery mechanism at hand, the following issues have to be resolved by discovery policies:

- Which policy does an individual helper follow on its assigned frequency channels?
- How many helpers shall be used?
- How shall these helpers share the work among each other?

3.3 Relaying

After neighboring BSNs have been discovered, the critical message has to be relayed to the foreign coordinator in order to be further transmitted to a gateway. The following three main design issues can be identified for the relay process:

- Which member of the BSN performs the relay?
- In which portion of the superframe does the relaying take place?
- How to enable inter-PAN communication between beacon-enabled PANs?

The first design issue resembles a similar issue with BSN discovery, since it shares similar problems concerning the coordinator and fulfulling the duties as the head of a BSN while performing the relay. Therefore, for relaying we again use an indirect approach, thus achieving similar benefits as for the discovery phase.

The active portion of an IEEE 802.15.4 superframe consists of the contention access period (CAP) in which all devices may transmit data to a coordinator using CSMA-CA and the optional contention free period (CFP) in which devices may reserve guaratenteed time slots (GTS). If the relaying should take place in the CFP using a GTS, devices would have to associate with the foreign coordinator since the standard requires that transmissions in the reserved slots shall only use short addresses which are allocated by the foreign coordinator.

Devices being member of a PAN employing the IEEE 802.15.4 beacon-enabled mode may have rather long inactive periods. To exchange data between different PANs (which may operate on different channels, at different beacon orders and phase shifts) a device has to be synchronized to multiple coordinators at the same time which is not supported by the IEEE 802.15.4 standard. A first approach is to intruct a device to diassociate with the home BSN, associate with the foreign coordinator, relay the message and reassociate with the home coordinator. This approach includes additional packet overhead due to the association but allows the usage of the CFP or CAP for communication.

The CMDP uses an indirect approach, in which associated devices of the home BSN are instructed to relay messages in the CAP of a foreign PAN without initiating an association procedure in the foreign PAN. After receiving the instruction to relay a message to a neighboring BSN the selected devices attempt to synchronize with the foreign coordinator. To support this, the relay instructions include information about frequency, beacon order and phase of the foreign PAN, if available. The helper saves key MAC attributes for its home PAN, including *macPANId* and *macCoorShortAddress* and afterwards sets them to the one specified in the relay instruction. The attribute *macShortAddress* is stored and overwritten with `0xFFFF` to prevent clashes with short addresses of regular members of the foreign BSN. The time of the next expected beacon transmission is included in the relay instruction as well as the beacon order of the neighbouring BSN to compute further beacon transmission times. Based on this information the relay helper attempts to synchronize with the foreign PAN. If the synchronization fails, the helper immediately resynchronizes to its home coordinator and issues an appropriate report.

If the synchronization is successful (i.e. neighboring BSN is in communication reach of the helper), the helper computes a random backoff in the foreign CAP to avoid collisions if several helpers are instructed to relay the message. The relay message is transmitted to the foreign coordinator by using the extended address of a device which is also used by the coordinator to address the device in the response. The response of the coordinator contains the status of the processing of the relay message, e.g. if the message is already present or known to be delivered to a gateway.

After receiving the response from the foreign coordinator a device computes the next beacon transmission of its home coordinator in the same way as in the discovery resynchronization procedure. Prior to the resynchronization request the original values of the altered MAC PIB attributes are restored. The devices report an updated status of neighbouring BSN and of the relay message to the home coordinator.

The CMDP protocol allows the users to either separate the discovery and relaying phase or to combine them. In the separated case, the relaying phase starts after the discovery helpers have reported back and the relaying helpers have been explicitly instructed by the home coordinator. The helpers used for discovery and relaying can be different. In the combined case, the discovery and relaying helpers are the same. The discovery helpers receive the actual message together with their discovery instructions and as soon as they have discovered a foreign PAN, they start relaying the message to it. This saves a round of signaling with the home coordinator, but gives the latter less control over which foreign PANs receive the message.

3.4 The CMDP implementation

The CMDP was implemented on two different hardware platforms and operating systems, on the Tmote Sky [14] mote platform using the TinyOS 2 [15] operating system and on the TI CC2430 [16] System-On-Chip platform combining a CC 2430 transceiver and an 8051-compatible microcontroller. For this platform a closed-source implementation of IEEE 802.15.4 is available[2] which runs under the OSAL operating system. The CMDP implementation on both platforms is slightly different: on the Tmote Sky we have assumed the beaconed mode, whereas on the CC2430-plus-z-Stack platform we have used the unbeaconed mode. All measurements presented in this document were collected using the Tmote Sky platform. The following data concerning the memory usage is also based on the TinyOS implementation. The CMDP core used about 13.1 kByte flash on the coordinator and 12.1 kByte on the device. The size of the policy modules used in the measurements was about 0.3 kByte each. The RAM usage

[2] The Z-Stack of Texas Instruments, see `http://focus.ti.com/docs/toolsw/folders/print/z-stack.html`.

heavily depends on the size of the structures used to store information about associated devices, discovered neighbors, messages and commands. The core itself only needs about 0.3 kByte RAM on the coordinator and 0.5 kByte on a device. For example, the configuration applied during the measurements used additional 1.8 kByte on the coordinator and 1.6 kByte to store and maintain the mentioned structures.

The CMDP consists of 11 core and two policy modules. The BeaconScheduler module runs on a coordinator and is responsible for assembling the beacon payload consisting of BSN information, discovery and relay commands. The counterpart on the device side is the BeaconTracker module which extracts necessary information from the beacon payload. The command module manages execution of received instructions and also provides the internal service interfaces for the policy modules to instruct devices. The data module is the interface of the CMDP to the MAC data service primitives. The coordinator has to monitor devices joining and leaving the BSN which is done in the DeviceTracker module. Furthermore, this module keeps the status of associated devices updated to provide a valid device list for the policy modules. Devices have to implement the Discovery module which provides all functionalities needed to process a discovery command including the optional desynchronization, scanning, resynchronization and reporting back to the coordinator. The Message module handles critical messages generated on a device itself or, when running on a coordinator, messages received from other PANs that have to be forwarded further. The information about discovered neighbored BSNs or gateways is maintained by the Neighborhood module. Public attributes of the CMDP as well as internal parameters such as the state of a node are stored and altered via the CIB (CMDP Information Base) module. The Relay module includes the functionalities to exchange data with foreign PANs (e.g. synchronize and communicate with the foreign coordinator) and to reintegrate into the home BSN. The Task module is a very simple component that runs only on a device. It selects the next command the device shall execute and passes it to the corresponding module. The policy modules, DiscoveryPolicy and RelayPolicy module, are scenario specific implementations which are responsible for fundamental decisions in the discovery and relay process and which jointly specify the “infection strategy”.

As for the underlying IEEE 802.15.4 implementation, we have used an open-source IEEE 802.15.4-2006 MAC implementation [17] available for the TinyOS 2 operating system. The experiments were made with the Tmote Sky mote platform, using the CC2420 radio, an IEEE 802.15.4 compliant RF transceiver operating in the 2.4 GHz band. We used the Tmote Sky platform with an add-on timer board [18] to comply with the tight timing constraints in the beacon-enabled mode.

Chapter 4

Passive BSN discovery – the Single-listener case

In this chapter we investigate more closely the problem of passive BSN discovery using a single listener. We consider a class of strategies by which a single node listens to the medium to discover beacons sent by another node (e.g. the coordinator of a foreign BSN). The primary goal of this investigation is to minimize the time a listener needs to detect a foreign BSN, if present. A Markovian model for the selected class of strategies is developed, validated against simulations and measurements and investigated numerically. The insights obtained by the Markovian model reveal a tradeoff between the detection probability and the average time required until detection, and therefore to guidelines for selecting good strategies out of the given class. We close this chapter by an investigation of a second model based on a Bayesian approach.

There are two major reasons for focusing on the discovery process instead of the relay process:

- From the operation of the relaying phase, it is comparably easy to determine the average forwarding delay: since listening PAN and foreign PAN are unsynchronized, a helper node first needs to find the foreign PANs beacon, which takes half a (foreign) beacon order on average. After finding the beacon, the helper associates, waits for the next beacon to receive the association response, immediately followed by transmission of the data packet. Finally, the helper must synchronize back to its home PAN, which on average takes half a (home) beacon period.
- In all our practical experiments (which, however, were carried out with relatively small foreign beacon orders) the relaying delay was much smaller than the discovery delay.

Please note for the following that we consider the problem "search until you find one BSN" and that we do not consider the problem "search until you have found all BSNs in range", which on average requires much more listening effort. We expect that for mobile BSN the time window in which BSNs can detect each other is relatively short, in the order of a few (tens) of seconds. Within such a time window we expect it to be less-time consuming to search until one BSN has been found instead of searching until all BSNs have been found.

4.1 Problem formulation for the single-listener case

We first consider a single listener, who wants to find a foreign BSN (also called mobile BSN). The listener works in slotted time. One time slot has the duration of $aBaseSuperframeDuration = 15.36$ ms and corresponds to the smallest beacon period with beacon order $BO = 0$. At time $t = 0$ the listener starts its search. Without loss of generality, the listener starts on frequency channel 1. A mobile BSN might or might not be present (i.e. within reception range of the listener). If it is present, then it operates on frequency channel $F \in \mathcal{F} = \{1, 2, \dots, F_{\text{max}}\}$ where F_{max} is the maximum allowed channel (without further restrictions we have $F_{\text{max}} = 16$ for the 2.4 GHz PHY). We assume that F is drawn randomly from $\mathcal{F}$ according to a uniform distribution. The mobile BSN operates with a beacon order $B \in \mathcal{B} = \{0, 1, \dots, B_{\text{max}}\}$ where B_{max} is the maximal allowed beacon order. Without further restrictions we would have $B_{\text{max}} = 14$. The actual beacon order B is drawn randomly from $\mathcal{B}$ with probability mass function $p_B(\cdot)$. The beacon period of the mobile BSN is thus 2^B slots. Since the foreign BSN can be operational for long time, we assume that its beacons have a certain *phase shift* Φ with respect to time $t = 0$. This phase shift depends on the foreign BSNs beacon order B and is assumed to be uniformly distributed over the interval $\{0, 1, \dots, 2^B - 1\}$. The random variables F and B are independent of each other, the phase shift Φ is independent of F and conditionally independent of B. Furthermore, all these random variables are independent of whether the mobile BSN is present or not. Of course, the realizations of F, B and Φ are not known to the listener at $t = 0$, neither does it know whether the mobile BSN is present or not. However, the listener knows the probability distributions of F and B as well as the probability ∂ that the mobile BSN is present.[1] We make the worst-case assumption that the mobile BSN only transmits beacons, i.e. there are no other packets which would allow the listener to detect its presence.[2] As a final assumption, we neglect packet losses in our model: when the mobile BSN is present and transmits a beacon and the listener happens to listen on channel F at this time, the listener reliably receives the beacon.

The listener listens on all channels of $\mathcal{F}$ to capture beacons. For any given listening strategy the major questions are the following:

- Given a finite time budget: what is the average probability that a mobile BSN is detected given that it is present? We refer to this probability as the *detection probability* or the *success probability*.
- Given a finite time budget: what is the average time required to detect a foreign BSN when it is present? We refer to this as the *average detection costs*.

Before presenting the listening strategy considered in this paper, we note a general rule that should apply to all listening strategies: The time the strategy listens consecutively on one channel should always be an integer multiple of the slot time. Fractional times are not used.[3]

[1] In practice, the listener will not know the distribution of B or F. In these cases, a natural choice is the maximum entropy distribution)which over finite ranges is the uniform distribution), since the choice of this distribution expresses maximum uncertainty.

[2] Even if other nodes transmit in the foreign BSN, the listener needs to acquire a beacon anyway since only the beacon contains relevant communication parameters like the beacon order and superframe order.

[3] When fractional times are used, it might well happen that a mobile BSN is never detected. To illustrate, assume that $F = 1$, $B = 0$ and $\Phi = 0.6$. Consider furthermore that only two channels are available (i.e. $F_{\text{max}} = 2$ and the mobile alternates between these two channels such that it spends 0.5 time on channel 1, then 0.5 time on channel two and then starting over.

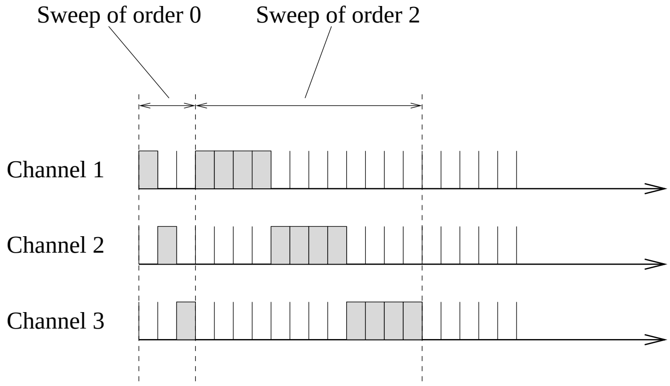

Figure 4.1: Example sweep strategy: $F_{\max} = 3$, one sweep of order zero followed by one sweep of order two, $\mathcal{S}_0 = \{0, 2\}$.

4.2 The considered listening strategy

The basic unit of our listening strategy is a *sweep* of a given *sweep order LO*: In a sweep the listener listens subsequently on all channels in $\mathcal{F}$, starting from channel one. On each channel the source BSN listens for a contiguous time of 2^{LO} slots, then the next channel is visited. The set of potentially useful sweep orders is of course given by $\mathcal{B}$. As an example, in Figure 4.1 a setup with three available channels ($F_{\max} = 3$) is shown, where two sweeps are performed, one of order zero and one of order two.

The listening strategy followed by the listener can be described by an ordered, non-empty subset $\mathcal{S}_0 = \{s_1, s_2, \ldots, s_k\} \subset \mathcal{B}$ in which each s_i occurs only once. For any such subset $\mathcal{S}_0$ there are $2^{|\mathcal{S}_0|}$ permutations. For reasons that become apparent later, we always choose the permutation that is sorted according to descending sweep orders, i.e. we always assume that $s_1 > s_2 > \ldots, s_k$. The listener operates as follows: At time $t = 0$ the mobile BSN starts with a sweep of sweep order $LO = s_1$, carried out subsequently on all channels. If a beacon is found, the search ends immediately and we declare *success*. If no beacon is found, then the next sweep order $LO = s_2$ is tried. This continues until either the mobile BSN is found or all sweep orders $s \in \mathcal{S}_0$ have been exhausted. If the mobile BSN is not found after exhausting all $s \in \mathcal{S}_0$ we declare *failure*. It is important to mention that this class of listening strategies can be expressed within the mechanisms offered by CMDP.

From the assumption of having no channel errors, when the mobile BSN is present and has a beacon order $B \leq s_i$ for some $s_i \in \mathcal{S}_0$, it is reliably detected. Clearly, by choosing s_1 as the maximum beacon order, we achieve that the mobile BSN is detected as early as possible.

To facilitate the development of a Markovian model, we assume that for a fixed channel the listening results of the different sweeps of $\mathcal{S}_0$ are stochastically independent. We will demonstrate later on, that the validity of this assumption depends on the spacing between the individual listening periods on one channel, which in turn depends on the number of other channels that are visited in between ($F_{\max} - 1$).

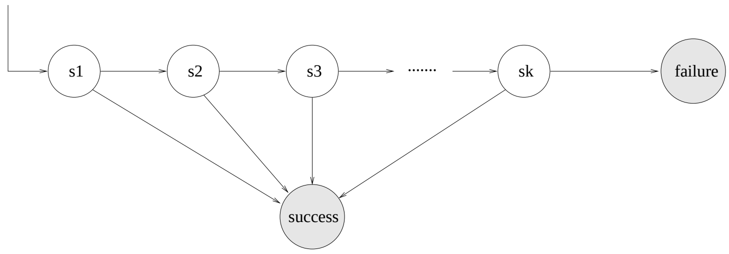

Figure 4.2: Markov model for discovery strategy based on $\mathcal{S}_0$

4.3 Markov model of the listening strategy

In this section we develop a Markov-chain model from which we later on derive the major performance measures. Fix a listening strategy $\mathcal{S}_0 = \{s_1, s_2, \ldots, s_k\}$. The Markov model addresses the case when the mobile BSN is present. When the mobile BSN is not present (which happens with probability ∂) then the time spent on one particular channel to achieve this diagnosis is given by

$$c(\mathcal{S}_0) = \sum_{s \in \mathcal{S}_0} 2^s$$

and the total time is $F_{\text{max}} \cdot c(\mathcal{S}_0)$. We refer to $c(\mathcal{S}_0)$ as the *cost* of the strategy $\mathcal{S}_0$ and note in passing that for each $c \in \left\{0, 1, 2, \ldots, 2^{B_{\text{max}}}\right\}$ there exists a unique strategy $\mathcal{S}_0 \subset \mathcal{B}$ having costs $c(\mathcal{S}_0) = c$, namely the strategy which includes the position i of every non-zero coefficient x_i in the binary expansion $c = x_0 2^0 + x_1 2^1 + \ldots + x_{B_{\text{max}}} 2^{B_{\text{max}}}$. Since for a chosen strategy always the permutation which is sorted according to descending sweep orders is used, the strategy is indeed uniquely determined.

Now suppose that the mobile is present. We model the search process followed by the listener on a particular channel as a time-homogeneous discrete-time Markov chain [19]. For this model $B = b$ is fixed, and the results are later on combined by conditioning on the random variable B. The Markov chain itself is a discrete sequence $(X_n)_{n \geq 0}$ of random variables. The state space of the model is given by:

$$\mathcal{S} = \{succ, fail\} \cup \mathcal{S}_0$$

The possible state transitions are shown in Figure 4.2. When in one particular state s_i the mobile BSN is discovered, the chain moves into state $succ$, otherwise it moves to the next state s_{i+1}. At the end, after exhausting all $s \in \mathcal{S}_0$ without locating the mobile BSN, the chain moves to state $fail$. The start state is $X_0 = s_1$, the states $succ$ and $fail$ are absorbing and denote the end of the search process.

To complete the Markov chain description, we need to derive the transition probabilities and the state transition matrix $\mathbf{P}$. For the probability to find the mobile BSN in one particular state s_i we have from our assumptions ($B = b$ fixed, independence of subsequent listening periods on the channel, uniform phase shift Φ) that

$$p_i = \begin{cases} 1 & : \quad s_i \geq b \\ \frac{2^{s_i}}{2^b} & : \quad s_i < b \end{cases}$$

The state transition matrix $\mathbf{P}$ is then given by:

$$\mathbf{P} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & 0 & 0 & \dots & 0 \\ p_1 & 0 & 0 & 1-p_1 & 0 & \dots & 0 \\ p_2 & 0 & 0 & 0 & 1-p_2 & \dots & 0 \\ \dots & & & & & & \\ p_{k-1} & 0 & 0 & 0 & 0 & \dots & 1-p_{k-1} \\ p_k & 1-p_k & 0 & 0 & 0 & \dots & 0 \end{pmatrix}$$

where the first two rows correspond to the states $succ$ and $fail$, respectively, and the further rows correspond to states $s_1, s_2, \ldots, s_k$. It is conceptually no problem to include simple channel error models into the Markov model. Namely, given a probability e that the listener does not successfully receive a beacon packet the structure of the Markov model would not change, only the probabilities p_i would have to modified as:

$$p_i = \begin{cases} e & : \quad s_i \geq b \\ e \cdot \frac{2^{s_i}}{2^b} & : \quad s_i < b \end{cases}$$

We define the *average success probability* of the listening strategy $\mathcal{S}_0$ as the probability to reach the (absorbing) success state $succ$. It is shown in the Appendix (Section A.1) using the theory of hitting times and hitting probabilities [19, Sec. 1.3] that for fixed $B = b$ the average success probability is the probability $h_1 = h_1(\mathcal{S}_0; b)$ to ever reach the absorbing state $succ$ starting from state s_1, and this probability can be obtained from solving the following set of of linear equations:

$$\begin{aligned} h_1 &= p_1 + (1-p_1)h_2 \\ h_2 &= p_2 + (1-p_2)h_3 \\ \dots & \\ h_{k-1} &= p_{k-1} + (1-p_{k-1})h_k \\ h_k &= p_k \end{aligned}$$

After conditioning over the random variable B, the overall average success probability is given by:

$$h_1(\mathcal{S}_0) = \sum_{b \in \mathcal{B}} p_B(b) \cdot h_1(\mathcal{S}_0; b)$$

It is shown in the Appendix (Section A.1) that the average success probability satisfies two important properties:

- For a given listening strategy $\mathcal{S}_0 = \{s_1, \ldots, s_k\}$ the success probability $h_1(\mathcal{S}_0)$ is the same for all permutations of $\mathcal{S}_0$.
- The average success probability is monotonic in the strategy costs: for different listening strategies $\mathcal{S}_0 \subset \mathcal{B}$ and $\mathcal{T}_0 \subset \mathcal{B}$ with $c(\mathcal{S}_0) < c(\mathcal{T}_0)$ we have $h_1(\mathcal{S}_0) \leq h_1(\mathcal{T}_0)$.

We next consider the average listening time on the channel for a given listening strategy $\mathcal{S}_0$ and assuming that the mobile BSN is present on this channel. We refer to this time as the *average listening costs*. We first formulate it for an arbitrary permutation of $\mathcal{S}_0$. It is shown in the Appendix (Section A.1) using the approach of first-step analysis [20, Sec. 3.4] that for fixed $B = b$ the computation of the average listening costs $c_1 = c_1(\mathcal{S}_0; b)$ must consider two cases. In the first case we have $b \leq s_i$ for some

$s_i \in \mathcal{S}_0$ with s_i being the first such value in $\mathcal{S}_0$. In this case c_1 is the solution of the following set of equations:

$$\begin{aligned}
c_1 &= p_1 \cdot \frac{2^{s_1}}{2} + (1-p_1)\left(2^{s_1} + c_2\right) \\
\ldots & \\
c_{i-1} &= p_{i-1} \cdot \frac{2^{s_{i-1}}}{2} + (1-p_{i-1})\left(2^{s_{i-1}} + c_i\right) \\
c_i &= \frac{2^b}{2}
\end{aligned}$$

In the other case we have $b > s_i$ for all $s_i \in \mathcal{S}_0$ and c_1 is the solution of:

$$\begin{aligned}
c_1 &= p_1 \cdot \frac{2^{s_1}}{2} + (1-p_1)\left(2^{s_1} + c_2\right) \\
\ldots & \\
c_{k-1} &= p_{k-1} \cdot \frac{2^{s_{k-1}}}{2} + (1-p_{k-1})\left(2^{s_{k-1}} + c_k\right) \\
c_k &= p_k \frac{2^{s_k}}{2} + (1-p_k)2^{s_k}
\end{aligned}$$

In both cases one can again solve for $c_1 = c_1\left(\mathcal{S}_0; b\right)$ backwards. The overall average listening time is then obtained by conditioning on B:

$$c_1\left(\mathcal{S}_0\right) = \sum_{b \in \mathcal{B}} p_B(b) \cdot c_1\left(\mathcal{S}_0; b\right)$$

It is shown in the appendix (Section A.3) that for the average listening costs the following properties hold:

- For a given strategy / subset $\mathcal{S}_0 \subset \mathcal{B}$ the permutation with the smallest average listening costs is the one which is sorted according to descending listening orders.
- The average listening costs are *not* monotonically increasing with the costs of the strategy. As one example, for $\mathcal{S}_0 = \{0, 1, 2, \ldots, 11\}$ with $c(\mathcal{S}_0) = 4095$ the average costs given by the Markov model are ≈ 823.16 slots, whereas for $\mathcal{S}_0 = \{12\}$ with $c(\mathcal{S}_0) = 4096$ we have average costs of ≈ 716.77 slots.

Please note that both $h_1(\mathcal{S}_0)$ and $c_1(\mathcal{S}_0)$ depend on the distribution $p_B(\cdot)$ of the beacon orders. Since for IEEE 802.15.4 we have $B_{\text{max}} \leq 14$ it is possible to calculate these expressions numerically with moderate effort.

4.4 Model validation and evaluation

In this section we provide some numerical examples. Please note that all listening costs (average and maximum) are expressed in slots, with one slot corresponding to a listening duration of $aBaseSuperframeDuration = 15.36$ ms. Within one second around 65 slots can be accommodated. In all of the following examples we assume that the mobile BSN chooses its beacon order B according to a uniform distribution over $\mathcal{B}$.

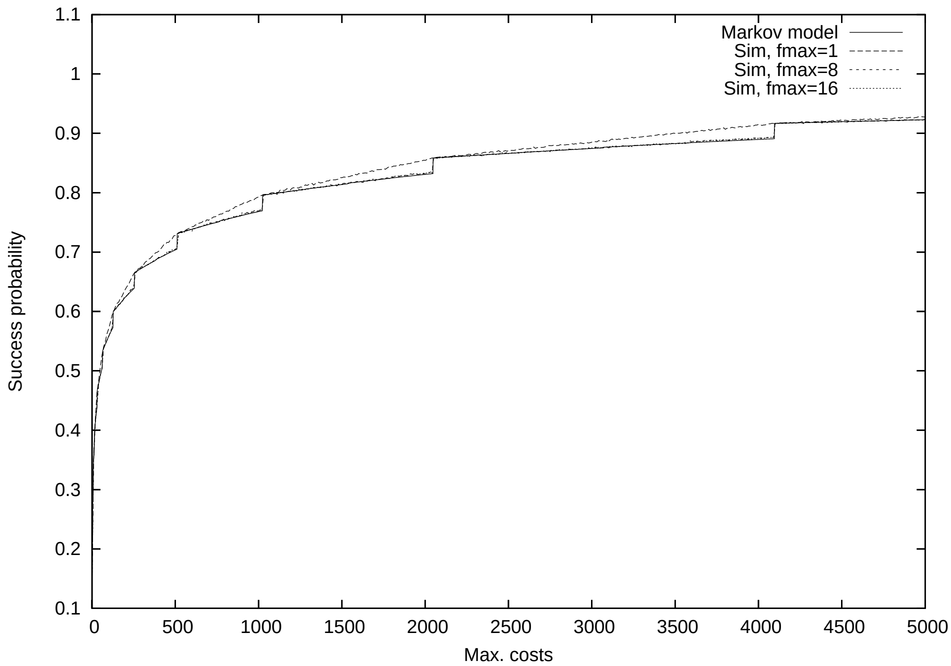

Figure 4.3: Comparison of detection probability predicted by the Markovian model with detection probability obtained by simulation for three different values of $F_{\text{max}} \in \{1, 8, 16\}$, $B_{\text{max}} = 14$ and for varying listening strategy $\mathcal{S}_0$ / allowable maximum costs $c(\mathcal{S}_0)$.

4.4.1 Model validation

We first validate the Markovian model presented in Section 4.3 against results obtained from a simple simulation model implemented in Common Lisp [21, 22]. The mobile BSN is assumed to be present, $B_{\text{max}} = 14$ and the beacon order distribution $p_B(\cdot)$ is uniform over $\mathcal{B}$.

In the simulation model the mobile BSN picks a frequency channel uniformly from $\{1, 2, \ldots, F_{\text{max}}\}$, a beacon order uniformly from $\{1, 2, \ldots, 14\}$ and a phase shift Φ uniformly from the time interval specified by the chosen beacon period. The listener starts at channel 1 and visits the channels according to the sweep orders given by a particular listening strategy $\mathcal{S}_0$. The simulator tests whether any of the generated beacons on the mobile BSNs channel would fall into one of the listening periods on this channel. If so, the simulator notifies a success and notes the time that the listener has listened *on this particular channel* when searching for the mobile BSN (the time spent on all other channels is not counted). Otherwise, the simulator notifies a failure and counts the whole listening costs $c(\mathcal{S}_0)$. For fixed $\mathcal{S}_0$, a number of 250,000 repetitions of this experiment have been made. Three different values for F_{max} have been considered: $F_{\text{max}} \in \{1, 8, 16\}$, and for each of these values we vary the allowed maximum costs $c(\mathcal{S}_0)$ of the listening strategy and therefore (by the one-to-one correspondence between listening strategies $\mathcal{S}_0$ and their costs $c(\mathcal{S}_0)$) the listening strategy itself.

In Figure 4.3 we show the obtained detection probability versus the allowed maximum costs. The following points are remarkable:

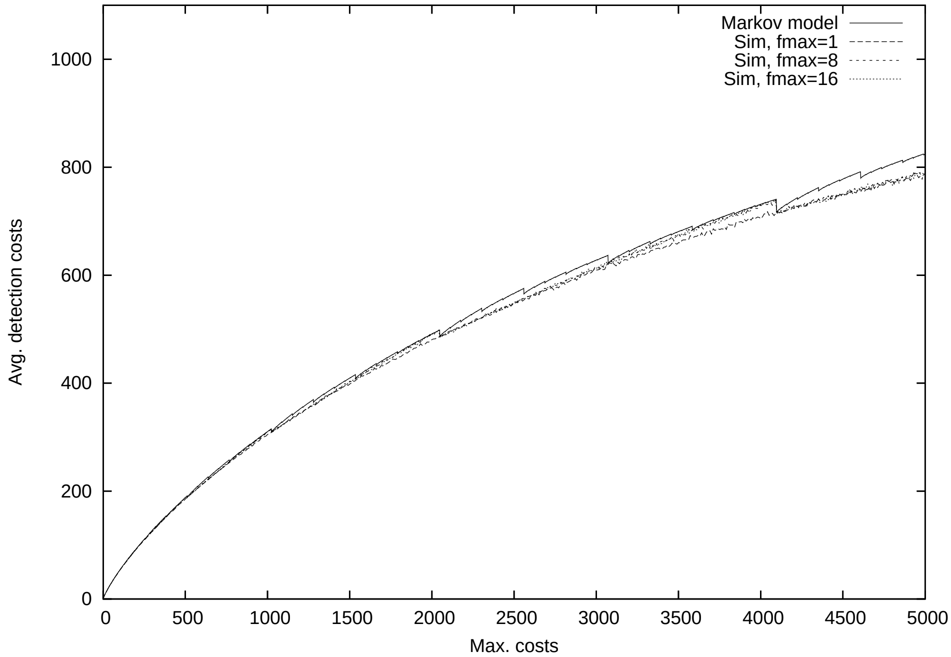

Figure 4.4: Comparison of average detection costs predicted by the Markovian model with average detection costs obtained by simulation for three different values of $F_{\text{max}} \in \{1, 8, 16\}$, $B_{\text{max}} = 14$ and for varying listening strategy $\mathcal{S}_0$ / allowable maximum costs $c(\mathcal{S}_0)$.

	Detection Probability	Avg. Costs
Model, strategy $\{2, 5, 6\}$	0.8878	24.977
Measurements, strategy $\{2, 5, 6\}$	0.8933	24.8
Model, strategy $\{3, 5\}$	0.779	15.10
Measurements, strategy $\{3, 5\}$	0.7789	15.33

Table 4.1: Comparison of model prediction with measurement results for two selected listening strategies, and $F_{\max} = 8$, $B_{\max} = 8$

- When $F_{\max} \in \{8, 16\}$, the Markovian model and the simulation model show very good agreement, whereas for $F_{\max} = 1$ there are noticeable differences between simulation and Markov model. Please note that in the case $F_{\max} = 1$ the listener stays all the time on one channel and the independence assumption for the subsequent listening periods on this single channel is not true anymore. For $F_{\max} \in \{8, 16\}$, however, the interruption of the listening activities on one channel through listening on all other ones makes the independence assumption a good approximation.
- Both the Markov model and the simulation model for $F_{\max} \in \{8, 16\}$ show jumps at certain points. The visible jump points occur at powers of two, for example for $\mathcal{S}_0 = \{10, 9, \ldots, 1, 0\}$ with $c(\mathcal{S}_0) = 2047$ we have $h_1(\mathcal{S}_0) \approx 0.832$, whereas for $\mathcal{S}_0 = \{11\}$ with $c(\mathcal{S}_0) = 2048$ we have $h_1(\mathcal{S}_0) \approx 0.858$, i.e. an increase of more than 2.5%. The reason for this is that with the inclusion of a higher-order listening period replacing several lower-order periods, we gain the ability to reliably detect mobile PANs with beacon orders of eleven without losing the ability to detect all beacon orders ≤ 10 reliably. In contrast, with 10 being the highest beacon order, mobile PANs with beacon order eleven are not reliably detected and the loss of memory between different listening periods reduces the detection probability as compared to the case of subsequent listening ($F_{\max} = 1$).
- The comparison of the results for $F_{\max} \in \{8, 16\}$ and of the Markov model with those obtained for $F_{\max} = 1$ leads to the interpretation that the loss of memory between different listening phases is not beneficial in terms of the detection probability. This would in turn suggest that it is better to contiguously listen on one channel for all the listening periods of a strategy $\mathcal{S}_0$ before switching to the next channel, instead of switching channels after testing one listening period as is done in the strategies defined in Section 4.2.

In Figure 4.4 we show the achieved average costs for the Markov model and the simulation model with $F_{\max} \in \{1, 8, 16\}$. It can be seen that the Markovian model and the simulation results again achieve a very good agreement, although visually it is not as good as for the detection probabilities. Please note that the Markov model shows a sawtooth pattern which at some points is followed by the simulation results. This confirms again that the average costs are not monotonically increasing with the allowed maximum costs.

To further validate the Markov model, we have also performed experimental evaluations with the Telos-based CMDP-implementation. These measurements have been made in a very setup where both BSNs (searching BSN and mobile BSN) were very close to each other and where almost no packet losses have been observed. For the measurements we have set $F_{\max} = 8$ and $B_{\max} = 8$. We have investigated two different

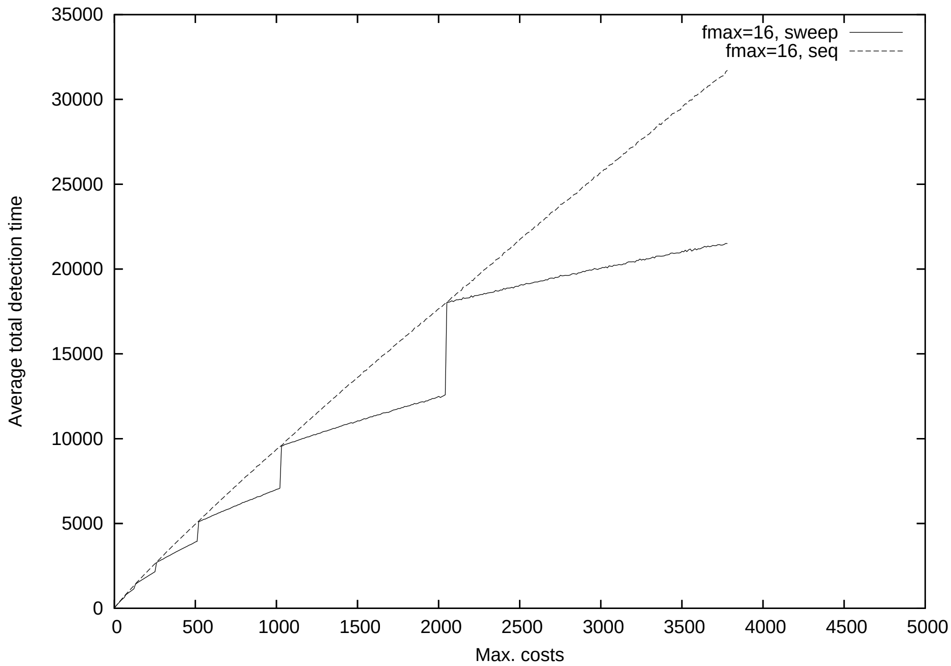

Figure 4.5: Comparison of total average detection time for the sweep strategy and the sequential strategy with $B_{\text{max}} = 14$ and $F_{\text{max}} = 16$

strategies, namely $\mathcal{S}_0 = \{2, 5, 6\}$ with $c(\mathcal{S}_0) = 100$ and furthermore $\mathcal{T}_0 = \{3, 5\}$ with $c(\mathcal{T}_0) = 40$. For each of these strategies 10,000 independent repetitions of the experiment have been made. The experiments have been carried out at a weekend in our institute building to reduce the influence of external interference. The results are listed in Table 4.1. There is a very good agreement between model and experiments.

4.4.2 Tradeoff between detection probability and total listening costs

We next want to shed a light on a certain design aspect of the considered class of strategies. In our sweeping approach, for a given strategy $\mathcal{S}_0 = \{s_1, s_2, \ldots, s_k\}$ we first choose listening order s_1 and listen subsequently on all channels for a time corresponding to this listening order. Then the next listening order s_2 is tried and so on. In the following we refer to this approach as the *sweep strategy*. An alternative would be to start on the first channel, subsequently try all defined listening orders s_i and then to switch to the next channel. We refer to this strategy as the *sequential stratey*. The sequential strategy would in fact be favorable in terms of the success probability, as we have elucidated in Figure 4.3, where the sequential strategy would correspond to $F_{\text{max}} = 1$. For these two strategies we compare the *total average time* until a mobile BSN (that is assumed to be present) is detected. In contrast to the previously discussed results for the average listening costs, this total time includes the listening time on *all* channels and accounts also for those channels which the mobile has not selected. The results are obtained by simulation, the same setup as before has been used. They are shown in Figure 4.5. It can be seen that the sweep strategy is on average significantly better than the sequential strategy, the only points where the two strategies meet are

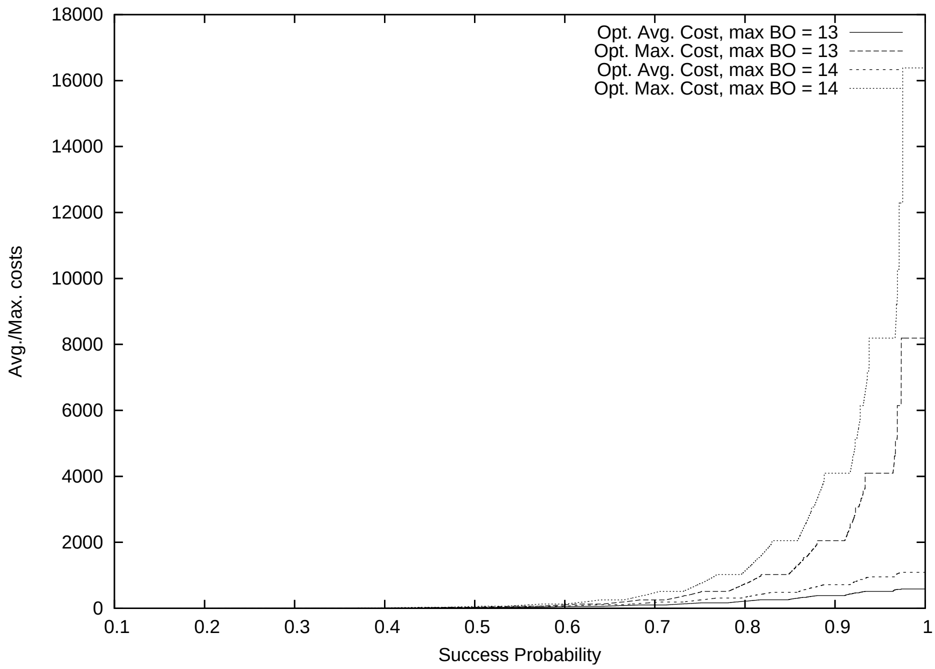

Figure 4.6: Best achievable average and maximum costs for given desired detection probability, uniform beacon order distributions with $B_{\max} = 13$ and $B_{\max} = 14$

those where the set of listening orders consists of just one element.

In summary, we can observe a tradeoff between detection probability and average listening costs: whenever the listening order set includes more than one element, our proposed sweep strategy has lower average total detection times but also lower detection probability. On the other hand, when the listening order set includes only one element, average total costs and detection probability agree. Therefore, a system designer that chooses to include more than one listening order into his listening strategy must decide which of the two performance measures is more important to him.

4.4.3 Influence of maximum beacon order

In the next evaluation of the Markovian model we compare model results for two different maximum beacon orders. Specifically, we consider $F_{\max} = 1$ and the two maximum beacon orders $B_{\max} = 13$ and $B_{\max} = 14$. We furthermore assume that the mobile is present.

In Figure 4.6 we determine for a given prescribed detection probability the policy which achieves this probability with the minimum average listening costs and for this policy we show both the average listening costs and the policy costs. For some selected detection probabilities the corresponding results are also listed in Tables 4.2 for $B_{\max} = 13$ and 4.3 for $B_{\max} = 14$. The following points are remarkable:

- The results show that by reducing $B_{\max}$ from 14 to 13 substantial energy savings / listening time savings can be achieved. This suggests that the largest beacon orders should be avoided in the configuration of mobile BSNs.

Required Det. Prob.	Avg. Cost	Max. Cost	$\mathcal{S}_0$
0.5	20.006235	33	$\{5, 0\}$
0.6	51.45266	105	$\{6, 5, 3, 0\}$
0.7	100.82143	256	$\{8\}$
0.8	217.945	744	$\{9, 7, 6, 5, 3\}$
0.9	383.9643	2048	$\{11\}$
0.95	511.9643	4096	$\{12\}$
0.99	585.1071	8192	$\{13\}$
0.999	585.1071	8192	$\{13\}$
1	585.1071	8192	$\{13\}$

Table 4.2: Best achievable average and maximum costs as well as the corresponding listening policies for selected prescribed detection probabilities, uniform beacon order distribution with $B_{\text{max}} = 13$.

Required Det. Prob.	Avg. Cost	Max. Cost	$\mathcal{S}_0$
0.5	33.680813	58	$\{5, 4, 3, 1\}$
0.6	65.06911	130	$\{7, 1\}$
0.7	180.42523	474	$\{8, 7, 6, 4, 3, 1\}$
0.8	338.30777	1131	$\{10, 6, 5, 3, 1, 0\}$
0.9	716.76666	4096	$\{12\}$
0.95	955.7	8192	$\{13\}$
0.99	1092.2333	16384	$\{14\}$
0.999	1092.2333	16384	$\{14\}$
1	1092.2333	16384	$\{14\}$

Table 4.3: Best achievable average and maximum costs as well as the corresponding listening policies for selected prescribed detection probabilities, uniform beacon order distribution with $B_{\text{max}} = 14$.

- For larger desired detection probabilities the averages are much smaller than the maximum costs, up to a factor of sixteen. This ratio, however, depends on the distribution $p_B(\cdot)$ of beacon orders.

4.5 A Bayesian approach to sequential listening

In this section we consider an alternative strategy, which resembles the sequential strategy discussed in Section 4.4.2. Fix a channel. The goal is to listen on this channel for a time long enough so that we either find a mobile BSN or are with high probability sure that no mobile BSN is present, or at least none with a reasonably low beacon order.

We utilize the theorem of Bayes [23]. For ease of exposition we encode the possibility that no mobile BSN is present as it having a beacon order $B_{\text{max}}+1$ and therefore the range of beacon orders is now the $\mathcal{B}' = \mathcal{B} \cup \{B_{\text{max}} + 1\}$. Let the random variable N_0 denote the number of subsequent empty slots that have been observed. From a simple application of Bayes theorem we obtain the following recursive relationship for the conditional probability of having a beacon order $B = b$ after observing $N_0 + 1$ empty slots, given the conditional probability of having a beacon order of $B = b$ after observing N_0 empty slots:

$$\begin{aligned} & \Pr\left[B = b \middle| N_0 = n + 1\right] \\ = \quad & \frac{\Pr\left[N_0 = n + 1 \middle| B = b, N_0 = n\right] \cdot \Pr\left[B = b \middle| N_0 = n\right]}{\alpha} \end{aligned}$$

where:[4]

- α is a normalizing constant chosen so that $\sum_{b \in \mathcal{B}'} \Pr\left[B = b \middle| N_0 = n + 1\right]$ sums up to one,
- $\Pr\left[B = b \middle| N_0 = n + 1\right]$ is called the posterior probability,
- $\Pr\left[N_n = n + 1 \middle| B = b, N_0 = n\right]$ is called the likelihood and
- $\Pr\left[B = b \middle| N_0 = n\right]$ is the prior.

The prior for $n = 0$ is simply given by

$$\Pr\left[B = b \middle| N_0 = 0\right] = \begin{cases} \partial \cdot p_B(b) & : \quad b \leq B_{\text{max}} \\ 1 - \partial & : \quad b = B_{\text{max}} + 1 \end{cases}$$

and the probability that the next slot is empty if the beacon order is b and the previous n slots have been empty as well is given by:

$$\Pr\left[N_0 = n + 1 \middle| B = b, N_0 = n\right] = \begin{cases} 0 & : \quad n \geq 2^b \\ 1 - \frac{1}{2^b - n} & : \quad n < 2^b \end{cases}$$

[4] This relationship can be easily seen as follows. We consider generic events M (which we regard as the "model") and two further events D_0, D_1 (which we regard as old observation, D_0, and having an updated observation, D_1. We then have:

$$\begin{aligned} \Pr\left[M \middle| D_0, D_1\right] &= \frac{\Pr\left[M, D_0, D_1\right]}{\Pr\left[D_0, D_1\right]} \\ &= \frac{\Pr\left[D_1 \middle| M, D_0\right] \cdot \Pr\left[M, D_0\right]}{\Pr\left[D_0, D_1\right]} \\ &= \frac{\Pr\left[D_1 \middle| M, D_0\right] \cdot \Pr\left[M \middle| D_0\right] \cdot \Pr\left[D_0\right]}{\Pr\left[D_0, D_1\right]} \end{aligned}$$

Setting $D_0 = \{N_0 = n\}$, $D_1 = \{N_0 = n + 1\}$ and $M = \{B = b\}$ and furthermore recognizing that $D_0 \subset D_1$ and therefore $\Pr\left[M \middle| D_0, D_1\right] = \Pr\left[M \middle| D_1\right]$ holds, gives the conjectured form.

∂	$n^*(0.01)$	$n^*(0.05)$	$n^*(0.1)$
0	246	199	128
0.01	246	197	127
0.05	244	189	121
0.1	242	177	113
0.2	237	150	94
0.3	230	124	69
0.4	222	109	53
0.5	209	87	34

Table 4.4: Minimum number $n^*(\epsilon)$ of slots that are needed to exclude mobile BSNs with beacon order of eight or less with maximum error probability of ϵ for varying ∂ and uniform beacon order distribution with $B_{\max} = 13$.

∂	$n^*(0.01)$	$n^*(0.05)$	$n^*(0.1)$
0	243	185	119
0.01	243	183	117
0.05	241	174	111
0.1	239	162	102
0.2	234	132	82
0.3	227	117	61
0.4	217	101	46
0.5	204	78	29

Table 4.5: Minimum number $n^*(\epsilon)$ of slots that are needed to exclude mobile BSNs with beacon order of eight or less with maximum error probability of ϵ for varying ∂ and uniform beacon order distribution with $B_{\max} = 14$.

Using these relationships we can, for given initial beacon order distribution $p_B(\cdot)$ and presence probability ∂, obtain a new probability distribution $\Pr[B = b | N_0 = n+1]$ of having a beacon order $B = b$ after $n+1$ observed empty slots, given the probability distribtion $\Pr[B = b | N_0 = n]$ of having $B = b$ after n empty slots.

We conclude this section by showing some numerical results for the Bayesian approach. Suppose that we are interested in finding "agile" mobile BSNs that have beacon orders of eight or less. We choose the uniform distribution with either $B_{\max} = 13$ or $B_{\max} = 14$ as prior distribution for the beacon orders, and we vary the probability ∂ that no mobile BSN is present. We are interested in the minimum number of empty slots that a listener must observe so that the hypothesis "no mobile BSN of beacon order eight or less is present" is true with an error probability of no more than $\epsilon > 0$. We refer to ϵ as the *error probability*. We are therefore interested in determining

$$n^*(\epsilon) = \min_{n \geq 0} \left\{ \sum_{b=0}^{8} \Pr[B = b | N_0 = n] < \epsilon \right\}$$

The results for the two investigated values of $B_{\max}$ and different error probabilities are shown in Tables 4.4 and 4.5, respectively. It can be observed that both ϵ and ∂ have an influence. For fixed ∂ the number $n^*(\epsilon)$ decreases significantly with relaxing the error probability ϵ.

Chapter 5

Passive BSN discovery – the Multiple-listener case

In this chapter we consider the usage of multiple listeners for searching a foreign BSN. More specifically, the main question is how the multiple listeners should divide the work among each other. Suppose that $N \geq 1$ helpers are available. For a given set $\mathcal{F} = \{1, 2, \ldots, F_{\text{max}}\}$ of available frequency channels we investigate two different options:

- *Partitioned listening*: In the first option the set of channels is subdivided into N nearly equal-sized partitions and to each listener one partition is assigned.
- *Overlapping listening*: In the second option each listener listens on all channels, but their start channels are spaced evenly.

If all channels and all transceivers are identical, there should be no significant difference between the average detection times obtained with either strategy. However, in practice we expect that the overlapping listening strategy has significant advantages over the partitioned listening strategy: it allows to exploit spatial diversity [24] and it can compensate hardware varieties.[1] In the partitioned strategy, if the foreign BSN is located on a frequency channel for which the associated listener has a very bad transceiver or which is currently shadowed, no other helper node can help.

[FIX!][2]

5.1 Experimental setup

The experimental setup used to obtain the discovery and relay delay is illustrated in Figure 5.1. A foreign PAN consisting only of one coordinator is connected via USB with a computer. The home PAN consists of the home coordinator and multiple devices. In our experiments, we use all these devices as helper nodes, their number depends on the number of helper nodes specified in the parameter set of the experiment. All nodes of the home PAN are also connected to the computer via USB. The helpers are placed in a row with distances of 5cm between them.

[1] As a matter of fact, we have often observed that different sensor nodes of the same type (vendor, brand) show significantly different behaviour. For example, everything else being equal, different receiver sensor nodes can exhibit vastly different packet loss rates for the same transmitter and at the same receiver location.

[2] **[AW]:** We should also show some results on the relay delay in this chapter

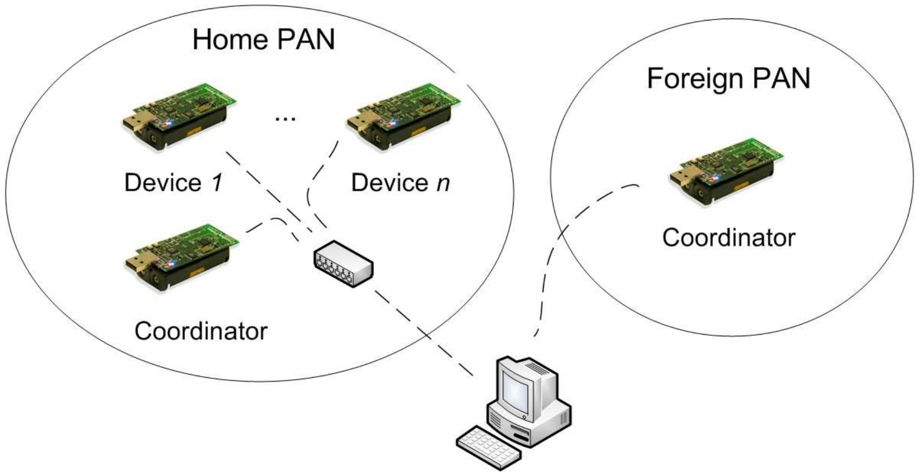

Figure 5.1: Experimental setup

The hardware platform used in the experiments was the Tmote Sky platform [25]. To avoid the necessity of synchronized nodes in order to take timestamps directly on each node, the timestamping is done on the computer for each serial message transmitted via USB from the sensor nodes. However, time measurement on the connected computer has the disadvantage of adding a (mostly) constant delay on each timestamp. A Java application is running on the computer controlling the sensor nodes and capturing incoming and outgoing serial messages. Prior to the start of each iteration of an experiment all nodes are initialized, this initialization includes the experimental parameters (number of helpers, beacon order) and furthermore the nodes are provided with different settings for their local random number generators. When all nodes are configured, the home coordinator starts the PAN and each device is instructed to associate with it. The foreign PAN is started after a random uniformly distributed waiting time. The foreign PAN selects a frequency channel randomly according to a uniform distribution out of the 15 unused channels. Therefore, the home and foreign PAN will never operate on the same channel. We have made the simplifying assumption that the foreign BSN always uses a beacon order of $B = 3$, and this is known to the home PAN.

A CMDP-DATA request is generated on the home coordinator at the same time at which the foreign PAN is started. The home coordinator instructs the configured number of helpers to perform a discovery. In case of the partitioning strategy a helper receives a list of channels to scan. For example, the 15 channels are in case of two helper nodes split into 7 and 8 channels. Each instructed node cycles through its channel list, restarting with the first if the end of the list is reached. On each channel it listens for a time corresponding to the beacon order $B = 3$, i.e. $\mathcal{S}_0 = \{3\}$. After 45 seconds a helper stops listening and returns no results. Whenever a helper discovers the foreign PAN, it reports back to the home coordinator. The home coordinator instructs the same number of devices as used during the discovery to relay the critical message to the discovered foreign coordinator.

The java application is capturing the complete communication to and from all nodes. However, there are three events which are interesting for computing the discovery and relay delay and which are consequently timestamped: (i) the CMDP-DATA request event is confirmed by the home coordinator; (ii) the home coordinator receives the discovery response from one of the instructed devices containing information about the discovered foreign PAN; and (iii) the foreign coordinator receives the relay request including the critical message. The discovery delay is defined as the difference between the timestamps for the second and the first event, the relay delay then as the difference in the timestamps of the third and the second event.

5.2 First experiment

In this first experiment the home BSN and the foreign BSN are located in the same room but with a distance at which transmission was less than perfect. The home BSN was located on a table in a height of 80 cm, the foreign BSN was located in 7m distance at a height of 2.5 m. For each number of helpers the measurements have been repeated 500 times. The transmit power of the foreign PAN coordinator has been configured to -25 dBm. The transmit power of the home PAN devices is -25 dBm. The home PAN coordinator uses -20 dBm to be better reachable. For the given distance, these transmit power settings give non-negligible packet loss rates.

In Figure 5.2 we show for a first set of experiments the average discovery delay for both strategies (partitioning and overlapping, for the partitioning strategy we show the results of two measurement runs) and varying numbers of helpers, and in Figure 5.3 we show the associated discovery probability (together with the total success probability to relay a message, including discovery and relay phase, to a foreign PAN). Please note that the delay values in Figure 5.2 include only the cases of successful discovery. From Figure 5.3 it can be seen that the overlapping strategy has significantly better detection probability than the partitioned strategy. In Table 5.1 we analyze the detection probability of the partitioning strategy on a per-node basis. The following observations can be made:

- In the case of two helpers we have a situation in which one node (node 12) completely fails to discover the foreign PAN. At the same time, node 12 always received eight channels to observe and node 7 only seven channels. Because both helper nodes were very close to each other and the path between both nodes and the foreign BSN was not obstructed, we attribute the differences to hardware varieties. The partitioning strategy suffers from this, whereas in the overlapping strategy the "good" sensor node 7 can compensate the weakness of node 12, which improves the detection probability (see also Table 5.2).

- The advantage in terms of average discovery delay that the partitioning strategy shows over the overlapping strategy in the two-helper case (see Figure 5.2) is an artifact of the convention to include only the discovery times of successful discoveries into the computation of the average listening time: in the partitioning strategy, when the foreign BSN falls in the frequencies allocated to node 7, on average only half of the frequencies allocated to node 7 (which is approximately one quarter of the total number of frequencies) are scanned, whereas in the overlapping strategy node 7 has to scan on average half of *all* available frequencies.

- In Figure 5.2) we can also observe that the average listening time for the partitioned strategy increases when three or four helpers are used. Consider the case of four helpers (see Table 5.1). One of the helpers (node id 27) shows very good performance, it always finds the mobile BSN. There are two other helpers, nodes 7 and 26, which find the mobile BSN only occasionally, but in the majority of the experiments they do not find him. As a possible explanation is that nodes 7

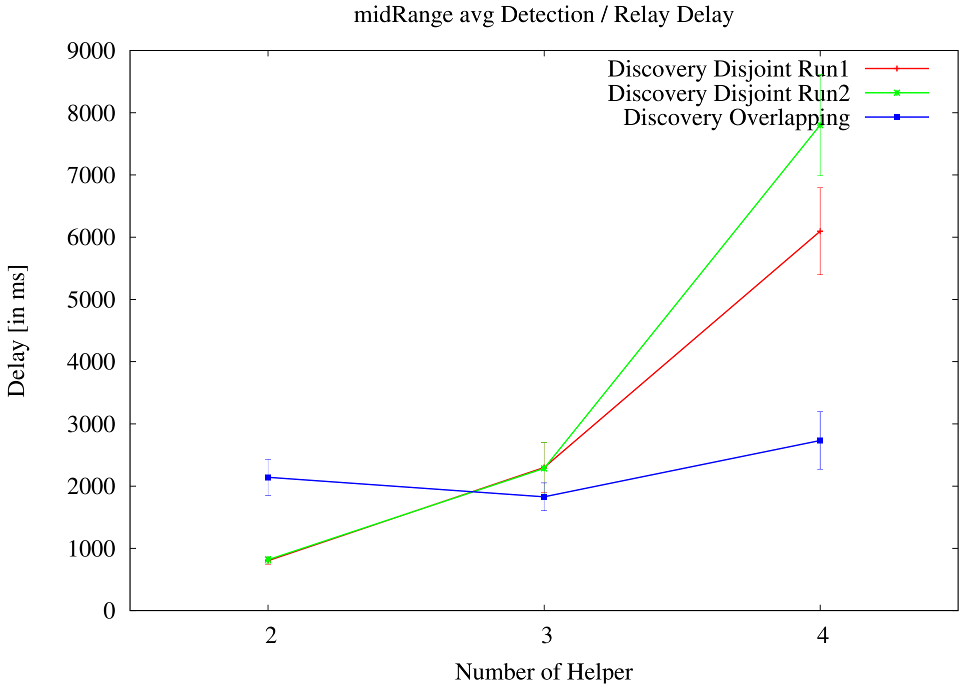

Figure 5.2: First experiment: Measured average discovery and relay delay for the overlapping listening strategy (one measurement of 500 repetitions) and the partitioned listening strategy (two runs) for varying number of helper nodes

and 26 experience comparably high packet loss rates and therefore need longer time on average before they detect the mobile BSN, thus contributing to higher average delays.

Please note that Figure 5.2 also shows the relay delay. The relay delay is measured between the time where the home coordinator acquires knowledge about successful discovery of a foreign PAN, and the time where the foreign PAN coordinator receives the message. It can be seen that the relay delay is substantially lower than the average discovery delays.

In Figure 5.3 we compare the discovery probabilities and the total success probabilities (including discovery and relay) of the different strategies. It can be seen that for both strategies the total success probability is always very close to the discovery probability. Stated differently: once the foreign PAN is discovered, the relay phase succeeds with high probability, and the total success probability is dominated by the discovery probability.

5.3 Second experiment

The measurement setup of the second experiment is identical to the setup of the first experiment, except that the (bad) node 12 is not used for discovery anymore and has been replaced by node 14. From Tables 5.3 and 5.4 it can be seen that node 14 is much

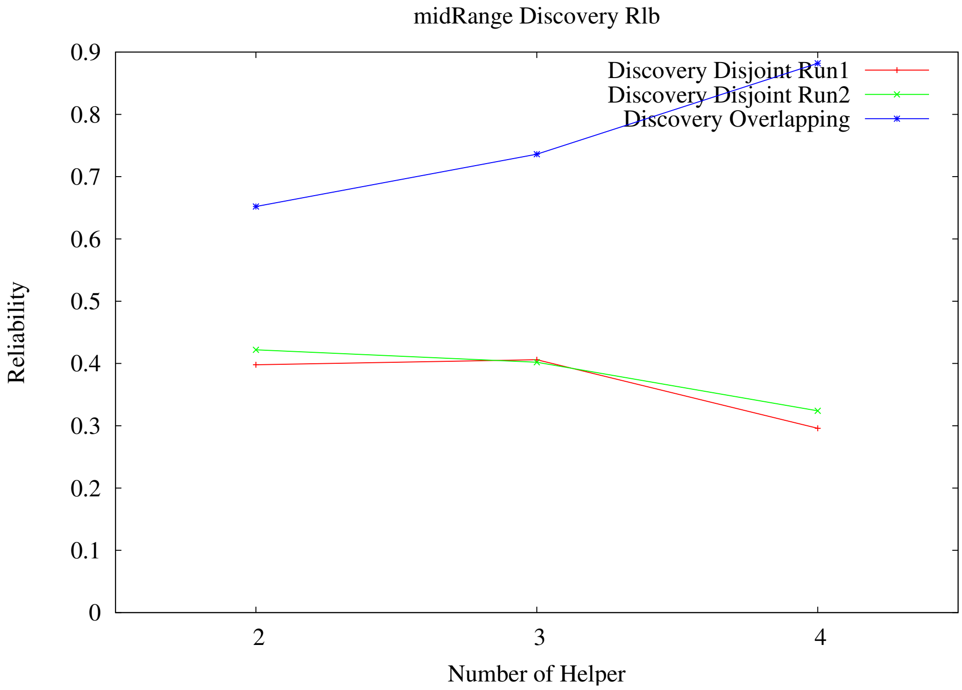

Figure 5.3: First experiment: Measured average detection probability for the overlapping listening strategy (one measurement of 500 repetitions) and the partitioned listening strategy (two runs) for varying number of helper nodes

Num. helpers	Node id	Discoveries	Failed	Max. Success
2	7	224	0	224
2	12	0	276	276
3	7	109	50	159
3	12	0	174	174
3	26	94	73	167
4	7	50	82	132
4	12	0	141	141
4	26	12	129	141
4	27	86	0	86

Table 5.1: First experiment: Per-node analysis of success and failures for the partitioned strategy (Run 1). Column **Discoveries** indicates how often a node has discovered the foreign PAN. Column **Failed** indicates how often a node should have discovered the foreign PAN (because it scans its frequency) but hasn't succeeded, and **Max. Success** indicates how often the foreign PAN was operating in one of the frequencies assigned to a node.

Num. helpers	Node id	Discoveries
2	7	328
2	12	3
3	7	221
3	12	0
3	26	151
4	7	227
4	12	0
4	26	37
4	27	186

Table 5.2: First experiment: Per-node analysis of success and failures for the overlapping strategy. Column **Discoveries** indicates how often a node has discovered the foreign PAN.

better than node 12.

In Figure 5.4 we show the average discovery delay and relay delay for the partitioned and overlapping strategies, whereas in Figure 5.5 the discovery probability and the total success probability are shown. The following points are noteworthy:

- If we compare the average relay delays, we can see that there are almost no differences to the first experiment: if a foreign PAN has been discovered, relay commences in a time below one second for both strategies and all numbers of helpers.

- If we compare the average discovery delays one can see that for the overlapping strategy the difference between experiment one and experiment two are not so pronounced (in both experiments the average discovery time fluctuates in the range between 1.5 and 2.5 seconds), whereas for the partitioning strategy we can observe a significant reduction as compared to the first experiment. We attribute this to the replacement of the bad node 12 by the better node 14. This indicates that the performance of the partitioning strategy is very sensitive against varieties in node qualities, whereas the overlapping strategy is relatively insensitive.

- From looking at the achieved discovery and total success probabilities, one can see for the overlapping strategy that both probabilities are almost the same, and, as compared to the first experiment, the discovery probability of the overlapping strategy is slightly improved. Clearly, the overlapping strategy benefits from the replaced node. The improvement for the partitioned strategy, however, is much larger: in the first experiment the discovery probability was in the range between approximately 0.3 to 0.5, whereas for the second experiment it is now in the range of 0.7 to 0.9. Again, the partitioned strategy seems to be more influenced by the node variety.

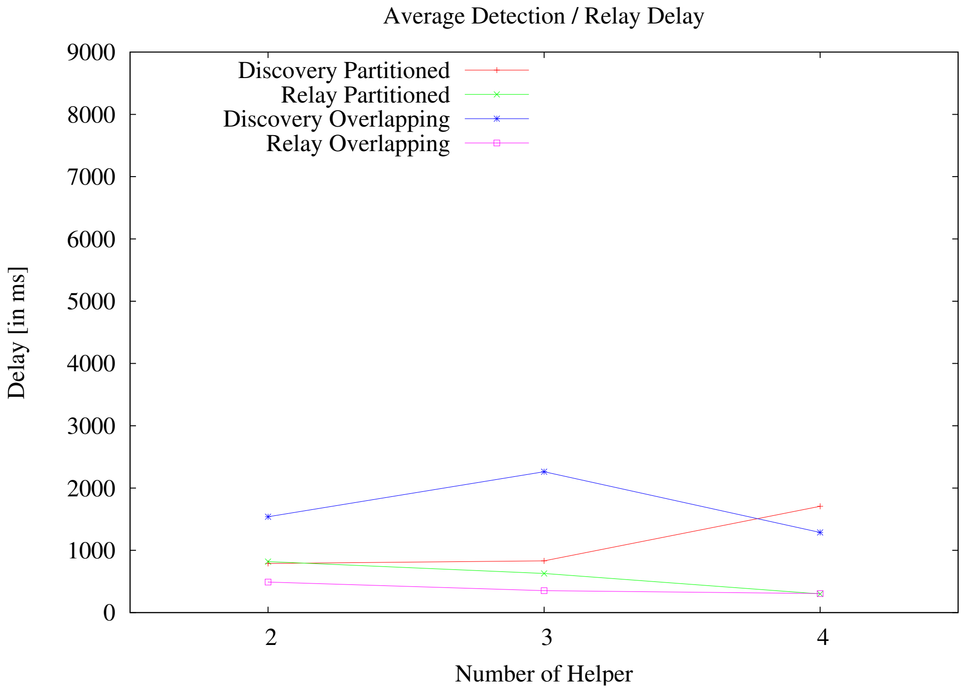

Figure 5.4: Second experiment: Measured average discovery delay for the overlapping listening strategy and the partitioned listening strategy for varying number of helper nodes

Num. helpers	Node id	Discoveries	Failed	Max. Success
2	7	247	0	247
2	14	206	47	253
3	7	97	52	149
3	14	174	0	174
3	26	104	73	177
4	7	130	1	131
4	14	116	0	116
4	26	33	119	152
4	27	101	0	101

Table 5.3: Second experiment: Per-node analysis of success and failures for the partitioned strategy. Column **Discoveries** indicates how often a node has discovered the foreign PAN. Column **Failed** indicates how often a node should have discovered the foreign PAN (because it scans its frequency) but hasn't succeeded, and **Max. Success** indicates how often the foreign PAN was operating in one of the frequencies assigned to a node.

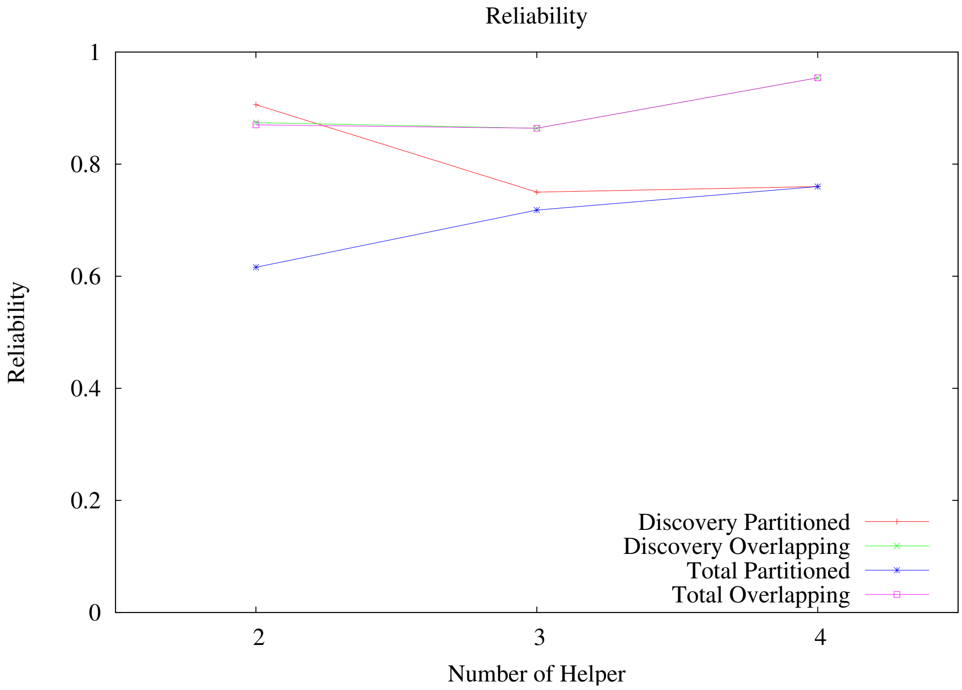

Figure 5.5: Second experiment: Measured average detection probability for the overlapping listening strategy and the partitioned listening strategy for varying number of helper nodes

Num. helpers	Node id	Discoveries
2	7	339
2	14	98
3	7	266
3	14	81
3	26	85
4	7	220
4	14	61
4	26	51
4	27	145

Table 5.4: Second experiment: Per-node analysis of success and failures for the overlapping strategy. Column **Discoveries** indicates how often a node has discovered the foreign PAN.

Chapter 6

Related work

In [26]**[FIX!]**[1] different approaches to interconnect IEEE 802.15.4 clusters to multi-cluster networks are described and analyzed. The communication is accomplished through shared nodes called bridges. Two different kind of bridges were considered: master-slave and slave-slave bridges.

In case of the master-slaves approach the bridge nodes are the coordinators of the interconnected clusters. The clusters operate in the beacon enabled mode with a superframe configuration consisting of an active and inactive period. The intercluster communication should take place in the inactive period of the source cluster and the active period of the sink cluster. This approach requires aligning of superframes of the partipating clusters. Since the bridges are also acting as coordinator in their own cluster, they can only spend a single active period in the sink cluster before returning and resuming the coordinator role.

The bridges in the slave-slave approach are ordinary nodes. The slave-slave bridge is not limited in the time connected to a sink cluter or in the number of interconnected clusters in contrast to the master-slave bridge. Furthermore, the interconnected cluster may operate independently. Superframes have not to be aligned and cluser may use different superframe configurations. The cluster coordinators do not have to be in transmission range allowing the clusters to be spaced further away.

Two possible ways to deliver data to the sink are proposed. Since all clusters operate in the beacon enabled mode a bridge may transmit data in the CAP using CSMA-CA and competing with other nodes for medium access or in the CFP using GTS which have to be requested from the sink coordinator.

The temporary interconnection of ZigBee PANs is described in [27]. Before the PANs are able to interconnect the PAN detection takes place. The approach to find a PAN in radio range depends on which channels the PANs are operating. If both use the same channel, PANs should detect each other by receiving beacon frames with the PAN coordinator subfield set and not matching the stored PAN Id or coordinator address. In case two PANs are operating on different channels the use of the active and energy detection scan is proposed without any discovery strategy.

Three different PAN interconnection methods are described: PAN bridge, PAN merge and Peer-to-Peer network usage. In the PAN bridge approach two PANs are interconnected by a single brigdge node. If both PANs operate on different channels the bridge should act in both PANs using time division. The bridge node alternately associates to the interconnected PANs, but only have to do an association process once

[1] **[NK]:**discovery ja/nein; relay vorgang genau beschreiben? sync hier sync da?

with each coordinator. In further interconnection the bridge can speed up the association by using the ZigBee rejoining procedure. In the PAN merge approach, two PANs are temporarily merged into one PAN. If they are operating on the same channel, one coordinator changes its role as router and joins the other PAN. If different channels are used, all nodes of one PAN change the channel and join the other PAN. In the Peer-to-Peer network the beacon mode is not used and it is assumed that both PANs operate on the same channel. Devices can communicate with each other if they are in communication range.

An analytical framework based on a Markov Model for finding a tradeoff between energy efficiency and discovery timeliness for neighborhood detection in self-organizing ad hoc and sensor networks is developed in [28]. Nodes searching for others nodes in reach perform a set of procedures which is called *Hunting Process*. The *Hunting Process* consists of two modes: the Inquiry and the Inquiry Scan mode. In the Inquiry mode the node broadcasts beacon messages in order to enable the detection by other nodes that are in the Inquiry Scan mode.

The concept of opportunistic message relaying has for example been investigated in the EU-IST HAGGLE project, see also [29], [30], [9]. In [31] the ZebraNet system is described, which can be considered as an early practical system based on opportunistic message relaying. Information-theoretic investigations regarding the achievable capacities can for example be found in [32]. In [33] the data mule approach is presented, in which not all networks are considered to be mobile, but instead mobile nodes visit stationary nodes and pick up their data for delivery at a base station. All these publications, however, consider the problem on the level of individual network nodes, whereas in our CMDP protocol multiple helper nodes present in a body sensor network can be used in parallel to search for other networks and relay data to them.

Chapter 7

Conclusions

In this report we have presented CMDP, a protocol which helps to use mobile IEEE 802.15.4-based body sensor networks as data mules by providing key functionalities like discovery of foreign BSNs and the transfer of data into foreign BSNs. A key concept which sets apart CMDP from the existing mechanisms in IEEE 802.15.4 is that in CMDP multiple helpers can be used to detect other BSNs and to transfer data to them. This provides additional robustness and reliability.

We have secondly investigated the passive discovery of beacon-enabled IEEE 802.15.4 PANs. Our results for the considered listening strategy opens up a tradeoff between detection reliability and listening costs. However, it must be kept in mind that for many scenarios, especially when the foreign PAN uses higher beacon orders, the detection times can be very high, or vice versa, the detection probability for given time budget can be low. This calls either for restricting the set of allowed beacon orders (i.e. making B_{max} smaller) or to design active discovery approaches which operate in the beaconed mode of 802.15.4. This, however, is a subject of future work.

Appendix A

Properties of the Markov model

In this appendix we state and prove some important properties of the Markovian model given in Chapter 4. For the convenience of the reader, we repeat here the definition of the Markov model: for a given listening strategy $\mathcal{S}_0 = \{s_1, s_2, \dots, s_k\} \subset \mathcal{B}$ the state space of the model is given by:

$$\mathcal{S} = \{succ, fail\} \cup \mathcal{S}_0$$

and the possible state transitions are shown in Figure 4.2. The start state is s_1. For the time being, we do not impose any restrictions on the ordering of the s_i, i.e. we do not fix any permutation of $\mathcal{S}_0$.

When the mobile BSN is present and has beacon order $B = b$, the probability to find the mobile BSN when the listener is in state s_i (i.e. it listens on one channel for a duration of 2^{s_i} slots) is due to the independence assumption with respect to previous listening periods and the zero-error assumption given by:

$$p_i = \begin{cases} 1 & : \quad s_i \geq b \\ \frac{2^{s_i}}{2^b} & : \quad s_i < b \end{cases}$$

and the state transition matrix of the Markov chain is given by:

$$\mathbf{P} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & 0 & 0 & \dots & 0 \\ p_1 & 0 & 0 & 1-p_1 & 0 & \dots & 0 \\ p_2 & 0 & 0 & 0 & 1-p_2 & \dots & 0 \\ \dots & & & & & & \\ p_{k-1} & 0 & 0 & 0 & 0 & \dots & 1-p_{k-1} \\ p_k & 1-p_k & 0 & 0 & 0 & \dots & 0 \end{pmatrix}$$

where the first two rows correspond to the states $succ$ and $fail$, respectively, and the further rows correspond to states $s_1, s_2, \dots, s_k$.

In this appendix, we fix the value $B = b$.

A.1 Average success probabilities and average listening times

We define the *average success probability* (also referred to as *detection probability*) of the listening strategy $\mathcal{S}_0$ as the probability to reach the (absorbing) success state

$succ$ after starting the chain in state s_1. Using the terminology defined in [19, Sec. 1.3] we define the *hitting time* to reach the state subset $\mathcal{A} = \{succ\}$ as $H^{\mathcal{A}} = \inf_{n \geq 0} \{X_n \in \mathcal{A}\}$ and the hitting probability to ever reach the state subset $\mathcal{A}$ when the chain starts in state s_i as

$$h_i = \Pr\left[H^{\mathcal{A}} < \infty \middle| X_0 = s_i\right].$$

With this definition, the hitting probability is just the average success probability defined above. According to [19, Theorem 1.3.2] the vector of hitting probabilities satisfies the following set of linear equations:

$$h_i = \begin{cases} 1 & : \quad i \in \mathcal{A} \\ \sum_{j \in \mathcal{S}} p_{i,j} \cdot h_j & : \quad i \notin \mathcal{A} \end{cases}$$

In our case this leads to the following set of equations:

$$\begin{aligned} h_{succ} &= 1 \\ h_{fail} &= 0 \\ h_1 &= p_1 + (1 - p_1)h_2 \\ h_2 &= p_2 + (1 - p_2)h_3 \\ \dots & \\ h_{k-1} &= p_{k-1} + (1 - p_{k-1})h_k \\ h_k &= p_k \end{aligned} \tag{A.1}$$

This can be solved backwards for $h_1 = h_1(\mathcal{S}_0; b)$, which is our desired average success probability. After conditioning over the random variable B, the overall average success probability is given by:

$$h_1(\mathcal{S}_0) = \sum_{b \in \mathcal{B}} p_B(b) \cdot h_1(\mathcal{S}_0; b)$$

Since for $s_i < b$ we have $0 < p_i < 1$ it is straightforward to check that for the average success probability we have:

- $h_1 < 1$ if $s_i < b$ for all $s_i \in \mathcal{S}_0$
- $h_1 = 1$ if $s_i \geq b$ for some $s_i \in \mathcal{S}_0$

For the derivation of the *average listening costs* we again assume that $B = b$ in order to use the Markov chain developed for the average success probability. As before, the overall average listening time on one particular channel is then obtained by conditioning on B. We approach this question by resting on first-step analysis [20, Sec. 3.4]. In a nutshell, one conditions (by the law of total probability) on the state of the Markov chain after one step, and from now on, by the Markov property, we can look at the chain $X_1, X_2, X_3, \dots$ as being a whole new Markov chain with known start state.

We first analyze the case where $b \leq s_i$ for some $s_i \in \mathcal{S}_0$ and assume that s_i is the first such value in $\mathcal{S}_0$. In any state $s_j < s_i$ we have with probability $p_j = \frac{2^{s_j}}{2^b}$ a success and in this case, by the assumption of a uniformly distributed phase shift Φ, the average listening costs c_j are half of the duration 2^{s_j}. With probability $1 - p_j$ we have no success in state s_j and therefore we have to listen for the full duration 2^{s_j} plus the whole average listening costs in the next state s_{j+1}. Summarizing and considering the border case we have:

$$
\begin{aligned}
c_1 &= p_1 \cdot \frac{2^{s_1}}{2} + (1 - p_1)\left(2^{s_1} + c_2\right) \\
\dots & \\
c_{i-1} &= p_{i-1} \cdot \frac{2^{s_{i-1}}}{2} + (1 - p_{i-1})\left(2^{s_{i-1}} + c_i\right) \\
c_i &= \frac{2^b}{2}
\end{aligned}
$$

In the other case we have $b > s_i$ for all $s_i \in \mathcal{B}$. A similar analysis leads to the equations

$$
\begin{aligned}
c_1 &= p_1 \cdot \frac{2^{s_1}}{2} + (1 - p_1)\left(2^{s_1} + c_2\right) \\
\dots & \\
c_{k-1} &= p_{k-1} \cdot \frac{2^{s_{k-1}}}{2} + (1 - p_{k-1})\left(2^{s_{k-1}} + c_k\right) \\
c_k &= p_k \frac{2^{s_k}}{2} + (1 - p_k) 2^{s_k}
\end{aligned}
$$

In both cases one can again solve for $c_1 = c_1(\mathcal{S}_0; b)$ backwards and c_1 is then just the average listening costs.

A.2 Properties of the success probability

- Property **P1** – *Invariance against permutations*: For a given $\mathcal{S}_0 = \{s_1, s_2, \dots, s_k\} \subset \mathcal{B}$ the success probability $h_1 = h_1(\mathcal{S}_0; b)$ does not depend on the order in which the s_i are tested, i.e. it is the same for all permutations of $\{s_1, s_2, \dots, s_k\}$. Since one permutation can be transformed into any other permutation by applying a sequence of simple permutations in which only neighbored elements are swapped, it suffices to check the claim for two permutations

  $$
  \begin{aligned}
  \pi_1 &= (s_1, s_2, \dots, s_{i-1}, s_i, s_{i+1}, s_{i+2}, \dots, s_k) \\
  \pi_2 &= (s_1, s_2, \dots, s_{i-1}, s_{i+1}, s_i, s_{i+2}, \dots, s_k).
  \end{aligned}
  $$

  We first consider the case $i = k - 1$, i.e. only the last two elements are swapped. In this case, from Equations A.1 we get for the last two lines:

  $$
  \begin{aligned}
  h_{k-1} &= p_{k-1} + (1 - p_{k-1}) p_k \\
  &= \frac{2^{b+s_{k-1}} + 2^{b+s_k} - 2^{s_{k-1}+s_k}}{2^{2b}}
  \end{aligned}
  $$

  which does not depend on how s_{k-1} and s_k are ordered. In the second case we have $i < k - 1$ and we get:

  $$
  \begin{aligned}
  h_i &= p_i + (1 - p_i)\, h_{i+1} \\
  &= p_i + (1 - p_i)\left(p_{i+1} + (1 - p_{i+1})\, h_{i+2}\right) \\
  &= \frac{2^{b+s_i}}{2^{2b}} + \frac{2^{b+s_{i+1}}}{2^{2b}} - \frac{2^{s_i+s_{i+1}}}{2^{2b}} + h_{i+2} \frac{2^{2b} - 2^{b+s_i} - 2^{b+s_{i+1}} + 2^{s_i+s_{i+1}}}{2^{2b}}
  \end{aligned}
  $$

  which again does not depend on the order of s_i and s_{i+1}. Please note that h_{i+2} is the same for both permutations.

- Property **P2** – *Adding listening periods improves success probability*: When a listening strategy $\mathcal{S}_0$ is extended by a new element $s \notin \mathcal{S}_0$ then for the extended strategy $\mathcal{S}'_0 = \mathcal{S}_0 \cup \{s\}$ in which the new period is appended we have $h_1(\mathcal{S}'_0; b) \geq h_1(\mathcal{S}_0; b)$, i.e. adding further listening periods never decreases the success probability. This property is immediately clear from the structure of the set of equations A.1. This also shows that removing an element from $\mathcal{S}_0$ never increases the success probability.

- Property **P3** – *Average success probability is monotonically increasing in listening strategy costs*: The average success probability $h_1(\mathcal{S}_0; b)$ is monotonically increasing in $c(\mathcal{S}_0)$, i.e. for different listening strategies $\mathcal{S}_0 \subset \mathcal{B}$ and $\mathcal{T}_0 \subset \mathcal{B}$ with $c(\mathcal{S}_0) < c(\mathcal{T}_0)$ we have $h_1(\mathcal{S}_0; b) \leq h_1(\mathcal{T}_0; b)$. To check this claim, assume that $\mathcal{S}_0 = \{s_1, s_2, \ldots, s_m\}$ and $\mathcal{T}_0 = \{t_1, t_2, \ldots, t_n\}$ are two listening strategies with $c(\mathcal{S}_0) < c(\mathcal{T}_0)$. From the invariance of the success probability against permutations (property **P1**), we may assume that $s_1 > s_2 > \ldots > s_m$ and $t_1 > t_2 > \ldots > t_n$, and from our assumptions on the admissible listening strategies it is clear that $t_1 \geq s_1$ holds. If $s_1 \geq b$ and $t_1 \geq b$ then $h_1(\mathcal{S}_0; b) = h_1(\mathcal{T}_0; b) = 1$ and the claim is true. If $s_1 < b$ and $t_1 \geq b$ then from above we have $h_1(\mathcal{S}_0; b) < 1$ and $h_1(\mathcal{T}_0; b) = 1$. Therefore, we now assume that $s_1 < b$ and $t_1 < b$ holds. We consider two cases:

  - First suppose that $s_1 < t_1$. We then define the new listening strategies $\mathcal{T}'_0 = \{t_1\} \subset \mathcal{T}_0$ and $\mathcal{S}'_0 = \{s_1, s_1 - 1, s_1 - 2, \ldots, 1, 0\} \supset \mathcal{S}_0$. In other words: from $\mathcal{T}_0$ we keep only the single listening period of the highest order, and $\mathcal{S}_0$ is extended to include *all* listening orders $\leq s_1$. From property **P2** we have $h_1(\mathcal{T}'_0; b) \leq h_1(\mathcal{T}_0; b)$ and $h_1(\mathcal{S}'_0; b) \geq h_1(\mathcal{S}_0; b)$. We show $h_1(\mathcal{T}'_0; b) \geq h_1(\mathcal{S}'_0; b)$. To see this, we write the equation system A.1 for $\mathcal{S}'_0$ in reverse order:

$$\begin{aligned} h_{s_1+1} &= p_0 \\ h_{s_1} &= p_1 + (1-p_1)h_{s_1+1} \leq p_1 + p_0 \\ h_{s_1-1} &= p_2 + (1-p_2)h_{s_1} \leq p_2 + p_1 + p_0 \\ \ldots & \\ h_1 &= p_{s_1} + (1-p_{s_1})h_2 \leq p_{s_1} + \ldots p_2 + p_1 + p_0 \end{aligned}$$

  Therefore:

$$h_1(\mathcal{S}'_0; b) \leq \sum_{k=0}^{s_1} p_k = \frac{\sum_{k=0}^{s_1} 2^k}{2^b} = \frac{2^{s_1+1} - 1}{2^b} \leq \frac{2^{t_1}}{2^b} = h_1(\mathcal{T}'_0; b)$$

  - Secondly, suppose that:

$$s_1 = t_1, s_2 = t_2, \ldots, s_{i-1} = t_{i-1}, s_i < t_i$$

  for some i. The proof can be accomplished by defining $\mathcal{T}'_0 = \{t_1, t_2, \ldots, t_{i-1}, t_i\} \subset \mathcal{T}_0$ and $\mathcal{S}'_0 = \{t_1, t_2, \ldots, t_{i-1}, s_i, s_i - 1, \ldots, 1, 0\} \supset \mathcal{S}_0$ and using a similar argument as in the first part of the proof.

A.3 Properties of the average listening costs

- Property **P4** – *For a fixed strategy, the permutation which is sorted according to descending listening orders has the least average costs*. Similar to the proof of property **P1**, it suffices to consider two permutations of a listening strategy $\mathcal{S}_0 = \{s_1, s_2, \ldots, s_k\}$ which are identical except that elements on two neighbored positions are swapped. We therefore consider two permutations

$$\begin{aligned}\pi_1 &= (s_1, s_2, \ldots, s_{i-1}, s_i, s_{i+1}, s_{i+2}, \ldots, s_k)\\ \pi_2 &= (s_1, s_2, \ldots, s_{i-1}, s_{i+1}, s_i, s_{i+2}, \ldots, s_k).\end{aligned}$$

If $s_j \geq b$ for some $j \in \{1, \ldots, i-1\}$, then there is nothing to show, since the mobile BSN will be found before the swapped positions are reached and both permutations have the same average costs. So we suppose that $s_j < b$ for all $j \in 1, \ldots, i-1$. We consider two cases:

- The first case is $i = k-1$, i.e. the last two positions are swapped. From Equations A.2 we get after simplification:

$$\begin{aligned}c_{k-1} &= p_{k-1}\frac{2^{s_{k-1}}}{2} + (1-p_{k-1})\left(2^{s_{k-1}} + \left(p_k\frac{2^{s_k}}{2} + (1-p_k)2^{s_k}\right)\right)\\ &= \left[-\frac{2^{2s_{k-1}}}{2^{b+1}} - \frac{2^{2s_k}}{2^{b+1}} + 2^{s_{k-1}} + 2^{s_k} - \frac{2^{s_k+s_{k-1}}}{2^b}\right] + \frac{2^{s_{k-1}+2s_k}}{2^{2b+1}}\end{aligned}$$

  where obviously the part in square brackets does not depend on the order of s_k and s_{k-1}, but the last term is minimized by having $s_{k-1} > s_k$.

- The second case is $i < k-1$, i.e. two positions in the middle are swapped. From Equations A.2 we get after simplification:

$$\begin{aligned}c_i &= p_i\frac{2^{s_i}}{2} + (1-p_i)\left(2^{s_i} + \left(p_{i+1}\frac{2^{s_{i+1}}}{2} + (1-p_{i+1})(2^{s_{i+1}} + c_{i+2})\right)\right)\\ &= \left[2^{s_i} + 2^{s_{i+1}} - \frac{2^{2s_i}}{2^{b+1}} - \frac{2^{2s_{i+1}}}{2^{b+1}} + c_{i+2}\right.\\ &\quad \left. -c_{i+2}\left(\frac{2^{s_i}}{2^b} + \frac{2^{s_{i+1}}}{2^b}\right) - \frac{2^{s_i+s_{i+1}}}{2^b} + c_{i+2}\frac{2^{s_i+s_{i+1}}}{2^{2b}}\right]\\ &\quad +\frac{2^{s_i+2s_{i+1}}}{2^{2b+1}}\end{aligned}$$

  where again the part in square brackets does not depend on the order of s_i and s_{i+1} but the last term, which is minimized when $s_i > s_{i+1}$. Please note that c_{i+2} is the same for both permutations.

- Property **P5** – *The average listening costs are not monotonically increasing in the listening strategy costs.* This can be shown by a counterexample. Consider $b = 14$, $\mathcal{S}_0 = \{11, 10, 9, \ldots, 1, 0\}$ with costs $c(\mathcal{S}_0) = 4095$ and $\mathcal{T}_0 = \{12\}$ with costs $c(\mathcal{T}_0) = 4096$. Then we have $c_1(\mathcal{S}_0; b) \approx 3601.2134$ and $c_1(\mathcal{T}_0; b) = 3584$.

- Property **P6** – *Appending a listening period to a given strategy never decreases the average costs.* Under the assumption that the new listening period is carried out at the end, this is immediately clear from the structure of Equations A.2 and A.2.

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