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– Master's Thesis –

Coexistence and Cooperation for IEEE 802.15.4 powered Wireless Health Care Applications in Scenarios with Dense Radio Conditions

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Abstract

Forecasts predict a future where health monitoring and health care are available almost everywhere through the omnipresence of network access. The “anywhere and anytime” availability leads to ubiquitous health care scenarios, especially through the use of wireless communication. A consequence of this ubiquity are dense radio conditions, because different wireless technologies are going to coexist on the radio channel.

Another important aspect of true ubiquity is the ability for cooperation to enable a flow of information over network and device boundaries. This thesis aims to investigate the aspects and problems of wireless health care solutions in terms of coexistence and cooperation in dense radio conditions, when IEEE 802.15.4 is used as the wireless communication technology.

Reference applications and scenarios are abstracted from state-of-the-art inquiries. With the help of simulation models built from the reference scenarios, simulative investigations and problem analyses are conducted. Solutions are proposed for the support of massive coexistence of devices and networks as well as strategies for supporting an Inter- and Intra-Network-Cooperation. The developed concepts are finally evaluated with theoretical and practical proof-of-concept investigations.

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1 Introduction

The first decade of the 21st century brought many important advances in the area of wireless network technologies and wireless transmission in general. Countless communication technology standards were introduced to conquer problems of wireless network access and interconnectivity of devices and users. Huge wireless telephone networks based on GSM and UMTS were created around the world and wireless metropolitan and Local Area Networks (LANs) are available in most parts of the industrialised world. With access to communication and information networks and a growing demand for interaction and information exchange, the communication technology advertises a future where network access and information usage will no longer depend on the location, but merely on the demands of a user.

A wide range of devices with wireless transceivers are available today. Many of them are becoming our everyday companions like smart phones or small netbooks [1]. Future prognoses describe a scenario where wireless technologies and wireless network access are omnipresent and available everywhere as the so-called *Ubiquitous Future*. Immediate wireless access and the interconnectivity between different device types are important aspects of ubiquitous network scenarios, where “everything of value is connected to the network” [2]. If everything should be connected, transceivers need to shrink in terms of size and costs – a development already started thanks to the advances in chip manufacturing. But not only the transceiver size is important; power consumption and communication range are equally important for any ubiquitous scenario.

UMTS, GSM, and WiMAX for example were created to cover long transmission distances. A relative new class of wireless technologies starts to conquer the shorter distances: the so-called Wireless Personal Area Network (WPAN) technologies. Devices from this class operate within a short communication range, normally between 1 to 25 meters, the Personal Operating Space (POS) of a user or a device. There are many different standards and transceiver types available, ranging from high data-rate technologies like Ultra-Wideband (UWB) to low data-rate and low-power consumption standards. An example for the second class are the Low Rate Wireless Personal Area Network (LR-WPAN) technologies, where IEEE 802.15.4 and ZigBee are two of the most important representatives. LR-WPAN transceivers can be found in many kinds of devices nowadays: in small sensors for monitoring and measuring applications, as low cost transceivers in cell phones for short communication ranges, as the ground laying basis for complex indoor-localisation platforms, or in wireless health care applications for example.

Health care applications and products with wireless transceivers are a major topic at the moment. The reasons for that are manifold. According to the *World Health Organization*, there were approximately 600 million people aged 60 years and older in 2000. Until 2025, this number will raise to 1.2 billion people worldwide. It is a wide known fact that the very old (age 80+) people are the fastest growing population group in the developed world. Statistically speaking, the life expectation of people in industrialised countries has increased over the last decades. In Germany, for example, the average lifespan of a new born male in 2007 was around 76 years and 82 years for females [3]. Increasing life expectations are possible due to advances in medical health care and treatment. Sale studies show that the market for current and emerging health care products will continue to grow in the next years with a sustainable growth rate, leading to the availability of products on every major market in the industrialised world.

Since cable connections often limit the usability of devices and systems, combining health care products with wireless communication components is a natural step. Low cost transceivers will help to raise the distribution of these products in the next years. For an ubiquitous future, this will lead to the point where an “ubiquitous health care service” will be available at any time and any place, if the end user has the necessary devices. This development will also lead to problems in terms of coexistence and concurrency of wireless technologies, since all wireless transmissions share the same medium – the radio channel. Technologies have to take care of concurrent channel access and interference within and in-between channels. These problems might not be serious for the current situation, but in an ubiquitous future where wireless technologies are widespread and available everywhere, dense and occupied radio conditions have to be considered.

1.1 Problem Domain and Context

This thesis deals with an investigation of wireless health care applications and their problems in dense radio conditions. In any ubiquitous scenario, dense radio conditions are a natural consequence of the “anywhere and anytime” availability of wireless services and network access. As a shared medium, the radio channel is used by all kinds of wireless technologies. Governmental regulations concerning radio channel usage try to give most applications enough space on the wireless medium with the help of regulated frequency bands. However, the limited number of free accessible frequency bands (e.g. 868, 915 MHz, and 2.45 GHz ISM bands) leads to dense radio conditions on these free frequencies again, if various technologies operate on them. The coexistence problems generated by dense radio conditions are one of the main topics dealt with in this work.

Cooperation is another essential part of this thesis. All kinds of devices should be able to interact with each other to enable ubiquity. Cooperation is hence an important issue for future applications, independent of their sole functionality. The ability to cooperate with different device classes can lead to new application types and different usage scenarios. Since wireless networks have the “integrated” support for ad hoc communication (wired networks need additional cable connections for this), the ability of cooperation between devices and networks should always be considered in an ubiquitous context.

This thesis only considers wireless health care applications, their usage scenarios, specifics, and requirements. As presented in the introduction, the general demographic development and the fast ageing population are the main reasons for the growing need of health care solutions. This work has a strong practical orientation and takes the availability of wireless health care solutions into consideration. To narrow the topic down even further, only applications and scenarios with wireless IEEE 802.15.4 transceivers are considered. Reasons why the LR-WPAN standard was chosen will be presented in later sections together with a introduction of the standard.

Since this work is connected to real-world problems, a main aspect will be the simulative investigation of IEEE 802.15.4 powered wireless health care applications in dense radio condition scenarios. Problem cases will be identified and solutions for coexistence and cooperation will be proposed and simulated. With these analyses and investigations, an attempt will be made to achieve new insights on the depicted LR-WPAN topics.

1.2 Objectives and Aims

The main aims of this thesis are: a proper state-of-the-art and problem analysis combined with a simulative investigation, to verify the argued problems with coexistence and to prove the need for cooperation; the development of scalable solution approaches; and further investigations that will prove the usefulness of developed solution concepts. The following list gives a summary of the necessary steps and objectives:

- Research on health care applications and their requirements;
- Definition of reference applications and scenarios for dense radio conditions;
- Simulative investigation of the IEEE 802.15.4 standard under consideration of the developed reference applications and scenarios;
- Analysis of the investigation outcomes and identification of problematic conditions;
- Research into the area of cooperation of independent IEEE 802.15.4 WPANs;
- Development of a solution approach for massive coexistence and cooperation of independent networks for dense radio condition scenarios;

In order to maintain the practical orientation, existing wireless health care solutions will be analysed to extract requirements and parameters. Realistic reference scenarios with limited radio resources and dense conditions will be created, e.g. the monitoring of athletes in a marathon. With these defined scenarios, the current IEEE 802.15.4 standard will be (theoretically and practically) investigated and an attempt will be made to identify problematic conditions of the standard in dense radio conditions. A solution to conquer the identified problems will be developed, which will include the extracted real-world requirements of typical health care applications. The solution shall also include the ability for scalable cooperation between multiple independent IEEE 802.15.4 networks, to satisfy the mentioned ubiquitous future, where cooperation between devices and networks plays an important role. The practical part includes various simulative investigations of the standard under the developed scenarios. The approach to solve the assumed coexistence problems will lean on a distributed algorithm for the allocation of channel resources. Cooperation in general and especially *Inter-Network* cooperation will be achieved with newly created strategies.

Resource assignment and channel access methods are well-established theoretical research areas. The scientific contribution of this thesis is therefore the analysis, development, and evaluation of practical applicable solutions with a focus on real-world problems and scenarios. The support of cooperation between multiple independent LR-WPANs in ubiquitous scenarios is another aspect that distinguishes this thesis from already established work, since almost all developed protocols for shared medium access of LR-WPANs are suited only for single networks with their devices.

1.3 Structure

The thesis structure follows a specific methodology. This first chapter presents a short introduction of the research field, of basic terms and fundamental concepts used throughout this thesis, e.g. health care applications, LR-WPANs, and the ubiquitous future scenario. With the given motivation and the main terms introduced, Chapter 2 describes wireless health care applications and the IEEE 802.15.4 standard in detail. Important parameters and specifics of existing health care applications are extracted and impairments of the standard are pointed out. Chapter 3 contains definitions of reference applications and scenarios. These references will be used for the simulative investigation of the standard. Chapter 4 presents the outcomes of a comprehensive investigation of IEEE 802.15.4 under the defined references. Problems of the current version of the standard are identified and discussed in this chapter. Related work is classified and described in Section 4.2, whereas differences between existing research work and this thesis are pointed out in detail. The solution development is described in Chapter 5. Solutions for coexistence and cooperation problems are presented together with an approach for the combination of both independent solutions. Chapter 6 contains information about the simulative investigation of IEEE 802.15.4 and the conducted evaluations. Detailed information about the simulation framework and comments about the implementation of the solution as well as general remarks about the simulation process are given in Section 6.1. The outcomes of performed simulations are described and analysed in Section 6.2. The achievements of this thesis are recapitulated in Chapter 7. The thesis is concluded with a survey of possible future directions and tasks.

2 Wireless Health Care and Underlying Communication Technologies

This chapter deals with wireless health care applications and the communication technologies behind them. Examples of health monitoring and care applications that use wireless communication are introduced here. Components and specifics of IEEE 802.15.4 as well as important details of the standard for the usage with health care applications are described and discussed. Requirements and important parameters of health care applications are extracted from the analysis for further research in this work while limitations and impairments of IEEE 802.15.4 are identified.

2.1 Wireless Health Care Applications and Systems

In a society where information and communication technologies revolutionised almost all sectors of the everyday life, health care and health monitoring are two important, yet still developing, areas. Both – health care and health monitoring – are becoming more personalised with the recent technological advances. A simple example: while a check-up for a cardiac problem in the '90s meant that the patient had to go to a doctor and take part in a series of stressful tests, today the patient gets a single electronic monitoring device and simply goes through his normal daily routine with it. The advances in microelectronics and communication technology lead to the availability of more and more products for personal health monitoring and advanced health care, with an already immense range of available products. From simple sensors for heartbeat or body temperature measuring to more complex devices for the regulation of the insulin level or even wireless connected cardiac pacemakers, applications and systems in all kinds of sizes with a wide range of functionalities are becoming available.

The introduction of modern telecommunication technologies in the health care environment and the usage of wireless communication for health care products has led to an increased usability and accessibility for both users and providers of health care services. The reasons for the growth in the use of wireless communication in health care solutions are manifold. A natural advance is the lack of cables for the interconnection of devices via wireless transceivers. Wireless interconnection leads to new usage possibilities like the regular transfer of measured data directly to a doctor with the help of a cellphone or the activation of an alarm in case of health emergencies. Wireless transceivers often allow for a simpler usage of devices and more flexibility for the user in the end. But they are also the reason why developers and researchers have to think about more advanced solutions in terms of coexistence, interference avoidance and cooperation for example.

Since this work focuses on communication technologies, medical and non-technical issues are not considered here. Readers interested in electronic health care in general should refer to material from the health care community, books or overview papers like [4]. The following part addresses examples, typical use cases and requirements of wireless health care applications, while the next section covers the technology issues.

2.1.1 Definition and Categorisation

> **Health care:** Care, services or supplies related to the health of an individual. Health care includes (. . .) preventive, diagnostic, therapeutic, rehabilitative, maintenance, mental health or palliative care and sale or dispensing of a drug, device, equipment or other item in accordance with a prescription.
>
> *(according to the Department of Welfare [5])*

Nowadays, health care and the available products and systems are often divided into electronic and non-electronic representatives. Non-electronic examples might be simple syringes or chemical analysis tests. Electronic health care can be further categorised in *e-Health* and *m-Health* [6]. While e-Health normally stands for the common health care practice with a support of electronic systems, processes and communication technologies, m-Health or mobile health refers especially to personal or public health practice supported by different mobile devices. e-Health examples are the electronic medical records of a patient or an Internet-based health care platform. Mobile health care applications range from real-time patient monitoring systems, data collecting via mobile phones or the provision of health care with mobile telemedicine (e.g. via mobile video conference) to advanced decision supporting systems for health care providers.

Another categorisation is the differentiation between health care and health monitoring. Health monitoring is often described as the passive monitoring of conditions, in contrast to health care, which has an integral active part, e.g. the active regulation of the insulin level. Applications and systems from both groups have different requirements when it comes to their underlying wireless communication technologies. The differences between passive and active systems also have important consequences for the communication in general. While a passive monitoring application will probably not get into serious trouble, when the connection to the home server can not be established, an active application must ensure the connection with its communication partner in case of an emergency. To enable a better understanding of the requirements and consequences for the underlying wireless technologies, the next two subsections present examples and different use cases of wireless health solutions. Since the focus will be on wireless communication, non-mobile e-Health will no longer be considered in this work.

2.1.2 State of the Art

Mobile health is surely the field where wireless communication has big chances for revolutionising medical monitoring and health care. Several research fields are currently emerging and the interest in wireless m-Health solutions goes in many directions [7]:

- Coordination and management of human resources
- Mobile telemedicine with diagnostics and decision support
- Monitoring and reporting for remote clinicians and their patients
- Health promotion and mobilisation of communities
- Extension of available health services with wireless technologies
- Emergency response systems
- Surveillance and control for disease outbreaks
- Remote patient monitoring

The following paragraphs introduce examples for wireless health care systems, selected throughout the market of available or emerging products and active research projects. The quoted examples are only an abstract of the huge amount of available solutions, further examples and information can be found in overview papers like [8] for example.

In case of university research, several systems and projects are already available or currently in research. *CodeBlue* [9, 10, 11] is an example, where a hard- and software platform for the exploration of medical sensor networks and appropriate applications is developed. The development of a Wireless Body Area Network (WBAN) architecture for health monitoring was conducted in [12]. Research in the field of remote health solutions were accomplished in [13] and [14], where a home gateway for the connection of wireless sensors with medical/health care providers over cable networks was developed and Powerline Communication (PLC) was used for the interconnection of ZigBee sensor nodes for remote health monitoring. In the same area, [15] addresses the usage of IEEE 802.15.4 sensor nodes in combination with GSM for remote data collection. The development of wearable health monitoring solutions is conducted in projects like [16], where a wrist wearable watch with built-in sensors and wireless communication was created, or [17, 18], where a wearable system-on-a-chip radar sensor for the detection of heart and breath rates with a ZigBee radio was developed, or [19], which addressed a wearable platform for the development and prototyping of health care solutions.

Industry research was conducted in similar areas over the last years. Products from the field of athlete or personal progress monitoring are available today, ranging from simple applications for training progress monitoring to complex systems with wearable sensors. Current corporate research focuses on wearable and context aware systems like [20] and [21], where wearable solutions for continual real-time monitoring of physiological signals were developed, or [22], where a WBAN for the ambulatory arousal monitoring was designed. Another focus of corporate research is health care in combination with smart home environments. Projects like *LifeMinder* [23] or *Elite Care* [24] engage in the area of assisted living and long-term health monitoring in combination with pervasive computing elements. Last but not least, research about the use of ZigBee sensors was conducted in [25, 26]. A system architecture was designed here, which includes body-attached sensors, local data processing servers and remote health providers. Examples like this show the possibilities for IEEE 802.15.4 and ZigBee in the area of health provision, especially in combination with smart home approaches.

From the quoted developments, research projects and market examples, one can deduct that the role of mobile devices in health care will grow even further. The increasing functionalities and capabilities of smart phones, PDAs, patient monitoring devices, mobile audio players and mobile care devices will be an integral part for all future mobile health solutions. Still, a single device can only have a limited number of capabilities. The main reasons are the size and costs of a device. If many different and specialised devices are available, the cooperation between such devices is even more important, since it will eventually lead to the creation of new application types or usage scenarios. To enable such a cooperation, the use of the built-in wireless transceivers is the best option, as shown by the WBAN examples presented in the previous paragraphs. Wireless Body Area Networks will therefore be examined further for the abstraction of reference scenarios and simulative investigations.

2.1.3 Usage Scenarios

Typical use cases can be deducted from the wide range of research projects, prototypes and available products. This section describes these scenarios. They are used in Chapter 3 for the specification of reference applications and scenarios with dense radio conditions, which will then be used for simulative investigations throughout this thesis.

The following list presents six typical use cases for wireless health care or health monitoring applications. The list represents an extract of the larger amount of possible scenarios; typical cases were abstracted and generalised, whereby this list is in no way exhaustive. All examples will be described in detail and issues, problems and advantages over non-wireless systems will be identified and discussed.

- *Patient monitoring with feedback*
- *Group health monitoring*
- *Personal health monitoring for the creation of a medical record*
- *Personal monitoring and regulation of the insulin level*
- *Emergency medical service*
- *Elderly monitoring and care*

Patient monitoring with feedback is a use case where a patient is monitored with the help of a sensor network after he has received stationary medical treatment and progressed to physical rehabilitation for example. A possible situation could be: A patient is recovering from a serious cardiac attack. After an operation, he is attending his physical rehabilitation. For the doctor, important information are the patient's rehabilitation progress, feedback about the patient's presence at the rehabilitation sessions and the effort of the patient in these sessions. For the patient, a general feedback as well as access to the evaluations from the doctor might be important.

A Body Area Network with monitoring sensors is used here. A patient wears several sensors, which provide a constant observation of medical and vital statistics during his rehabilitation period. Different sensor types are used, similar configurations can be found in the *Human++* project [22]. The sensors transfer their data to a data collector (Patient Monitoring Unit (PMU) or PDA) or directly to a data server in radio range. Since the transmission ranges of WPAN technologies are normally under 50 meters, the PMU includes a WLAN transceiver to cover longer distances. For covering even greater distances, a UMTS cell phone could be used. For this option, the cell phone needs a WLAN or WPAN radio to cooperate with the PMU or directly with the sensors. As shown in Figure 2.1, data is also collected from medial devices and units in the rehabilitation centre. All data is transferred over the appropriate technologies and connections to the doctor's server. After an analysis, outcomes and feedback are transferred back to the PMU of the patient and (optionally) to his cell phone.

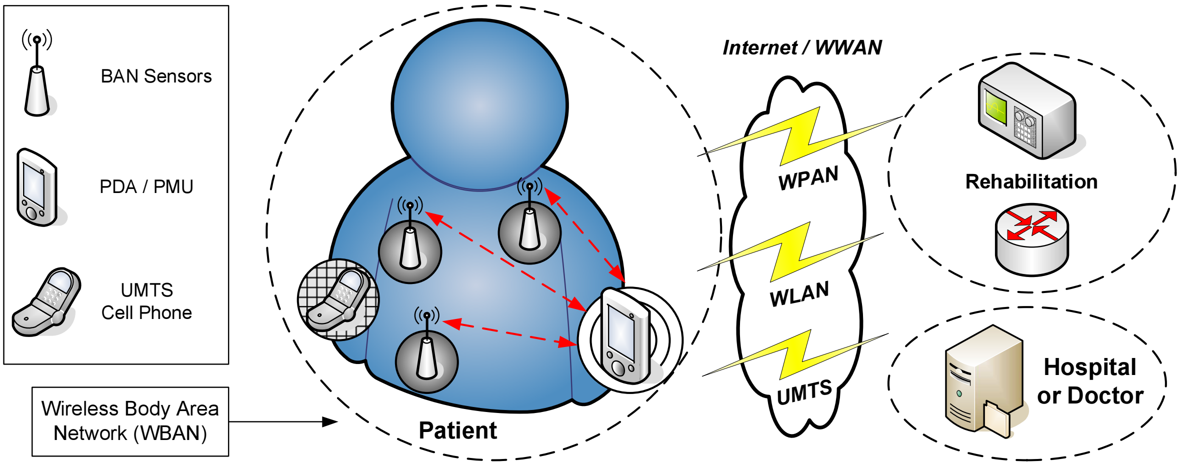


Figure 2.1: Usage Scenario 1 – Patient Monitoring with Feedback

This scenario shows the amount of wireless technologies involved in personal health care. Up to three different wireless technologies coexist at the same time. With the available connection to the internet, both doctor and patient can access the information from every place. The combination of exercise data and personal monitored health conditions will allow for a better estimation of the rehabilitation progress and a reduction of doctor's office or hospital visits for the patient. The passive sensors in this scenario can also be exchanged with active sensors if needed, depending on the type of rehabilitation. Combinations with emergency call features are also possible, further information about these application types will be given in the following scenarios.

Group health monitoring is another use case were WBANs play an important role. This scenario extends the first use case. Here, every person wears a WBAN with sensors and a central data collector (PMU, PDA or cell phone). The main difference in relation to the first scenario is the number of persons in radio range. While single persons or small groups were considerer in the first scenario, this scenario describes a situation where large numbers of persons with their WBANs coexist in radio vicinity. A general example could be the monitoring of athletes in a sport contest. Sensor types and device configurations are comparable with the first scenario, except that each user wears a central data collector, which collects the data (via push or pull methods) from the sensors. Depending on the application, the data collector sends the collected information in intervals to a central server where the information are further analysed or processed. The central server will normally be reached over WLAN, UMTS or WiMAX maybe. In use cases where user monitoring needs to be carried out regularly and constantly, serious coexistence problems on the wireless channel access can occur.

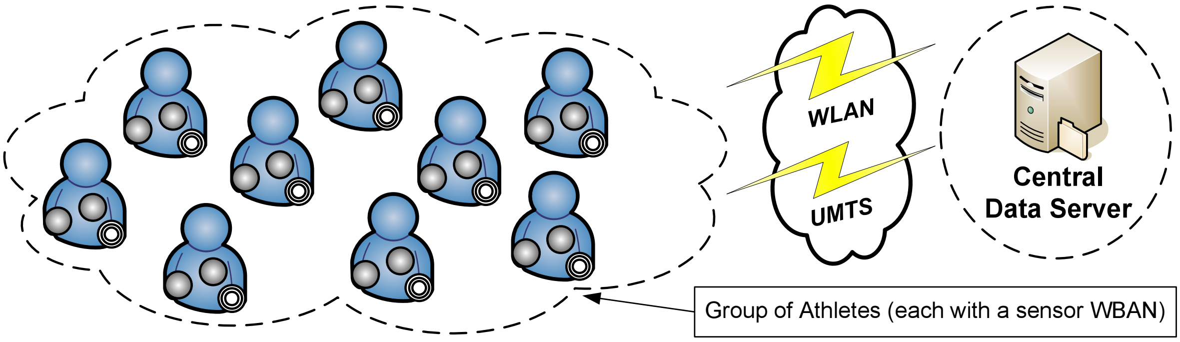


Figure 2.2: Usage Scenario 2 – Group Health Monitoring

The coexistence problems in this scenario can be divided into *Inter-* and *Intra-WBAN* coexistence issues. Since many persons with separate WBANs exist in radio range, the channel access has to be divided between devices inside a single WBAN and devices from other coexisting WBANs. The same differentiation can be made for the interference problematic. Both *Inter-Channel* and *Inter-Technology* interference are important in this case and both types can cause serious problems for IEEE 802.15.4. Since IEEE 802.11 b/g and 802.15.4 use the same frequency band, the wireless access can be disturbed for IEEE 802.15.4 devices, when WLANs operate on the same or a neighbour radio channel. More details on this will be given in Subsection 2.2.4 and Chapter 4.

Personal health monitoring for the creation of a medical record describes a scenario where a user wears a couple of non-invasive body attached sensors (combined in a WBAN) for the creation of a medical chronicle or histogram. This scenario is similar to the first one (*Patient monitoring with feedback*) in terms of used hardware and network configuration. The most important difference here is that the WBAN sensors monitor the user twenty-four-seven. Bigger memory capacities or regular data collection and transfer to a server unit are therefore necessary in this scenario. The regular reporting (transfer of information to a data collecting unit) of measured or sensed data marks an important characteristic, since it can be interpreted as a must-be-guaranteed fact. If the regular reporting can not be guaranteed, sensed data can get lost (limited memory capacity) and the whole medical record or histogram is useless.

Problems in this scenario will surely derive from the real-time conditions of regular information transfer and exchange. Coexistence with different IEEE 802.15.4 networks or other wireless technologies, interference on the radio channel and regular channel access itself lead to problematic conditions for the WBAN. The inclusion of cooperation between different WBANs can lead to more problems or, on the other hand, to the creation of new strategies for addressing these problems with the help of cooperation schemes. More details will again be presented in the appropriate sections and chapters.

Personal monitoring and active regulation of the insulin level is a scenario that combines the previous mentioned scenarios, where single users or user groups are monitored together with the inclusion of active medical health treatment. Diabetics need regular injections for the regulation of their insulin level. Each insulin injection must be adapted to the blood sugar level, which must be either measured or estimated by the patient himself. Combinations of insulin-injectors and blood sugar sensors, which communicate via wireless technologies like IEEE 802.15.4, can help patients to gain a significant improvement over the traditional estimated syringe insulin injection. The combined wireless sensor and actuator solution can constantly measure and regulate the insulin level, while the standard syringe does not allow for this flexibility. A comparable example that falls in the same category are neurological systems for epileptic patients. Traditional systems for stimulating defective brain regions require hard-wired sensors and actuators, which have to be implanted into the patients body. Wireless non-invasive solutions would provide much more flexibility and comfort for the patients.

The most important part of this scenario is the guarantee of functionality. Neither coexistence with other networks, devices, or technologies nor interference should disturb the necessary wireless transmissions (requirements for other system components are not considered here). Therefore a certain level of service has to be guaranteed in this scenario. The combination of sensors and actuators and the ability of cooperation can introduce new application types for the introduced scenario. A simple extension may be an alarm function: the cell phone gets a warning message from the sensors whenever the patient is in serious danger and the cell phone immediately makes an emergency call. Such a scenario is going to be described in the following example.

Emergency medical service is a scenario that describes an extension of the previous mentioned examples and scenarios. All previous use cases used sensors for the monitoring of health conditions. While simple monitoring might be the first step, taking actions in emergency cases is a natural next step. An example situation could be the following: a older person is wearing several sensors while carrying out his usual sports program, which includes running and walking. While running through a non-populated area, the senior gets a slight apoplectic stroke. Since no other person is around, no one would make an emergency call or inform the medical service of the accident. This situation is a chance for an automated emergency call service. The body-attached sensors of the senior are monitoring his health during the training. They instantly recognise the apoplectic stroke and inform a central unit (e.g. a PDA or a cell phone) about the problem. The central unit then decides how serious the problem is, based on the sensed information. In case of serious or dangerous emergencies, an automatic call or data message is sent to the emergency service.

The above described case can be enhanced with additional technologies and assumptions. If the cell phone has an embedded Global Positioning System (GPS) receiver, the position information (e.g. location coordinates or street name) of the senior can be sent to an emergency service. The seriousness of the situation could be evaluated by combining several measurements from different sensor types. Already available shoe sensors used for the measurement of the walking or running distance can be used in this scenario to detect the standstill of the user. Sensors for fall detection could also be included to enhance the WBAN functionality. Information about the situation and the circumstances could be sent directly to the emergency authorities so that they can evaluate the situation. These possibilities are just extracts since the range of sensor combinations for additional benefits goes far beyond the scope of this work's topic.

Important in this scenario is the ability of communication and cooperation. A group of devices is considered here, with different wireless technologies and a similar "backbone" communication technology, IEEE 802.15.4 for example. Even the cooperation with devices from other users should be possible. In case someone does not carry a cell phone, the WBAN of the person in the emergency situation could try to contact another WBAN in radio range. Figure 2.3 outlines the use case. In the figure, only a single user is considered, for the mentioned cooperation between WBANs, configurations and characteristics similar to the *group health monitoring* scenario can be assumed.

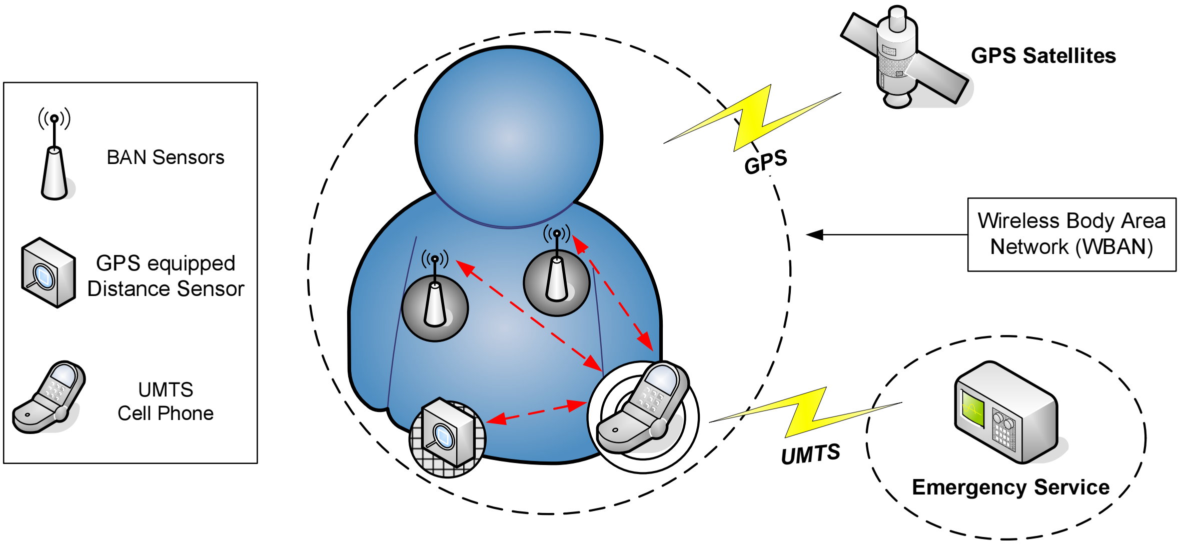


Figure 2.3: Usage Scenario 5 – Emergency Medical Service

Elderly monitoring and care stands for a scenario similar to some of the described available example systems (e.g. *Elite Care*). Sensors and systems from the smart home area are combined in this scenario with wearable WBANs and health care devices. Several seniors live in a apartment or housing complex, which is equipped with deployed sensors for different applications (e.g. fall detection, acoustic monitoring, temperature sensing). The seniors themselves wear body attached sensors for additional monitoring applications or possible active health regulating systems. Central coordination devices can be distributed in the house or combined with the wearable WBANs.

The use of BANs, health monitoring sensors and WPAN technologies allows for a new type of around the clock monitoring and caring of elderly and seniors. The systems can register many kinds of incidents or accidents twenty-four-seven and inform the medical care of the current situation. With the help of WPAN technologies, indoor positioning can be achieved and seamless cooperation between different devices classes and networks could be enabled. Figure 2.4 displays such a scenario, where parts of all previous described use cases are combined. Important research issues here are the coexistence and the guarantee of functionality, as mentioned before.

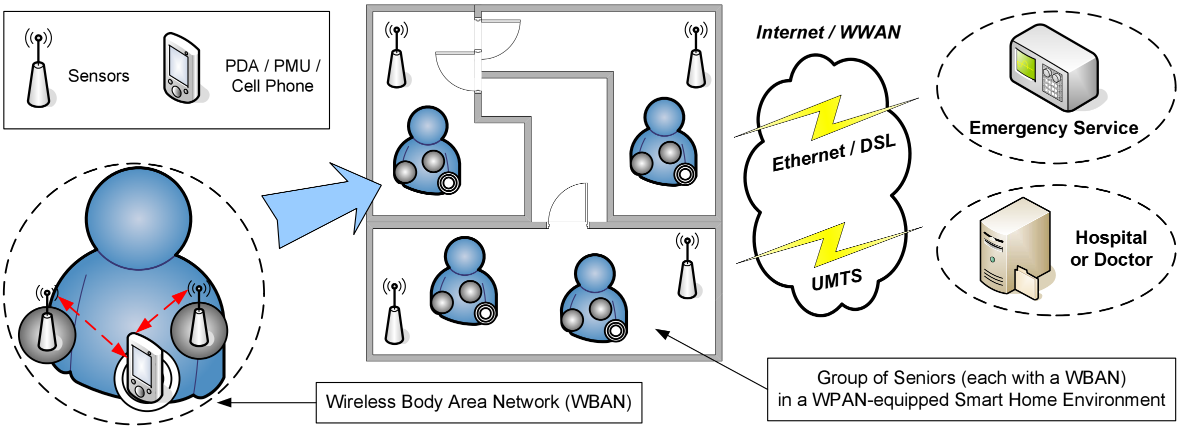


Figure 2.4: Usage Scenario 6 – Elderly Monitoring and Care

2.1.4 Important Parameters and Specifics

Based on the described example applications and systems, and the accompanied use cases and scenarios, important parameters and specifics of health monitoring and health care scenarios can now be extracted. Four important parameters are presented and defined in this section. These parameters will be used for the modelling of reference applications, for algorithmic calculations of wireless radio channel access schemes (refer to Section 5.1), for an evaluation of the current standard of the chosen wireless communication technology and later on for an evaluation of developed solution approaches.

The first parameters, which has an important influence on any of the scenarios from the previous section, is the **Memory Capacity of a Device**. A device can be either a sensor, which senses certain data, or a data collector, which collects data from sensors. Both device types usually have a limited memory capacity, because of the device cost and size. Especially low cost sensors that could be distributed in big numbers normally have small memory capacities. This parameter is important, since the memory capacity limits the time amount that a sensor or data collector can work without sending the information to the next-higher system in the application hierarchy (e.g. for sensors this is usually the data collector and for data collectors probably a higher server entity). The memory capacity limits the interval where devices probably do not need to access the radio channel. The **Sensing Interval** and the **Sensed Data Amount** have a direct influence on the memory capacity. Both values together can be used for the calculation of the time until the memory is full. They determine the time boundary when data has to be sent to the next higher entity (a server or a user).

Next to the memory capacity, the **Reporting Interval** is a similar parameter with different characteristics. In normal monitoring applications, a sensor would probably sense data until the memory is nearly full and then transmit the data to another entity. In certain health care or monitoring applications (e.g. cardiac arrhythmia or blood pressure monitoring), the sensed data has to be delivered to a higher entity in fixed time limits. Especially in (weak or strong) real-time systems this time boundary is an important parameter that has to be guaranteed.

With the help of these four parameters, radio access characteristics of almost all thinkable health monitoring or health care applications can be modelled and described. It is important to define these parameters, since the modelling of usable scenarios with modifiable parameters is an important requirement for any performance evaluation or simulative investigation, which is a part of this thesis. The parameters will therefore be used along with the insights gained from this section's investigation for the creation of scenarios with dense radio conditions and all subsequent parts of the thesis.

2.2 Introduction to IEEE 802.15.4

Wireless transmission technologies are nowadays available for a wide range of use cases and scenarios. For wireless health care and monitoring solutions, several technologies were promoted over the last years. Currently, Bluetooth, Infrared according to the Infrared Data Association (IrDA) standard, Z-Wave, IEEE 802.15.4 or ZigBee are used, while IEEE 802.15.4 is one of the most widespread standards in this area.

The focus of the thesis lies on IEEE 802.15.4 (abbreviated 802.15.4 consecutively). The reasons are manifold: some technologies like Z-Wave are proprietary while other technologies like ZigBee already use 802.15.4 as an underlying framework. Infrared on the other hand needs Line of Sight (LOS) connections, which reduces the flexibility. The other important candidate for WPANs is Bluetooth. 802.15.4 is often preferred over Bluetooth, because it only standardises the basic communication layers. Applications, network configuration, routing protocols and other parts are not standardised by 802.15.4, which gives researchers the possibility to use their own developments. For developers, it is important that 802.15.4 uses the 2.45 GHz ISM band, because it is freely accessible worldwide. 802.15.4 was designed to support low power usage and low cost transceivers, which try to minimize the *Inter-Technology Interference* by using small output powers. Small chip and antenna sizes and already available hardware are other reasons. The combination of these reasons is the determining factor for the selection of 802.15.4 as the wireless technology of choice for further investigations in this thesis.

Using IEEE 802.15.4 for Health Care Applications

Reasons for the use of wireless communication in the area of health care (e.g. enhanced flexibility and comfort) were already given in the previous sections. The usage of 802.15.4 for health care was also proposed by other authors. In [27], the authors researched about the performance of 802.15.4 WBANs for health care solutions. The outcomes showed that the standard is usable when configured properly. Other research and white papers like [17, 20, 28] also showed that health care solutions with 802.15.4 are feasible. The design considerations of 802.15.4 enable the standard to be used in flexible ways for different application types. Some design considerations are on the other hand the reason for disadvantages of 802.15.4, which will be examined in Subsection 2.2.4. The following subsections present the standard's evolution, its architecture and components.

2.2.1 Evolution of the Standard

802.15.4 was standardised by the Institute of Electrical and Electronics Engineers (IEEE). The standard belongs to the IEEE 802.15 working group, which consists of six different task groups that are all engaged in the WPAN field. 802.15.4 and its associated task group focuses on low data rates, long battery lifetime, low complexity and therewith low hardware costs. The typical applications in this area are different from standards like WLAN or WiMAX. Next to health care solutions, 802.15.4 hardware is often used to provide low power radios for nodes in wireless sensor networks or transceivers for industrial tracking, surveillance or home automation solutions. The support for a high device count inside a single network is a feature that distinguishes 802.15.4. Other WPAN standards like IEEE 802.15.3a Ultra-Wideband (UWB) for example are used in non-battery-powered scenarios with less participants and higher data rates.

The first version of the standard was published in 2003 [29]. A second revision "*extends the market applicability of IEEE Std. 802.15.4, removes ambiguities in the standard, and makes improvements revealed by implementations of IEEE Std 802.15.4-2003*" [30]. It was released in 2006. Since then an additional enhancement was made with the amendment of [31] in 2007, to support an UWB PHY. Over the years, most of the extensions and enhancements were made in the area of modulation schemes and different data rates for the supported frequency bands of 868/915 MHz and 2.45 GHz.

2.2.2 An Overview of IEEE 802.15.4-2006

The rest of this section considers only the 2006 revision [30] of the standard. To date, it is the revision of choice for implementations and evaluations, and supporting hardware is already available. The additional features (e.g. UWB) of the 2007 amendment are not of interest for the mentioned reasons (e.g. non-battery operation).

802.15.4 is a standard uniquely designed for Low Rate Wireless Personal Area Networks (LR-WPANs). With the already mentioned design principles (*low data rate, low power consumption, low hardware cost*), the standard's goal is to provide a physical (PHY) and a medium access control (MAC) layer for networks and applications following these design principles. Upper layers (e.g. application or network layer according to the TCP-IP reference model) and enhanced security features are not covered by the standard, but left open for additional frameworks like ZigBee or own developments.

Several PHYs with various data rates and modulation schemes are specified in the standard, current standard conform devices operate on 868/915 MHz and 2.45 GHz with data rates and modulations as specified in the Table 2.1. Next to the Physical Layer (PHY), a Medium Access Control (MAC) Layer is defined in the standard. The typical protocol stack of a compliant device is shown in Figure 2.5. The upper layers shall provide a network layer to support the network configuration and message routing, and an application layer, which provides the intended function of the sole device. As mentioned, the definition of these upper layers is outside the scope of the standard.

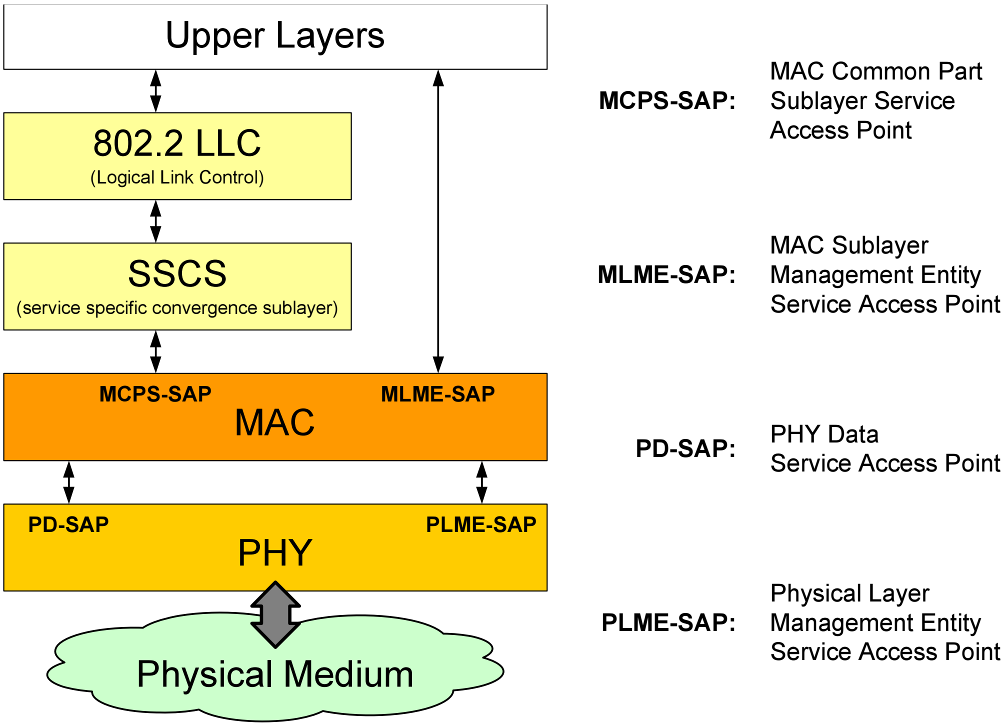


Figure 2.5: IEEE 802.15.4 Protocol Stack (based on [30])

As shown in Table 2.1, over-the-air data rates of 20 kbit/s, 40 kbit/s, and optionally 100 kbit/s and 250 kbit/s are supported by the standard. The choice of a PHY depends on the local restrictions, regulations and preference of the researcher or developer. The various PHYs have different characteristics, regarding the power consumption for transmitting and receiving processes, regarding the transmission distance they cover and the receiver sensitivity. These characteristics can have a big impact on the general systems performance. Unless otherwise noted, the 2.45 GHz PHY with 250 kbit/s is used throughout the thesis, since the 2.45 GHz frequency band is available worldwide.

Frequency Band (MHz)	**Chip Rate (kchip/s)**	**Modulation**	**Bit Rate (kbit/s)**	**Symbol Rate (ksymbol/s)**
868 – 868.6	300	BPSK	20	20
902 – 928	600	BPSK	40	40
868 – 868.6	400	ASK	250	12.5
902 – 928	1600	ASK	250	50
868 – 868.6	400	O-QPSK	100	25
902 – 928	1000	O-QPSK	250	62.5
2400 - 2483.5	1600	O-QPSK	250	62.5

Table 2.1: IEEE 802.15.4 Physical Layers with according Parameters

The PHY also standardises the radio channels. With the 2006 revision, sixteen radio channels are available in the 2.45 GHz band, ten in the 915 MHz band, and one in the 868 MHz band. Channel assignments are defined through a combination of channel numbers and channel pages. The channel centre frequencies are defined as follows:

$F_c = 868.3$ in Megahertz, for $k = 0$
$F_c = 906 + 2\ (k - 1)$ in Megahertz, for $k = 1, 2, \ldots, 10$
and $F_c = 2405 + 5\ (k - 11)$ in Megahertz, for $k = 11, 12, \ldots, 26$

where

k is the channel number.

The PHY provides the interface between the MAC and the physical radio channel. The transceiver hardware and its firmware are accessed over the PHY interfaces. Management functions are consolidated in the PHY Management Entity (PLME), an entity that provides the necessary layer management functions. The PLME is also responsible for the management of important parameters, objects and other manageable information of the PHY. These information are concentrated in the PAN Information Base (PIB). Important PIB attributes are shown in [30, Table 23]. The PHY also supports important functions like Energy Detection, Link Quality Indicator or Clear Channel Assessment. These features will be described together with other important aspects in Subsection 2.2.3.

The MAC sublayer is the second layer specified in the standard. It provides two services, a data and a management service, both accessible through different interfaces.

Responsibilities of the MAC include the concurring physical radio channel access management, the creation of network beacons and the according synchronisation operations, the mechanisms to structure devices inside a network, the provision of a reliable link between peer MAC entities and the device security mechanisms, namely the support for AES encrypted communication. Management information are again maintained in a PIB, information about the attributes of this database can be found in [30, Table 86].

The standard specifies three device kinds: Full-Function Devices (FFDs) that support the complete standard, Reduced-Function Devices (RFDs) that support only a subset of mandatory parts, and the Personal Area Network (PAN) Coordinator, a FFD that is the central management entity inside a network. RFDs are only able to communicate with FFDs, they are normally used for simple operations like plain sensing. FFDs are used to build and set-up 802.15.4 networks. The strict role allocation can be transcribed onto health care applications with ease, devices from the scenarios of Subsection 2.1.3 can be matched exactly to RFDs and FFDs. The role management is strictly connected with the set-up process of a new network topology. The FFD that starts and builds up a new network is normally selected as the PAN Coordinator (cp. Figure 2.6).

Two basic topologies are defined in the standard: the *Peer-to-Peer (P2P) Topology* and the *Star Topology*. Both topologies and their specific communication flows are shown in Figure 2.6. In a Star topology, all messages are transferred over the PAN Coordinator. In P2P topologies, the coordinator still provides management functionalities, but the normal communication takes place directly between entities, without the assistance of the coordinator. Different usage scenarios are therefore possible with these different topologies. An example of a 802.15.4 P2P topology is the *Cluster Tree Network*: different networks are arranged in a tree topology, whereby several networks are combined into a bigger one. This topology is often used in Wireless Sensor Network (WSN) scenarios.

Since the 802.15.4 standard does not specify the upper layers (refer to Figure 2.5), additional standards are needed here. ZigBee™ [32] is an example of an industry standard, which incorporates IEEE 802.15.4 and defines the network layer and application framework on top of the standardized PHY and MAC. ZigBee provides more security features and different application profiles. With ZigBee, routing, network management, data transmissions between entities and security functions are specified and standardized. Therefore, researchers often use the sole 802.15.4 layers as the basic underlying framework for their own developed MAC, routing or network management protocols.

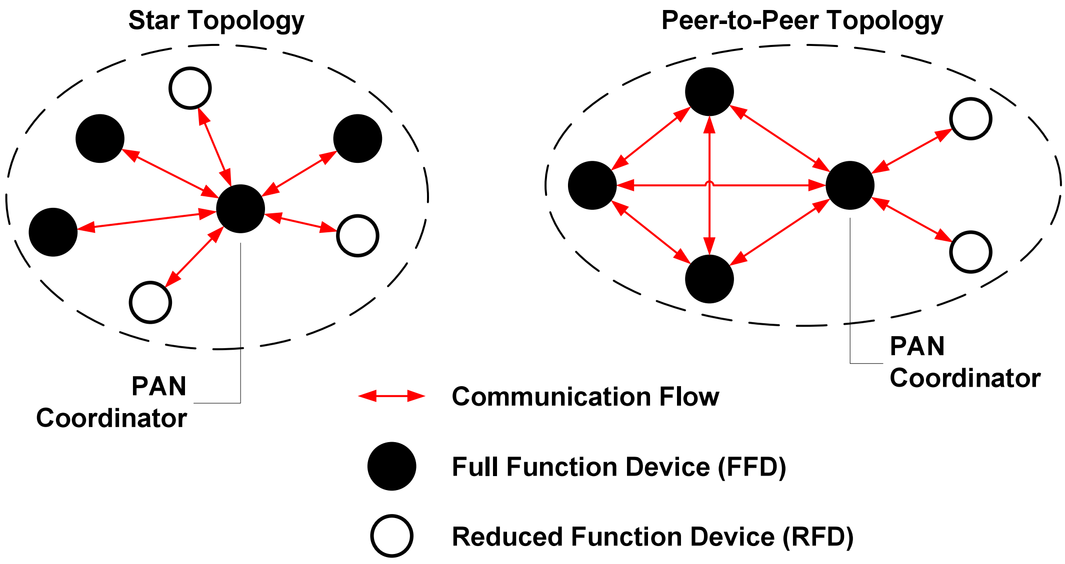


Figure 2.6: IEEE 802.15.4 Topologies and Device Roles (based on [30])

2.2.3 Important Mechanisms, Functions, and Features

This section presents different parts of the standard, which are important for further investigations. The selection is based on the influence on channel access, resource allocation and other aspects that are important for health monitoring and care solutions.

Frame Structure

Frame structures are very important for the system performance. An efficient message exchange needs slim yet expandable and robust frames. The 802.15.4 standard keeps the complexity of the frame structures low. Mechanisms to secure the frames against interference on noisy channels are included in the frame structure. Each frame type is equipped with a 16-bit frame check sequence where a Cyclic Redundancy Check (CRC) algorithm is used. Four different frame types are defined in the standard:

- *MAC* command frame
- *DATA* frame
- *BEACON* frame
- *ACKNOWLEDGMENT* (ACK) frame

The standard follows the OSI principle for layered communication systems. Each layer of the protocol stack adds to the structure of the four frame types with layer-specific headers and footers. The *MAC* frame is used for handling the control transmissions while the *DATA* frame is used for all data transmissions. *ACKNOWLEDGMENT* frames are used to confirm a successful reception and *BEACON* frames are used by the PAN coordinator for the beacon distribution. The exact frame type structures are listed in [30]. The detection of frame types and borders is a hard- and firmware task.

Data Transfer Model

Three different transmission types are defined in 802.15.4. Star topology networks only support the first two transaction types, as shown in Figure 2.6. In P2P topologies, all three types of transmissions are possible. The three types are:

- Transmissions from a device to the PAN coordinator (ACK optional)
- Transmissions from the PAN coordinator to a device (ACK mandatory)
- Transmissions between any two devices (FFD or RFD, not PAN coordinator)

Superframes and Beacons

802.15.4 supports a so-called superframe structure. The superframe format is defined by the PAN coordinator through parameters (BO and SO), included in network beacons. The superframe itself regulates the sending periods of all devices inside the local PAN. The boundaries of a superframe are the network beacons (see Figure 2.7), which are sent by the PAN coordinator. All devices inside a PAN receive the beacons and derive the rules for sending, receiving and sleeping from the included parameters. As shown in Figure 2.7, a superframe is divided into active and inactive portions. The inactive periods are used to put radios and devices to sleep, power management goes therefore hand in hand with the use of superframes. The active portion consists of a Contention Access Period (CAP) and a Contention Free Period (CFP). In the CAP, devices content for the channel access with the help of a CSMA-CA algorithm. In the CFP, devices can reserve Guaranteed Time Slot (GTS) for non-contented channel access. Inside a GTS, devices transmit without using Carrier Sense Multiple Access Collision Avoidance (CSMA-CA). GTSs are often used for time-critical or low-latency applications. If a PAN coordinator does not wish to use superframes, it simply turns off the transmission of the beacons.

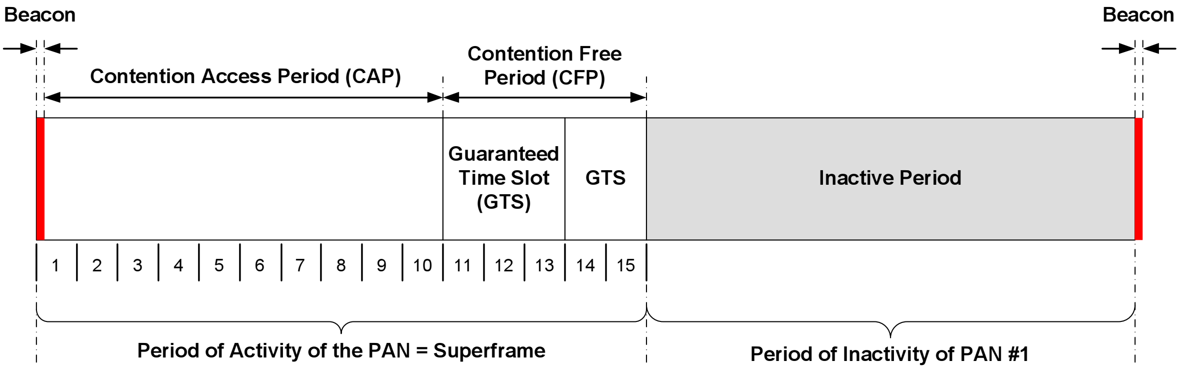


Figure 2.7: IEEE 802.15.4 Superframe Structure (based on [30])

CSMA-CA

The Carrier Sense Multiple Access Collision Avoidance (CSMA-CA) algorithm is used to avoid concurrent transmissions in wireless systems. 802.15.4 specifies a slotted and an unslotted CSMA-CA version. Unslotted CSMA-CA is used by non-beacon-enabled PANs for channel access management. Each time a device wants to transmit, it waits for a random time period (*backoff*). After this backoff, the devices samples the channel. If the channel is empty, the device transmits its data; if the channel is busy, the device refrains from accessing the channel and waits for another backoff interval. If no channel access is possible after (max) 5 retries, the MAC reports an error back to the upper layer. If the message was successfully sent, the following acknowledgement is sent without using CSMA-CA. Beacon-enabled PANs use the slotted CSMA-CA version. The backoff periods are aligned with the start of the beacon transmissions. If a device wants to access the channel during a CAP it waits for a random number of backoff slots. If the channel is busy, the device waits for another random number of backoff slots before trying to access the channel again. The CAP boundaries are included in the beacon frame, the devices listen for the beacon to align their backoff periods to the start of it. In this mode, acknowledgements and beacon frames are sent without using CSMA-CA. The CSMA-CA parameters can be adjusted on the different layers with command frames. Default values are specified in the standard [30, Table 86].

ED, LQI, and CCA

The CSMA-CA algorithm needs mechanisms to decide if a channel is busy or not. Next to this decision, the general transmission quality on the physical radio channel is also important. 802.15.4 applies three mechanisms for these tasks: Energy Detection (ED), the Link Quality Indicator (LQI), and the Clear Channel Assessment (CCA). These three features are used in the channel selection and evaluation process, the evaluation of the transmission quality and the sampling of a channel for the CSMA-CA algorithm.

ED is a functionality that provides a measurement of the received signal power within the bandwidth of the selected radio channel. A simple dB amount is reported back to the MAC management entity and no identification or decoding of signals is performed. The process and the outcomes are highly dependent on the receiver type and the actual hardware transceiver sensitivity. The ED function is used in the CCA process. CCA, in 802.15.4, stands for three different methods that are used to estimate the usage of the physical radio channel. These three methods are:

- CCA Mode 1 - Energy above threshold measurement
- CCA Mode 2 - Carrier sensing only
- CCA Mode 3 - Carrier sensing and energy above threshold measurement

The first CCA mode covers a simple measurement of the energy level on the physical channel. If the detected energy level is above a certain threshold, the medium is reported back busy. In the second CCA mode, the PHY samples the channel and tries to detect a signal compliant with the 802.15.4 standard. The PHY checks the modulation and spreading characteristics; the energy level of the signal is not checked in this method. The third CCA method tries to determine if a signal is been sent on the active channel and if the energy level of that signal is above a certain threshold. The threshold value must be set to a level where the receiver can still recover the signal at a certain quality. If the signal quality is too low the receiver needs a higher sensitivity, the frame needs more redundancy data or the antenna receive-gain needs to be higher. Parameters for the threshold value are depending on the transceiver hardware.

The Link Quality Indicator (LQI) is another feature of the PHY that gives a feedback about the quality of incoming packets. The LQI reports back a measurement of the received packet signal strength. Since the 802.15.4 standard does not specify how LQI is implemented, it depends on the hardware vendors. Different implementations are possible: a simple receiver ED or a signal-to-noise ratio estimation could be used. Even combinations of different methods are thinkable.

2.2.4 Possible Critical Aspects

Several aspects of 802.15.4 can be determined as possibly critical for the coexistence and cooperation of devices in dense radio conditions. This section lists components and specifications that might lead to shortcomings for the use of health care solutions in the aspired scenarios. The mentioned points will be re-evaluated extensively in Chapter 4.

Frequency Band Selection: As stated before, the 2.45 GHz ISM band is the preferred frequency band for 802.15.4, since this frequency is available world wide. A shortcoming of 2.45 GHz is the crowdedness: Bluetooth, microwave ovens, IEEE 802.11 WLAN and other WPAN technologies operate on this frequency. Crowdedness and density in the frequency band can lead to serious performance problems due to the design considerations (small output power) of 802.15.4. Another drawback of the 2.45 GHz band is the bigger attenuation for higher frequencies, compared to the 868/915 MHz band. Antennas and transceivers must deal deal with these challenging radio conditions.

Sending Power Output: 802.15.4 was designed for low power consumption. To support this, the sending output power was restricted to -25 – 0 dBm (e.g. TI Chipcon 2420 radios). Other technologies like IEEE 802.11 use much higher output powers. They have a highly disturbing influence on 802.15.4 devices if they are used on the same or even adjacent channels. The reason is the logarithmic character of the decibel-related output power ratio, shown in the following formula (referenced to one milliwatt):

$$\mathrm{dBm} = 10\log\left(\mathit{Power\ Output}\ /\ 1\,\mathrm{mW}\right) \tag{2.1}$$

Zero dBm equal one milliwatt. A value of 3 dBm represents already double the output power, which means it equals roughly 2 mW. 802.15.4 with its 0 dBm or 1 mW output power is highly overpowered by 802.11 transceivers (usually 15 dBm or 32 mW), wireless 802.11 routers (up to 20 dBm or 100 mW) and even Bluetooth Class 2 radios (4 dBm or 2.5 mW). This overpowering can lead to serious coexistence issues.

802.15.4's low output power is on the other hand an advantage for using it in health care scenarios, since the transceivers are often attached to the body. Health and communication system regulations forbid high output and radiation (EIRP) powers in these cases. 802.15.4 radios are therefore perfectly suited for these WBAN scenarios.

GTS Usage: Guaranteed Time Slots were already introduced as a mechanism of 802.15.4 for supporting low latency and near-real-time applications. One of the drawbacks of using GTS is that the receiver of a device that has any “receive GTS” needs to remain on for the whole duration of the GTS, regardless of the size of the data packet that he is receiving. This is a major drawback for a low energy consumption, since the receiver can be deactivated in non-GTS use cases after receiving the data packet.

Hidden Terminal Problems: Wireless communication systems have to deal with the hidden terminal problem. This problem refers to the case where one node is visible from a central device but not for other nodes that are communicating with the central device. Problems for the concurrent medium access will occur. The CSMA-CA mechanism is useless in this case. Normally, mechanisms like RTS/CTS are used to overcome these problems. But RTS/CTS was dropped in the 802.15.4 standard because of the expected low duty cycle. For high duty cycle applications (e.g. ongoing cardiac monitoring), problems might arise if the network traffic exceeds a certain limit.

Cooperation between different Networks: Cooperation between different independent networks is not specified in any 802.15.4 revision. No messages or information exchanges are specified. New approaches are therefore needed to handle these deficits.

3 Reference Applications and Scenarios

Examples for health care solutions with 802.15.4 transceivers were already presented in Chapter 1 and Subsection 2.1.2. This chapter intends to abstract and specify reference applications and scenarios from the described examples for further usage in the thesis. The extracted four important parameters of health care solutions are specified here for the modelling process and further simulative investigations and evaluations.

Reference descriptions and specifications of applications and scenarios, where these applications are used, are necessary for any transparent investigation. Comparability and traceability of simulations and investigations are only possible when actors, components, features, and parameters are specified and well documented. Chapter 3 serves this purpose by specifying the applications and scenarios used for all further investigations.

3.1 Specification of Reference Applications

A health monitoring or care solution serves a specific purpose or function. This purpose is usually concealed in the application running on top of the different used devices or in a application distributed inside the used network. The specification of an application is therefore necessary for the correct modelling of use cases and scenarios. The already introduced architecture of 802.15.4 (refer to Subsection 2.2.2 and Figure 2.5) does not define any specific application layer. Hence, this section contains the descriptions of two configurable reference applications, namely:

1. *Cardiac Arrhythmia Monitoring with ECG*
2. *Body Constitution Monitoring*

3.1.1 Cardiac Arrhythmia Monitoring with ECG

An Electrocardiogram (ECG) is the process of recording the electrical activity of the heart over a time period with the help of an electrocardiograph [33]. The recording is carried out by body attached non-invasive electrodes. ECG was first used in the 19th century and made its breakthrough with new invented technologies at the beginning of the 20th century. Today it is widely used to monitor the activity of the heart muscle and to detect non-rhythmic activities. Measurements of multiple ECG sensors are used to compute the heterogeneity (difference between successive waveforms) of an ECG. Dangerous cardiac arrhythmias can be detected thereby. Future developments and trends involve the extension of implanted ECG sensors with active components to act in case of arrhythmia conditions (e.g. nerve stimulation or drug deliverance). A WBAN with ECG functionalities is thus used as a starting candidate for the investigations.

Network Layout

The cardiac arrhythmia monitoring is provided by multiple body attached sensors. The exact sensor placement is more of a medical topic, since it depends on the wanted ECG outcomes. Different electrode placements lead to different measurements with room for variable outcome interpretations. Two basic strategies are normally used: placing the sensors on the chest area or placing them on the extremities. The two basic layouts with the sensor electrodes and the central controlling device are shown in Figure 3.1.

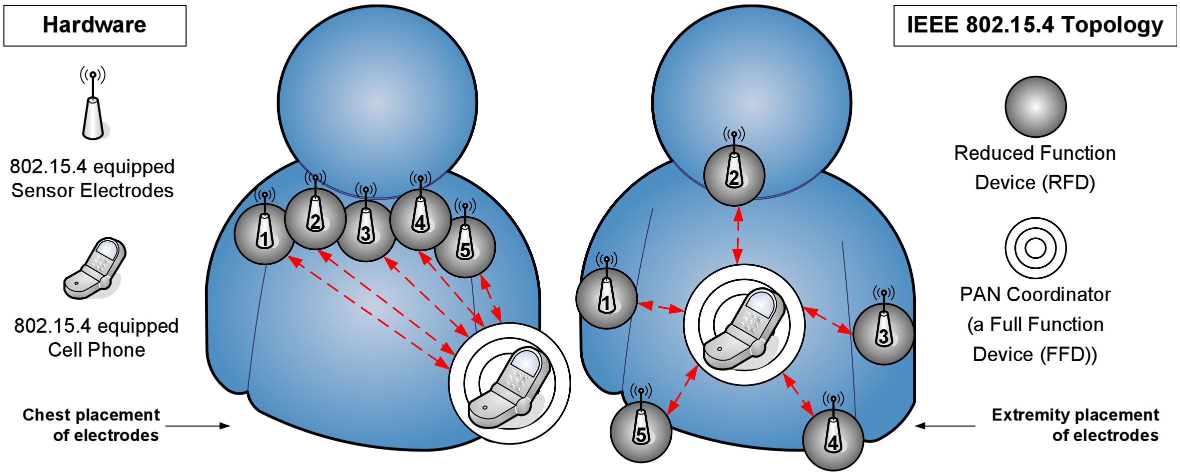


Figure 3.1: Reference Application 1 - Body Area Network Layouts

As shown in Figure 3.1, a 802.15.4 *Star Topology* with RFDs and a FFD as the PAN Coordinator are used in this application. Routing is therefore simple because all data from the sensors is sent directly to the PAN Coordinator. The controlling device for this reference application can be a cell phone with a 802.15.4 radio. The RFDs can also be exchanged with FFDs without the need for network layout changes. The measurements of the five electrodes are sent to the displayed central unit, where everything is computed and evaluated. The exact type of evaluation is not considered here; just giving the possibility for different ECG outcomes by including five sensors is sufficient.

Hardware and Specifics

If a cell phone should be used as data collector and PAN Coordinator, as shown in Figure 3.1, then it needs a 802.15.4 transceiver. Currently only add-on transceivers (as presented on the ZigBee Tokyo Open House exhibition for example) are available. These add-on transceivers with micro-SD card format can be used to extend the capabilities of normal cell phones with micro-SD slots. A Java environment on the cell phone can be used to deploy the necessary software. The fusion of ECG sensor electrodes and 802.15.4 transceivers is a hardware task that is not considered any further. A substitution of the cell phone with a PDA, a netbook, or a patient monitoring devices is possible. This merely depends on the scenario and situation where this application should be used.

Parameter Values

The important parameters for this application are the **Reporting Interval**, which defines how often the sensors report their sensed data back to the PAN Coordinator, and the **Sensing Interval** and **Sensed Data Amount**, which determine how much data has to be transferred to the PAN Coordinator each time. The **Memory Capacity of the Device** is expected to be big enough to store measurements until the previous transmission attempt was successful and the next reporting interval was triggered.

The guideline values for these important parameters are shown in Table 3.1. These values are derived from characteristic values of proposed wireless ECG sensor platforms like [12] or [10, 11] and available ECG electrodes like [34] for example. The **Sensing Interval** depends on the number of samples per second that the sensor electrode is measuring. The **Sensed Data Amount** depends on the sensor electrode type, the

Analog-to-Digital Converter (ADC), and its resolution (between 6–14 bit). The ECG electrode from [34] generates 4 byte per sample with a 12 bit resolution, other electrodes generate 1 or 2 bytes per sample for example. Depending on the **Sensing Interval**, different data rates per sensor are possible, the calculation is shown in Equation (3.1):

$$\texttt{Sensing Data Rate} = \texttt{Sampling Rate} \times \texttt{Data}\,/\,\texttt{Sample} \tag{3.1}$$

Using the above stated equation, the following *data rates per second* result from multiplying different sample rates with 4 bytes per sensor per sample (as in [34]):

$$\begin{aligned}
100\,\text{Hz}\ \texttt{Sampling Rate} \Rightarrow \texttt{Sensing Data Rate} &= 3200\,\text{bit/s} = 3.2\,\text{kbit/s}\\
250\,\text{Hz}\ \texttt{Sampling Rate} \Rightarrow \texttt{Sensing Data Rate} &= 8000\,\text{bit/s} = 8\,\text{kbit/s}\\
500\,\text{Hz}\ \texttt{Sampling Rate} \Rightarrow \texttt{Sensing Data Rate} &= 16000\,\text{bit/s} = 16\,\text{kbit/s}
\end{aligned} \tag{3.2}$$

Depending on the sample size of the electrode, different data rates are achieved. The continuous data stream is transferred from the electrode to the PAN coordinator. To model this **Reporting Interval**, the packet and payload size of 802.15.4 must be considered. The calculation of effective data rates out of the gross data rates is described in Subsection 4.1.4. For now, an estimation with a usable payload of 100 bytes is calculated. These assumptions lead to the following *packets per second rate* (P/sec) and the appropriate *time interval* in which a packet must be generated and sent:

$$\begin{aligned}
100\,\text{Hz and } 3.2\,\text{kbit/s} \Rightarrow \texttt{Packet Rate} &= 4\ \text{P/sec} \mapsto \texttt{Interval} = 250\,\text{ms}\\
250\,\text{Hz and } 8.0\,\text{kbit/s} \Rightarrow \texttt{Packet Rate} &= 10\ \text{P/sec} \mapsto \texttt{Interval} = 100\,\text{ms}\\
500\,\text{Hz and } 16.0\,\text{kbit/s} \Rightarrow \texttt{Packet Rate} &= 20\ \text{P/sec} \mapsto \texttt{Interval} = 50\,\text{ms}
\end{aligned} \tag{3.3}$$

For the example calculations with a 4 byte sample size, transfer and processing times between 250 ms and 50 ms are needed, depending on the electrodes sampling rate. Other research work (e.g. [28]) shows that data rates of 4 kbit/s and end-to-end transmission delays below 500 ms are appropriate for the ECG application. Table 3.1 contains the parameter values for this reference application, including minimum, ideal and maximum values, which were derived from the calculations presented in this subsection as well as information gathered from related work. Since the *Sensing Interval* is equivalent to the *Sample Rate*, these values are given in Hertz.

	Parameter Values		
Parameter Name	*min.*	*ideal*	*max.*
`Sensed Data Amount` (per Sample)	2 bytes	4 bytes	6 bytes
`Sensing Interval`	100 Hz	125 Hz	250 Hz
`Data Rate` (per Sensor)	1.6 kbit/s	4 kbit/s	12 kbit/s
`Reporting Interval`	< 500 ms	< 250 ms	< 100 ms

Table 3.1: Parameter Specifications for Cardiac Monitoring

3.1.2 Body Constitution Monitoring

The second reference application describes a Body Area Network (BAN) with different sensors for various measurement types. While the first reference application considered a single use case (ECG), the second one spreads the focus on different use cases and various monitoring applications running on-top of a BAN. The constitution monitoring of a person depends on multiple measurements, e.g. skin temperature, humidity, activity and position recognition, stress level, heart rate, oxygen saturation, and others. To enable such a variable use case, several sensors with different working paradigms coexist inside a BAN, while the time constraints are looser compared to the ECG application.

Examples of body constitution monitoring are the observation of athletes in sport competitions or the surveillance of soldiers. With the data from the various sensors, valuable information about the performance of the monitored persons can be gathered. For athletes, the extensive analysis could lead to better training strategies and performance enhancements. For military scenarios, a monitoring of soldiers brings advantages in terms of health care in time-critical situations. Military research like [35] shows that these ideas are currently investigated. Since this application can also be used for investigations of *Inter-Network Cooperation*, it is included as a reference application.

Network Layout

Because this application's BAN is supposed to monitor various conditions, different sensor types are used. Comparable configurations can be found in the area of activity recognition. Figure 3.2 shows an example layout with 8 different sensors, each with a 802.15.4 transceiver. Six of the 8 sensors are passive, e.g. for monitoring the temperature, humidity, heart rate, oxygen saturation or for activity recognition (limb mounted sensors). The two active sensors shall have several functions, namely temperature or heart rate monitoring and other active regulation functions (e.g. insulin or anodyne injections).

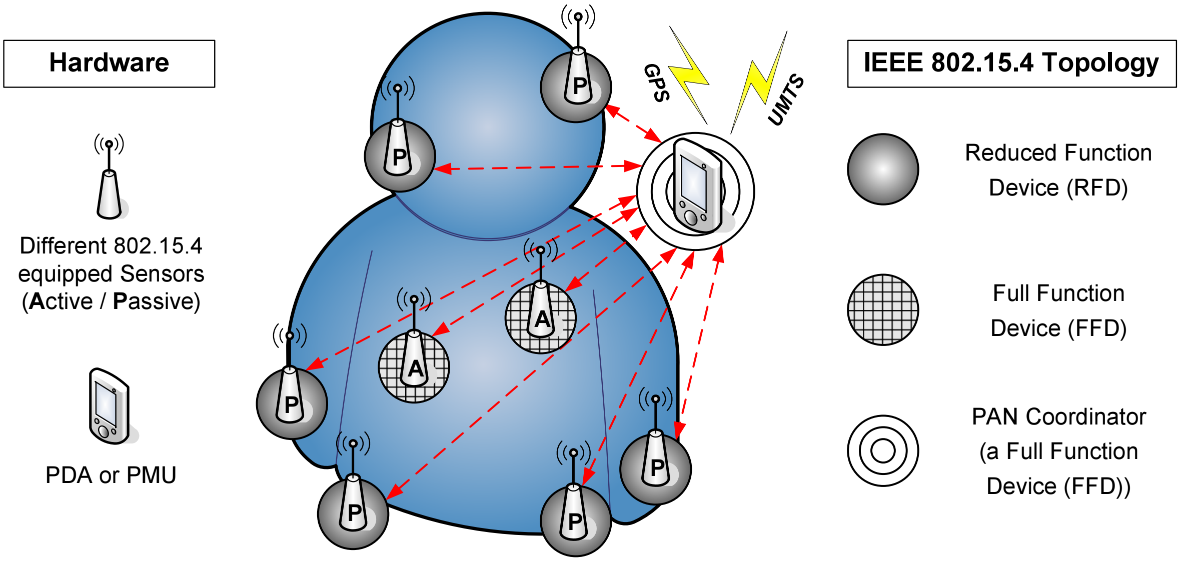


Figure 3.2: Reference Application 2 - Body Area Network Layouts

As shown in Figure 3.2, a *Star Topology* is used again to connect the different sensors and the central device. In this case a PDA or a Patient Monitoring Unit (PMU) is preferred over a cell phone. Depending on the actual usage environment, long distance communication or GPS could be included in the used devices, if they are needed.

Hardware and Specifics

The availability of sensor hardware and 802.15.4 add-on transceivers is comparable to the first reference application. Non-invasive sensors for the described sensing applications are available, examples are: blood oxygen sensor module (from *Shanghai Berry Electronics*), blood glucose meter, blood pressure, and pulse meter (from *TaiDoc Technology Corporation*). The combination of such example sensors with 802.15.4 transceivers is again a hardware development task. Other introduced research projects, like *CodeBlue* [11], have already developed sensors with 802.15.4 transceivers. An example is the pulse oximeter [11], which measures heart rate and blood oxygen saturation by using a non-invasive finger-attached sensor. These parameters are important in emergency situations. Constant monitoring of them is therefore very valuable.

The sensors used in this application transmit their sensed data back to the PDA or PMU. After collecting the data, the central device evaluates it and decides about further measures, e.g. an active regulation of health conditions or an emergency call. With the combination of information from different sensors, more adequate decisions about the constitution and the necessary steps based on the current situation of the monitored person can be made. To enable the identification of a symptom correlation, the PAN Coordinator collects all data from the sensors and evaluates it with algorithms and software, which contain the required medical knowledge. The possibility of a cooperation of different networks depends on the central device. Since the sensors are mostly just RFDs, the PAN coordinator must perform the necessary tasks for the cooperation with other PANs. The necessary cooperation strategy will be developed in Chapter 5.

Parameter Values

Important parameters in this case are the **Reporting Interval** and the **Memory Capacity of a Device**, especially of the sensors. Since the memory capacity usage can be modelled with the **Sensing Interval** and the **Sensed Data Amount**, these two parameters are used again, similar to the first reference application. A memory size is assumed that is big enough to store all measurements of the sensor until the last transmitted ones were successfully received. With the help of the equations (3.1) to (3.3) necessary parameter values can be calculated again. They are presented in Table 3.2, this time split up for the different sensor and application types.

The parameters were again deducted from available hardware and related research like [11]. The presented values are given per sensor. For the heart rate, the value range normally lies between 0 and 250 beats per minute; a sensing interval of 200 ms or five sensing operations per second are therefore sufficient to accurately detect the heart rate. With a differential encoding, 4 bytes per data sample are sufficient. The oxygen saturation (between 0–99%) can be measured with the same parameters. For the temperature, 4 bytes per data sample and two samples per second are adequate. The active sensors can switch between different sensing modes (e.g. temperature, heart rate, or other values). Their maximum operation parameters are included in the table, lower achieved parameter values are possible, but not required. The values for the activity recognition sensors are derived from example sensors [36] and according research [37].

Parameter Name	**Parameter Values** *Heart Rate & Blood Oxygen*	*Temperature*	*Activity Recognition*	*Active FFD Sensors*
`Sensed Data Amount`	4 bytes	4 bytes	25 bytes	8 bytes
`Sensing Interval`	200 ms	500 ms	100 ms	100 Hz
`Data Rate`	160 bit/s	64 bit/s	2 kbit/s	6.4 kbit/s
`Reporting Interval`	< 2 sec	< 2 sec	< 1 sec	< 1 sec

Table 3.2: Parameter Specifications for Body Constitution Monitoring

3.2 Specification of Reference Scenarios

For a simulative investigation, the previously introduced reference applications are not enough. A complete modelling is only possible when coexistence, cooperation, and interaction of actors and entities is specified in clear defined boundaries, namely scenarios. The scenarios describe the usage of the specified applications and the interaction of entities executing these applications. The descriptions contain specifications and settings which will be used for the implementation of *virtual reproductions* of the specified scenarios. Simulative investigations can then be conducted on the virtual scenarios. This section consequently contains two scenario types with three different settings:

1. *Monitoring of Large Groups*
2. *Health Care in Smart Home and Hospital Environments*

3.2.1 Monitoring of Large Groups

This scenario describes a setting where multiple persons with independent BANs coexist. The scenario's main objective is the modelling of *Intra-Technology Coexistence* and *Cooperation* features. Two different real life situations are considered for this.

Sport Contest: A great number of people get together for a sport contest or competition (e.g. a marathon). Their performance and health conditions are monitored with the help of WPANs with body-attached sensors. The sole sensors perform their tasks according to the specified second reference application (*Body Constitution Monitoring*). The sensed data is collected, examined, and evaluated by the respective PAN Coordinator, who later on sends the data to a central data server for further usage.

Military Appliance: Military training and battle operations include a big number of soldiers. Even today, the majority of involved soldiers are foot soldiers. Their performances in training simulations and their health conditions especially in battle or war operations are important aspects. WPANs with body attached sensors are used to monitor these conditions and give a feedback about the current status of the soldiers.

A serious problem in these example situations is the high concentration of similar wireless devices in a small area, the so-called *Intra-Technology Coexistence*. The high concentration and the resulting dense radio conditions lead to serious problems for the coexistence of devices and their applications. A conflict free and distributed assignment of radio resources (bandwidth, channels, radio time) to independent WPANs is the most important task here, to raise the number of coexisting networks and to guarantee application parameters to a certain degree. To enable a research of these conditions, a number of coexisting LR-WPANs is set on a playground, each with the network layout and configuration of the second reference application as shown in Figure 3.3.

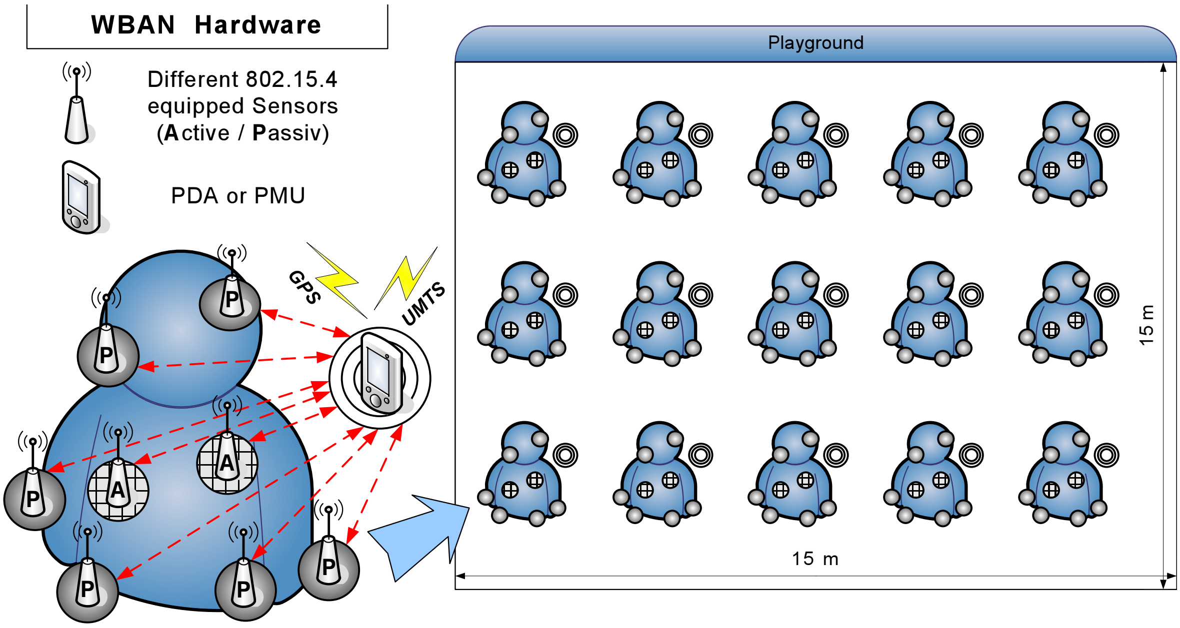


Figure 3.3: Reference Scenario 1 - Monitoring of large Groups

The displayed playground is the simulation area: within its boundaries, coexistence, interference, and cooperation of sole devices and independent networks are considered and simulated. In Figure 3.3, only 15 users with their WBANs are displayed for the lack of space. In a simulation, even higher numbers of users will be investigated. This reference scenario will be implemented without any mobility aspects. Future work could include user mobility. The different users with their WBANs will primarily coexist in radio vicinity. *Intra-Technology Cooperation* of the different WBANs will be considered in terms of information and data exchange between independent networks. A possible use case for the cooperation is the replacement of a device (e.g. the GPS receiver) via data exchange between different WBANs. Simulations will be made with the according parameter values of the second reference application introduced in Subsection 3.1.2.

3.2.2 Health Care in Smart Home and Hospital Environments

The second reference scenario describes situations where multiple wireless technologies are used in proximity. The scenario's main objective is the modelling of *Inter-Technology Coexistence* and possibilities for *Inter- and Intra-Technology Cooperation*. Only wireless technologies that operate on the 2.45 GHz ISM band are considered to empower this function. The following paragraphs introduce two examples to illustrate this scenario.

Health Care in Smart Homes: This case is comparable to the *Elderly Monitoring and Care* case, presented in Subsection 2.1.3 and Figure 2.4. Different wireless technologies are used inside a housing environment to enable ubiquitous health monitoring and care. Patients and users wear body-attached sensors that enable location tracking and passive condition monitoring. Active health regulation applications are supported as well.

Health Care in Hospitals: Monitoring in hospitals is comparable to the first example in terms of coexisting wireless technologies. Patients in hospital beds wear sensors for condition monitoring. The data is collected and evaluated by a central coordinator. The coordinator registers emergencies and reports them to a doctor in charge for example. A compliance with important parameters of the used application is essential.

Especially in medical care environments, the use of wireless frequencies is limited to restricted frequency bands, so that the used wireless technologies do not interfere with the stationary medical equipment. An important fact for these examples is therefore the possible interference caused by the coexistence of different wireless technologies operating on the same wireless band (e.g. 2.45 GHz ISM band). This can lead to problems in terms of service guarantee or quality. But it also enables the cooperation between different technologies, when a single device offers various wireless technologies.

The first example is modelled in Figure 3.4, where a smart home equipped housing environment is displayed. Several users wear WBANs with the network layout according to the second reference application. A person's constitution is monitored with the sensors from the WBAN. WLAN and Bluetooth are also used in radio vicinity to provide other smart home services. Because of these concurring technologies, not all available channels of 802.15.4 can be used without interference. The WLANs use the three most apart channels available for this wireless technology. Since the WLAN frequency channels overlay those of 802.15.4, there are only a limited number of non-interfered channels left for 802.15.4. Investigations will be made with the given playground size, the limited channel resources and the application parameters according to the specified second reference application. The user number will again be alternated for the investigations.

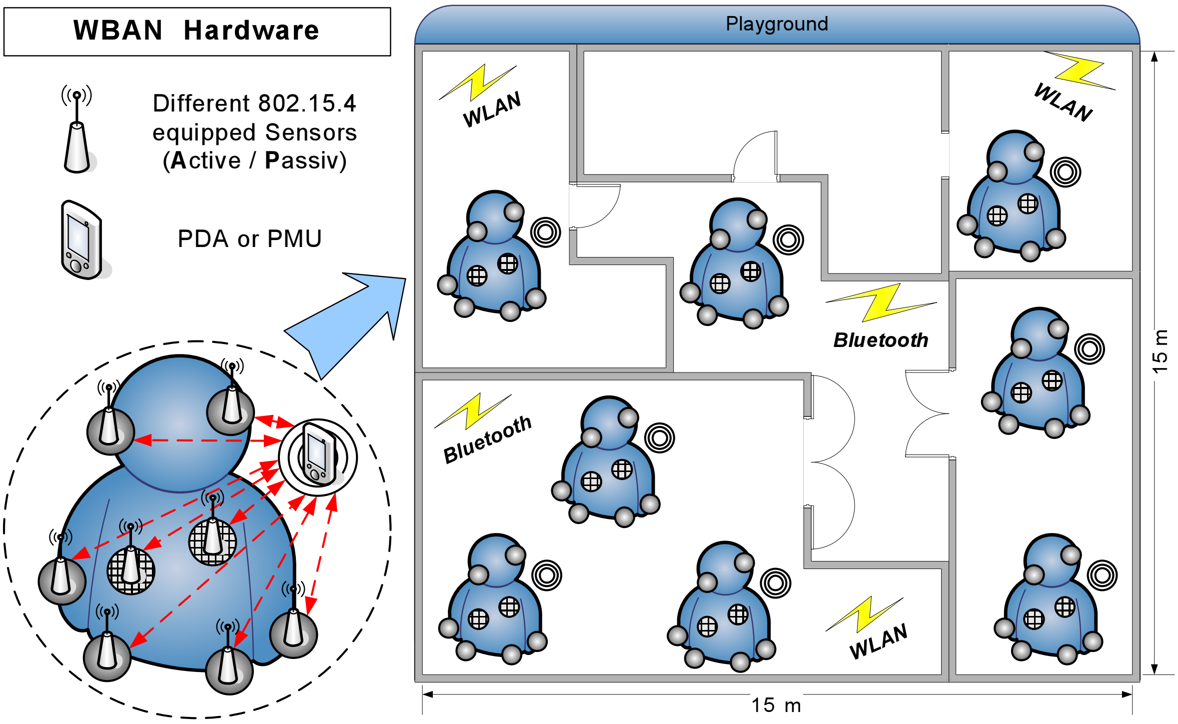


Figure 3.4: Reference Scenario 2.I - Health Care in Smart Homes

The model for the second example (*Health Care in Hospital Environments*) is shown in Figure 3.5. A number of patients in hospital beds is considered here. They wear WBANs which execute the first introduced reference application. A single WLAN is used in the same room. Bluetooth base stations are installed on the four corners of the room for additional medical systems. A similar scenario was described in [28]. The number of patients in a room is usually fixed, ranging between 2 to 10 persons in a single room. With the help of simulations, the maximum number of supported WBANs in radio vicinity can hopefully be determined. The specified parameters from the first reference application (ECG) will be used for the implementation of this scenario scenario.

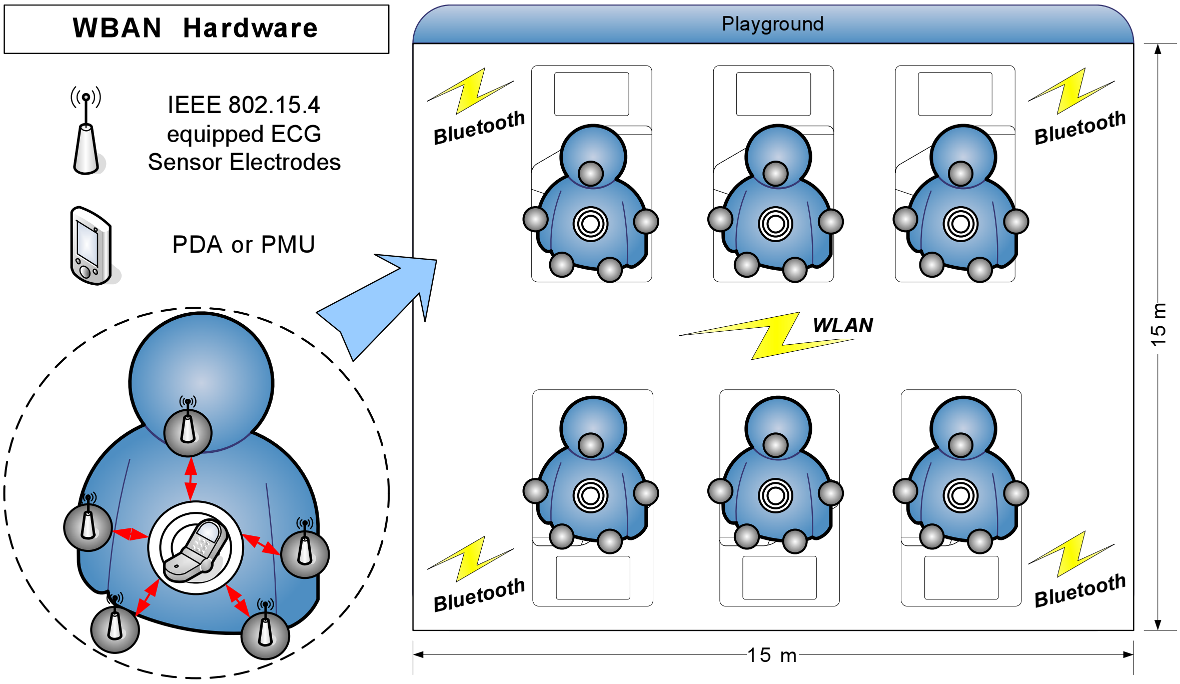


Figure 3.5: Reference Scenario 2.II - Health Care in Hospital Environments

Mobile users and general mobility aspects (e.g. multipath propagation, shadowing, fading, or refraction) are not considered in both settings of the second reference scenario. The described two examples put the focus on dense radio conditions in terms of *Inter-Technology Coexistence* and limited radio resources, just like the first reference scenario. Cooperation between different LR-WPANs are not emphasised in these scenarios, but they are nonetheless possible. Cooperation options could involve the inclusion of external actors (e.g. doctors, nurses) and the independent networks worn by these actors.

4 Coexistence and Cooperation Issues

The theoretical and practical (simulative) investigation of the 2006 revision of 802.15.4 is addressed in this chapter. The reference applications and scenarios developed in Chapter 3 were used to analyse 802.15.4 in terms of *Intra-/Inter-Network* and *-Technology Coexistence* and *Cooperation* problems. Identified issues are described in Section 4.1. Comparable research work is listed in Section 4.2, in which differences in approaches and assumptions in relation to this thesis are pointed out to round off the chapter.

4.1 Identified Problems and Issues

4.1.1 Inter-Technology Interference

802.15.4 has a low output power compared to other technologies operating on the 2.45 GHz ISM band, as already pointed out in Subsection 2.2.4. Due to the objective of low power consumption and governmental regulations, the normal radio sending power is restricted to -25 – 0 dBm. The calculation and logarithmic character of the decibel-related output power ratio are explained in Equation (2.1). Other technologies like 802.11 WLAN or Bluetooth can easily overpower 802.15.4. This issue is already covered by [38], [39], [40], or the 802.15.4 specification [29] itself for example.

While the low sending power is hardware-given and fixed, 802.15.4 already includes several mechanisms to cope with the coexistence with other IEEE wireless technologies. The Clear Channel Assessment (CCA) mechanism for example is used to evaluate the channel state before a 802.15.4 device starts to access the channel. If another wireless technology blocks the channel (the 802.15.4 device measures the energy/noise level on the radio channel), the 802.15.4 devices performs a backoff instead of accessing the channel. This mechanism supports the coexistence with other wireless technologies on the cost of performance, since a backoff extends the transmission time. Especially in the reference scenarios where different wireless technologies are used in radio vicinity (e.g. medical care in hospitals or smart home environments), serious performance drops of 802.15.4 are the consequence. [39] covers this issue. The authors performed simulations with 802.11 systems and various application types running on-top of the WLAN systems. Because the 802.11 WLAN was not idle, the packet loss of a 802.15.4 network operating on the same frequency was going up to almost 100%. The throughput dropped to zero and the 802.15.4 network was almost incapacitated.

The simplest solution for this problem is to use another radio channel that is not interfered by any 802.11 system. This approach leads to the second problem in terms of *Inter-Technology Interference*: limited radio resources. 802.15.4 has a limited number of sixteen channels on the 2.45 GHz ISM frequency band, as described in Subsection 2.2.2. The overlapping of 802.11 and 802.15.4 radio channels is displayed in Figure 4.1.

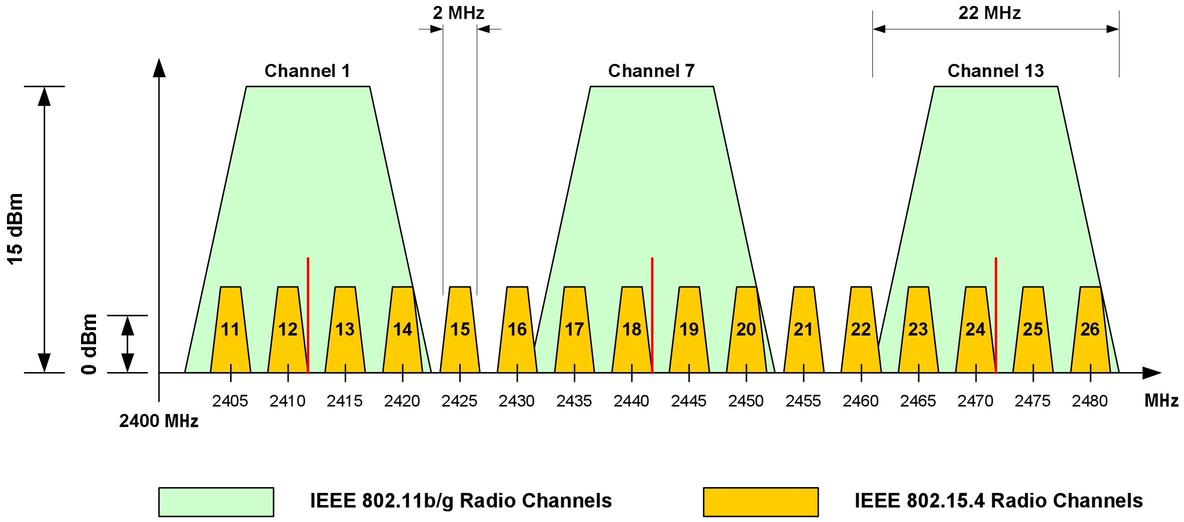


Figure 4.1: Overlapping of IEEE 802.11 b/g and IEEE 802.15.4 Radio Channels

802.15.4 radio channels are 2 MHz and 802.11 b/g channels 22 MHz wide, while the middle frequencies of neighbour channels are 5 MHz apart from each other in both technologies. 802.11 channels overlap 802.15.4 channels in terms of size (22 MHz over just 2 MHz) and output power (around 15 dBm over 0 dBm). If, for example, three independent 802.11 networks are used in radio vicinity together with 802.15.4 networks, only 4 non-interfered radio channels are left for 802.15.4 (as shown in Figure 4.1 for a non-overlapping 802.11 European channel selection). These four channels (15, 16, 21 and 22) fall in the guard bands between the three 802.11 channels. The energy level on these four channels will not be zero, but significantly lower compared to the other radio channels. Such an example situation is specified in the second reference scenario (*Health Care in Smart Home and Hospital Environments*). The number of non-interfered radio channels therefore depends on the scenario and the appearance of other wireless technologies with higher output power. If interfering systems are stationed in vicinity, non-interfered radio resources for 802.15.4 decrease significantly.

4.1.2 Intra-Technology Interference

Another problem occurs when many 802.15.4 nodes operate in radio vicinity. If the nodes are grouped in independent networks, up to sixteen networks can coexist at the same time in the 2.45 GHz band if all radio channels are usable and non-interfered. In this case no interference between the independent networks should occur. The interference and performance inside a single network on the other hand depend heavily on the node count and traffic load inside the network. If a certain limit of either traffic load or node count is exceeded, serious performance drops occur because packet collisions increase.

To demonstrate this problem, multiple simulations with modified parameters were performed. The basics for all conducted simulations are described in Section 6, while the specific evaluation outcomes are described and analysed in Subsection 6.3.1. At this point, it is important to know that in the simulations, traffic load, data source (node) count, and superframe parameters of 802.15.4 were varied together, to enable an evaluation of 802.15.4's performance limits in case of *Intra-Technology Interference* and dense radio conditions. A characteristic outcome chart is shown in Figure 4.2. The chart shows that the goodput (throughput on the application layer) reaches a limit for settings with many sources much earlier compared to settings with less sources. The maximum goodput for 10 or 15 sources is already reached with a traffic load of 10 packets/second while the maximum goodput for 5 sources is reached with 40 packets/second. For even less sources, a goodput limit cannot be observed in the outcomes.

The reasons for this limitation of goodput are connected with the sensitivity of 802.15.4 to *Intra-Technology Interference*. If many nodes or even networks operate on the same radio channel, more packets will be dropped on the nodes in case of blocked channels

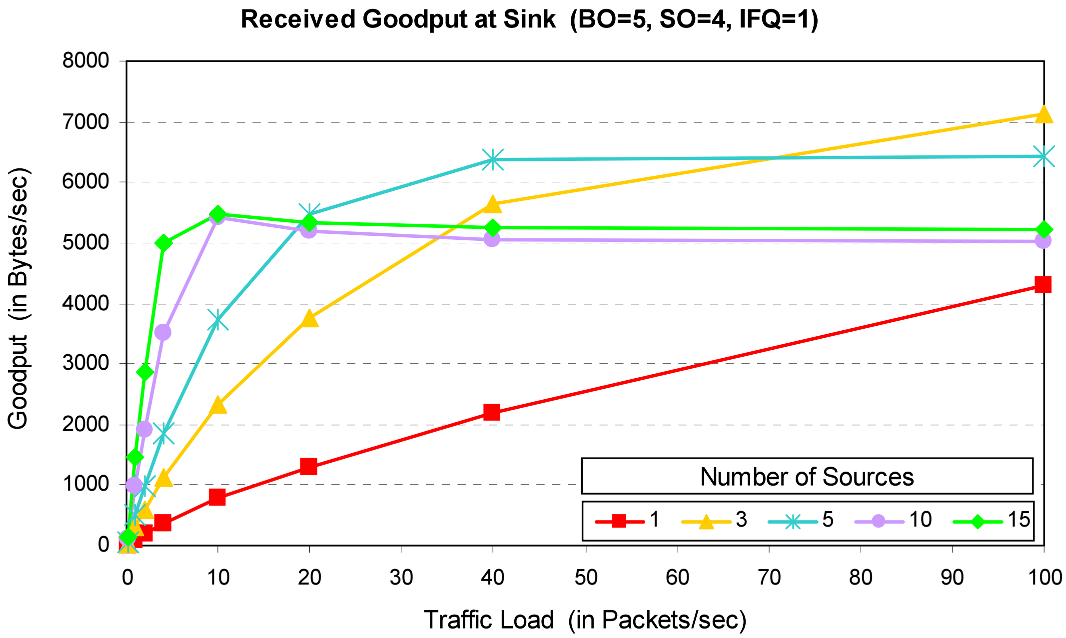


Figure 4.2: Outcome Chart for Simulative Investigation of the Application Goodput with various *Number of Sources* and Traffic Loads *(Packets/sec)*

(maximum number of retransmissions reached) or get destroyed because of overlapping transmissions (through concurrent radio channel access). Other tests (e.g. [39]) also showed that the impact of 802.15.4 WPAN on WPAN interference can be significant, even if just two 802.15.4 WPANs with their nodes are used on the same channel without any additional measures for *Intra-Technology Coexistence*.

The outcomes of these various simulations (see Subsection 6.3.1) can be transcribed to the specified reference scenarios where high traffic loads and many data sources inside a WPAN are used. Problems for the performance of the reference applications will be the consequence if multiple 802.15.4 WPANs have to be used on the same radio channel, in case of limited wireless radio resources.

Another aspect of *Intra-Technology Coexistence* is the described *Ubiquitous Future* and the *Internet of Things* trend. Both terms characterise scenarios where high numbers of devices are interconnected over the Internet. The development of Internet Protocol Version 6 (IPv6) was a first step into this future. Almost unlimited numbers of devices can be connected to a network with the help of IPv6, this protocol is a basic element of the ubiquitous future. Recent developments made it possible to include a IPv6 stack into almost all kinds of devices due to the shrinking of the memory footprint of the stack down to 11 KiB of Flash memory for the code and only 2 KiB of SRAM for the data structures and buffers [41]. Recent research in this area focuses on the combination of this small IPv6 stack with the standard 802.15.4 stack. Devices emerging from this could form the basis for an ubiquitous deployment of 802.15.4. Therefore *Intra-Technology Interference* must be considered in any practical solution approach.

4.1.3 CSMA-CA Algorithm and Back-off Interval

CSMA-CA was already introduced in Subsection 2.2.3. The algorithm (in a slotted and unslotted version) is used to avoid time- and power-consuming collisions when multiple wireless transmissions occur simultaneously from different devices. The slotted version of CSMA-CA is employed in beacon-enabled networks. CSMA-CA is then used in the CAP part of the superframe while the start of the backoff period is aligned with the beacon start. Unslotted CSMA-CA is employed in non-beacon networks. In this case no time link between the backoff periods of the devices inside a network is made.

In order to manage the transmission attempts, three variables are used: the Backoff Exponent (BE), the Contention Window Length (CW) and the Number of Backoffs (NB). The interaction of these parameters in the CSMA-CA algorithm is shown in Figure 4.3 on page 48. NB (range between 0 and 5) specifies the number of times CSMA-CA was required to backoff while trying to access the channel for transmitting. CW is only used for slotted CSMA-CA; it specifies the length (default value is 2) of the contention window, where no channel activity should occur prior to any transmission start. The backoff exponent BE is used to calculate a random value of initial backoff periods before the devices samples the radio channel for activity. While BE's maximum was initially static, the 2006 revision [30] specified an expansion of BE's range to a value between 3 and 8 (default 5), to extend the range of possible initial backoff periods.

A problem of CSMA-CA is the short default backoff period that leads to frequent repeated collisions if multiple devices access the radio channel. Especially if different networks with their devices have to operate on the same channel regularly, the backoff period range is too short and the contention window too long for the amount devices concurring for channel access. Research like [42] showed that the performance of 802.15.4's CSMA-CA algorithm drops for higher duty cycles. Very low duty cycles can help to

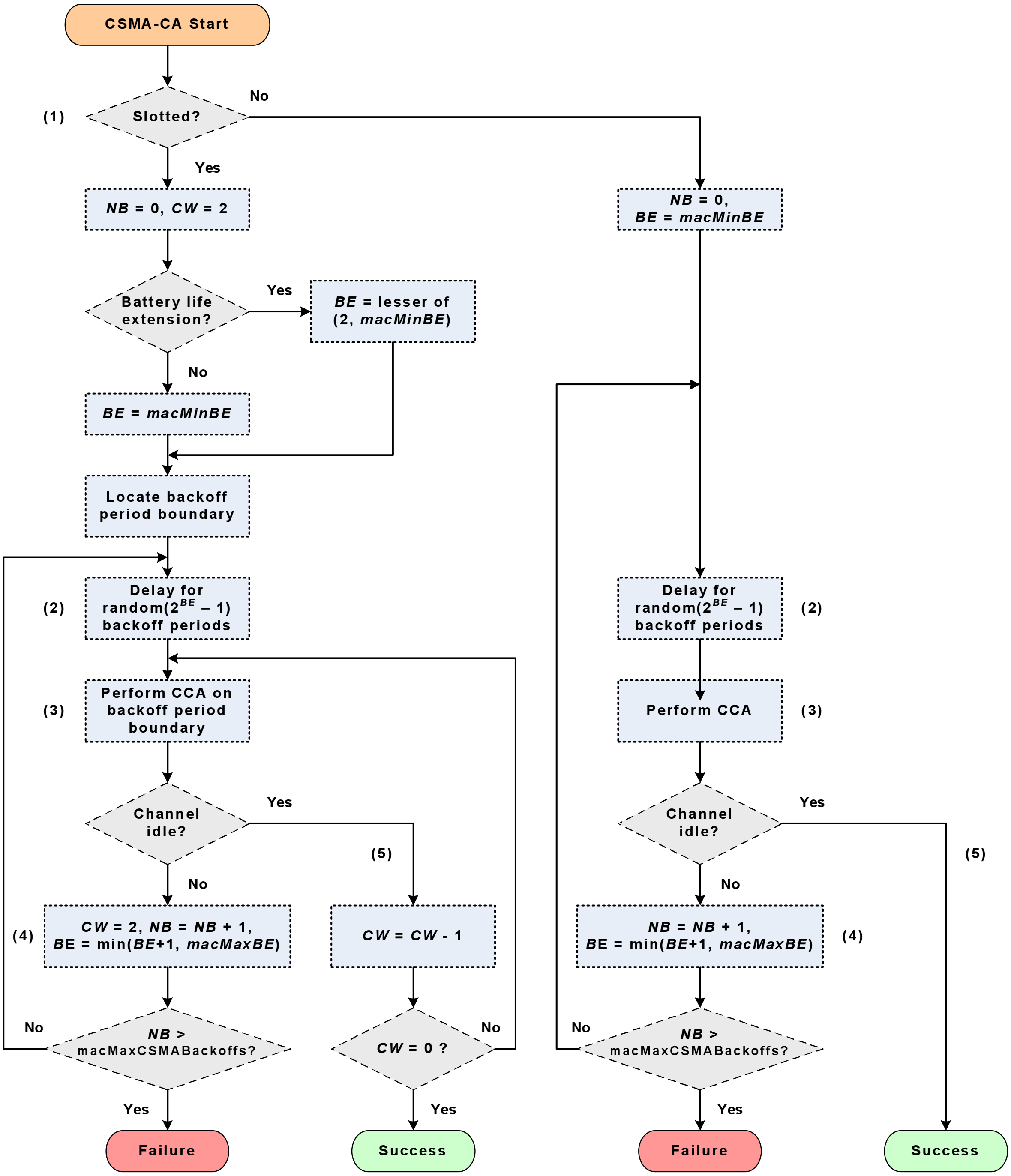


Figure 4.3: IEEE 802.15.4 CSMA-CA Algorithm (according to [30])

lower the number of collisions and therefore increase the network throughput (as shown in [42]). Since the specified reference applications (constitution monitoring and ECG) require high duty cycles and therewith less sleeping periods, performance drops because of frequent occuring collisions can be expected.

The slotted version of CSMA-CA is also prone to the problem of CCA deference and successive collisions. Each operation of the slotted CSMA-CA (channel access, backoff count, CCA) can only occur at the boundary of a backoff period (see operation (3) in Figure 4.3). Slotted CSMA-CA is used inside the CAP of a superframe; if a device can not complete its transactions before the end of the CAP, the device shall defer its transmission until the CAP of the following superframe. If many devices can not complete their transmissions, they start to sample the channel simultaneously. Since the initial CW value is static (default is 2), all devices will wait for two backoff periods and then access the channel at the same time, leading to packet collisions. This problem is shown in Figure 4.4 for two devices and the consequent transmission collisions.

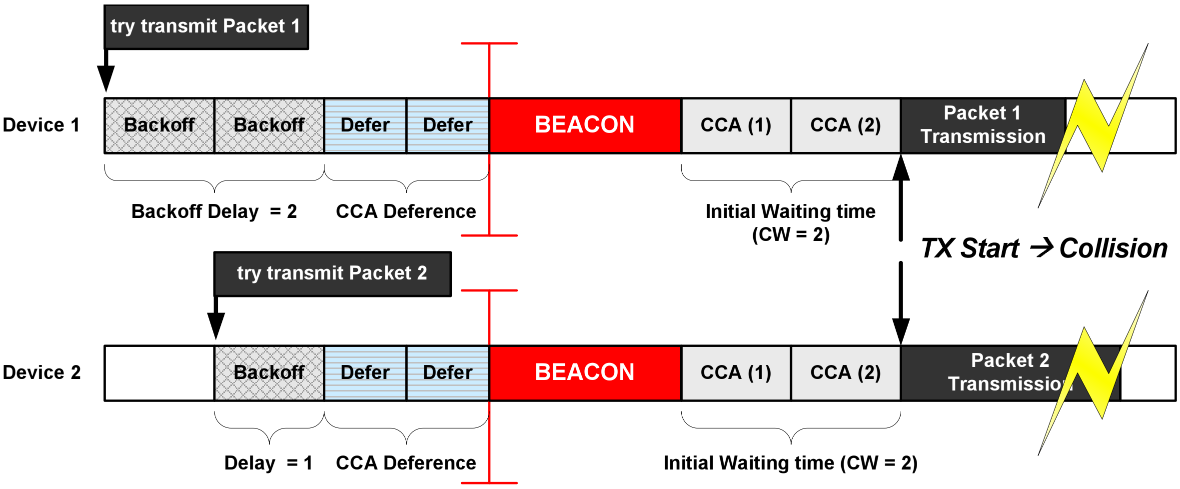


Figure 4.4: CCA Deference and the consequent Collisions for the Slotted Version of IEEE 802.15.4 CSMA-CA

If higher duty cycles, smaller superframe orders and shorter sleeping periods are used in combination with a high traffic load, CCA deference and consecutive collisions are bound to happen regularly. Since these described problematic conditions may influence the performance of devices in the specified reference applications and scenarios, approaches and methods to conquer these problems must be investigated.

4.1.4 Gross and Effective Data Rates

802.15.4 supports various data rates in combination with different PHYs. The standard specifies a data rate of 250 kbit/s for the 2.45 GHz band. These 250 kbit/s are a theoretic maximum over-the-air data rate. In practice, the achieved data rates are somewhat lower due to protocol overhead (e.g. protocol layer headers), frame acknowledgements, and data verification blocks. To calculate the effective data rate, the available data payload is needed first. This value and the necessary calculation is shown in Equation (4.1):

$$\texttt{aMaxMACFrameSize} = \texttt{aMaxPHYPacketSize} - \texttt{aMinMPDUOverhead} \tag{4.1}$$

$$\left.\begin{aligned} \texttt{aMaxPHYPacketSize} &= 127\,\text{bytes} \\ \texttt{aMinMPDUOverhead} &= 9\,\text{bytes} \\ \texttt{aMaxMPDUOverhead} &= 25\,\text{bytes} \end{aligned}\right\} \quad \text{according to the 2006 revision [30]}$$

The maximum payload of a single data packet is 118 bytes. These 118 bytes are only available in star topology networks when only source addressing fields are specified. Such frames are only accepted by the PAN coordinator when the source PAN identifier (the network ID) of the frame matches the one of the PAN coordinator. If normal addressing mode is used, then $aMinMPDUOverhead = 13\,\text{bytes}$; the total usable payload decreases to 114 bytes. These 114 bytes will be further used since the reference applications include RFDs and FFDs. The complete addressing support is necessary, because FFDs could receive messages from other nodes in the network.

The achievable data rate for beacon-enabled WPANs, which use the slotted CSMA-CA version, is also reduced by the initial random backoff, which is performed before the radio channel is sampled for the first time. Part (2) of Figure 4.3 shows this fact. This initial delay has a major influence on the effective data rate, depending on the length of the random backoff period. Example calculations are shown in the following equations:

$$\texttt{InitialBackoff} = (2^{BE} - 1) \times \texttt{aUnitBackoffPeriod} + \text{CCA} \tag{4.2}$$

$$\begin{aligned} \texttt{RangeofBE} &= [\,3 \ldots 8\,];\ \text{initial BE} = \texttt{macMinBE} = 3\ \text{(default value)} \\ 1\ \text{Symbol Period} &= 16\,\mu\text{s} \\ \texttt{aUnitBackoffPeriod} &= 20\ \text{Symbol Periods} = 20 \times 16\,\mu\text{s} = 320\,\mu\text{s} \\ \texttt{CCADetectionTime} &= 8\ \text{Symbol Periods} = 8 \times 16\,\mu\text{s} = 128\,\mu\text{s} \end{aligned}$$

$$\begin{aligned}
\texttt{Min.InitialBackoff} &= (2^1 - 1) \times 320\,\mu\text{s} + 128\,\mu\text{s} = 448\,\mu\text{s} = 0.45\,\text{ms}\\
\texttt{DefaultInitialBackoff} &= (2^3 - 1) \times 320\,\mu\text{s} + 128\,\mu\text{s} = 2368\,\mu\text{s} = 2.37\,\text{ms}\\
\texttt{Max.InitialBackoff} &= (2^8 - 1) \times 320\,\mu\text{s} + 128\,\mu\text{s} = 81728\,\mu\text{s} = 81.7\,\text{ms}
\end{aligned}$$

Note that if the BE value is set to zero, collision avoidance is disabled during the first algorithm iteration. A value of $BE = 1$ is therefore used for the minimal initial backoff period to enable collision avoidance. As shown in (4.2), an initial delay between 0.45 ms and 81.7 ms can occur before the radio channel is sampled for the first time. With default values, the delay is approx. 2.37 ms. The values includes the CCA waiting period (refer to Part (3) of Figure 4.3). To get the initial delay before the first packet is sent, the values from Equation (4.2) need to be increased by another CCA waiting period and the CW time (see Part (5) of Figure 4.3). The channel state must be included in such considerations too, because busy channels lead to additional backoff periods.

The presented long initial backoff periods also collude with the CCA deference introduced in Subsection 4.1.2. In case of slotted CSMA-CA, it is also important that each action (CCA or transmission) starts at the boundary of the next backoff period ($\texttt{aUnitBackoffPeriod} = 320\,\mu\text{s}$). This induces additional delays and leads therefore to a decrease of achievable effective data rates.

To calculate the effective data rate, the data frame transfer time is also needed. Equation (4.3) shows the calculation for a maximum data payload of 114 bytes, the `aMaxPHYPacketSize` of 127 bytes plus a 6- byte packet overhead due to the inclusion of the necessary synchronisation header (SHR) and the PHY packet header (PHR):

$$\begin{aligned}
\frac{(\texttt{aMaxPHYPacketSize} + \texttt{SHR} + \texttt{PHR}) \times 8}{250\,\text{kbit/s} \times 10^3} &= \frac{(127\,\text{bytes} + 5\,\text{bytes} + 1\,\text{byte}) \times 8}{250\,\text{kbit/s} \times 10^3}\\
\texttt{Data Frame Transfer Time} &= 0.004256\,\text{s} = 4.256\,\text{ms}
\end{aligned} \tag{4.3}$$

With the raw data frame transfer time of 4.256 ms and the default initial backoff of 2.368 ms, an approximation of the effective data rate can be calculated. Necessary are the overall delay for the transfer of a data frame and the maximal usable payload:

$$\texttt{Overall Transfer Delay} = \texttt{Default Initial Backoff} + \texttt{Data Frame Transfer Time}$$

$$
\begin{aligned}
\texttt{Effective Data Rate} &= \frac{(\texttt{Maximum Payload} \times 8)}{(\texttt{Overall Transfer Delay} \times 10^{-3})} \qquad (4.4)\\
&= \frac{(114 \times 8)}{(6.624\,\mathrm{ms} \times 10^{-3})} \approx 137681\,\mathrm{bit/s} \approx 137\,\mathrm{kbit/s}
\end{aligned}
$$

As shown in Equation (4.4), the effective data rate is around 137 kbit/s and therewith lower then the specified over-the-air data rate of 250 kbit/s. It is important to point out that in this approximation no acknowledgement transmissions, no busy channels, no additional delays due to superframe and beacon borders (slotted CSMA-CA) and no turnaround times of the radio (time to switch between transmit and receive state) were considered. With these additional delays also included, the effective data rate will decrease even more. Since low effective data rates will bring additional problems for scenarios with high network load, any solution approach should include the fact that the effective data rates are smaller then the gross data rates specified in the standard.

4.1.5 Hidden Terminal Problem for IEEE 802.15.4

The term hidden terminal refers to the case when one node is visible and reachable from another middle node, but not from other nodes communicating with that middle node. This leads to difficulties in media access control because collisions can occur at the middle node, which are undetected by the communication partners.

An usual approach for wireless systems to deal with this problem is the inclusion of the Request to Send (RTS)/Clear to Send (CTS) mechanism. With RTS/CTS, the middle node receives RTS signals from his communication partners and distributes CTS signals whereas other nodes can overhead that the middle node will receive a packet, even if they can not detect the presence of his communication partner. They defer their transmission in this case and no collision occurs at the middle node. RTS/CTS was dropped in 802.15.4 because of the expected low duty cycle. Problems might arise if the network traffic exceeds a certain limit, depending on the exact scenario and application.

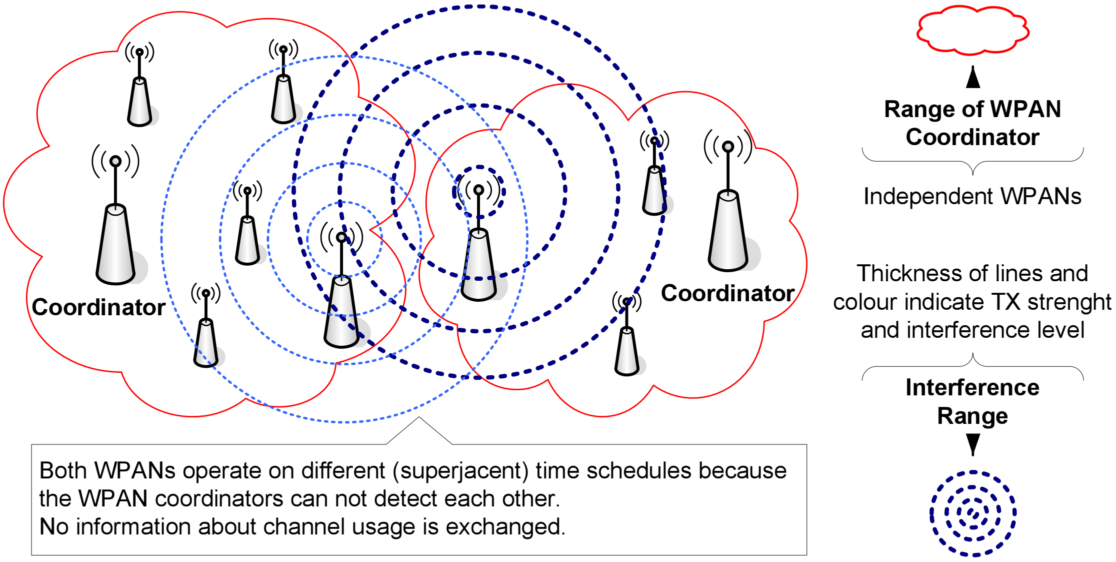
For scenarios and applications as proposed in Chapter 3, the hidden terminal problem is not expected to be the main cause of low effective data rates or high collisions, since the general playground for the specified scenarios is normally within the limits of 802.15.4 transmissions. Situations where a middle node can be reached by two other nodes that are not able to detect each others transmissions are therefore not common. These situations could only occur with an increasing chance if the Transmitting (TX) and Receiving (RX) power of 802.15.4 nodes is controlled and lowered, since the TX and RX range decreases with a lower power. Such a scenario is thinkable when transmission power control strategies are used to increase the number of coexisting devices and decrease the chance of *Intra-Technology Interference*. The hidden terminal problem must be re-evaluated if such approaches shall be used.

4.1.6 Inter-WPAN Cooperation

As mentioned in Chapter 1, the possibility of *Intra-* and *Inter-Network* information exchange is necessary to achieve true ubiquity. Information exchange and thus cooperation between different independent networks (WPANs) is not specified in any 802.15.4 revision. 802.15.4 hence lacks an important mechanism to enable true ubiquity. Measures to solve these shortcomings shall therefore be researched and developed in this thesis.

The idea of enabling cooperation between separate WPANs brings additional problems, since 802.15.4 does not specify any kind of *Inter-WPAN* communication. A solution would be to use a P2P network that includes all devices in range, instead of using independent WPANs. A problem for this lies in the standard specification itself. 802.15.4 specifies that all networks must include a distinguished PAN coordinator. Multiple or no PAN coordinators at all are not allowed. If the specified health care applications shall work for single and multiple users at the same time, then one PAN coordinator per network is required. Separate network topologies (e.g. Star or Tree topologies) are necessary to support an independent usage of networks and their respective applications. Other solutions are needed to assure a possible independent usage and to give the option for *Inter-WPAN* communication. Solution approaches are presented in Subsection 5.2.

Since there is no regulation of interaction between different WPANs, no information about channel access schemes or radio resource usage is exchanged between independent 802.15.4 networks. A channel access management across WPAN borders is therefore not available. Figure 4.5 shows a scenario where this deficit is depicted. In the figure two independent WPANs are displayed, each with a PAN coordinator. The coordinators can not hear each other, so they can set up the networks on the same or adjacent channels. Other nodes in each network can overhear and interfere each other (displayed with blue circles). The MAC performance of 802.15.4 will suffer in this scenario when devices from the other network access the channel and block it thereby. There is no synchronisation between the time schedules, wake-up or sleeping periods and channel access schemes of the different networks. If both networks operate on the same radio channel an exchange of such information would allow for an optimal co-allocation of time slots and a better resource usage. With the possibility of *Inter-WPAN* cooperation, such information could be exchanged and *Inter-Network* channel access management could be introduced. *Inter-WPAN* cooperation could therefore be used to increase the number of coexisting networks and devices. Appropriate solutions are a focus of this thesis.



Both WPANs operate on different (superjacent) time schedules because the WPAN coordinators can not detect each other.
No information about channel usage is exchanged.

Figure 4.5: Collision of Concurrent Transmissions of Independent IEEE 802.15.4 WPANs

Several issues and problematic conditions were identified during the investigation in this section, considering the reference applications and scenarios from Chapter 3. Based on these problems and the initial aims from Section 1.2, the creation of *Inter-* and *Intra-WPAN* coexistence and cooperation approaches is the topic of the next chapter.

4.2 Related Work

The areas of wireless health care and LR-WPAN are filled with a tremendous amount of research work. This section presents important work related to this thesis and its topics. Similarities and differences are identified and highlighted. The initial ideas for this thesis and the solution approach were published by the author of the thesis in [43]. This paper covers the basic principles and fundamentals behind the health care scenario and the idea of a distributed resource assignment to solve the identified problems.

Resource Allocation and Coexistence of IEEE 802.15.4

An example for research in the area of resource allocation for coexisting LR-WPANs can be found in [44]. Here, the authors propose a simple distributed calculation scheme, which assigns time slots to different devices. The authors consider only single devices, they do not differentiate between independent networks and do not consider cooperation between networks, in contrast to the assumptions of this thesis. The authors of [45] propose a distributed Time Division Multiple Access (TDMA) scheduling approach suited for wireless sensor networks. The proposed algorithm calculates a solution for the graph distance colouring problem. Each link with a distinctive computed colour corresponds to a distinctive time slot for the scheduling. With the algorithm, a global minimum of colours shall be achieved. A globally synchronized CSMA-CA slot is used for the exchange of management data. Since this paper considers only sole devices and no network topologies, the proposed algorithm cannot be used for the scenarios in this thesis. [46] also uses an algorithm to solve the 2-hop colouring problem to enable a distributed channel allocation. The focus of this paper lies on the inclusion of interference avoidance and energy constraints of sensor networks. Network topology specifics, cooperation, and enhancements of coexistence are not considered in this work.

Another work with similar topics was published in [47]. The authors propose the concept of “virtual channels” to maximise the number of coexisting 802.15.4 WPANs. The approach uses the sleeping time of a WPAN to deploy many other WPANs on the same logical radio channel with the help of the superframe structure. The basic idea is similar to the solution approach for coexistence pursued in this thesis. The main differences are that cooperation of independent networks, *Inter-* or *Intra-Network* interferences, and parameter adaptability during runtime were not considered in [47].

Distinctive IEEE 802.15.4 Mechanisms and Features

Most of the distinctive features of 802.15.4 (GTS or superframe usage, CSMA-CA algorithm) were already researched and covered in various publications. In [48], the authors propose an adaptive GTS allocation scheme for 802.15.4, where especially fairness and low latency are considered. The paper focuses more on the improvement of the original specified GTS allocation scheme then on the use of the GTS mechanism to enhance coexistence of devices and networks. [49] presents another approach for the allocation of Guaranteed Time Slots. Here, the guarantee of delay and bandwidth requirements is considered for time critical applications, an aspect also considered in this thesis. Other aspects of this thesis (cooperation, interference, enhanced coexistence) are not considered further in this publication. A plain analysis of the GTS allocation mechanism can be found in [50].

The CSMA-CA algorithm of 802.15.4 is the focus of various publications, examples are [42], [51], and [52], and . The authors of [51] analysed the Backoff Exponent management inside the CSMA-CA algorithm and proposed an adaptive management of this parameter to reduce the chance of packet collisions. This is an approach to enhance coexistence, although the authors focused more on throughput increase. In [52], the authors evaluated the CSMA-CA mechanism, with a focus on the relationship between the throughput and parameters related to it. Aspects like coexistence or cooperation are not considered in this work. [42] presents an analysis of the performance limits of the slotted CSMA-CA mechanism for broadcast transmissions in wireless sensor networks. Although the topics of this publication differ from this thesis, the evaluation approaches are comparable in terms of the analysis of protocol attributes and their impact on the network performance (e.g. throughout or delay).

Another aspect of 802.15.4, the Contention Access Period (CAP) part of the superframe, was analysed in [53]. The publication presents an analysis of the CAP in terms of throughput and energy consumption. Here, only the power savings due to disabled radios during inactive periods in the superframe are researched. Other usage aspects of the inactive superframe portions are not considered.

Cooperation and Network Interconnection for IEEE 802.15.4

The cooperation of independent 802.15.4 networks is a relative new research field. The author of [54] researched the possibility of handover for ZigBee, which uses 802.15.4 as an underlying framework. [55] deals with different possibilities of ZigBee network interconnection. Both dissertations provide interesting approaches for the cooperation of independent LR-WPANs. The main similarity with this thesis is the idea of exchanging information between independent networks. Coexistence or medical applications are not considered in neither of the two dissertations.

A recent publication in the field of WPAN cooperation is [56], where the authors research different approaches to connect two independent WPANs. The authors present simulation outcomes for a specific health care scenario where mobile WPANs cooperate to forward their data to a collection centre. The scenarios proposed in [56] differ from the introduced reference scenarios from Section 3.2, where data is normally collected by the PAN coordinator (e.g. a cell phone, PDA, or PMU).

Performance Evaluations of IEEE 802.15.4

Various publications deal with performance evaluations of 802.15.4 in various scenarios. An example is [57], where a simulative investigation was performed with data gathered from a specific transceiver type. [57] deals mainly with the analysis of energy consumption and network performance in a simulation model of 802.15.4 under the NS-2 network simulator. This thesis considers completely different scenarios and applications.

The list of publications dealing with 802.15.4 performance evaluations is exhausting: [27, 39, 40, 58, 59, 60, 61] are only a few examples. Important for this thesis are especially [27] and [39], because both publications consider the use of 802.15.4 for medial care applications. Although both publications have different scenarios compared to this thesis (use of implanted medical sensors or different network layout), there are similarities in concepts and approaches. Medical applications like the ECG are considered and investigated in [39], while [27] investigated the choice of beacon-enabled or non-beacon-enabled networks for medical applications. Both publications can therefore be used as references in this thesis.

5 New Solution Approaches for Coexistence and Cooperation in Dense Radio Conditions

As described in the methodology, this chapter contains the developed solution approaches for the identified problems from Section 4.1 and the stated objectives from Section 1.2. The solution approaches for the enhanced coexistence and Inter-WPAN cooperation support are introduced separately with descriptions and specifications in Section 5.1 and Section 5.2 respectively. A separate description facilitates the autonomous use of developed ideas and concepts. A beneficial combination of both solution approaches is described in Section 5.3. Through the combination, additional benefits can be exploited because several components of the two approaches superpose or extend each other and information from different components can be used for a mutual completion.

5.1 Strategy for Enhanced WPAN Coexistence

802.15.4 has problems when the number of nodes inside a single network exceeds a certain limit, as shown in Section 4.1. If multiple networks are used on the same radio channel these dense radio conditions can lead to even higher performance degradations. To support such scenarios (e.g. the first reference scenario *monitoring of large groups*), a new approach for enhanced 802.15.4 WPAN coexistence is introduced in this section.

The coexistence approach includes measures to detect and avoid interference, since the evaluation of the 802.15.4 standard also showed that both *Inter-* and *Intra-Technology* interference have a high influence on the performance of 802.15.4. Due to the fact that the proposed reference applications (*ECG monitoring* and *body constitution monitoring*) specify certain critical parameters, the coexistence solution also contains a parameter-adoptable resource assignment component that enables the allocation of resources inside a single network and between independent networks to meet these critical requirements. A resource allocation between independent networks is useful for the enhancement of network coexistence on the same channel and for the support of 802.15.4 *Inter-WPAN* cooperation. Last but not least, solution ideas for the identified hidden terminal problem and the *Inter-Technology* interference problems are included and presented.

5.1.1 Overview of the WPAN Coexistence Strategy

In Figure 5.1 an overview of the proposed WPAN coexistence strategy is depicted in form of an abstract state machine. The coexistence mode is in general terms the realisation of processes that enable various independent 802.15.4 networks and their nodes to coexist (with preferably least possible interference and best possible performance) at the same time in radio range. Important components and parts of the coexistence mode are:

- *Starting/Joining a WPAN* (refer to Subsection 5.1.2)
- *Interference Detection Part* (refer to Subsection 5.1.3)
- *Interference Avoidance Part* (refer to Subsection 5.1.4)
- *Resource Assignment Strategy* (refer to Subsection 5.1.5)
- *Monitoring and Maintenance Part* (refer to Subsection 5.1.6)

The main process of the strategy is executed on every node while other parts are not executed on certain nodes, since the node capabilities are different (RFD abilities compared to FFD). The resource assignment management, for example, is only done by the PAN coordinator because it distributes network beacons and therefore controls the network resource usage. It thus makes the central decisions, after necessary information are gathered from other nodes.

The strategy's execution starts with the formation of a WPAN. The PAN coordinator (either a designated device/node or the primarily started FFD) performs interference detection, interference avoidance and *Intra-WPAN* resource assignment before the network is set-up. This way, a new WPAN can be created with already well chosen network resources (in case resource sharing with other WPANs is necessary). The interference detection component includes different measures to detect noise and interference on the radio channel. The outcome of this process (see Point (3) in Figure 5.1) is a list of

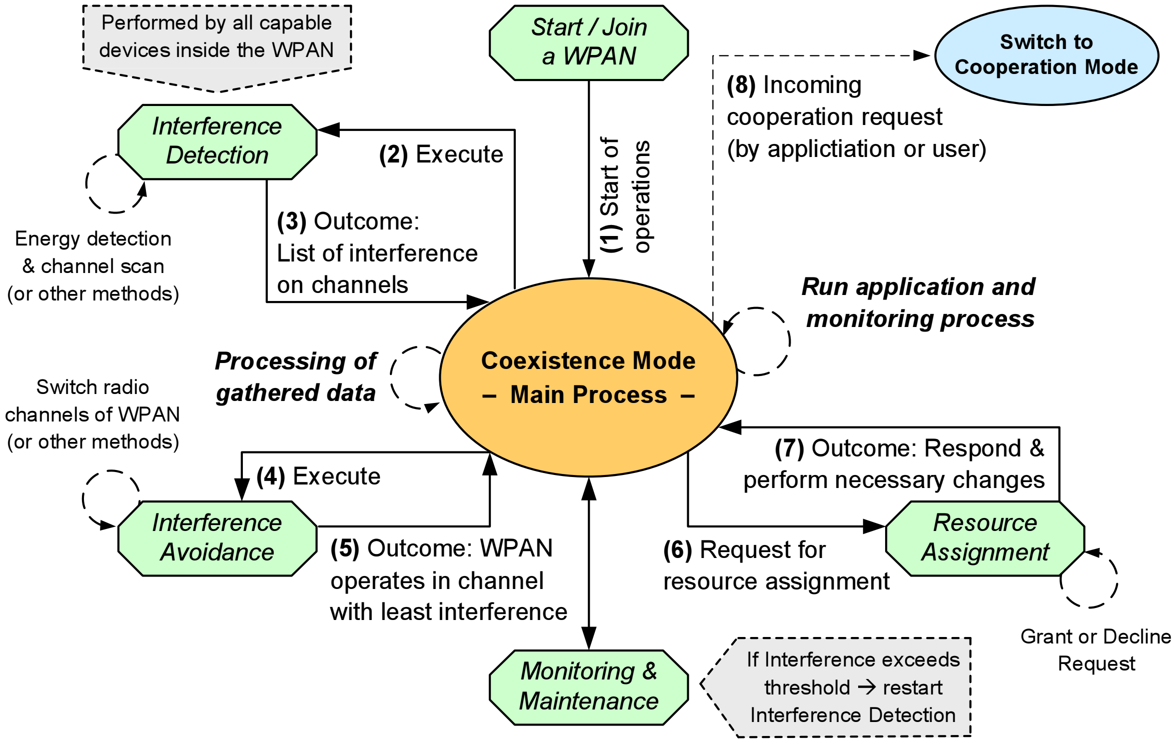


Figure 5.1: Abstract State Machine for the WPAN Coexistence Strategy

interference levels from each radio channel. With these informations, the interference avoidance process performs the necessary tasks so that the WPAN operates on the radio channel with the least possible interferences and optionally with the most available resources (see Point (5) in Figure 5.1). The resource assignment process has two important main tasks: the organisation of resource assignments and resource sharing inside a single network as well as between independent WPANs. Resources inside a WPAN are organised with the help of the 802.15.4 superframe, while resources between independent WPANs are organised in a distributed way. This process also handles resource requests, when other WPANs want to coexist on the same radio channel.

The monitoring of varying network resources is the task of the monitoring and maintenance process. This process collects statistics (e.g. LQI or packet failure rates) and determines the state of the radio channel and the used network resources. A change of network resources (radio channel, superframe structure, MAC timing) after the set-up of a WPAN is started by either this process (e.g. when the interference level rises over a certain threshold) or when an application or the user wants to switch the operation mode (e.g. to cooperate with another WPAN). The general working scheme of the strategy is based on the request-respond principles of packet communication. Data processing, monitoring, and the application running on top of the device are executed as soon as the basic network set-up procedures are completed.

The coexistence strategy (in the form of the *Coexistence Mode Main Process*) runs in parallel to other applications. Global error processing, monitoring and maintenance, resource request and response handling, interference detection and avoidance, and the execution of operation mode switches are all controlled by the main process. The sequence of events is not bound to be in the same order as it is shown in the conceptional state machine in Figure 5.1. Depending on occurring events, different chains of events are possible to handle a new situation. The individual components of the coexistence strategy are described in the following subsections. If an application or the user himself wants to initiate a cooperation with another WPAN, a cooperation request process is initiated. This switch of operation modes is part of the combination of coexistence and *Inter-WPAN* cooperation strategy described in Section 5.3. The main process regulates the execution of all sub-processes. It is responsible for the exchange of all request and response messages between the sub-processes. The main process is rather a software development issue than a research topic.

5.1.2 Starting/Joining a WPAN

The PAN coordinator takes on the central role in the WPAN. All network management and important resource assignment processes are consolidated in this node. It is usually the first node that is started (if the PAN coordinator role is fixed). If the PAN coordinator choice is not fixed then the primarily started FFD sets up the network. It is therefore elected as the PAN coordinator. For the scenarios specified in this thesis, the PAN coordinator role is normally predetermined, when specific devices (e.g. cell phone or PMU) with special capabilities are used in a WPAN.

The first action of the dedicated PAN coordinator is the network set-up process (*Start WPAN* process in Figure 5.1). The typical process of forming a new WPAN is described in [30, Section 7.5.2.3]. The WPAN is started by the dedicated device after: a MAC sublayer reset was performed via the `MLME-RESET.request` (MAC Layer Management Entity) primitive, an active channel scan was executed, and a suitable PAN Identifier (PAN-ID) was chosen. The WPAN operation then starts when the dedicated FFD issues the `MLME-START.request` primitive with the parameter `PANCoordinator` set to `TRUE` and the `CoordRealignment` parameter set to `FALSE`. The `CoordRealignment` parameter is used to indicate changes of the superframe configuration or the channel parameters. It is important for other parts of the coexistence strategy. After this primitive is sent, the MAC sublayer issues the `MLME-START.confirm` primitive with a `SUCCESS` status. The dedicated device operates as a PAN coordinator afterwards.

This standard process of starting up a WPAN is extended to a certain degree to improve the coexistence of devices and networks. The active channel scan at the beginning is used to determine how high the interference levels on each radio channel are and which radio channels are already being used by other WPANs. Gathered information about the radio channels are saved for later usage. If an unused radio channel with a interference level under a certain threshold is found then this channel is used for the set-up of a new WPAN. If all channels are already being used then the dedicated PAN coordinator requests resources from another WPAN. The handling of incoming resource requests (see Point (6) in Figure 5.1) is swapped out into a separate process described in Subsection 5.1.5. An error is thrown if no resource requests are granted. The subsequent error processing is out of the scope of this thesis. The outcomes of the resource requests are radio resources (channel and time) that can be used by the new PAN coordinator. A new WPAN is formed with these radio resources (either shared with another WPAN or used solitary). The chain of events for the starting of a new WPAN is shown in Figure 5.2. These actions are only performed by the PAN coordinator. All other devices perform different actions to join an already existing WPAN.

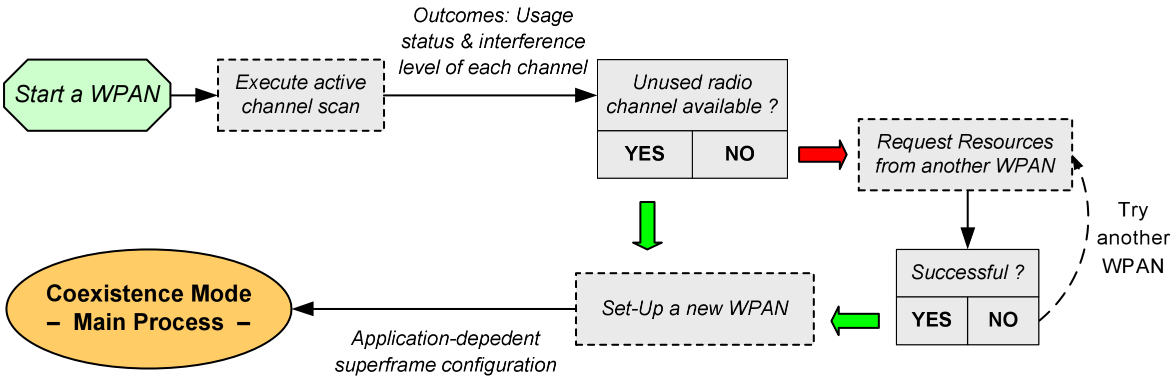


Figure 5.2: Chain of Events for the Starting of a new WPAN

During the set-up process of the new WPAN, the PAN coordinator chooses the parameter values for the attributes of the PAN Information Base (PIB) (cp. Subsection 2.2.2). Important at this point are the parameters for the superframe configuration. An optimal configuration of the superframe is essential for the application Quality of Service (QoS), since it determines the channel access scheme. Different approaches are needed here, in case resources are shared or used individually. At this point it is enough to know that an algorithmic approach tries to determine the optimal superframe parameters, depending on the available resources. A profound description of the calculation of optimal superframe parameters is given in Subsection 5.1.5. The outcomes of the algorithmic approach are calculated values which are used to set the according parameters in the PIB with the proper service primitives. After a new WPAN was successfully formed and started, the coexistence main process is executed on the PAN coordinator.

Since a new WPAN is set-up by the PAN coordinator, all other devices (RFDs, other FFDs) only have to join an existing WPAN (*Join WPAN* process in Figure 5.1). Joining a WPAN (also called associating) is done in the same way as specified in the 802.15.4 standard [30, Section 7.5.3]. To ensure that devices associate only with the PAN coordinator of the user's WPAN, appropriate measures have to be taken. These may include the setting of a default `CoordPANId` parameter (identifier of the PAN coordinator addressed by the association request) or other higher layer measures. A higher layer solution for the association task depends on the hardware capabilities of the devices. Solution approaches may involve a manual start of the association process by the user, or GUI dialogues where the user can choose from the available coordinators in radio range. A precise solution is outside the scope of this work. After the FFD or RFD joined its home WPAN, the coexistence main process is started on the device.

5.1.3 Interference Detection

The interference detection component of the coexistence strategy is used during the formation of a PAN and during the normal runtime, in the monitoring and maintenance process. The functionality of this component depends on the device type and the hardware. If the transceiver hardware does not support active channel scans, only passive channel scans or ED functions can be used. Results from the interference detection process shall be reported back to the PAN coordinator in general, apart from any hardware constraints of a device. This way, problems of *Inter-WPAN* interference can hopefully be detected. An example was already presented in Figure 4.5. Here, devices from a WPAN interfere with certain devices from another WPAN. If only interference levels of the PAN coordinator are considered, these kinds of interference can not be detected when only a subset of devices in the WPAN is disturbed.

Various approaches for the exchange of interference level information are possible. Since devices perform active or passive channel scans before they associate with a WPAN, a simple solution would be the saving of outcomes of channel scans and a transmission of outcomes to the PAN coordinator after the association process is finished. This approach is possible as long as the device has a re-writeable memory with enough capacity to hold the additional information about the radio channel interference levels. The gathered information could then be transmitted in an extra data packet or piggybacked with other data packets. A realisation depends on the actual hard- and software platform.

A possible extension of this idea is the creation of a request-response scheme to support the querying of devices about the interference level from their “viewpoint”. In such a scheme, the PAN coordinator would broadcast a `InterferenceReport.request` message inside his WPAN. The other devices would receive the coordinator’s request, gather the information (via channel scan methods) and transmit them back in `InterferenceReport.response` messages to the PAN coordinator. The creation of according service primitives (request, indication, response, confirmation) goes hand in hand with the realisation of such an interference report mechanism.

Next to this plain request-response scheme, regular transmitting of interference reports or continuous monitoring of interference levels and reporting in case of exceeded thresholds are also possible solutions. A continuous monitoring approach is favoured because it can be combined with the aspired monitoring and maintenance process (refer to Subsection 5.1.6). In this case, information about the interference level is gathered in an active (channel scans) and passive (LQI and packet failure rates) fashion and monitored continually. If a certain threshold of interference or packet failures is exceeded, interference detection is performed by the device and a report about the outcomes is transmitted to the PAN coordinator. The coordinator himself performs interference avoidance measures afterwards. Next to these ideas, other research work like the *Radio Interference Detection* (RID) protocol, proposed in [62], may be implemented and used in accordance with the rest of the coexistence strategy.

5.1.4 Interference Avoidance

The problems of 802.15.4 with *Inter-* and *Intra-Technology* interference (cp. Section 4.1.1 and 4.1.2) can be avoided with the help of interference avoidance strategies. Such strategies are necessary if 802.15.4 networks are used in high numbers or in radio range with other technologies like Bluetooth or 802.11 WLAN. The plausibility of such settings is given through the specified reference scenarios from Section 3.2.

A simple preliminary measure to overcome the *Inter-Technology* interference problem in case of coexisting 802.11 WLANs is the specification of a reduced list of radio channels for the use within a 802.15.4 WPAN. It was shown in Figure 4.1 that four 802.15.4 radio channels (number 15, 16, 21, and 22) fall between the guard bands of 802.11 b/g WLANs. If 802.15.4 networks shall operate in radio range with multiple 802.11 networks the usable channels for 802.15.4 may be reduced to these four radio channels by reducing the list of channels for the active channel scan of the PAN coordinator during the WPAN formation process. If only a small number of independent 802.11 WLAN networks shall be used in radio vicinity the affected subset of channels (interfered by 802.11 WLANs) can be made unavailable for the use within 802.15.4.

To overcome *Intra-Technology* interference a consolidated cooperation in terms of resource assignment and resource usage is pursued. Such a cooperation is enabled through the use of a distributed *Inter-WPAN* resource assignment and resource sharing strategy. A suitable strategy is described in Subsection 5.1.5. With this strategy, networks operating on the same radio channel try to avoid any kind of interference.

If a high interference level (regardless of *Intra-* or *Inter-Technology* interference) is detected by the PAN coordinator or another device (and thus reported back to the PAN coordinator), supplementary interference avoidance measures are needed. The easiest solution for disturbance on the current radio channel is a channel switch. This solution has drawbacks because a channel switch represents additional workload for the WPAN and its devices. To reduce the possibility of unnecessary workload due to overhasty channel switches, a detailed analysis of the occurring interference prior to any channel switching is necessary. Such an analysis should consider if the interference is occurring on a permanent time base (e.g. "permanent" disturbance due to a microwave) or only temporarily (e.g. other wireless technologies operating on the same radio channel). If interferences are occurring temporarily or even on a regular basis, the affected WPAN could try to adopt its medium access scheme to avoid accessing the radio channel during interference periods, e.g. by adjusting the active and passive portions of the superframe accordingly, so that WPAN devices sleep during interference periods. If the disturbance seems to be permanent, a channel switch might be the only option to overcome it. To reduce the chance of overhasty channel switching a certain threshold for an interference length shall be considered in any case before a channel switch is performed.

Other methods for interference avoidance like radio channel hopping (comparable to the Bluetooth frequency hopping approach) are problematic to realise, since the 802.15.4 standard has no measures for a rapid synchronisation of channel switches. If future versions of 802.15.4 should include these or other measures for interference avoidance, an adaptation of this part of the coexistence strategy is possible without problems.

5.1.5 Resource Assignment

The assignment of resources is the most important component of the coexistence strategy. It can be divided into the assignment of resources for devices operating within the WPAN and the assignment and sharing of resources with other independent WPANs. The resource assignment part consists of different elements which are used by various other parts of the coexistence strategy. Three main elements are distinguished, namely:

- the calculation of superframe configurations,
- the *Intra-WPAN* resource assignment,
- and the *Inter-WPAN* resource sharing component.

These three elements are described in the following paragraphs. Together, they are used to provide resource assignment and sharing for the coexistence strategy. Service primitives, which are necessary for the functionality of the elements, have to be created during an implementation of the strategy. A description of them is only given in case that interesting solution approaches were developed to solve specific problems.

Algorithmic Approach for the Calculation of Superframe Configurations

A regulation of medium access with the 802.15.4 superframe structure (cp. Subsection 2.2.3) can be used for all devices associated with the local WPAN. The active (sending) period and the passive (sleeping) period of the superframe structure are shown in Figure 5.3. The active period is determined by the Superframe Duration (SD) value, which itself is calculated with the help of the `aBaseSuperframeDuration` value and the Superframe Order (SO) parameter. The complete superframe length (active and passive period) is limited by network beacons. The Beacon Interval (BI) is therefore the representation of the complete superframe length. It is again calculated with the help of the `aBaseSuperframeDuration` value and this time with the Beacon Order (BO) parameter. The calculation formulas are also shown in Figure 5.3.

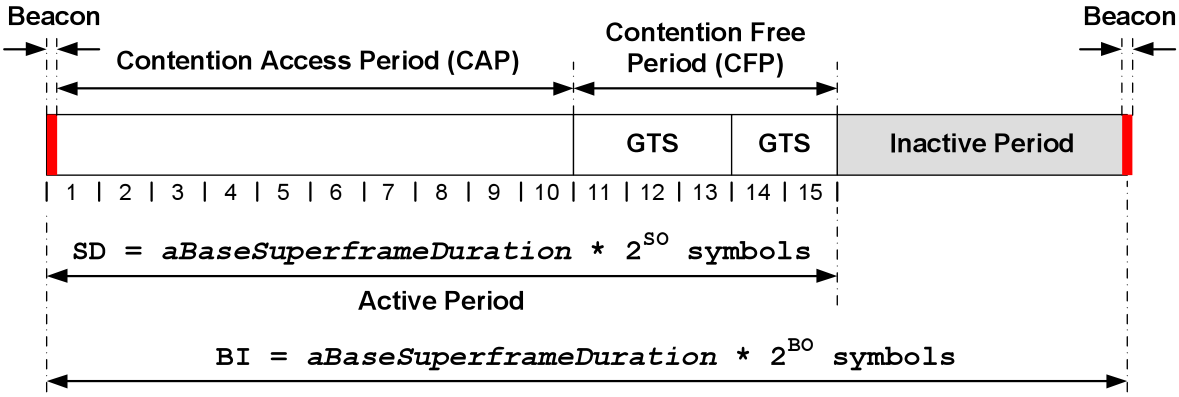


Figure 5.3: Basic Calculation of IEEE 802.15.4 Superframe Parameters

To enable the calculation of optimal superframe configurations parameter values for BO and SO are needed. `aBaseSuperframeDuration` has a fixed value, determined by the number of slots inside a superframe and the basic duration of a single slot (`aBaseSuperframeDuration = aBaseSlotDuration * aNumSuperframeSlots`). Both values are predetermined by the 802.15.4 standard. Different duty cycles and active/-passive period lengths are possible with different BO and SO values, the range of both values is: $0 \leq SO \leq BO \leq 14$. BO can be set to 15 to transmit data without using the superframe structure. The duration of a superframe (BI) ranges from 0.0154 s (for $BO = 0$) to 251.6 s (for $BO = 14$). Since this parameter range and the thus possible duty cycles (between 0.006% and 100%) enable a wide range of configurations for the superframe, a calculation of optimal parameter values is needed.

To enable a calculation of superframe configurations, application characteristics, and QoS aspects have to be considered. If an application running on top of a WPAN requires short regular transfer intervals (e.g. the described ECG reference application), low duty cycles and long beacon intervals (BI) are counter-productive. The extracted important parameters from Subsection 2.1.4 (*Memory Capacity, Sensed Data Amount, Sensing*

Interval, Reporting Interval) are therefore used in the calculation process. With these parameters, all specified reference scenarios and applications can be modelled accordingly to the presented specifications from Chapter 3. Two different calculation approaches are therefore given to cover all possible application types:

A.I: The first approach uses the *Memory Capacity, Sensing Interval,* and *Sensed Data Amount* parameters. A device senses data until its memory capacity is depleted to a certain degree (e.g. body constitution monitoring). The time interval until the memory is full can be calculated with the sensing interval and the sensed data amount. This interval corresponds to the *Reporting Interval* (used in **A.II**).

A.II: The second approach uses the *Reporting Interval* parameter. A reporting interval of an application specifies the next transfer time for data (e.g. regular sending of ECG data). Since a large enough memory capacity is assumed here, neither the sensed data amount nor the memory capacity are important.

The outcome of both approaches is the time interval when the next transmission needs to be performed. Next to this interval, the data amount that needs to be transferred and the channel conditions are also included in the calculation of a superframe configuration. Channel conditions and data amount are necessary to model the time it takes to successfully transfer the accumulated data on a device. Channel state information, e.g. LQI values or Packet Error Rates (PERs), are used to enhance the estimation of the data transfer time because collisions and packet failures lead to retransmissions and therefore additional transfer times. These three parameters (reporting interval, data amount to transfer, channel conditions) enable a calculation of superframe parameters. This way, an estimation of channel access schemes and transfer times is enabled. This estimation is then used to enhance the coexistence of 802.15.4 devices inside a single WPAN and the coexistence between independent WPANs on the same radio channel.

To enable a better understanding of the approach, an example calculation for both approaches is given in the following paragraph. Calculation inputs are various IEEE 802.15.4 constants, channel conditions (PER in the example), the *Sensing Interval*, and *Sensed Data Amount* for **A.I**, or the *Reporting Interval* for **A.II**. The outcomes of the calculations are the maximum BO and SO values that determine a superframe structure, under which a transmission can be achieved for the given channel conditions.

$$\begin{aligned} \texttt{Packet Error Rate} &= 12.5\% & \texttt{Number of Retries} &= 1 \\ \texttt{Memory Capacity} &= 4000\,\text{bytes} & \texttt{TX @ memory fill level} &= 50\% \\ \texttt{Sensing Interval} &= 0.1\,\text{s} & \texttt{Reporting Interval} &= 0.5\,\text{s} \\ \texttt{Sensed Data Amount} &= 25\,\text{bytes} & \texttt{Reported Data Amount} &= 500\,\text{bytes} \end{aligned} \tag{5.1}$$

$$\texttt{Time until Memory is } x\%\texttt{ full} = \frac{(\texttt{Sensing Interval} \times \texttt{Memory Capacity})}{\texttt{Sensed Data Amount}} \tag{5.2}$$

A fill status of 50% of the memory capacity is achieved after 8 seconds with the given values for sensing interval and sensed data amount. This leads to a “reporting interval” of 8 s for the approach **A.I**. For approach **A.II**, a predetermined reporting interval of 0.5 seconds is used. The next step is the calculation of an estimated data frame transfer time and an estimated data rate. The basic calculations for the data rate and the data frame transfer time were already presented in Subsection 4.1.4. Equations (4.1) to (4.4) are used again here. These formulas are now enhanced with the given *Number of Retries* (retransmission number) and the PER value. Both values are estimations in the example. In real-world applications, feedback from the PHY can be used to adapt these parameters to realistic and accurate values. Additionally, ACKs from the PAN coordinator and ACK waiting durations are considered, as well as transceiver *turnaround* times (time it takes for the transceiver to switch between TX and RX mode). These additions are necessary to include possible retransmissions through packet failures.

$$\texttt{CCA for Data Frame} = \texttt{Default Initial Backoff} = 2.368\,\text{ms} \tag{5.3a}$$

$$\texttt{Data Frame Transfer Time} = \frac{(\texttt{aMaxPHYPacketSize} + \texttt{SHR} + \texttt{PHR}) \times 8}{250\,\text{kbit/s} \times 10^3} \tag{5.3b}$$

$$\texttt{aTurnaroundTime} = 12 \text{ Symbol Periods} = 12 \times 16\,\mu\text{s} = 0.192\,\text{ms} \tag{5.3c}$$

$$\texttt{ACK Frame Transfer Time} = \frac{(\texttt{AckFrameSize} + \texttt{SHR} + \texttt{PHR}) \times 8}{250\,\text{kbit/s} \times 10^3} \tag{5.3d}$$

$$\texttt{MacAckWaitDuration} = 54 \text{ Symbol Periods} = 54 \times 16\,\mu\text{s} = 0.864\,\text{ms} \tag{5.3e}$$

With the stated equations and parameter values, a data frame transfer time of 4.256 ms (via Equation 5.3b) and a ACK frame transfer time of 0.352 ms (via Equation 5.3d) can be calculated. Other necessary values are given in Equations (5.3a), (5.3c), and (5.3e).

These formulas and values are now used for the calculation of the total time it takes to transfer a data frame (including the ACK) without any retransmissions and the total time including retransmissions (number of retransmissions = 1):

$$\begin{aligned}
\texttt{Total Time w/o Retry} &= \texttt{CCA for Data Frame} + \texttt{Data Frame Transfer Time}\\
&\quad + \texttt{aTurnaroundTime} + \texttt{ACK Frame Transfer Time}\\
&= 7.168\,\mathrm{ms} = 0.007168\,\mathrm{s}
\end{aligned}$$

$$\begin{aligned}
\texttt{Total Time with Retry} &= (\texttt{CCA for Data Frame} + \texttt{Data Frame Transfer Time})\\
&\quad + \Big((\texttt{CCA for Data Frame} + \texttt{Data Frame Transfer Time}\\
&\quad + \texttt{MacAckWaitDuration}) \times \texttt{Number of Retries}\Big)\\
&\quad + \texttt{aTurnaroundTime} + \texttt{ACK Frame Transfer Time}\\
&= 14.656\,\mathrm{ms} = 0.014656\,\mathrm{s}
\end{aligned}$$

The calculation of the estimated frame time and the estimated data rate under the given channel conditions (PER) is now possible. With a PER of 12.5%, 87.5% of the data frames take 7.168 ms and 12.5% of the data frames take 14.656 ms, leading to:

$$\texttt{Estimated Frame TX Time} = (7.168\,\mathrm{ms} \times 0.875) + (14.656\,\mathrm{ms} \times 0.125) = 8,104\,\mathrm{ms}$$

$$\begin{aligned}
\texttt{Estimated Data Rate} &= \frac{(\texttt{Available Payload} \times 8)}{(\texttt{Estimated Frame TX Time} \times 10^{-}3)}\\
&= 112.537\,\mathrm{bit/s} \approx 112\,\mathrm{kbit/s}
\end{aligned}$$

The data rate is calculated with a payload of 114 bytes. Before the superframe parameters can be calculated, two more values need to be considered: the data amount that needs to be transferred and the time it takes to transfer the accumulated data. Both values can be derived and calculated from the given parameters in (5.1):

$$\texttt{Data Amount to TX} = \frac{\texttt{Time until Memory is } x\%\texttt{ full}}{\texttt{Sensing Interval}} \times \texttt{Sensed Data Amount}$$

$$\texttt{Time to TX Data Amount} = \left\lceil \frac{\texttt{Data Amount to TX}}{\texttt{Available Payload}} \right\rceil \times \texttt{Estimated Frame TX Time}$$

The last step of the calculation is the conversion of time intervals and periods into BO and SO values. For this, the active period (Superframe Duration) of the superframe has to be derived from the `Time to TX Data Amount`. The "reporting interval" is used to calculate the Beacon Interval (BI) (time until the next active period is started). SD must be bigger then the `Time to TX Data Amount`; how big is determined later on when other devices with their transmissions are considered (*Intra-WPAN Resource Assignment*). BI on the other hand must be smaller then the `Reporting Interval`, so that the active period of the device starts again before the next transmission is scheduled:

$$\texttt{Time to TX Data Amount} < \mathrm{SD} \leq \mathrm{BI} < \texttt{Reporting Interval} \tag{5.4}$$

With the relation (5.4) and the following formulas, SO and BO can be calculated, to complete the configuration of the superframe. SD and BI can be calculated from the SO and BO values with the help of the formulas shown in Figure 5.3.

$$\texttt{min.}\ \mathrm{SO} = \left\lceil \log_2 \left| \frac{\Big(\texttt{Time to TX Data Amount} \times (\texttt{PHY Symbol Rate} \times 1000)\Big)}{\texttt{aBaseSuperframeDuration}} \right| \right\rceil \tag{5.5}$$

$$\texttt{max.}\ \mathrm{BO} = \left\lceil \log_2 \left| \frac{\Big(\texttt{Reporting Interval} \times (\texttt{PHY Symbol Rate} \times 1000)\Big)}{\texttt{aBaseSuperframeDuration}} \right| \right\rceil \tag{5.6}$$

Based on the predetermined values (5.1) and the Equations (5.2) – (5.6), all values necessary for the determination of the superframe configuration can now be calculated for the example approaches **A.I** and **A.II**. The outcomes are presented in Table 5.1.

Parameter Name	**A.I**	**A.II**
`Data Amount to TX`	$= 2000\,\mathrm{bytes}$	$= 500\,\mathrm{bytes}$
`Est. Frame TX Time`	$= 8,104\,\mathrm{ms}$	$= 8,104\,\mathrm{ms}$
`Time to TX Data Amount`	$= 145.87\,\mathrm{ms}$	$= 35.544\,\mathrm{ms}$
`min.` SO	$= \lceil 3.247 \rceil \,\widehat{=}\, 4$	$= \lceil 1.210 \rceil \,\widehat{=}\, 2$
`min.` BO	$= \lfloor 9.025 \rfloor \,\widehat{=}\, 9$	$= \lfloor 5.025 \rfloor \,\widehat{=}\, 5$
`min. Duty Cycle` (SD/BI × 100%)	$= 3.125\%$	$= 12.5\%$

Table 5.1: Outcomes for the Example Calculation of Approach **A.I** and **A.II**

This example shows that superframe configurations can be derived and calculated with the help of the specified four parameters **Memory Capacity**, **Sensing Interval**, **Sensed Data Amount**, and **Reporting Interval**. Since these four parameters allow a modelling of transfer and traffic processes of all specified reference applications and scenarios, superframe configurations for all reference applications can be derived now.

This draft includes only the Packet Error Rate (PER) as a substitute for channel conditions and a fixed number of retransmissions. For a practical realisation, both values can be derived directly from the hardware during runtime. A learning-by-feedback approach could improve the proposed formulas and calculations, so that an automatic adaptation to variable channel conditions during runtime is enabled. Such an approach shall be realised when the solution is implemented.

Intra-WPAN Resource Assignment

The assignment of resources inside a WPAN is provided through the superframe structure of 802.15.4. The assignment depends on the needs of applications running on single devices or inside the WPAN. The PAN coordinator collects “requests for resources” from the devices associated with it and updates the superframe configuration accordingly to meet the application needs (`Time to TX Data Amount` and `Reporting Interval`) of the devices. The maximum BO and minimum SO values have to be chosen carefully in order to meet all application requirements. The mentioned “requests for resources” are messages where the application requirements of a device are included. These messages could either get piggybacked on other messages during the PAN association process or get realised as extra messages, which are sent after the association process to the PAN coordinator. Piggybacking requires a change of the association process, while the posterior exchange via normal data messages requires a higher layer solution. A decision about a realisation has to be made during the implementation.

It is important to add that this exchange of “resource requests” is only necessary if different or unknown applications are used in the WPAN. If predetermined applications are used where the PAN coordinator acts as the central device or data collector and the roles of all other nodes (FFDs and RFDs) are fixed, then application parameters can be hard-coded during the software development process. This way, an exchange with the PAN coordinator becomes obsolete. This hard-coding of application requirements is the case for the specified reference applications where all nodes have fixed parameters and roles (refer to Section 3.1). Thus, default application parameters (e.g. ECG monitoring interval) can be specified at the PAN coordinator. Further resource requests for devices inside a single WPAN are not necessary in this case.

The organisation of transmissions of devices inside the WPAN can be disorganised (e.g. random access during the superframe CAP) or organised with Guaranteed Time Slots (GTSs) (time slots to reserve for non-contented channel access). Since the 802.15.4 standard specifies that there can only be a limited number of GTSs during a superframe's active period, only a limited number of devices can achieve a GTS assignment. A solution for this problem involves the extension of the GTS concept for the full superframe length. This means that all 15 slots of the active superframe period (refer to Figure 5.3) are used as "virtual" GTS slots. Thus, the PAN coordinator can divide and relate the full active superframe period to different devices by assigning a number of "virtual" slots to them. This approach requires a higher layer solution and modifications to the standard. The advantage is that transmission collisions inside a WPAN can be avoided when devices transmit one after another. A strong time synchronisation is required for this approach. Other research work like [48] or [49] deals with the allocation of GTS. Ideas from these sources can also be used to extend the proposed "virtual" GTS idea.

The nodes of the WPAN keep on operating and transmitting until a change of the superframe structure becomes necessary, once the superframe parameters are chosen and distributed (through the beacons of the PAN coordinator). Such a change can be initiated in case of interference or disturbance on the radio channel (via interference detection and subsequent interference avoidance process). A change can also be necessary when additional nodes join the WPAN or when other independent networks want to initiate a cooperation. The updating of superframe parameters goes hand in hand with the updating of PIB attributes. Necessary service primitives and messages are already specified in the 802.15.4 standard and can therefore be used without problems.

Inter-WPAN Resource Assignment and Resource Sharing

The resource assignment is also responsible for the handling of resource requests from other independent WPANs. The sharing of radio resources between different WPANs is decoupled from the assignment of resources inside a single WPAN, since the *Inter-WPAN* resource sharing requires additional concepts for the exchange of status information, approaches for a synchronisation of resource usage and new ideas for the assignment of resources over network borders. The split-up into *Intra-* and *Inter-WPAN* resource assignment also enables a separate usage of ideas from both approaches.

The *Inter-WPAN* resource assignment extends the *Intra-WPAN* resource assignment approaches with additional concepts for the exchange of resource usage information and new messages to request resources from other WPANs. The additional messages ("requests for resources" and according "replies") are exchanged between the PAN coordinators of different WPANs. When a PAN coordinator receives one of these messages, the resource assignment process is started, the request is analysed and a decision about the granting of the request is made. A "reply" message is then sent back to the requesting PAN coordinator with the decision and additional information in case of a positive reply. Based on this reply, a sharing of resources is either initialized or not. According transitions are shown in Figure 5.1, in Point (6) and (7). An exemplification of the process is given in Figure 5.4. In order to simplify the approach description, in this example only two radio channels and four WPANs are used.

Step (1) and (2) in Figure 5.4 show the deployment of two independent WPANs on the two available radio channels. Both WPANs decide to use a separate radio channel and assign the resources inside the WPAN as needed, with the help of the superframe structure and GTS. Radio resources shall be shared if a radio channel is already used by another WPAN, as shown in Step (3) in Figure 5.4. If devices from different networks operate on the same radio channel, the performance can drop seriously, since both networks use different channel access schemes (refer to Subsection 4.1.2). The organised usage of wireless resources is the main goal to minimize the interference and disturbance between independent WPANs.

WPAN C detects (via active channel scan) during the WPAN formation process that all available radio channels are already occupied. The affected WPAN decides therefore to request resources from WPANs A and B. The request is sent by the PAN coordinator of WPAN C to the PAN coordinators from WPANs A and B. The other coordinators receive the request and decide about it. In the example, resources are assigned based on the number of devices inside a network. Since WPAN A consists of 7 devices, it occupies more resources. WPAN B consists only of 3 devices and therefore occupies less resources.

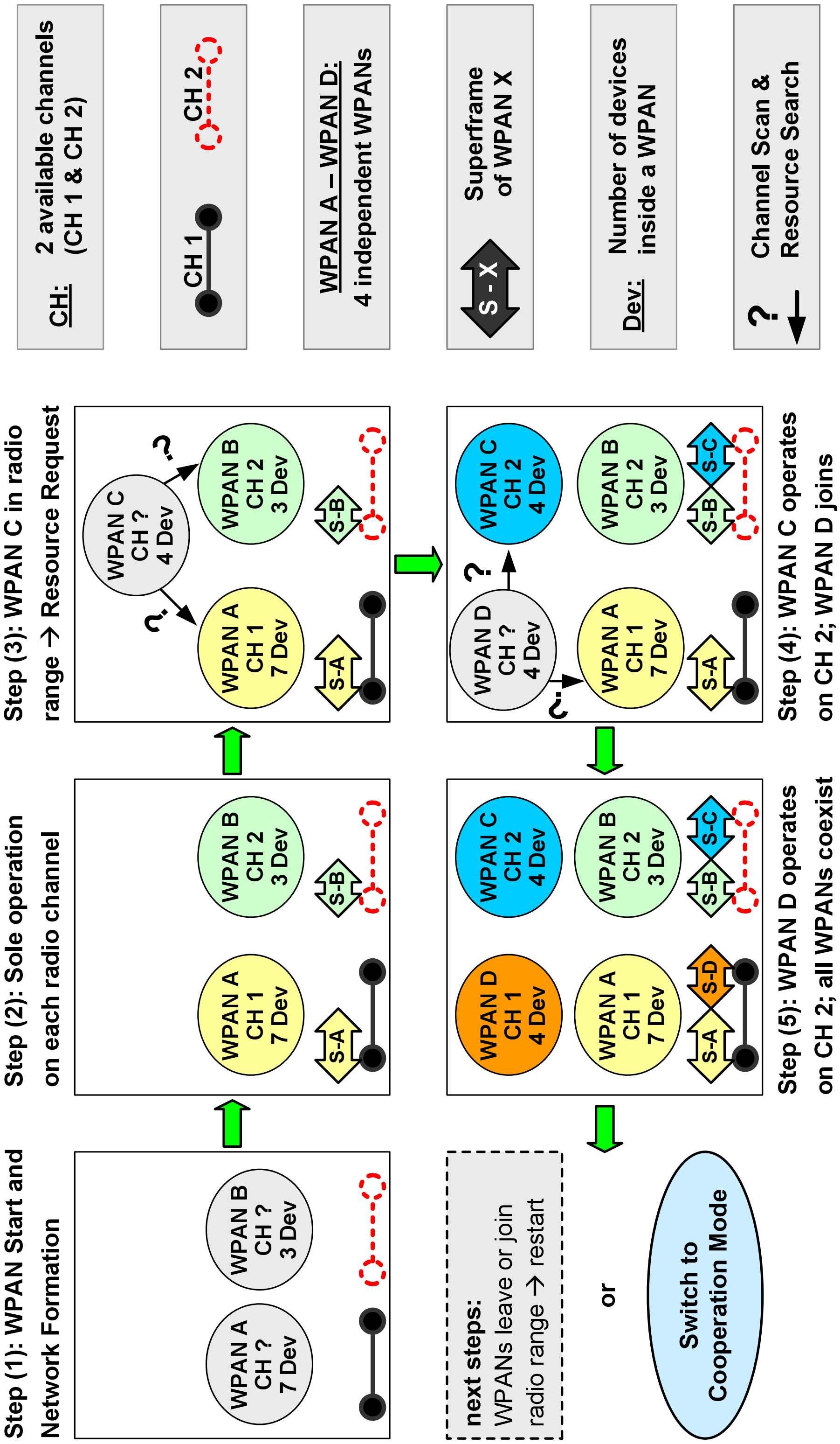


Figure 5.4: Exemplification of the Inter-WPAN Resource Sharing

Both WPANs reply to the resource request with data about the resource amount that both can give to WPAN C. WPAN C decides that it will share radio resources with WPAN B, since B has fewer devices than A. WPAN C can therefore get more resources on radio channel 2 in this example. Other examples could use additional application parameters or QoS demands for the decision about resource sharing.

WPAN C coexists with WPAN B on radio channel 2 after the exchange of resource requests and the necessary adaptations of the superframe structure of WPAN C (to initiate the coexistence). WPAN D joins the other WPANs in radio range later on. D also scans the radio channel for already existing WPANs and requests resources from the existing WPANs, just like WPAN C did. This time, WPAN A and C are addressed by the requests, since A operates individually on radio channel 1 and WPAN C is the latest accrued WPAN on radio channel 2. A and C respond again with information about available wireless resources and WPAN D decides to share resources with WPAN A on radio channel 1. After the subsequent initiation of resource sharing, all four WPANs coexist in radio range. Changes or additional operations start afterwards, when channel conditions change, additional WPANs appear in radio range, existing WPANs leave radio range, or WPANs want to initiate a cooperation.

Important details for the described process are the detection of already existing WPANs, the requesting of resource usage information, the subsequent initiation of resource sharing, and the maintenance of the coexistence state. The detection of other WPANs is enabled through the usage of active channel scans (performed through `NLME-NETWORK-DISCOVERY.request` service primitive). These scans send requests for network beacons on all specified radio channels. Existing WPANs receive these requests and reply with a network beacon (reply type depends on beacon usage in the according WPAN). With these scans, a device is able to locate any PAN coordinator transmitting network beacons within its receiver range.

As soon as the PAN coordinator of the new WPAN receives a beacon of an existing WPAN, it analyses the channel usage information included in the network beacon. Since the superframe parameters of the existing WPAN are included in the network beacon, the new PAN coordinator can detect the active and passive periods of the existing WPAN. It waits until the active period of the WPAN has ended and performs another channel scan to detect if other WPANs are already coexisting with the other WPAN.

The idea behind this is that additional WPANs use the inactive sleeping periods of already existing WPANs to transmit their data. Figure 5.5 shows the concept: four WPANs operate on the same radio channel, while WPAN B, C, and D are operating in the inactive period of WPAN A's superframe. If the new PAN coordinator detects that another WPAN is already operating in the inactive period of the primary detected WPAN, it will wait for the inactive period of the second WPAN to perform another channel scan. As soon as the new PAN coordinator has found an unoccupied inactive superframe period from any existing WPAN, it sends the request for resources to the existing WPAN coordinator. The transceiver of the last active PAN coordinator therefore needs to be in a receive state to receive any incoming resource requests. If the radio channel is fully occupied (as shown in Figure 5.5), the new PAN coordinator must switch to another channel to try to get resources from other WPANs. Future extensions could include a mechanism for the downsizing of superframe structures of existing WPANs to gather free resources for new WPANs.

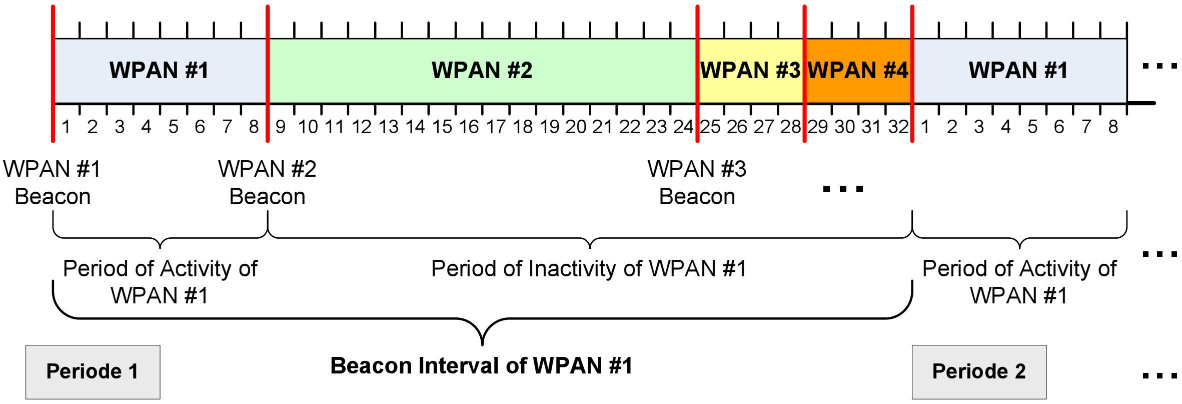


Figure 5.5: Sharing of Wireless Resources between Independent WPANs

The last existing PAN coordinator receives the resource requests and replies with information about the channel usage. The existing WPAN does not change its superframe configuration, only the new WPAN has to adapt its superframe parameters accordingly. The exchange of channel usage information is necessary to make sure that the new PAN coordinator has all necessary information (list of all WPANs on the channel and superframe parameters of all WPANs). Thus the existing WPAN also knows that another WPAN is occupying the resources of its inactive period. The PAN coordinator of the existing WPAN can deactivate its receiver after the successful coexistence initiation, since another WPAN is now the last existing one.

The new WPAN can determine the available amount of resources from the information from the last existing WPAN based on the information about the superframe parameters of all other WPANs on the radio channel. It can afterwards assign resources in a *Intra-WPAN* level. The maintenance of the coexistence state is regulated through the exchange of beacon messages. This way, additional overhead is minimized because network beacons are transmitted anyway. The exchange of resource information via beacons is hence named *forward information exchange*: forward, since it starts with the first existing WPAN and then transcends to all other WPANs. To enable a direct information exchange between all WPANs a new approach is needed. This approach, called *backward information exchange*, uses a specified time slot of all superframes of each WPAN for the exchange of messages inside this slot. Information about this slot has to be synchronised between all WPANs on the radio channel or a time slot may be specified by default. During this time slot, all PAN coordinators should active their receivers or transmit information messages (while using CSMA-CA for the channel access). This way, messages between all existing WPANs can be exchanged.

With the forward and backward exchange of information, the coexistence state can be maintained and regulated and the original goal of the strategy, the coexistence and assignment of resources between independent 802.15.4 networks, can be achieved. Improvements and extensions could include additional QoS or security features for the described processes. These extensions go beyond the scope of this thesis.

5.1.6 Monitoring and Maintenance

The functionality of the monitoring and maintenance part of the coexistence strategy is the continuous monitoring of channel conditions and other parameters that are used for the provision of coexistence services. The monitoring itself can be active or passive. Active monitoring stands for all processes and operations that are started by the monitoring part. Examples are the execution of the interference detection process, requests for active channel scans, or requests for ED feedback. Passive monitoring describes the non-active supervision of parameters, variables, results, or values that occur during normal operations of a device. Examples for these monitored objects are accumulated and collected LQI values, channel statistics like the PER or the number of retransmissions, or the number of lost ACK, data, or beacon packets. Suggestions and estimations of the radio channel are possible with a monitoring of these parameters.

If the monitoring process detects a change of radio channel conditions or other alterations of important parameters, it starts the maintenance process that decides what actions shall be taken. An example situation could be: the monitoring process detects that the PER and the number of retransmissions are rapidly rising. The maintenance process is informed of these parameter changes. It decides to execute the interference detection process, to gather more information about the type of channel interference. If the interference is detected by any other device than the PAN coordinator, then this device shall try to contact the coordinator and inform it about the current situation immediately. Monitoring and maintenance therefore go hand in hand with other processes and the described exchange of status information between the devices of a WPAN.

5.2 Strategy for Inter-WPAN Cooperation Support

The non-available support for *Inter-WPAN* cooperation was already explained in Subsection 4.1.6. To enable cooperation and therewith the possibility for ubiquity a new compound strategy for *Inter-WPAN* cooperation support is proposed in this section.

The cooperation strategy includes different components and three different strategies for the specific realisation of *Inter-WPAN* cooperation. The inclusion of three strategies for cooperation realisation was made due to the differences in performance and maintenance characteristics of these strategies. If just one strategy is included the whole cooperation support might be too restrictive in terms of usability for applications. The inclusion of different strategies and the ability of selecting a specific one expands the *Inter-WPAN* cooperation support to more application and usage types, what is one of the main goals of this thesis. An overview of the complete strategy is presented in Subsection 5.2.1 whereas the specifications of the single components and functions are given afterwards in Subsections 5.2.2 to 5.2.7.

5.2.1 Overview of the Inter-WPAN Cooperation Strategy

The cooperation strategy is split up into several parts and processes controlled again by a main process. The used basic communication principle is the request and response scheme comparable to the coexistence strategy. A conceptual state machine for the cooperation strategy is shown in Figure 5.6. Important parts of the strategy are:

- *Cooperation Request Processes* (refer to Subsection 5.2.2)
- *Topology Switching Approach* (refer to Subsection 5.2.3)
- *Inter-WPAN Handover Approach* (refer to Subsection 5.2.4)
- *Inter-WPAN Bridging Approach* (refer to Subsection 5.2.5)
- *Monitoring and Maintenance Part* (refer to Subsection 5.2.6)
- *Abort Cooperation Part* (refer to Subsection 5.2.7)

The cooperation process is activated when either an user or an application requests a cooperation or when a cooperation request from another WPAN is received. Two different processes (see Points I and II in Figure 5.6) take over the responsibility of processing any request or reply for cooperation. The WPAN switches back to plain coexistence if a cooperation between participating WPANs cannot be initiated successfully at this point. The cooperation main process is started when requests and replies are exchanged successfully. This process runs simultaneously with other applications, the assurance of application QoS is important for the realisation of any cooperation. Steps have to be taken in order to ensure that all applications can run without any constraints.

The cooperation main process gathers information about the wanted type of cooperation. A specific strategy for the enabling of *Inter-WPAN* cooperation (either *Topology Switching*, *Inter-WPAN Handover*, or *Inter-WPAN Bridging*) is chosen by the main process based on the gathered data. These three strategies are suited for different cooperation and application needs, specific descriptions are given in the according subsections. A monitoring and maintenance process is executed next to the realisation of the cooperation strategy. Important changes in network topology, radio channel usage, interference levels, or application parameters are monitored by this process and necessary changes and adaptations of the cooperation strategy are carried out accordingly.

The last process handles the abort functionality. It tries to restore the normal coexistence state of the engaged WPANs. A switch back to the plain coexistence mode is also performed in case of occurring errors during other processes. General error treatment and processing is again performed by the main process. The main process also handles the exchange of request and response messages between the different sub-processes and components of the cooperation strategy. It is again a mere software development task, comparable to the coexistence mode main process.

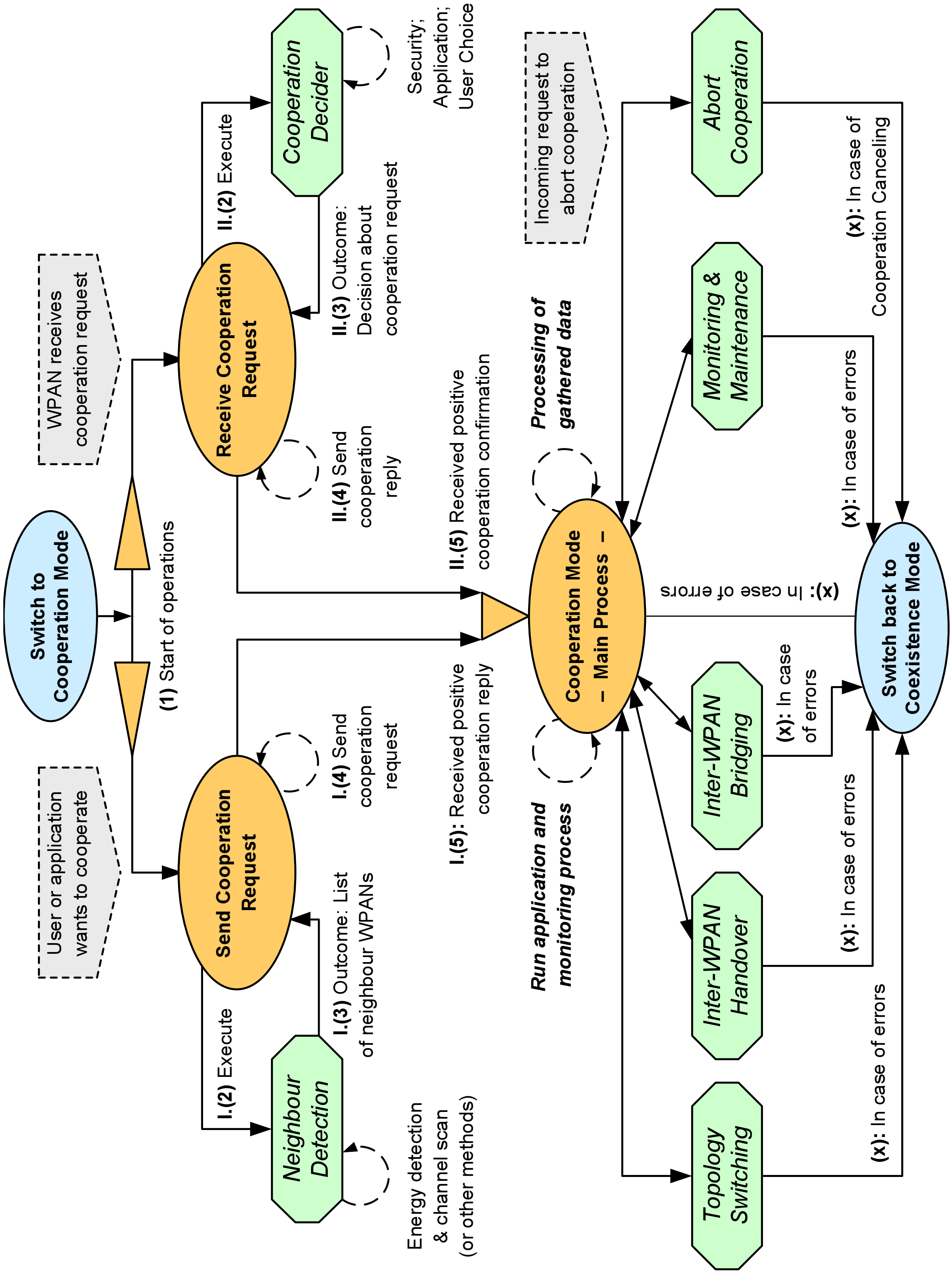


Figure 5.6: Conceptual State Machine for the Inter-WPAN Cooperation Strategy

5.2.2 Cooperation Request Processes

Before any cooperation between WPANs is started, a request and a decision about a request for cooperation have to be generated and exchanged. The *Send Cooperation Request* and the *Receive Cooperation Request* process are responsible for the according generating of messages and the exchange of them.

The sending of cooperation requests is started, when an application or a user wants to cooperate with another WPAN. Reasons for a cooperation can be manifold: from plain information exchange to distributed use of specific services, various scenarios are thinkable. The detection of neighbour WPANs is started by the PAN coordinator with the wish for a initiation of a cooperation. This sub-process performs necessary actions to detect WPANs in radio vicinity of the PAN coordinator. The detection is done with the help of standard specified ED and active channel scan functions. Procedures from the WPAN association process are used to detect other WPANs in radio vicinity. The outcome of the detection sub-process is a list of neighbour networks.

The send cooperation request process then informs the application or the user about the detected neighbour WPANs. A specific cooperation partner needs to be chosen from the list of neighbours, the functionality of the choice process is merely an implementation task and therefore out of the scope of this thesis. Once a cooperation partner is chosen, a request for cooperation message is sent to the PAN coordinator of the chosen cooperation partner. This request is a newly specified message wrapped in a data message with sending parameters set in a way that the receiver PAN coordinator can actually receive the request. To enable the reception a broadcast address is used and other message header fields are set in a way similar to messages used for the joining of orphaned nodes (nodes that lost the connection with their specific PAN coordinator). Thus the cooperation partner's PAN coordinator can receive the cooperation request.

An incoming request for cooperation starts the *Receive Cooperation Request* process on the other WPAN. Similarly, this process would be started on the original WPAN if another WPAN would request a cooperation. The receive cooperation request process analyses the incoming request and starts the *Cooperation Decider* sub-process. This sub-process includes the necessary higher layer intelligence to decide if a cooperation request should be accepted or not. Since a decision choice depends on many aspects (e.g. security aspects, available resources, application QoS, choice of the user), an outsourcing of associated operations is aspired, so that this part can be changed without any influence on the rest of the cooperation process. A realisation of the cooperation decider is again an implementation and specification task, depending on the possible application types and the needs of the user. It is not further pursued in this thesis.

Once the cooperation decider has made a decision about the granting or declining of the cooperation request, the according reply message is generated and sent back to the originator of the cooperation request. The cooperation main process is started afterwards in case of a positive decision or the reception of a positive reply. The use of a 3-way handshake with acknowledgements is striven here to eliminate the possibility of lost messages. Additional information about the wanted cooperation are included in the request and reply messages to enable a decision about the specific realisation of cooperation. Such information includes the number of nodes of the participating WPANs, data about the application type, the traffic profile, superframe parameters as well as QoS related information. The cooperation main processes (started on both PAN coordinators of the participating WPANs) decide about the next steps.

5.2.3 Topology Switching Approach

As soon as the cooperation main process is started, a choice about the specific realisation of cooperation is made. Needed information are exchanged during the cooperation request part. Based on these information, one of the three available strategies for *Inter-WPAN* cooperation realisation is chosen by the main process. The choice is influenced by the parameters of the cooperation. These parameters describe if devices from the cooperation partners want to exchange data on a regular interval or just sporadically. QoS and security parameters are other influencing factors for the decision process, although security aspects are not considered in the thesis and left open for future extensions.

The topology switching approach is chosen when the majority of nodes from the cooperating WPANs want to exchange data, when the use of a specific network topology is aspired by any running application, or when the cooperation should last for a longer period of time (e.g. hours to days). Other strategies are chosen when the cooperation should only last for a short time amount (e.g. minutes) or when only specific devices want to exchange information with each other. A change in network topologies or the initiation of cooperation should in any case be transparent to higher layer applications.

Since 802.15.4 supports different network topologies, different variances of the topology switching approach are possible. Depending on the topology of the participating WPANs and the radio reception relations, one of the following three forms is chosen:

- Star Topology Cooperation (refer to Figure 5.7)
  ↪ chosen in case a star topology is wanted during the execution of the cooperation; all devices need to be in radio range
- Tree Topology Cooperation (refer to Figure 5.8)
  ↪ chosen in case a tree topology is wanted during the execution of the cooperation; the PAN coordinator of the cooperation partner must be in radio vicinity of the originator PAN coordinator or one FFD of the originator WPAN
- Mesh / P2P Topology Cooperation (refer to Figure 5.9)
  ↪ chosen in case a Mesh/P2P topology is wanted during the cooperation execution; the PAN coordinator of the cooperation partner must again be in radio vicinity of the originator PAN coordinator or any FFD of its WPAN

Different compound topologies are generated during the cooperation process, exploiting the different aspects, strengths and weaknesses of the three different 802.15.4 topologies. The star topology cooperation for example is chosen, when a low message latency and a centralized network control is required. For star topologies, it is necessary that all nodes from the cooperating partner WPAN are in radio range of the PAN coordinator of the other WPAN (see Figure 5.7) because star topologies only support 1-hop routing. The cooperation partner PAN coordinator (called “switched coordinator”) is treated like a normal FFD by the other PAN coordinator. All devices are included in the global new star topology. The necessary PAN coordinator realignment procedures and messages are already specified in the standard. A higher layer controlling solution is needed to support this approach. It is important that all devices participating in a topology switching cooperation switch to a mutual radio channel to exchange data messages. This is a main difference of the topology switching approach (and its three variants) compared to the other two strategies for *Inter-WPAN* cooperation.

The tree topology variant is chosen when WPANs with a large amount of devices want to cooperate. The tree topology and the according cooperation mode is especially useful for scenarios where data aggregation or data fusion is used, since the data messages usually go through the parent nodes (natural aggregation points) in the tree before they

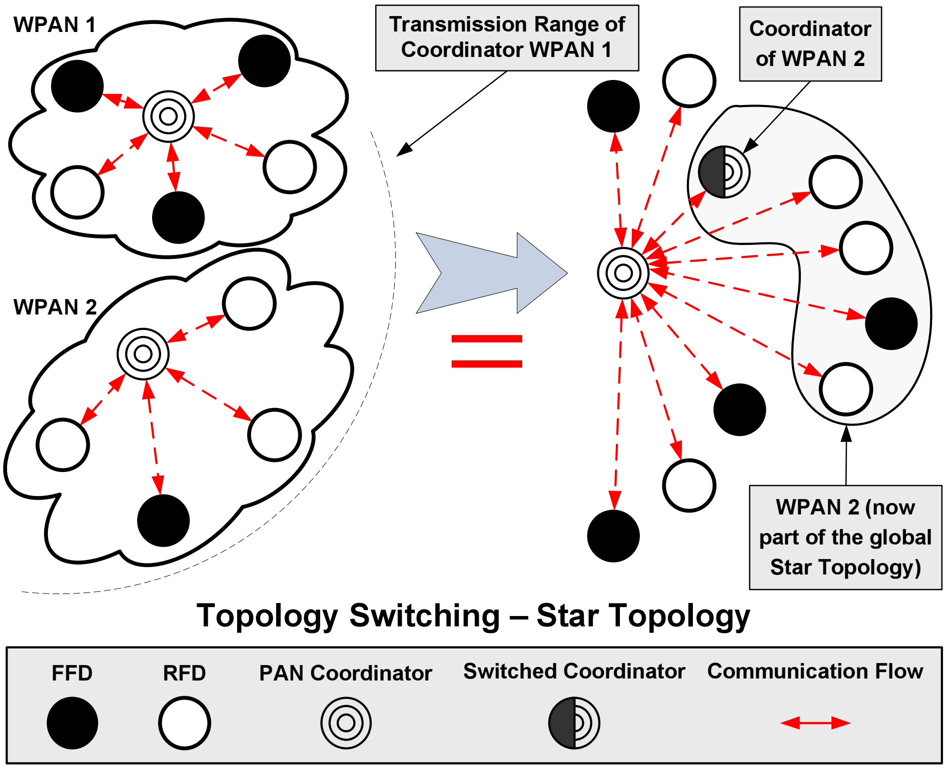


Figure 5.7: Star Topology Switching Exemplification

arrive at the leaves. Routing and management operations in this topology are done the same way as specified in the standard. The cooperating WPAN is inserted as a FFD tree node with leaves (the other nodes from the cooperating WPAN). Maintenance overhead and uneven power consumption due to the tree routing protocol are drawbacks of this topology, a decision for the tree topology mode has to consider these overhead factors.

The last topology switching mode is the mesh/P2P topology variant. This version is usually used when WPANs that are distributed over a large area want to cooperate. Multihop routing is used in this cooperation mode, the nodes from the cooperating WPAN can therefore get included at any other node in the cooperation partners WPAN. The realignment of the PAN coordinator is again supported through messages and processes specified in the 802.15.4 standard. The mesh topology allows for direct communication between all capable nodes and multihop routing in case a direct connection is not available. This might introduce a significant higher message latency compared to the star topology for example. Application QoS parameters must be considered during

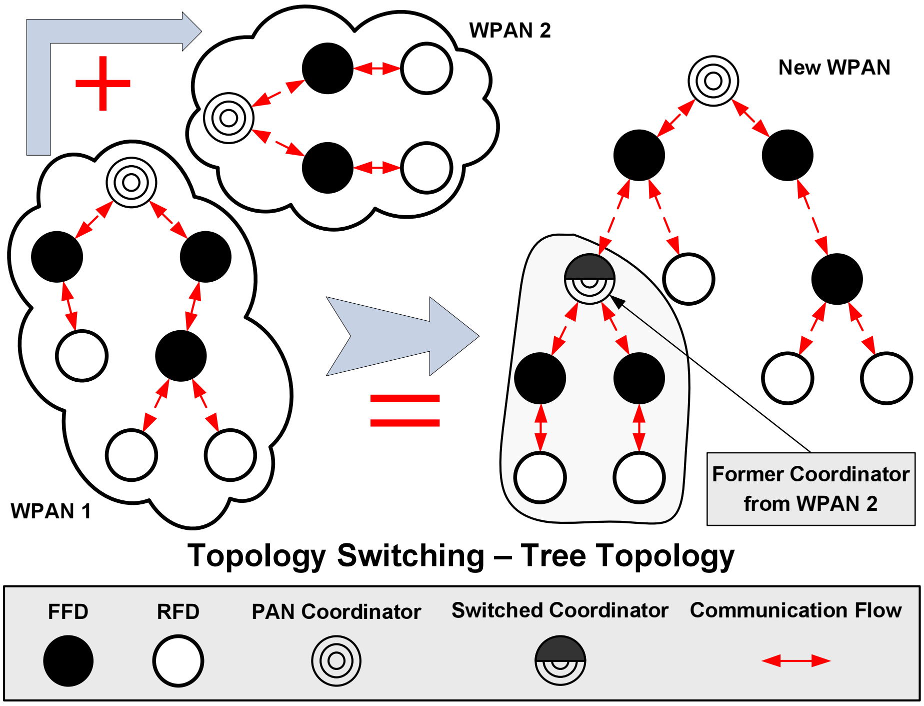


Figure 5.8: Tree Topology Switching Exemplification

the decision about the use of the mesh/P2P topology variant.

5.2.4 Inter-WPAN Handover Approach

The topology switching approach shall be used in case of lasting cooperation processes. This is not the case when only few messages should be exchanged or when mobile or moving WPANs are considered. A more suitable cooperation strategy for these cases is the *Inter-WPAN* handover that normally describes the switching of a communication link between two base stations in wireless communication. For 802.15.4, a handover is used as a synonym for the changing/switching between PAN coordinators. A node, which normally belongs to a certain WPAN, changes to another WPAN during the handover and switches PAN coordinators during the process. When the device is connected to the other WPAN, it can communicate with the associated devices in this new WPAN and exchange the necessary information. The basic idea described here is shown in an exemplification depicted in Figure 5.10.

In Figure 5.10 two devices are changing between WPAN 1 and 2. The handover process can therefore be executed for a single node or for a couple of nodes. It is important that in this approach, only information between the changing node and the new WPAN is exchanged. No general communication flow between the two WPANs is possible during the handover. Nodes should therefore perform a handover only when they want to exchange data or when they are used as a “mobile data volume” for the exchange of information. The necessary PAN `JOIN`, `LEAVE`, and `REJOIN` procedures and messages are already specified in the standard. A higher layer controlling solution is again necessary for the implementation of this solution approach.

Other research work also considers handover between 802.15.4 or ZigBee WPANs as a method for data exchange between independent WPANs and as an approach for ZigBee *Interconnection*. Example works are [54] and [55]. Ideas from these examples may also be included in the proposed *Inter-WPAN* cooperation strategy, as long as the approaches are compatible to the 802.15.4 standard.

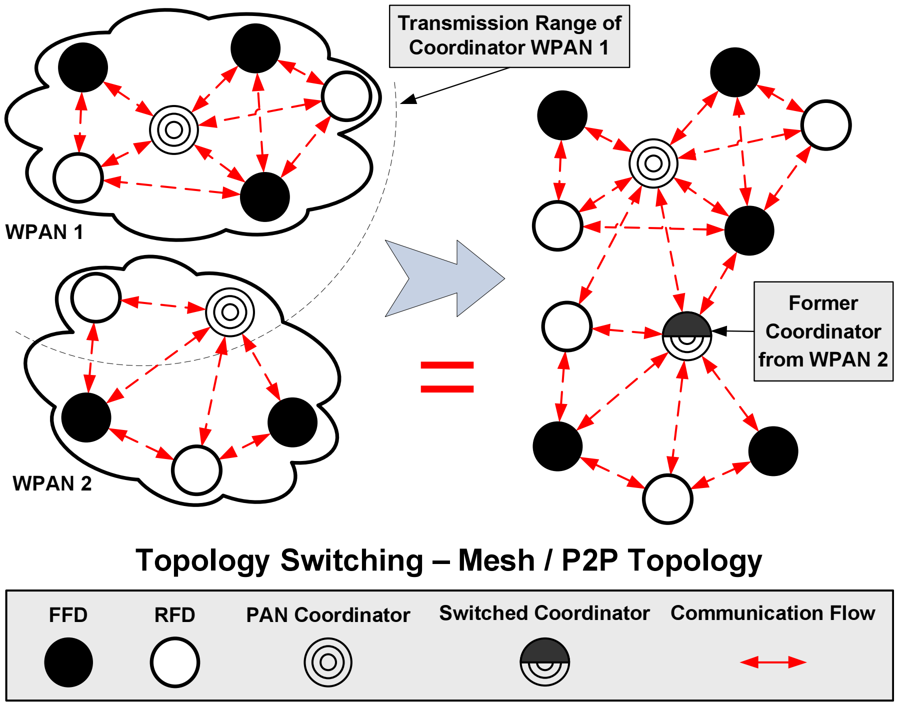


Figure 5.9: Mesh/P2P Topology Switching Exemplification

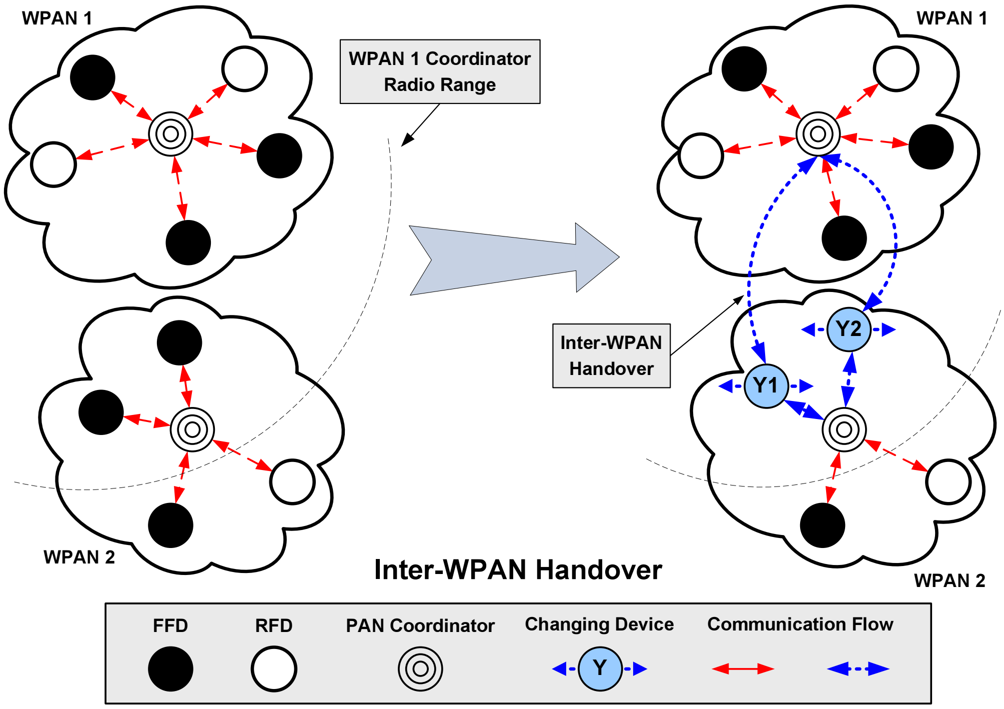


Figure 5.10: Inter-WPAN Handover Approach Exemplification

5.2.5 Inter-WPAN Bridging Approach

While the handover between two networks is an approach from the mobile communications area, *Inter-WPAN* bridging relates to the bridging concept known from the wired network communication area. Bridging is used to provide a stable link between two independent networks without the need for any topology change. It can therefore be used for scenarios where data should be exchanged between participating networks in general over the so-called bridge. This idea was previously researched in [55], where the bridging method was evaluated.

The exemplification of the bridging approach is presented in Figure 5.11, where a cooperation request from WPAN 1 is received by a FFD from WPAN 2. The FFD forwards the request to the PAN coordinator of WPAN 2. The coordinator decides to use the bridging mode for the realisation of the *Inter-WPAN* cooperation because both PAN coordinators cannot reach each other. Another not prosecuted option in this case would be the topology switching into a mes/P2P topology. During the cooperation the FFD from WPAN 2 joins WPAN 1 temporarily while still being connected to WPAN 2. Hence it can receive messages from both WPANs and forward them accordingly. The bridging device needs to switch radio channels and superframe configurations permanently between the participating WPANs to facilitate this idea. Energy consumption can be a problem for this scenario if the bridging device has a limited energy source. Another aspect for bridging is the adaptation of routes and the propagation of changed routing information, so that nodes from the other WPAN can be addressed and reached over the bridge. This requires a higher layer solution that should also include the rest of the necessary bridging mode management and maintenance operations. An approach for the routing problem may involve the PAN-ID parameter in the MAC packet header. The routing could be adopted so that packets with the PAN-ID of the own WPAN are routed inside the local WPAN while packets with other PAN-IDs are forwarded to the bridge, where they are transferred to the cooperating WPAN.

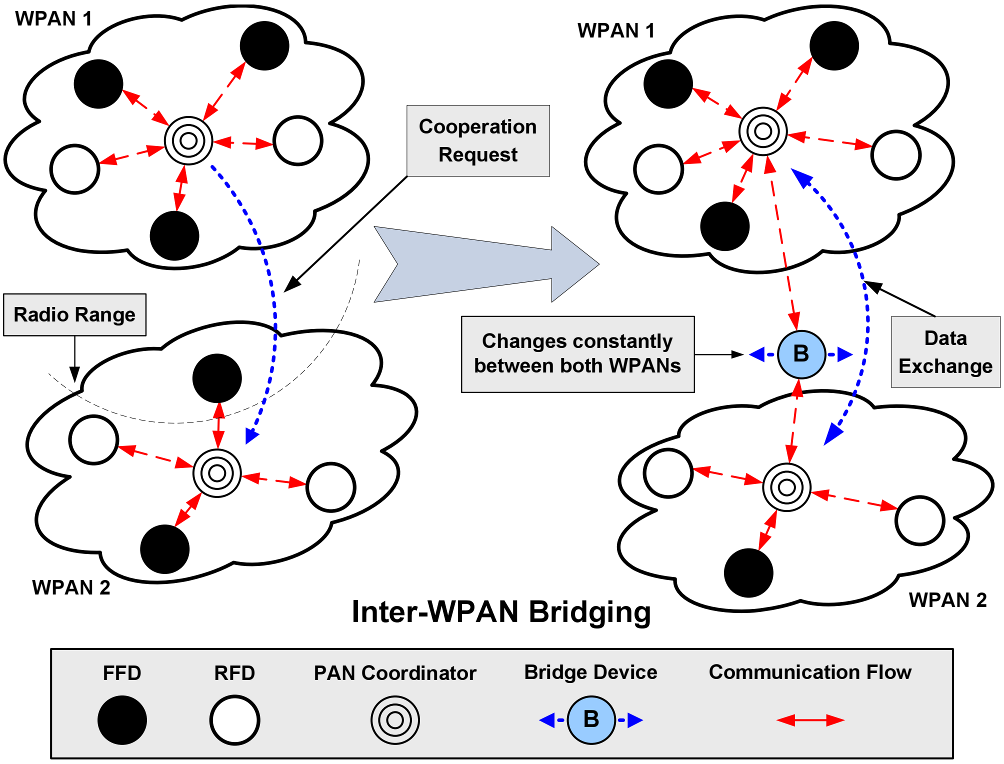


Figure 5.11: Inter-WPAN Bridging Mode Exemplification

5.2.6 Monitoring and Maintenance

All components and parts of the cooperation strategy need constant monitoring and maintenance in case of errors or failures, changed channel conditions, changed cooperation parameters, or other changed circumstances. This monitoring is again provided by an outsourced monitoring and maintenance process comparable to the one presented in the coexistence strategy in Subsection 5.1.6. Monitoring can again be performed in an active (e.g. starting of interference detection processes) or passive (e.g. monitoring of accumulated data transfer statistics) fashion. Once a change of conditions is monitored, the according decisions have to be taken in the maintenance process. Example situations may involve the sudden appearance of interference on the radio channel during a cooperation of independent WPANs. A proper reaction in this case would be the analysis of the interference (comparable to the coexistence mode), a decision about a channel switch and the distribution of maintenance messages to inform all participating networks and nodes about the chosen measures (e.g. switch the radio channel to an non-interfered channel). The monitoring and maintenance part is again merely an implementation task. Decisions about the design of this process shall be made during an implementation.

5.2.7 Aborting a Cooperation

This process has to restore the superframe configuration, the network topology, all routing tables, and other parameters that were changed during the cooperation period to their respective original values and states. The abort functionality can either be initiated in case of errors, failures, or by request from both initiator and cooperation partners at any point in time during the cooperation. Corresponding messages and service primitives for the handling of abort requests are again a task for an implementation of the cooperation strategy. A definition is therefore out of the scope of this work.

5.3 Combination of both Strategies

The proposed concepts and ideas were in general developed to meet the requirements of the specified reference applications and scenarios. Both ideas can be used independently or combined for other purposes or applications. In this case, certain adaptations or changes in the presented algorithms or alterations of the parameter values or formulas may be necessary. A consideration of additional applications and scenarios outside the health care area falls aside the scope of this work.

A combination of cooperation and coexistence strategies is possible because both strategies normally operate one after another. A split-up into different operation modes is hence preferred. A possible flow of events between "cooperation mode" and "coexistence mode" is depicted in Figure 5.12. After a WPAN's formation, it normally starts and operates in the coexistence mode. A switch to the cooperation mode is performed after a cooperation is requested or a request for cooperation was received. Once the cooperation is cancelled or ended, the participating WPANs switch back to coexistence mode. Both strategies with their respective components can therefore be integrated into a combined solution approach. Several methods (e.g. interference detection) are used by both strategies, gathered and accumulated information from such methods and processes should therefore be made available for both operation modes and their components. A combination of both strategies should consider "cross-layer" and "cross-strategy" convergences to achieve an optimisation during a combined implementation and realisation of the two strategies for coexistence and cooperation.

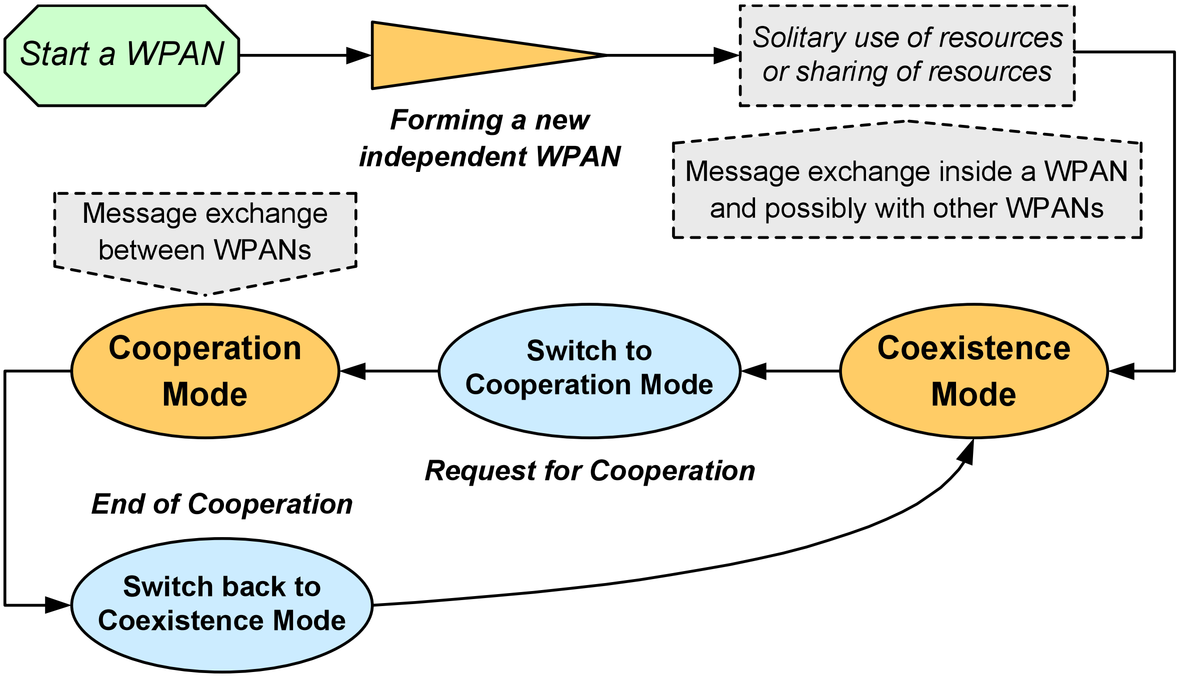


Figure 5.12: Proposed Operation Modes and Event Flow

6 Simulative Investigations and Evaluations

Simulative investigations and evaluations are fundamental parts of this work. The first part of Chapter 6 describes the simulation practice and the used simulation framework and model, while the second part presents conducted evaluations and their outcomes.

6.1 The OMNeT++ Simulation Framework and the Used Simulation Model

Simulation model, simulation framework, or simulation environment are terms referring to various aspects of the simulation practice. A clarification of terms is needed before more information about the used simulator and model are given. The first step in a simulation process is the creation of a simulation model, which is a more or less realistic and accurate representation of the situation, process, or scenery that is intended to be examined. The software implementation of a simulation model is called a simulator. The simulator is executed at runtime to provide the environment where examinations and investigations take place. Simulation frameworks like OMNeT++ provide flexible environments for different simulation models. The combination of an implemented simulation model and a surrounding framework produces the simulator.

Nowadays various simulation frameworks are available. From the wide range of products, the OMNeT++ simulation framework was chosen for the conduction of investigations in this thesis. OMNeT++ is a public-source and open-architecture framework with a component-based and expendable modular structure. It has a strong GUI support and versatile debugging functionalities compared to other simulation frameworks like `NS-2` for example. OMNeT++'s primary application field are simulations of (mobile and static) communication networks. Second to this, OMNeT++ has been used for IT systems simulations, analyses of queueing networks, and hardware architectures as well as the modulation and simulative investigation of business processes.

OMNeT++ belongs to the class of discrete event simulation environments. Discrete event simulation describes the process of simulating a system, where one or more phenomena of interest change their values or states at discrete points in time. Discrete event simulators like OMNeT++ are therefore the opposite of simulators for continuous simulations, where changes occur fluent and continuously [63]. OMNeT++ provides a component-based architecture for the creation of simulation models. The different components are programmed in `C++`. The usually small components (`C++` classes derived from a basic standard class) are assembled into larger components or models, thanks to a flexible hierarchy provided by OMNeT++. A different language is used for the assembling of components and the description of scenarios or topologies: the Network Topology Description (NED) language. NED is derived from the `Tcl` script language. With the help of NED, a modular description of communication networks can be achieved. The descriptions of simple modules, compound modules, topologies, and interconnection of modules can be reused in other network descriptions. An interchangeability is hence possible, while using OMNeT++ simulation models. This bi-language programming approach is also used in other simulation frameworks like `NS-2`.

OMNeT++ is not a network simulator itself, it strongly depends on implemented simulation models. Various communication protocols, queueing algorithms, network components, and much more are available from the research community. The two biggest frameworks of models are the *INET Framework* and the *Mobility Framework*. While the Mobility Framework is intended for wireless and mobile simulations within OMNeT++ with a focus on the lower layers, the INET Framework focuses on the higher layers (network, transport, and application) of wired, wireless, and ad-hoc networks. The INET Framework includes implementations of IPv4 and IPv6, UDP/TCP, Ethernet, PPP, and several routing, signalling, and management protocols. The support for mobility and wireless communication in INET has been derived from the Mobility Framework. Several additional models use the INET Framework's basic functionalities and extend them with specific protocols or technologies. One of these extensions is a simulation model of the IEEE 802.15.4 standard. It is described in the following subsection.

6.1.1 The IEEE 802.15.4 Model for OMNeT++/INET

The IEEE 802.15.4 simulation model for the OMNeT++/INET simulation environment was created and published in [64] by Feng Chen and Falko Dressler from the university of Erlangen-Nuremberg, Germany. This simulation model is used as the basis for all simulative investigations in this thesis. The following paragraphs introduce the architecture, components and functionalities of the simulation model. Changes and extensions of the original model are described at the end of this section.

The model from Cheng and Dressler uses the *INET Framework* as the underlying basic structure. Architecture, layer set-up, and composition are comparable to the standard 802.15.4 architecture. The model architecture and its components are shown in Figure 6.1. The model itself is a compound model made up from three sub-models: PHY, MAC, and traffic. These sub-models and their components match the different layers from the 802.15.4 standard, as it is shown in Figure 6.1.

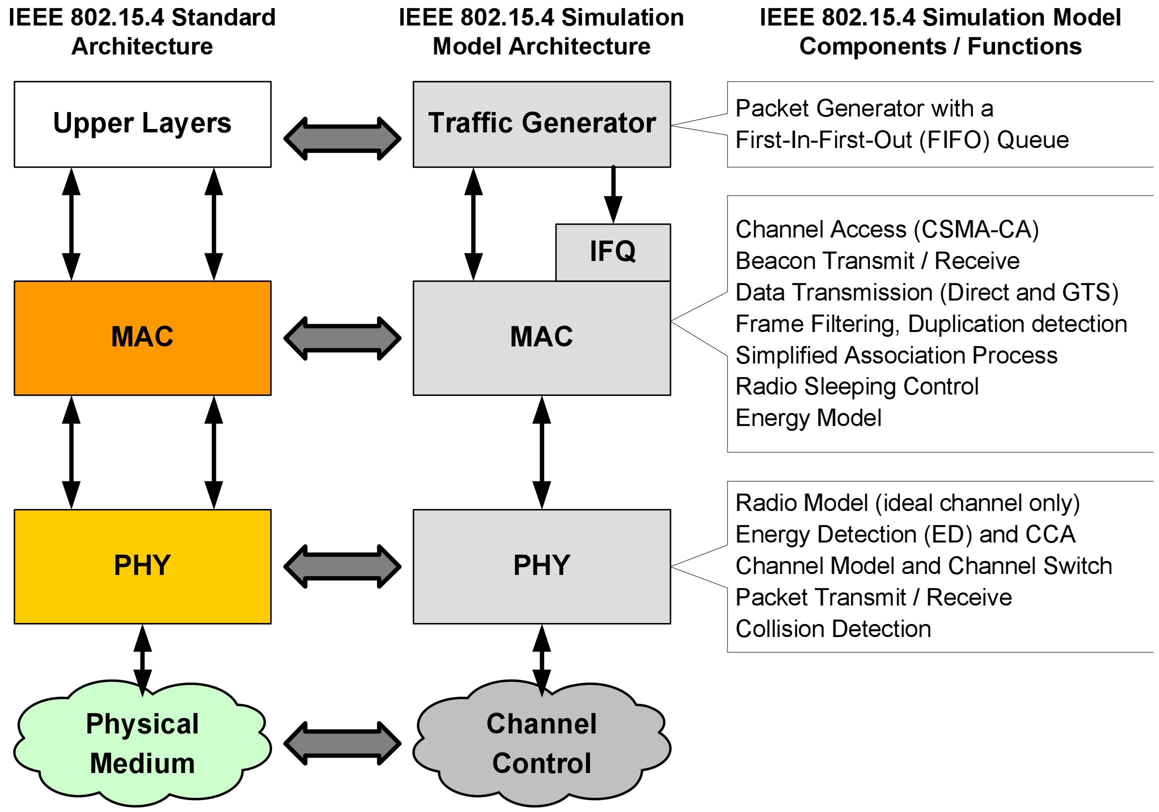


Figure 6.1: Architecture of the IEEE 802.15.4 Model for OMNeT++/INET

The model implementation relates to the IEEE 802.11 model from the INET Framework. Each of the three sub-models is a independent module and inherited from the standard OMNeT++ `C++` class `cSimpleModul`. The models are connected with each other and communicate via message exchange through these connections. The different sub-models and their functionalities are introduced in the following paragraphs.

PHY Module

For the PHY, the generic module `AbstractRadio` from the INET Framework was adapted and enhanced to match the needs of 802.15.4. The radio states were redefined according to the 2006 revision of the standard. Three different states are therefore supported: transmitter enabled, transceiver disabled, and receiver enabled. The MAC module controls the different radio states via request primitives. Channel state feedback for the Clear Channel Assessment function is also implemented and accessible through the appropriate request and confirm service primitives. The receiving process is currently simplified. A packet is received when its receiving energy is above the sensitivity value of the receiver. Channel interference measurements are possible through the measurement of the energy level and the reporting to the MAC layer. A total number of 27 radio channels and three different data rates are supported by the PHY in accordance with [30]. Dynamic channel switching throughout the simulation process is also possible.

MAC Module

The MAC sub-module consists of four main parts: channel access management, beacon mechanism and PAN management, a MAC packet queue and the energy model.

Channel Access: The major functions and primitives for the management of the channel access, as defined in the specification, are available in the simulation model, as shown in Figure 6.1. Currently only direct and GTS data transfer modes are supported as well as the (slotted and unslotted) CSMA-CA algorithm. MAC frame filtering, functions for the detection of duplicate received packets and considerations of the Inter Frame Spacing (IFS) delay complement the channel access management.

Beacon Mechanism and PAN management: The simulation model supports the formation of star and cluster tree topologies. PAN coordinators can be chosen through set-up parameters. The overall PAN association process is simplified; a node will associate with the coordinator, from which he receives the first beacon. Neither PAN dissociation processes nor channel scan functions are included in the current version of the model.

Packet Queue: Since the 802.15.4 standard does not specify any explicit MAC buffer, an Interface Queue (IFQ) was added to the MAC sub-module by the model creators. The IFQ is an adjustable drop-tail FIFO queue, which acts as a buffer on the MAC and buffers data packets from the upper layers until a request from the MAC arrives.

Energy Model: The simulation model simplifies the energy model by reducing the energy consumption down to the energy consumed by the radio. The time that the radio spends in one of the three different radio states (cp. PHY module description) is measured and counted. The radio power consumption for each state is therefore necessary to calculate the total energy consumption.

Traffic Module

To enable investigations, a traffic generator was included in the simulation model. The original generator was developed by Isabel Dietrich [65]. The traffic module uses the generator as a traffic source (generating packets) and a traffic sink (collecting received packets). A `XML`-based parameter structure is used for the description of adaptable traffic patterns. Traffic type, packet size, destination (including broadcast) and packet inter departure times (time until the next data packet is generated) can be specified in the `XML` traffic description. More information can be found under [65].

Parameters for the Configuration of the Model

Various parameters are accessible in the simulation module, namely: TX power for packet sending, RX sensitivity, background noise, signal/noise threshold, parameters of the PAN management and parameters of the superframe format (BO and SO).

6.1.2 Changes and Extensions of the IEEE 802.15.4 Model

The last subsection described the capabilities of the current version of the model (during the writing of this thesis, draft version 0.2 of the model was available). Since the investigations in this thesis covered several aspects of the 802.15.4 standard, some additions and extensions of the original simulation model had to be implemented.

Important alterations inside the simulation model were made to support more than the predetermined superframe configurations. In its original state, the model only supported beacon-enabled WPANs with the following SO and BO configurations: $0 \leq SO < BO < 15$. To enable a research on all possible settings, the model was changed to support the full extent of superframe parameter configurations. Next to these changes, the reference scenarios and applications defined in Sections 3.1 and 3.2 were implemented. Traffic profiles according to the parameter specifications from Tables 3.1 and 3.2 were created to enable further investigations. Another extension of the simulation model was the inclusion of various statistical parameters, which are recorded during the simulation runtime for later evaluation. Such statistics include the through- and goodput of applications, statistics that represent the behaviour and characteristics of WPANs and additional parameters on each of the two lower protocol layers (e.g. recording of retransmission tries per node or number of CCA operations).

Additional simulation model extensions are necessary for future directions of the thesis and further tasks. The completion of PAN management functions is necessary for further investigations of *Inter-WPAN* cooperation strategies and for the inclusion of all standard specified association and dissociation procedures. Indirect data transfer may be included in the future to enable simulative investigations of the third data transfer model.

6.1.3 Simulation Process

Before a simulation can be started, simulation parameters have to be set. In OMNeT++ simulations, almost all parameters are specified in the `omnetpp.ini` configuration file. A code block from an example `omnetpp.ini` is included in the Appendix B. Various sections group the parameters into categories inside the configuration file, e.g. *General*, *Mobility*, *MAC*, *PHY*, *Battery* or *Statistic* parameters (see code lines 1, 18, 38, 51, 59, and 67 in Listing B.1). Several of the 802.15.4 model parameters can be adjusted during runtime to analyse the system's reaction on sudden parameter or network changes. Important parameters for the simulations in this thesis are the superframe parameters BO and SO, the packet size, the number of nodes inside a network, the MAC IFQ queue length, and the general network set-up (node positions, network structure, network topology). The actual values of these parameters are given in Section 6.2 together with the achieved evaluation outcomes.

The implementation of the defined reference applications and scenarios is necessary before parameters for a simulation run can bet set up. With scenarios and parameters fixed, OMNeT++ can be started to gather statistical data and to enable a graphical representation of the simulation. As depicted in Figure 6.2, OMNeT++ allows for an evaluation during and after the simulation runtime. The evaluation during the simulation runtime is used to determine the correctness of implemented simulation models, set-ups and scenarios. Basic parameter values and histograms of transient data (e.g. end-to-end delay) can also be evaluated during runtime.

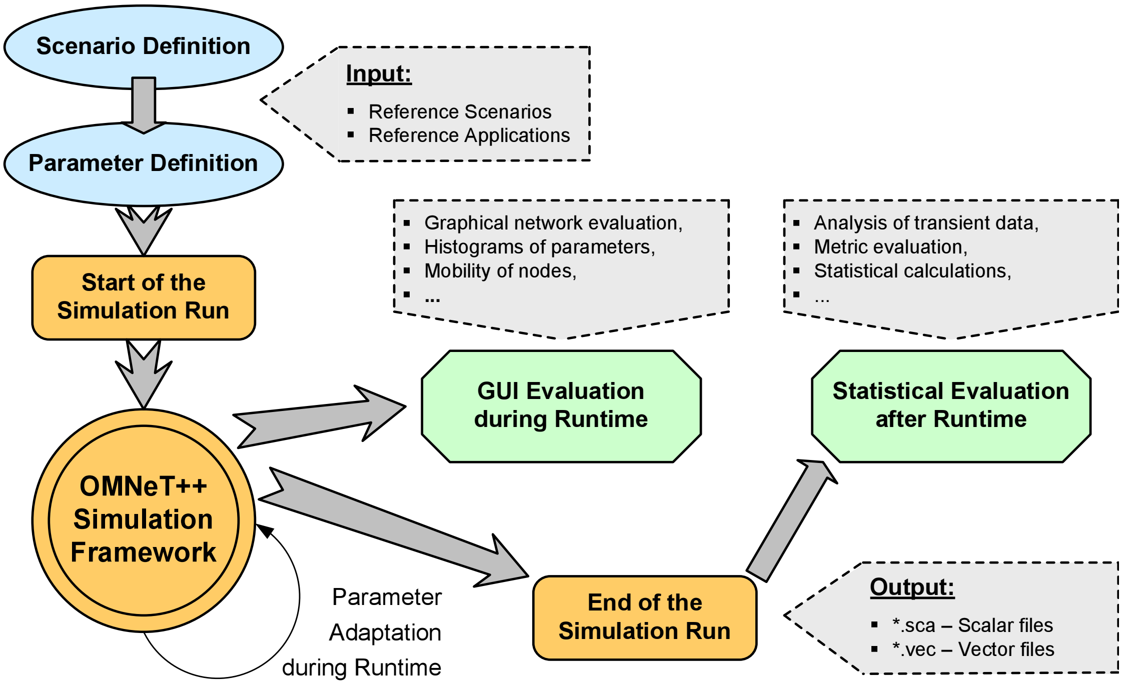


Figure 6.2: Simulation Process Structure

OMNeT++'s ability of tracing statistical parameters enables an evaluation after the simulation ends. OMNeT++ collects data in two separate file structures: `*.sca` (*Scalar*) files collect values of predetermined parameters (e.g. number of collisions or retransmissions of a node), while `*.vec` (*Vector*) files collect transient data streams (e.g. end-to-end delay) together with timestamps over a specified time period. Examples for both statistical classes can be found in Appendix B in Listings B.3 and B.4. With the help of both data evaluation structures, different (performance) metrics can be analysed and evaluated. The performance metrics (e.g. goodput or mean end-to-end delay), which are used for statistical evaluations, are specified and explained in Subsection 6.2.2.

6.2 Background for the Evaluations

Before outcomes of conducted simulations are described, fundamentals and backgrounds for the evaluation need to be introduced. Important simulation parameters and performance metrics are described in this section.

6.2.1 Simulation Specific Parameters

This subsection focuses on the identification of parameters for the simulative investigation of 802.15.4 WPANs and for the evaluation of the proposed solution approaches for massive coexistence and *Inter-WPAN* cooperation. The identified parameters are grouped into three categories: network, node, and traffic parameters. The parameter values are adjusted according to the reference applications and scenarios.

Network Parameters

This category includes all parameters that are connected with network topology, mobility, or placement of nodes and set-up processes of a network.

Playground Size: The playground is the area of interest in the simulation. Nodes and networks are placed inside the playground and the mobility of nodes is restricted to the playground. The playground size is determined by X and Y coordinates in the `omnetpp.ini`, as shown in the example code snippet B.1 in code lines 15–16.

Node Mobility: The mobility of nodes is defined through the setting of a mobility model in OMNeT++. Since node placement and mobility are static in the simulations, “*Static Mobility*” is the mobility model of choice (cp. code line 23 in Listing B.1). Further tasks may include an evaluation of node or even network mobility.

Node Placement: The placement on the playground is defined by X and Y coordinates. In wireless scenarios the placement is important for radio wave propagation and interference evaluations. For WBANs, it becomes less important because the transceiver range normally exceeds the required communication ranges. The placement becomes relevant again, when hidden terminal scenarios are modelled and simulated. The placement is specified in the `omnetpp.ini` again (code lines 19–22 in Listing B.1). In the example, `host[0]` is placed in the playground centre, while all other nodes (`host[*]`) are spread randomly (value `-1`) on the playground. Actual simulation node placements were made according to the reference applications *ECG* and *Body Constitution Monitoring*.

Number of Nodes: This parameter defines how many instances of the generic 802.15.4 node are created in a simulation scenario. This value was altered in various simulation runs for the problem analysis. For the evaluation of the reference scenarios, the number of nodes was fixed to the predetermined values specified in the scenarios.

PAN Coordinator: Since every 802.15.4 network needs a PAN coordinator for the network management, this role has to be assigned to a certain 802.15.4 node. The assignment is made through this parameter (code lines 31–32 in Listing B.1). The dedicated coordinator takes on the management tasks (e.g. creation and distribution of beacons) after the simulation is started. A posterior change of the coordinator role is not possible. Simulations of *Inter-WPAN Cooperation* approaches are hence limited.

Superframe and GTS Parameters: Important for network operations in the GTS data transfer mode are the superframe parameters BO and SO. The assigned PAN coordinator distributes the beacons and thereby the superframe structure (active and passive periods) throughout the network. Superframe and general GTS parameters are set in the `omnetpp.ini` file (code lines 42–49 in Listing B.1). A parameter adaptation during a simulation is not possible in the current version of the simulation model.

Node Parameters

The second category includes all parameters that are connected with the single node.

Energy Consumption Parameters: Different operation modes and tasks of a node consume different amounts of energy. To simulate the energy consumption, several parameters are set in the `omnetpp.ini`, as shown in Listing B.1 on code lines 60–65.

IFQ Parameters: The function of the Interface Queue (IFQ) was already described in Section 6.1.1. The size of the queue (`frame Capacity`) and type of the queue (in the example a `Drop Tail Queue`) can be set in the `omnetpp.ini` file, as shown in Listing B.1 in code lines 35–36. Different simulation runs with various values were conducted to gather information about the influence of the queue length on the network performance. Queue sizes are always specified together with the other simulation parameters.

PHY Layer Parameters: This part combines all parameters that are connected with the wireless transceiver (e.g. TX power, RX sensitivity, thermal background noise, path loss and more) of a node. The various parameters are adjusted in the `omnetpp.ini` (code lines 52–57 in Listing B.1). A calibration of PHY parameters according to an existing wireless transceiver can be achieved by adjusting the adequate values.

Traffic Parameters

This category includes parameters that determine the node or application traffic.

Packet Size: This parameter determines the size of the payload of a data packet. It can be set in the traffic description `XML` file, which is referenced inside the `omnetpp.ini`. An example of such a traffic description file is presented in Listing B.2.

Inter Departure Time: This value determines the time until a new data packet from the given packet size is ready. All generated packets will be delivered to the IFQ and from there to the MAC layer if the buffer is not overflowing. With this parameter, the sensing interval of the reference applications is modelled. The inter departure time can be a constant value or a distribution, as depicted in the example Listing B.2.

Traffic Destination: For the destination of a packet, either a specific node address or a broadcast address can be given. For the reference applications, the traffic destination is usually the PAN coordinator ,which is the data collector.

Traffic Type: Different types of traffic can be set, for example a constant stream of data packets or on-and-off traffic, which enables the modelling of WSN or health care scenarios. The parameters are again set in the traffic `XML` description file.

6.2.2 Performance Metrics

The performance of a system or a technology is usually characterised with the help of several metrics. Prior to the evaluation of the simulation outcomes, these performance metrics are introduced and explained. An assortment of metrics was selected, which is suitable for an evaluation of 802.15.4 under the given reference applications and scenarios, to verify the need and usefulness of the proposed solution approaches.

Energy consumption metrics are often used for the evaluation of 802.15.4 networks and applications. A pure evaluation of the energy consumption of the 802.15.4 transceiver does not allow for a decent characterisation of the whole system consumption because the sensors and actuators use a certain amount of energy too. An investigation of energy consumption is therefore not considered here but classified as future work.

Application Goodput and Network Throughput

Throughput is the measured amount of data transferred from a source to a sink over a period of time. Throughput measured on the PHY or the MAC layer is usually a non-practical value because packet overhead and additional information, which are not used on the highest layer, are also considered in the calculation. For accurate evaluations, the *Application Goodput* metric is preferred. This metric only considers the data that is sent on the application layer and the time it takes until the application layer of the destination node receives the original data. Packet failures and retransmissions influence the transmission time and therefore have a direct influence on the goodput, which is the reason why the application goodput enables a good evaluation of the actual data rates between application layers of sources and sinks.

The goodput is measured in received bytes per second. The value is generated by counting the total number of successful received packets at the application layer and dividing this by the time since the first data packet has been received. The network throughput is calculated by adding the total throughput of all nodes that are involved in data transfers and dividing this by the total number of nodes in the network.

$$\texttt{Application Goodput} = \frac{\sum(\texttt{Total Bytes Received})}{(\texttt{Simulation Time} - \texttt{First Packet Time})} \tag{6.1}$$

$$\texttt{Network Throughput} = \frac{\sum(\texttt{Application Goodput of active Sinks})}{\sum(\texttt{Number of all Nodes})} \tag{6.2}$$

Application End-to-End Delay

The delay metric can be divided into plain *End-to-End (E2E)* delay measurements, embracing *Mean-E2E* delay values, or the decision if application delay bounds are under or over a certain borderline. The E2E delay is defined by the time that a packet takes until it reaches its destination. For this thesis, the E2E delay is calculated by measuring the simulation time beginning from the creation of a packet until the destination application has received the packet. The Mean-E2E delay is the average delay, where all E2E delays are accumulated and divided by the number of received packets. Thus, the delay metric is only relevant for successfully received packets.

The propagation delay has an important influence on the application E2E delay. Within the used simulation model the propagation delay is automatically calculated as: $\texttt{Propagation Delay} = \texttt{Distance} / \texttt{Speed of Light}$. The distance is calculated based on the placement of nodes (defined through the node placement parameters, according to the specified reference applications). The influence of the propagation delay is negligible because short distances between nodes are used (placement in a Body Area Network).

$$\texttt{E2E Delay} = (\texttt{Packet Reception Time} - \texttt{Packet Creation Time}) \tag{6.3}$$

$$\texttt{Mean E2E Delay} = \frac{\sum(\texttt{E2E Delays})}{\sum(\texttt{Number of received Packets})} \tag{6.4}$$

Packet Delivery Ratio

This metric indicates the percentage of all transmitted data packets compared to the successfully received packets. It can be used to demonstrate the goodput at application level on a percentage scale, which enables an easier comparability. It is an important characterisation for wireless systems because it indicates congested networks (e.g. many data packets are lost ⇒ low delivery ratio). The metric is calculated by accumulating the total number of received packets at the sink and the total number of transmitted packets at the source(s). The packet delivery ratio is then calculated as the percentage of received packets to the transmitted packets. The number of dropped packets and retransmissions influence the delivery ratio directly; they are used as standalone attributes to evaluate the channel state (described in the next paragraph).

$$\texttt{Packet Delivery Ratio} = \frac{\sum(\texttt{Number of received Packets})}{\sum(\texttt{Number of transmitted Packets})} \tag{6.5}$$

Channel State Variables

The term channel state summarises different variables that describe several aspects of the wireless radio channel. Since the wireless channel is fundamentally different from the wired channel (e.g. Ethernet cable), several aspects like background noise, interference level, or obstacles have a strong influence on the performance of any wireless technology. Variables that enable an evaluation of the channel state are therefore measured and analysed to give a feedback about the channel state after an evaluation. Another usage aspect of these variables is connected with the interference avoidance process of the proposed enhanced coexistence solution. Channel state feedback variables are used in the interference avoidance process to dynamically adapt the resource assignment. For simulative evaluations, the following variables are measured:

- `Number of Collisions` (on the radio channel)
- `Number of Retransmissions` (due to packet failures and missing ACKs)
- `Number of Dropped Packets` (due to blocked radio channels during CCA)

These different variables are used for the explanation and description of the evaluation outcomes presented in the following section.

6.3 Evaluation Outcomes

This section presents a selection of the conducted evaluations and their outcomes. Analyses are explained and outcome charts are presented to illustrate the need, usefulness, and usability of the proposed solution approach for enhanced coexistence. Evaluations of the proposed *Inter-WPAN* cooperation strategies were not performed, due to the limited amount of time and the restrictions of the simulation model (cp. Subsection 6.2.1) in terms of possible changes of certain simulation parameters during simulation runtime (e.g. allocation of PAN coordinator role and superframe parameters are not adaptable during runtime). Simulative investigations and evaluations of the cooperation approach are hence classified as future work. Other research work, like [55] for example, may be used as a reference for such prospective investigations.

6.3.1 Intra-Technology Interference Evaluation

The problem of *Intra-Technology* interference was already pointed out in Subsection 4.1.2, where an example chart from a series of simulations was presented. This very subsection presents detailed information about the conducted simulations and outcomes.

Different superframe parameters and Interface Queue (IFQ) sizes (simple packet buffer on the MAC layer, cp. Subsection 6.1.1) were simulated and analysed, to enable a general evaluation of the performance of 802.15.4 WPANs in case of different numbers of nodes. In these simulations, a single sink (the PAN coordinator) counts the data packets received from various sources (the other nodes inside the WPAN). The outcome charts are shown in Appendix A in Figures A.1 to A.3. Measurements were taken for different exponential *Packet Inter Departure Times*, which describe the time until the next packet is ready (under an exponential distribution around the values of 0.01 s to 10 s). A logarithmic scaling has been used on the horizontal axis on all graphs due to the range of inter departure times. Other important simulation parameters are:

`Playground Size` : $50 \times 50\,\mathrm{m}$
`Superframe` : $BO = 5$ & $BO = 8$
`Number of Sources` : 1, 3, 5, 10, 15
`Transmitter Power` : 0 dBm / 1 mW
`Simulation Time` : 1000 s
`IFQ Capacity` : 1 & 10
`Payload Size` : 100 bytes
`Radio Channel` : 11 (@ 2.45 GHz)

A traffic load (either in bytes/ s or in packets / s) was derived from the packet inter departure time and the specified packet size. Charts with the derived traffic load (see Figures A.2 and A.3) are presented to enable other viewpoints on the performance aspects and interference problems of 802.15.4. The superframe parameters (BO/SO) were set to 5/4 and 8/7 to simulate different superframe configurations, each with a duty cycle of 50%. Together with two different IFQ sizes (1 and 10), a general evaluation of the performance of 802.15.4 networks with various numbers of sources was possible.

Figures A.1 and A.2 show that the application goodput depends on the number of sources and the traffic load inside the WPAN. More sources or higher traffic load do not automatically lead to a higher application goodput in any case. Figure A.2, for example, shows that the maximum goodput for settings with 10 and 15 sources is already reached with a traffic load of 10 packets / s. Higher traffic loads do not increase the goodput. For 5 or less sources, a higher maximum application goodput can be observed.

The simulation outcomes from Figure A.2 also show that the application goodput can be increased to a certain level with a larger IFQ. A problem of larger queue buffers is that the delay spread between the generation of data values and the reception of them at the sink increases. The timeliness of data values decreases therefore with larger queues. This is important for near real-time applications like the specified health care applications, where data actuality is a critical aspect. The IFQ size should therefore be kept at a low value to increase the actuality of sent data values. If packets are dropped in the IFQ, then the monitoring and maintenance process of the coexistence strategy must start either the interference detection process or evaluate if the resource assignment is not optimal anymore because of changes in the application parameters.

The charts also show that higher BO values do not lead to significant higher goodput rates. The additional transmission time inside the superframe (BO value of 8 compared to 5) does not compensate the limited buffer size. Since a source has to wait longer until the next (active) transmission period starts, more packets will also appear at the MAC buffer. A buffer overflow and significant packet drops are the consequence. If different superframe lengths are used with similar traffic loads, then buffer sizes must be adopted accordingly, although the problem of data timeliness and actuality arises again with larger buffer sizes. An optimal relation between superframe length, IFQ size, sensing interval, and sensed data amount must be calculated during runtime because the range of possible parameter settings is too great for an anterior calculation.

Figure A.3 shows the outcomes of the packet delivery ratio evaluation. The percentage of successful received packets at the sink in comparison to the actual sent packages from all sources drops fast with increasing traffic loads and higher numbers of sources. The limited IFQ size plays an important role for this case. If the IFQ size is increased (cp. outcome charts for IFQ = 10 in Figure A.3), the packet delivery ratio increases accordingly. This effect is more dramatic for smaller superframe lengths (BO=5) compared to larger ones (BO=8). The reason is again the number of packets that accumulate during the inactive period of the superframe and the successive drops inside the buffer.

6.3.2 GTS Usage Evaluation

The concept of “virtual” Guaranteed Time Slots (GTSs) (cp. Subsection 5.1.5) was proposed to solve the problems of limited numbers of GTS for allocations in case of large numbers of devices inside a WPAN. According evaluations showed that with the current standard not enough Guaranteed Time Slots can be provided for scenarios with many devices (e.g. the first reference scenario). If many devices compete for a GTS allocation, not all of them can achieve a correct allocation since the time period for the allocation phase is relative short and the number of slots is restricted. During the simulation with the traffic profile set according to the second reference application (*Body Constitution Monitoring*), not all devices could acquire a GTS allocation. The simulation model halted/aborted the simulation process after the failed allocation. The number of failed GTS allocations was counted with the help of a bypass routine. The simulation model was altered and the error processing routine for failed GTS allocations was simply switched-off. The number of failed GTS allocations increased abruptly as soon as more devices then available Guaranteed Time Slots were used. Further analyses were not possible at this stage since failed GTS allocations are not treated in the simulation model. An extension of the model is hence necessary for further investigations. Due to the limited scope of the thesis, this extension is classified as future work.

6.3.3 Mean End-to-End Delay Evaluation

The following evaluations were performed with the settings from the ECG reference application and the *Health Care in Hospital Environments* reference scenario, as presented in Subsection 3.2.2 and depicted in Figure 3.5. Important simulation parameters are:

`Playground Size` : $15 \times 15\,\mathrm{m}$
`Superframe` : various settings
`Number of Sources` : 5
`Transmitter Power` : 0 dBm / 1 mW
`Simulation Time` : 1500 s
`IFQ Capacity` : 10
`Payload Size` : 100 bytes
`Radio Channel` : 11 (@ 2.45 GHz)

The evaluation illustrates outside influences for the mean E2E delay. The traffic settings are derived from the ECG reference application, whereas a data rate (per sensor) of 4 kbit/s leads to approx. 5 packet transmissions per second (every 0.2 s a new packet at the source). These packets include the information from the ECG sensors. They are sent directly to the PAN coordinator. The starting time of the five different sensors is manipulated in the evaluation, so that all sensors start one after another with a delay. This starting delay enables an analysis of the influence of appearing sources on the mean E2E delay. Figure 6.3 depicts the outcomes of the simulation.

Important is the transient recovery time (or settling phase) at the beginning of each gradient. The first source starts transmitting at $t = 1\,\mathrm{s}$ while all other sources start one after another with a delay of $t = 300\,\mathrm{s}$. After the initial transient phase the mean E2E delay settles in for a constant value until the next source is started. This can be seen at $t = 300\,\text{s}$ for example: when source 2 starts transmitting, all gradients increase. At the next starting interval (source 3 starts at $t = 600\,\text{s}$) another raise occurs in the different gradients. This behaviour continues until the end of the simulation (at $t = 1500\,\text{s}$). The overall raise of the different gradients is neither typically exponential nor really linear. Still, it is clear that the delay increases with each additional source.

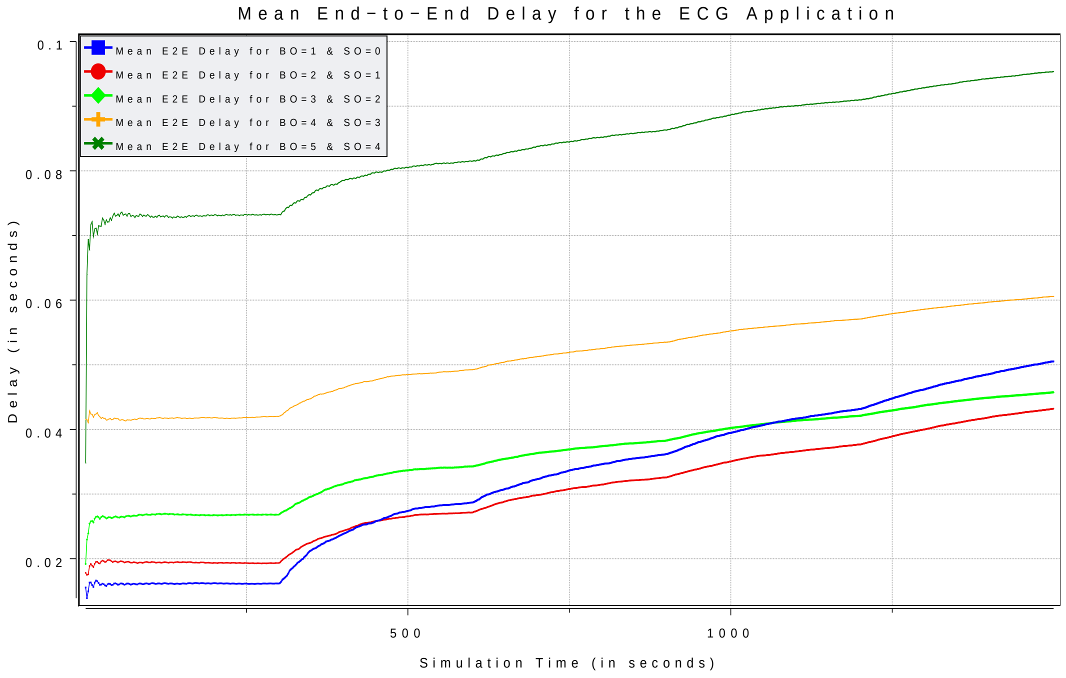


Figure 6.3: Mean End-to-End Delay Evaluation of the ECG Application

The five different gradients stand for different superframe configurations. The Beacon Order (BO) was varied between $BO = 1$ and $BO = 5$ to show the differences between the superframe configurations. The gradient for $BO = 1$ shows a strong increase compared to the other gradient curves: even before the the third source starts transmitting, the delay for $BO = 1$ is higher then the delay for $BO = 2$. The gradient of $BO = 1$ continues to increase faster then the other curves, at approx. $t = 1100\,\text{s}$ it intersects and passes the gradient for $BO = 3$. Lower beacon orders and shorter superframe durations are hence more susceptible then longer superframe durations and higher beacon orders. The chart generally shows that the delay increases with additional sources. Packet failures due to congestion and overlapping transmissions, successive retransmissions, and longer waiting times due to additional necessary backoffs are the reasons.

The shorter active period of smaller Beacon Orders (BOs) leads to more congestion during the channel access and therewith to a higher packet failure rate. Figure 6.4 shows that the number of packet failures is much higher for smaller superframe lengths (e.g. $BO = 1$) compared to longer superframes. Due to the congestion and the number of packet failures, the overall number of retransmissions increases. This leads to the longer transmission delays shown in the previous Figure 6.3.

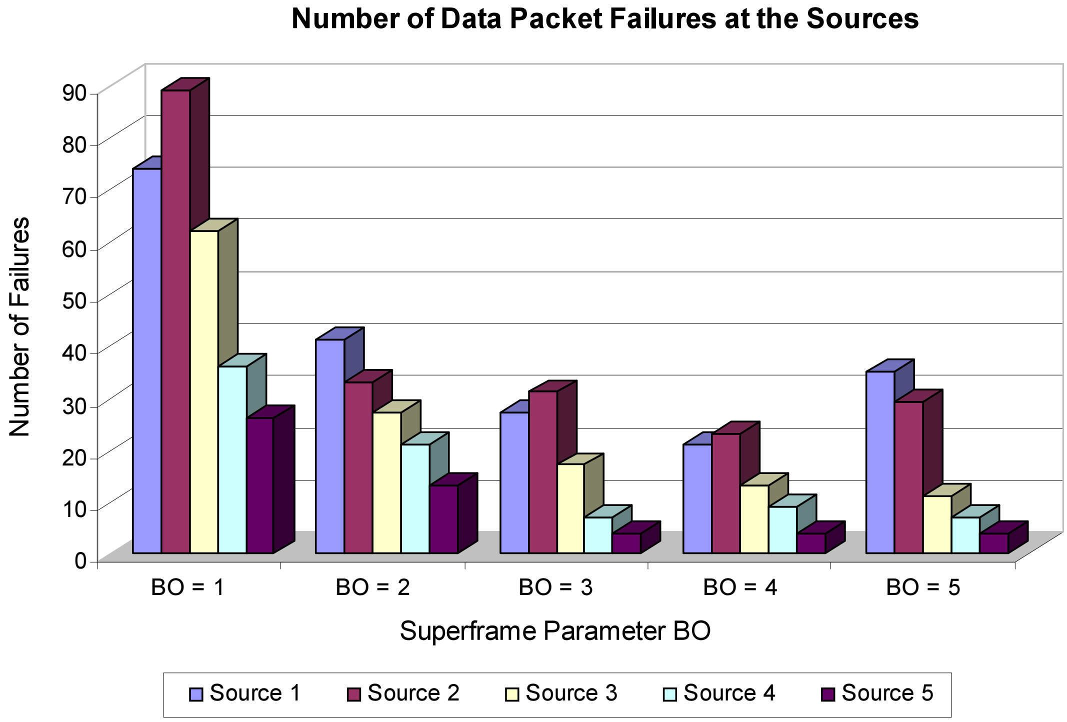


Figure 6.4: Number of Data Packet Failures at the Sources

A non-regulated channel access, as it was simulated here, makes it hard to achieve certain delay bounds. The organised and structured channel access according to the proposed enhanced coexistence strategy provides the regimentation needed for low and manageable delay bounds. A deployment of applications like the proposed ECG in health care scenarios is only possible when delay bounds of time critical applications can be maintained. The proposed resource assignment process takes care of these critical aspects. An integration into time critical applications should therefore be aspired.

7 Conclusions and Future Work

The final chapter summarises the results achieved throughout this thesis. Based on the topics and aspects that were not covered in the thesis, a set of potential directions for future research is given at the end of the chapter.

Strategies for enhanced 802.15.4 WPAN coexistence and cooperation were researched and developed in the context of this thesis. With the help of these strategies, health monitoring and care solutions shall be enabled to coexist in large numbers and have the possibility of *Inter-Network* cooperation, making a true ubiquity possible. For the development of these strategies, existing health care systems and the underlying wireless communication technology (802.15.4) were investigated theoretically and practically to identify problematic conditions in case of dense radio conditions. The focus on dense radio conditions is based on the underlying ubiquitous scenario where several different wireless technologies are coexisting at the same time in radio range. Based on the conducted investigations and identified problems, independent solution approaches were developed and analysed during the thesis. An interaction and co-operation of these independent approaches was also proposed for the utilisation of several benefits.

7.1 Achievement Overview

The first part of the thesis described the research on health care applications and their requirements and introduced the underlying wireless communication technology 802.15.4 (as the chosen representative). Wireless technologies will play an important role in the area of personal and professional health care because the use of wireless technologies instead of wired connections for the interconnection of devices, sensors, and actuators brings more flexibility and comfort for the user. Wireless technologies like 802.15.4 will lead the advent of the era of ubiquitous health care (health care services at any time and any place). This ubiquity will on the other hand also lead to problematic conditions for wireless technologies because dense radio conditions are a consequence of the "any time and any place" access. To conquer these problematic conditions, existing health monitoring and care solutions and current research activities were investigated for the extraction of specifics and important parameters of health care use cases. Four important parameters (*Reporting Interval, Memory Capacity, Sensing Interval,* and *Sensed Data Amount*) were identified during the investigation. They were used for further modelling and investigation tasks during the thesis.

The second part of the thesis provided the specifications for reference applications and the arrangement and organisation of these applications in scenarios with dense radio conditions. Network layout, used hardware, and important parameters were laid down for two different applications, namely *Cardiac Arrhythmia Monitoring with ECG sensors* and *Body Constitution Monitoring*. With the specification of the basic applications, the interaction and arrangement of devices was specified in different reference scenarios: *Monitoring of Large Groups*, *Health Care in Smart Home* and *Hospital Environments*. These scenarios defined the necessary playground boundaries and the environment for further simulations and investigations, whether they were theoretical or practical.

The outcomes of a theoretical and practical investigation of 802.15.4 were presented in the third part. Several problematic aspects were identified: 802.15.4's *Inter-* and *Intra-Technology* interference problems, the parameters of the CSMA-CA algorithm, the CCA deference aspects and the accompanied performance degradations, the difference between gross and net data rates, the problems in hidden terminal scenarios, and the non-available support for *Inter-WPAN* cooperation (needed for true ubiquity).

The fourth part described the solution approaches developed in the thesis. Two strategies were independently presented: a strategy for enhanced WPAN coexistence and a strategy for *Inter-WPAN* cooperation. The proposed coexistence strategy considers the specified reference applications and scenarios and the identified problems to enable the assignment of resources on a *Intra-* and *Inter-WPAN* level. A new parameter adaptable resource assignment approach was proposed together with concepts for the sharing of resources between independent WPANs. An *Inter-WPAN* cooperation strategy was proposed, to support a cooperation of devices over network boundaries. Necessary components and functions of the cooperation strategy were introduced together with three different realisations approaches: *Topology Switching*, *Inter-WPAN Handover*, and *Inter-WPAN Bridging*. Different application types and use cases can be realised with the help of these approaches for *Inter-WPAN* cooperation. A broad applicability was hence enabled. A co-operation and combination of both individual strategies was proposed in the end to exploit benefits of the combination of superimposed components.

The last part of the thesis presented the simulation framework and the simulation model, which were used for the conducted simulative investigations. In addition, selected evaluations and their outcomes were presented to verify the need for additional solutions and to prove the usefulness of developed solution approaches.

7.2 Contributions

The contributions of this thesis can be divided into theoretical and practical analysis and evaluation insights, specification outcomes, and realisation results. The thesis dealt with the terms of *Intra-WPAN* and *Inter-WPAN Coexistence* and *Cooperation* through distributed resource assignment and channel access control. Resource assignment and channel access are already established research areas. The scientific contribution of this thesis was the development and appliance of solutions to real-world scenarios. The concentration on real-world aspects brought the necessary separation from other strictly theoretical research work. The inclusion of communication between independent LR-WPANs is also a relatively new idea since most protocols for shared medium access of LR-WPANs are suited for single networks only. Thus, the support for multiple independent networks is also a specification contribution of this thesis. Another specification contribution of the thesis are the described reference applications and scenarios, which can be used for future investigations of the wireless health care topic. In summary the thesis showed that dense radio conditions lead to problems for the coexistence of 802.15.4 WPANs but also create the possibility of *Inter-WPAN* cooperation.

7.3 Future Work

Since this work deals with an extensive research area, not all aspects and parts could be analysed in detail. This last section summarises interesting aspects that may be utilised and considered for further research and developments.

Self Organising Aspects: Self organisation is an important research aspect, especially for Wireless Sensor Networks (WSNs). Mechanisms of self organisation and self healing cannot be used in the introduced health care scenarios yet because current self organisation approaches consider homogeneous devices without unique features. In health care scenarios, devices often have unique abilities (e.g. UMTS cell phone), what opposes a simple replacement. The inclusion of intelligent routing and *Inter-WPAN* cooperation may be used to replace defect devices with similar ones from other WPANs. This points out to the necessity of more research on *Inter-Network* self-organising approaches.

Security Aspects: This thesis did not cover security aspects. Yet this part is very important for critical applications like health care solutions. The 802.15.4 standard provides encryption functions based on Advanced Encryption Standard (AES). These can hopefully be used as basic elements of a complex security framework, which has to deal with the different actors and roles in health care scenarios. Such a framework and the according demands and requirements could be researched in the future.

Energy Consumption Aspects: Future work could consider implanted sensor or health care devices with a restricted energy supply. The area of energy consumption needs a further evaluation with a calculation and simulation of the typical energy consumption values of the proposed health care scenarios.

Mobility of Entities: The focus of the scenarios and applications described in Chapter 3 does not lie on mobility aspects. Further research could include mobile users and movement schemes for simulations and investigations. This task can be very complex, depending on the level of detail for the modelling of the mobility itself. The inclusion of decent mobility aspects could be used to enhance the developed solutions for even more use cases and scenarios. Further research in this area could therefore be useful.

Simulation Model Extensions: The used 802.15.4 simulation could be extended in terms of PAN association procedures and the possibility of dynamic 802.15.4 parameter changing during simulation runtime to enable the investigation of *Inter-WPAN* cooperation and to enhance the investigation possibilities of the model.

It is clear that there is a great potential for the field of wireless health care. More research on the topic of coexistence and cooperation as well as the other mentioned topics is needed for a full utilization of 802.15.4's potential in this application field.

A Evaluation Outcomes

Charts

Spreadsheets

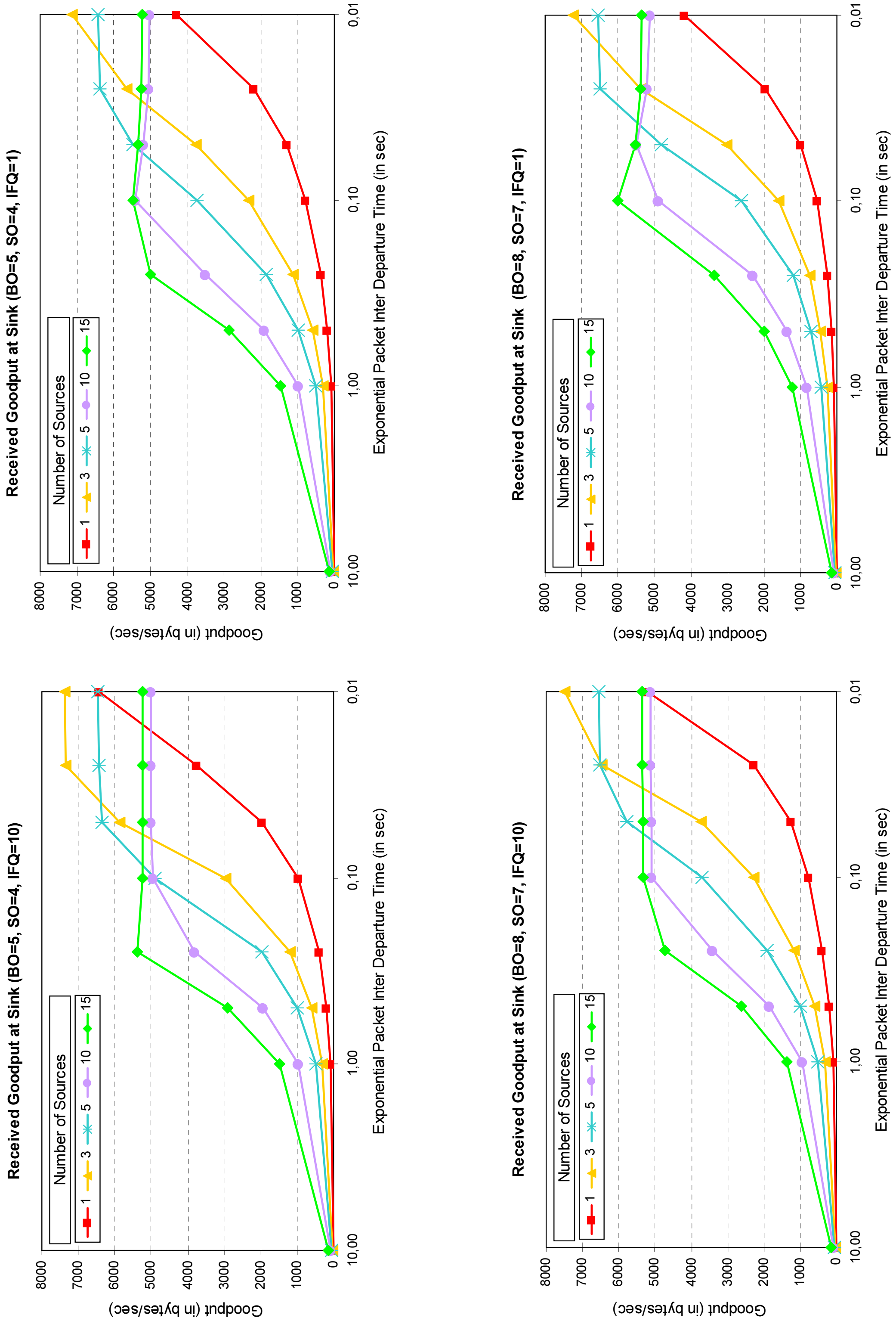


Chart A.1: Goodput with various *Number of Sources* and *Packet Departure Times*

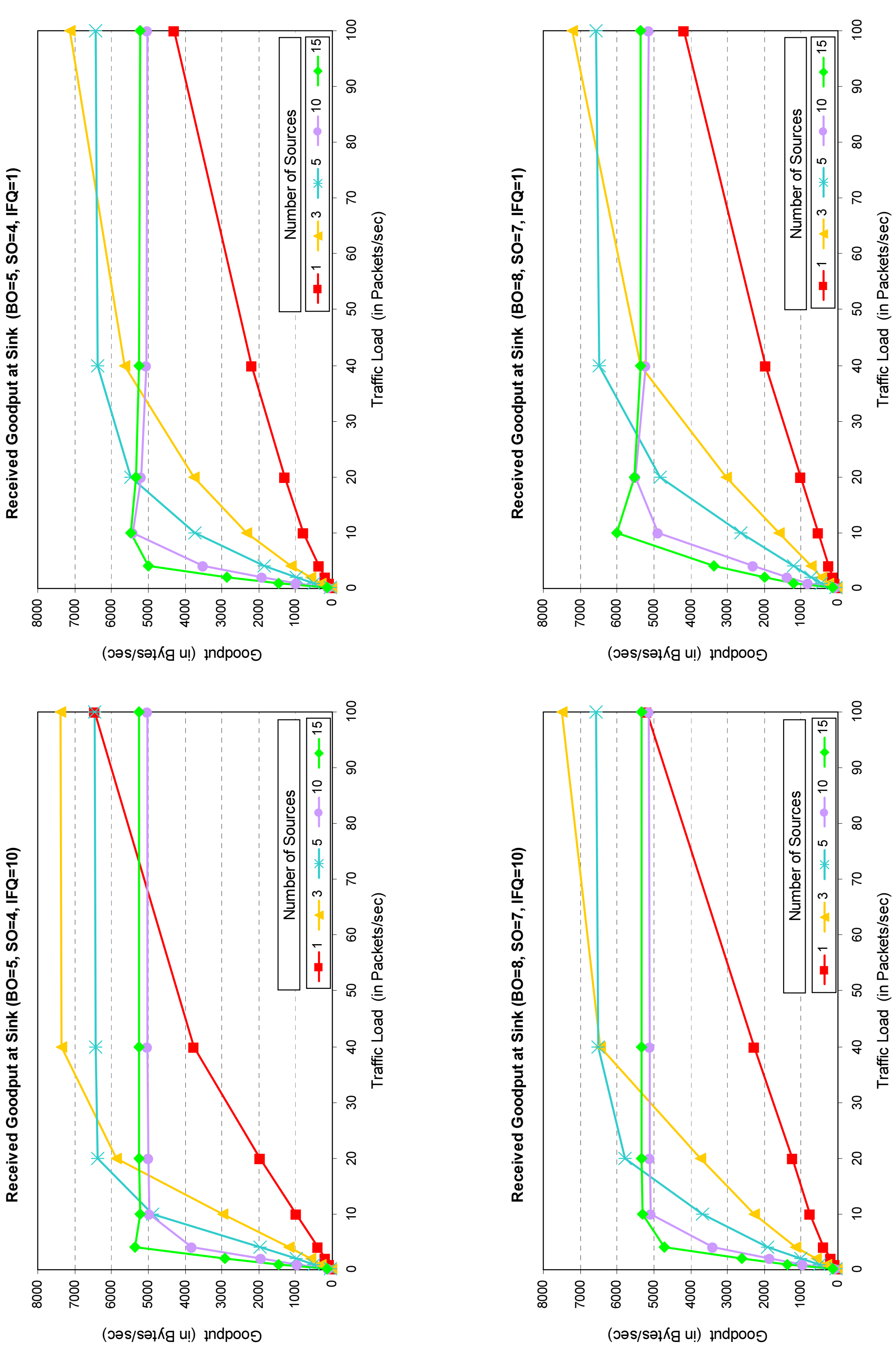


Chart A.2: Goodput with various *Number of Sources* and *Traffic Loads (Packets/s)*

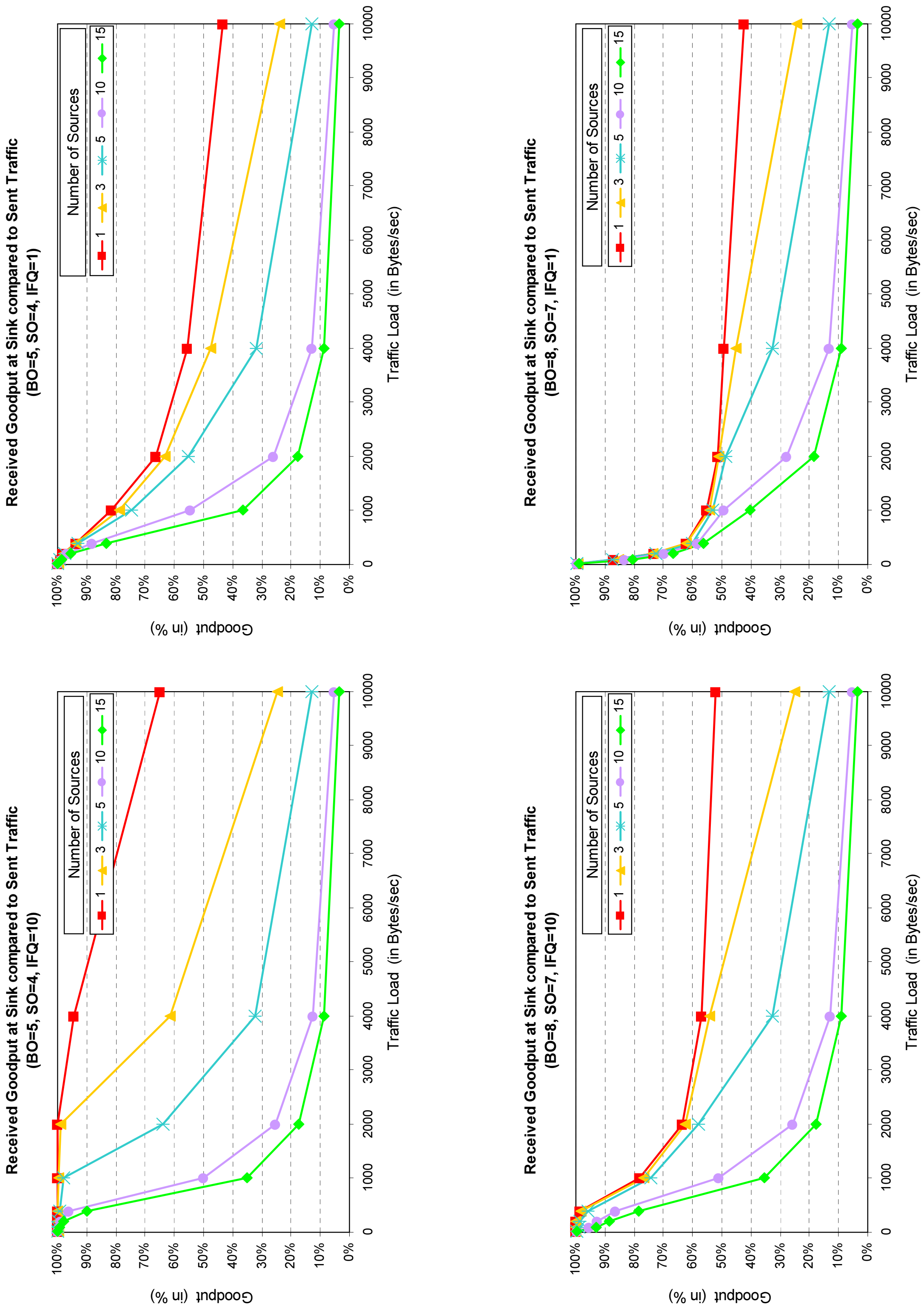


Chart A.3: Goodput with various *Number of Sources* and *Traffic Loads (Bytes/s)*

	Exp. Inter Departure Time of Packets (in s)								
Sources	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.50**	**1.00**	**10.0**	
1	4301	2195	1304	790	364	194	97	10	
3	7121	5649	3763	2337	1110	587	302	31	*all values*
5	6432	6377	5476	3720	1848	974	495	52	
10	5037	5064	5199	5404	3498	1920	981	99	*in Bytes/s*
15	5233	5255	5333	5485	4988	2854	1450	144	

Table A.1: *Received Goodput (Bytes/s)* at the Sink under various *Number of Sources* and *Packet Inter Departure Times* with **BO = 5** and **IFQ = 1**

	Traffic Loads (in Packets/ s)								
Sources	**100**	**40**	**20**	**10**	**4**	**2**	**1**	**0.1**	
1	43059	21973	13062	7913	3645	1942	972	106	*values in*
3	71287	56553	37676	23402	11112	5883	3028	311	
5	64387	63842	54824	37246	18505	9755	4957	523	*Nr. of*
10	50430	50696	52044	54101	35022	19227	9826	996	*Packets*
15	52392	52612	53389	54912	49933	28579	14515	1446	

Table A.2: *Received Packets at the Sink* under various *Number of Sources* and *Traffic Loads (Packets/s)* with **BO = 5** and **IFQ = 1**

	Traffic Loads (in Packets/ s)								
Sources	**100**	**40**	**20**	**10**	**4**	**2**	**1**	**0.1**	
1	99235	39667	19654	9688	3888	1973	982	106	*all*
3	298701	119064	59661	29738	11873	6017	3041	312	*values*
5	498830	199905	99540	49788	19912	9985	4997	523	*in Nr.*
10	995504	396989	199477	99533	39716	19873	9967	996	*of*
15	1497043	598815	299177	150054	59809	29982	14705	1447	*Packets*

Table A.3: *Sent Packets from the Sources* under various *Number of Sources* and *Traffic Loads (Packets/s)* with **BO = 5** and **IFQ = 1**

	Exp. Inter Departure Time of Packets (in s)								
Sources	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.50**	**1.00**	**10.0**	
1	6448	3752	1964	976	393	195	97	10	
3	7372	7347	5878	2970	1185	597	304	31	*all values*
5	6451	6437	6361	4889	1969	991	497	52	
10	5017	5014	5000	4965	3814	1940	966	99	*in Bytes/s*
15	5250	5238	5236	5229	5372	2907	1468	144	

Table A.4: *Received Goodput (Bytes/s)* at the Sink under various *Number of Sources* and *Packet Inter Departure Times* with **BO = 5** and **IFQ = 10**

	Traffic Loads (in Packets/ s)								
Sources	**100**	**40**	**20**	**10**	**4**	**2**	**1**	**0.1**	
1	64549	37565	19668	9775	3940	1957	980	106	*values in*
3	73801	73551	58845	29740	11862	5986	3045	311	
5	64578	64438	63682	48943	19720	9923	4977	523	*Nr. of*
10	50226	50196	50056	49705	38182	19425	9671	996	*Packets*
15	52557	52441	52415	52352	53775	29103	14698	1446	

Table A.5: *Received Packets at the Sink* under various *Number of Sources* and *Traffic Loads (Packets/s)* with **BO = 5** and **IFQ = 10**

	Traffic Loads (in Packets/ s)								
Sources	**100**	**40**	**20**	**10**	**4**	**2**	**1**	**0.1**	
1	99406	39754	19696	9776	3940	1958	980	106	*all*
3	298388	119822	59384	29806	11868	5988	3046	312	*values*
5	498945	200191	99488	49968	19849	9942	4982	523	*in Nr.*
10	996041	398497	198649	99369	39698	19637	9729	996	*of*
15	1496993	597769	299029	149690	59684	29699	14784	1447	*Packets*

Table A.6: *Sent Packets from the Sources* under various *Number of Sources* and *Traffic Loads (Packets/s)* with **BO = 5** and **IFQ = 10**

	Exp. Inter Departure Time of Packets (in s)								
Sources	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.50**	**1.00**	**10.0**	
1	4188	1956	1007	539	244	145	83	11	
3	7226	5371	3020	1602	738	444	257	32	*all values*
5	6557	6481	4822	2629	1204	721	436	49	
10	5127	5210	5498	4892	2315	1380	813	96	*in Bytes/s*
15	5355	5370	5520	6005	3358	1991	1210	148	

Table A.7: *Received Goodput (Bytes/s)* at the Sink under various *Number of Sources* and *Packet Inter Departure Times* with **BO = 8** and **IFQ = 1**

	Traffic Loads (in Packets/ s)								
Sources	**100**	**40**	**20**	**10**	**4**	**2**	**1**	**0.1**	
1	41928	19587	10083	5400	2450	1452	831	111	*values in*
3	72338	53766	30239	16038	7390	4447	2579	330	
5	65644	64883	48271	26319	12059	7222	4367	496	*Nr. of*
10	51331	52160	55039	48970	23182	13823	8142	963	*Packets*
15	53609	53759	55263	60116	33616	19937	12113	1488	

Table A.8: *Received Packets at the Sink* under various *Number of Sources* and *Traffic Loads (Packets/s)* with **BO = 8** and **IFQ = 1**

	Traffic Loads (in Packets/ s)								
Sources	**100**	**40**	**20**	**10**	**4**	**2**	**1**	**0.1**	
1	99163	39766	19617	9771	3940	1983	954	112	*all*
3	297846	119417	59443	29602	11900	6051	3018	332	*values*
5	499880	199821	99140	49556	20047	9943	5000	498	*in Nr.*
10	994734	397299	199360	99077	39651	19785	9788	968	*of*
15	1495957	598836	299499	149327	59600	29898	15050	1503	*Packets*

Table A.9: *Sent Packets from the Sources* under various *Number of Sources* and *Traffic Loads (Packets/s)* with **BO = 8** and **IFQ = 1**

	Exp. Inter Departure Time of Packets (in s)								
Sources	**0.01**	**0.025**	**0.05**	**0.10**	**0.25**	**0.50**	**1.00**	**10.0**	
1	5199	2264	1245	765	388	196	97	11	
3	7493	6451	3722	2287	1162	594	302	32	*all values*
5	6561	6509	5784	3691	1914	1002	502	50	
10	5133	5113	5099	5094	3410	1854	943	96	*in Bytes/s*
15	5347	5339	5335	5314	4717	2619	1375	146	

Table A.10: *Received Goodput (Bytes/s)* at the Sink under various *Number of Sources* and *Packet Inter Departure Times* with **BO = 8** and **IFQ = 10**

	Traffic Loads (in Packets/ s)								
Sources	**100**	**40**	**20**	**10**	**4**	**2**	**1**	**0.1**	
1	52048	22672	12466	7658	3890	1971	977	112	*values in*
3	75014	64576	37263	22895	11637	5950	3031	324	
5	65685	65163	57906	36948	19161	10031	5033	506	*Nr. of*
10	51385	51182	51042	50994	34140	18561	9449	963	*Packets*
15	53533	53447	53407	53197	47219	26223	13770	1466	

Table A.11: *Received Packets at the Sink* under various *Number of Sources* and *Traffic Loads (Packets/s)* with **BO = 8** and **IFQ = 10**

	Traffic Loads (in Packets/ s)								
Sources	**100**	**40**	**20**	**10**	**4**	**2**	**1**	**0.1**	
1	99827	39861	19626	9786	3947	1972	977	112	*all*
3	298853	119113	59749	29861	11834	5960	3032	324	*values*
5	498718	199860	99628	49634	19963	10183	5078	507	*in Nr.*
10	995182	398001	199250	99921	39496	20026	9882	968	*of*
15	1496481	598492	299114	149710	60084	29650	14812	1472	*Packets*

Table A.12: *Sent Packets from the Sources* under various *Number of Sources* and *Traffic Loads (Packets/s)* with **BO = 8** and **IFQ = 10**

B Code Blocks and Code Snippets

Listing B.1: An Example omnetpp.ini File

```
[General]
preload-ned-files                   = *.ned @../../../nedfiles.lst
network                             = networkName
sim-time-limit                      = 1h

[Parameters]
**.app.debug                        = false
**.battery.debug                    = false
**.net.debug                        = false
**.mac.debug                        = false
**.phy.debug                        = true

### ### ###     Network Settings
**.numHosts                         = 10
**.playgroundSizeX                  = 150
**.playgroundSizeY                  = 150

### ### ###     Mobility Settings
**.host[0].mobility.x               = 75
**.host[0].mobility.y               = 75
**.host[*].mobility.x               = -1
**.host[*].mobility.y               = -1
**.host*.mobilityType               = "StaticMobility"

### ### ###     Parameters for the Application Layer
**.host[0].app.defaultTrafConfigId  = -1
**.host[*].app.defaultTrafConfigId  = 0
**.app.trafConfig                   = xmldoc("trafconfig.xml")

### ### ###     Parameters for the Network Layer
**.host[0].net.isPANCoor            = true
**.host[*].net.isPANCoor            = false

### ### ###     Parameters for the Network Interface and IFQ
**.nic.ifqType                      = "DropTailQueue"
**.ifq.frameCapacity                = 1

### ### ###     Parameters for MAC Layer
**.host[0].**.mac.isPANCoor         = true
```

```
**.host[*].**.mac.isPANCoor          = false
**.mac.panCoorName                   = "host[0]"
**.mac.BO                            = 8
**.mac.SO                            = 7
# GTS settings
**.host[*].**.mac.ack4Gts            = true
**.host[*].**.mac.gtsPayload         = 50
**.host[*].**.mac.dataTransMode      = 1     ; 1: direct; 3: GTS
**.host[0].**.mac.isRecvGTS          = false ; transmit GTS
**.host[*].**.mac.isRecvGTS          = true  ; receive GTS

### ### ###     Parameters for PHY Layer
**.phy.channelNumber                 = 11    ; default 2.4GHz,
**.phy.transmitterPower              = 1.0   ;[mW]
**.phy.sensitivity                   = -85   ;[dBm]
**.phy.thermalNoise                  = -110  ;[dBm]
**.phy.pathLossAlpha                 = 2
**.phy.snirThreshold                 = 4

### ### ###     Parameters for the Energy Model
**.battery.batteryCapacity           = 25    ;[mAh]
**.battery.meanTimeToFailure         = -1
**.battery.usage_radio_idle          = 0.37  ;[mA]
**.battery.usage_radio_recv          = 19.47 ;[mA]
**.battery.usage_radio_sleep         = 0.02  ;[mA]
**.battery.transmitterPower          = 1.0   ;[mW]

### ### ###     Statistical Output Vectors
[OutVectors]
**.End-to-end delay.enabled          = yes
**.Mean end-to-end delay.enabled     = yes

### ### ###     Simulation Runs

#   Specification of various parameters possible
#   specific for a simulation run only
```

Listing B.1: An Example omnetpp.ini File

```
<?xml version="1.0" ?>
<configurations>
    <config
        id="0"
        packetSize="50"
        interDepartureTime="uniform(1,5)"
        firstPacketTime="5"
        trafDest="host[5]"
    />
</configurations>
```

Listing B.2: An Example Traffic Definition XML File

```
run 1 "starNet"
scalar "starNet.host[0].battery"    "Energy consumed (mAh)"             0.613321684729
scalar "starNet.host[0].battery"    "Battery energy left (percentage)"  0.987733566305
scalar "starNet.host[0].battery"    "Radio duty cycle"                  0.481790080104
scalar "starNet.host[0].app"        "App Traffic Msg Sent"              0
scalar "starNet.host[0].app"        "App Traffic Msg Received"          14547
scalar "starNet.host[0].app"        "App Total Bytes Send"              0
scalar "starNet.host[0].app"        "App Total Bytes Received"          1454700
scalar "starNet.host[0].app"        "Total Time"                        300.000000061
scalar "starNet.host[0].app"        "App Send Goodput (Bytes/s)"        0
scalar "starNet.host[0].app"        "App Received Goodput (Bytes/s)"    4848.99999902
scalar "starNet.host[0].net"        "num of pkts forwarded"             0
scalar "starNet.host[0].nic.ifq"    "packets received by queue"         0
scalar "starNet.host[0].nic.ifq"    "packets dropped by queue"          0
scalar "starNet.host[0].nic.mac"    "Total simulation time"             300.000000061
scalar "starNet.host[0].nic.mac"    "num of BEACON pkts sent"           306
scalar "starNet.host[0].nic.mac"    "num of DATA pkts sent successful"  0
scalar "starNet.host[0].nic.mac"    "num of DATA pkts failed"           0
scalar "starNet.host[0].nic.mac"    "num of DATA pkts sent suc. in GTS" 0
scalar "starNet.host[0].nic.mac"    "num of DATA pkts failed in GTS"    0
scalar "starNet.host[0].nic.mac"    "num of ACK pkts sent"              14604
scalar "starNet.host[0].nic.mac"    "num of DATA pkts received"         14547
scalar "starNet.host[0].nic.mac"    "num of DATA pkts received in GTS"  0
scalar "starNet.host[0].nic.mac"    "num of ACK pkts received"          0
scalar "starNet.host[0].nic.mac"    "num of collisions"                 11474
```

Listing B.3: An Example *.sca (Scalar) File

```
vector 1  "starNet.host[0].app"  "End-to-end delay"  1
1   1.017312    0.017312
vector 2  "starNet.host[0].app"  "Mean end-to-end delay"  1
2   1.017312    0.017312
1   1.028192    0.0117548603645
2   1.028192    0.0145334301823
1   1.039392    0.039392
2   1.039392    0.0228196201215
1   1.056352    0.056352
2   1.056352    0.0312027150911
1   1.062432    0.0596477215239
2   1.062432    0.0368917163777
1   1.073952    0.0095355891998
2   1.073952    0.032332361848
1   1.079712    0.079712
2   1.079712    0.039100881584
1   1.085152    0.085152
```

Listing B.4: An Example *.vec (Vector) File

Acronyms

ACK	Acknowledgement
ADC	Analog-to-Digital Converter
AES	Advanced Encryption Standard
ASK	Amplitude Shift Keying
BAN	Body Area Network
BI	Beacon Interval
BE	Backoff Exponent
BO	Beacon Order
BPSK	Binary Phase Shift Keying
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period
CRC	Cyclic Redundancy Check
CSMA-CA	Carrier Sense Multiple Access Collision Avoidance
CTS	Clear to Send
CW	Contention Window Length
E2E	End-to-End
ECG	Electrocardiogram
ED	Energy Detection
EIRP	Equivalent Isotropically Radiated Power
FFD	Full-Function Device
FIFO	First In – First Out
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GTS	Guaranteed Time Slot
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
IFS	Inter Frame Spacing
IFQ	Interface Queue
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
IrDA	Infrared Data Association

ISM	Industrial, Scientific, and Medical
LAN	Local Area Network
LOS	Line of Sight
LQI	Link Quality Indicator
LR-WPAN	Low Rate Wireless Personal Area Network
MAC	Medium Access Control
NB	Number of Backoffs
NED	Network Topology Description
O-QPSK	Offset Quadrature Phase Shift Keying
OSI	Open Systems Interconnection
P2P	Peer-to-Peer
PAN	Personal Area Network
PAN-ID	PAN Identifier
PDA	Personal Digital Assistent
PER	Packet Error Rate
PHY	Physical Layer
PIB	PAN Information Base
PLC	Powerline Communication
PLME	PHY Management Entity
PMU	Patient Monitoring Unit
POS	Personal Operating Space
PPP	Point-to-Point Protocol
QoS	Quality of Service
RFD	Reduced-Function Device
RTS	Request to Send
RX	Receiving
SD	Superframe Duration
SO	Superframe Order
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TX	Transmitting
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
UWB	Ultra-Wideband
WiMAX	Worldwide Interoperability for Microwave Access
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

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