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Wireless UWB Aircraft Cabin Communication System

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Preface

This thesis is a result of my research at EADS Innovation Works Germany from May 2007 to December 2010. I worked in the team On-Board Architectures & Networks on new concepts for wireless communication inside commercial aircraft cabins. The work is based on projects together with the aircraft manufacturer Airbus and the EU funded research project EUWB. It was a great pleasure to work on such fascinating topics in a very innovative environment. The diverse tasks, ranging from concepts and theoretical studies to practical work like programming, allowed me to work on different aspects of the research and pre-development process. I would therefore like to thank EADS for providing me the opportunity of researching my PhD thesis in the corporation. My special thanks go to Josef Schalk, my manager and to Dr. Sergio Bovelli, my project leader and advisor of the thesis. Further on I thank my colleagues for having a wonderful time at EADS.

Being an external PhD candidate at the Institute for Communication Networks (LKN) of the Technische Universität München was a great experience. The guidance and supervision of Univ.-Prof. Dr.-Ing. Jörg Eberspächer was excellent and inspiring. Without him I could not have assembled this thesis. Thank you very much. Also I would like to thank the colleagues of LKN, which always welcomed me on my visits. Including me in the teaching for supervising seminar students was a great experience. The diploma and master theses students supervised by myself assisted me in my work. Guiding them was an enriching assignment.

Finally I thank my family, especially my parents and my wonderful wife, for supporting me throughout my research and my life.

Munich, June 2011 | Frank M. Leipold

Abstract

The recent use of wireless communication for a range of diverse applications demonstrates the efficiency, success and new opportunities associated with wireless technology. For aircraft cabins there are many advantages to be gained with a wireless cabin management system. The cabin assembly and maintenance will be simplified significantly and many new types of devices, such as mobile crew intercoms, are possible. Some of the aircraft cabin systems have critical reliability classification and wireless technology has not been used for these systems in the past. In this work new approaches and concepts are developed with focus on the reliability demands from aircraft certification.

The most suitable technology is the emerging Ultra-wideband (UWB) technology in the frequency range from 3.1 to 10.6 GHz. It provides high data rates, robust radio channels, sufficient spectrum resources, worldwide usage free of frequency licensing and a convenient spatial containment. The ECMA-368 standard is the first to describe a physical layer and Medium Access Control (MAC) layer definition for a high data rate UWB communication. An analysis of the protocol examines the behaviour in critical situations. In analytical and simulated computations the node density is investigated and a strict upper limit is defined. In the aircraft environment a high node density is expected; therefore techniques are presented to overcome this limitation. Simulations of the start-up time, the time shortly after the network has been powered, reveal a significant longer stabilisation time for networks with more than 40 nodes. The distributed beaconing algorithm with contraction mechanism requires several iterations to converge to a stable state. This convergence results in an exponential correlation with the number of neighbours. Other critical parameters being investigated are the expected throughput and influences of alien devices.

With the identified limits of the communication protocol it was possible to develop new algorithms for resource management. An integer linear program calculates the access point positions and default channel allocations. These calculations are done during the design phase of the cabin and special attention is given to the unique features of the communication protocol that will have significant influence on the results. Later, during operation of the aircraft, a real-time algorithm dynamically calculates the resource reservation, depending on changes in the available spectrum, blocked or failed devices and traffic requirements. The algorithm is distributed to sustain communication even if the network is parted.

In order to enable mobility in the aircraft existing mobility protocols have been investigated and enhanced. The combination of Mobile IPv6 and Fast Handovers for Mobile IPv6 (FMIPv6) shows good results, but still lacks in non-interruptible communication for reactive handovers. Enhancements to FMIPv6 are presented that overcome this problem by defining backup access routers that receive duplicates of transmitted packets and will resend those packets in case of connection loss between the mobile node and the current access router. This approach is technology independent and can be used in the dual interface cabin concept to enable hot redundant transmissions over different technologies.

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Chapter 1

Introduction

Wireless information transfer is actually an old technology and has been used operationally for more than one century. In aeronautics radio communication has been an inherent component from the very beginning and is a vital part of the modern civil air industry. However, the wireless links all served air-to-ground or air-to-air communication paths. Inside the aircraft cabin wireless transmissions were avoided, due to the risk of interfering with the aircraft's communication and navigation systems. This understanding has recently changed, because several studies showed that some wireless standards have no significant impact on the aircraft flight systems. Hence, the way is paved to design new services for aircraft cabins with emerging and promising wireless short range communication networks.

Wireless communication networks have significantly changed our everyday life and enabled products now indispensable for all of us. Twenty years ago wireless networks were a technology that most people had little knowledge of, unless work-related. It was either very expensive, like the mobile radio telephones in cars, or it was for private interest, such as amateur radio. In the nineties, first the pager and then the mobile phone became popular and mass market products. In the late nineties, wireless data networks at home, such as IEEE 802.11b or Bluetooth, became popular consumer products. Today, ten years later, a huge number of wireless communications standards exist for all kinds of applications.

Today, wireless networks are used in many different situations. In the past they were mostly used when placing cables was not possible, for instance in mobile systems. Today the device and operating costs are so low that the criteria often changes from one of necessity to comfort and unique selling points.

Inside aircraft cabins WLAN and mobile phone services are available and have been in use for several years now. They provide Internet access for passengers via a satellite link or terrestrial networks. These passenger only services are effectively isolated from the aircraft systems, because of safety concerns.

1.1 Motivation

Wireless systems for aircraft infrastructure have the attention of the aircraft industries for several years now. The benefits would be reduced weight, simplified maintenance and flexible cabin architectures. But no successful system is available in commercial aircraft cabins today. One reason for this might be, to anticipate some of the results made in this research, that the requirements to develop a wireless system comparable or better than the existing wired solutions are very strict and exacerbate the challenge significantly. Indeed some wireless solutions used with dedicated device types inside aircraft exist, but they are a completely independent system and are used in addition to the wired system. A wireless solution providing connectivity to uncritical and critical devices and replacing parts of the wired infrastructure does not exist.

The increased difficulty for a wireless communication network inside the cabin results from the reliability demands from the aircraft certification requirements. Speakers for instance have a medium criticality level. They should not fail, especially in emergency situations. Common wireless protocols, such as Wi-Fi, Bluetooth or ZigBee either lack in the data rates or in the available wireless resources to maintain operation in the event of passengers unintentionally turning on a device on the same frequency.

Recently Ultra-wideband (UWB) technology was applied in several short range communication protocols. The WiMedia Alliance defined a high data rate UWB protocol with the ECMA-368 standard. ECMA is the short form for European Computer Manufacturers Association. UWB has the promising quality of providing relatively good signal propagation, even in harsh environments such as an aircraft. Furthermore, the standard provides enough non-overlapping channels to enable non-interfering usage of multiple ECMA-368 devices in parallel.

In this work a wireless network architecture for the aircraft cabin management system has been developed. To increase the availability of the communications, especially in critical situations, two physically independent interfaces are deployed. One of them is using ECMA-368 and the other is not defined yet. Possible candidates could be based on infrared or 60 GHz technology. Central aspects in this work are network topology and management, starting from fundamental design questions and algorithms for solving resource management problems, and mobility support for mobile devices moving through the cabin.

One prerequisite is to build on as much off-the-shelf-components as possible, especially for the hardware. Designing custom short range transceivers is very expensive and not efficient with the relatively low volumes requested by the aircraft industry. Thus, modifications to the transceivers or standard protocols should be done carefully, to avoid divergence from widespread solutions and thereby increasing the effort to maintain the technology for the aircraft domain.

1.2 Contributions

The subject of this work is a wireless network architecture for airliner cabins. The communication protocol under investigation is the ECMA-368 standard. It uses UWB technology, which is superior to other communication standards in the aircraft cabin, due to the available resources and high data rates. Researched topics are protocol limitations, resource management, mobility and a redundant network design that is developed to increase communication reliability in the aircraft. Even though the target architecture for this research is an aircraft, several results can be used in environments with a similar network topology, such as an office.

In Chapter 3 the ECMA-368 protocol is tested for specific characteristics. Scalability limitations are identified that can be helpful for creating a new network. Simulations show the limitation of real networks, and analytical calculations reveal the worst case and best case limits. The results are only related to the protocol under test and have nothing to do with the environment of an aircraft. With an implementation of the MAC protocol in an event discrete simulator the timing behaviour of the ECMA-368 protocol is investigated. The simulated situations are system activation, topology changes and influences of foreign nodes. The results show the maximal number of neighbours per node that is possible to allow proper operation of the network.

Another problem that is addressed is resource management. An integer linear optimisation algorithm is developed to calculate the access point positions and a default channel allocation based on the policies of the ECMA-368 protocol and interference caused by other nodes of the network. The optimisation algorithm can be used for designing the cabin layout. During the operation of the aircraft the available resource will change. To maintain the operation of the network in these situations a distributed algorithm is proposed, which continuously monitors the status and distributes the available resources. The distribution takes into account the data rates and delay requirements of each node to guarantee the usability of the device applications.

Some of the research focuses on mobility support for the aircraft network. The existing protocols MIPv6 and FMIPv6 are inspected and tested with real hardware. Shortcomings of the protocols for the aircraft network environment are identified. Modifications to enhance FMIPv6 are developed to efficiently handle redundancies in the topology. With these modification fast handovers between the access points are now possible with minimal delays and no packet losses.

Based on the network architecture for the aircraft cabin, a system is designed to manage the entire network. A hierarchical model assigns different tasks in the network to specific modules. The tasks range from managing access point connections to updating routing tables.

The work is focussed on perceived commercial aircraft cabin requirements. The contribution of this work is a holistic concept for a wireless cabin management system and identifying technology related issues of the relatively new ECMA-368 protocol in the aircraft environment. Future work on wireless cabin networks can benefit from these results.

1.3 Document structure

The document consists of seven chapters, including this introduction. In Chapter 2 the scenario and technology selection are described. First the cabin management system of an aircraft is explained; in order to describe the role of the network and the existing infrastructure the wireless system will build on. Then the advantages of wireless systems are explained, followed by the new network architecture and the key challenges that exist. Chapter 3 examines closely the limitations of the ECMA-368 standard. Limitations of the communication protocols are calculated and effects to the aircraft scenario shown. The focus lies on the timing behaviour to start the network and on its scalability to support high density networks. In Chapter 4 the resource planning and management are discussed for the ECMA-368 network in the aircraft. The former addresses the problems of access point placement and channel allocation, to guarantee the connectivity for all end devices. An integer linear program is developed to calculate the positions of the nodes, considering the specialities of the protocol. Network planning in this work relates to the resources distribution during operation of the network. Changing conditions must be reacted to and resources dynamically redistributed. Chapter 5 addresses mobility in the wireless cabin network. To support mobile audio devices strict requirements on the handover delay apply. The problem is handled with standard solutions with some enhancements. In Chapter 6 a concept is developed for managing an aircraft cabin network with two independent transceiver interfaces. Finally Chapter 7 concludes this work.

Figure 1.1 shows the key chapters in relation to the life cycle of an aircraft. The chapters for the protocol studies, mobility support and network management concept discuss fundamental design questions of the wireless system. They are part of the aircraft design. The algorithm presented in the resource planning section is part of the aircraft configuration and layout. Resource management addresses the network algorithms during the operational phase of the aircraft.

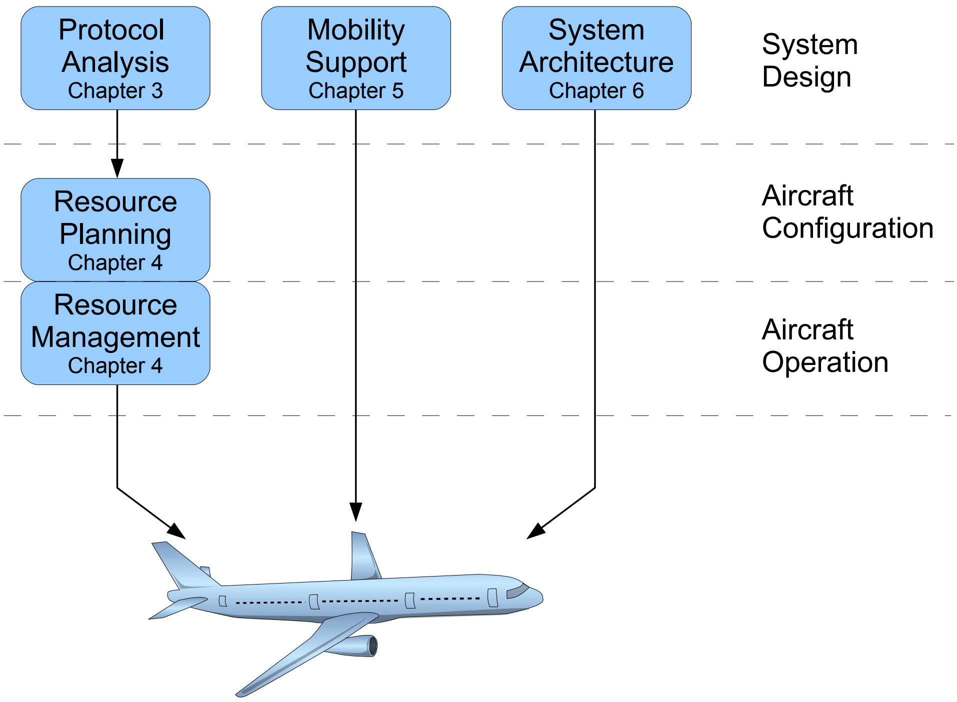


Figure 1.1: Document structure

Chapter 2

Wireless aircraft cabin management

The application that this research builds on is the Cabin Management System (CMS) of an aircraft, which is the network of most of the electronic devices inside the passenger section of an aircraft cabin. It is present in every airliner and is a major system in the aircraft. The complexity varies from reduced features in single aisle aircraft, for instance the A320, to complete systems like those in the A380 with section control, enhanced climate control or flight status displays.

To follow the approaches in this research, this chapter describes the CMS and the need to develop a wireless CMS. The wireless system concept is described and challenges are identified. The challenges are addressed in Chapters 3 to 6.

2.1 Cabin Management System

The CMS in an aircraft is a networked system of electrical devices inside the cabin area. Functions handled by this system range from reading lights, passenger calls or speakers to climate control, water waste monitoring or fire and smoke detection. Table 2.1 shows most of the functions. Many of them are monitored and controlled by the CMS-server and accessible through the Flight Attendant Panel (FAP), a touch screen console located in the front door area.

The systems in an aircraft are categorised in Design Assurance Levels (DALs) (see Table 2.2), which specify the criticality of the system. DAL-A rated systems are most critical and usually cause death in a case of failure. DAL-E means no effect on safety or the aircraft. Since the CMS is a DAL-C system, it can only control other DAL-C and lower systems. The cargo smoke detection is a DAL-B system and operates completely independent from the CMS. But still the CMS has a unidirectional link to the smoke detection system and can visualise the status or give alert messages. Thus, for DAL-B and DAL-A the CMS has only a monitoring function.

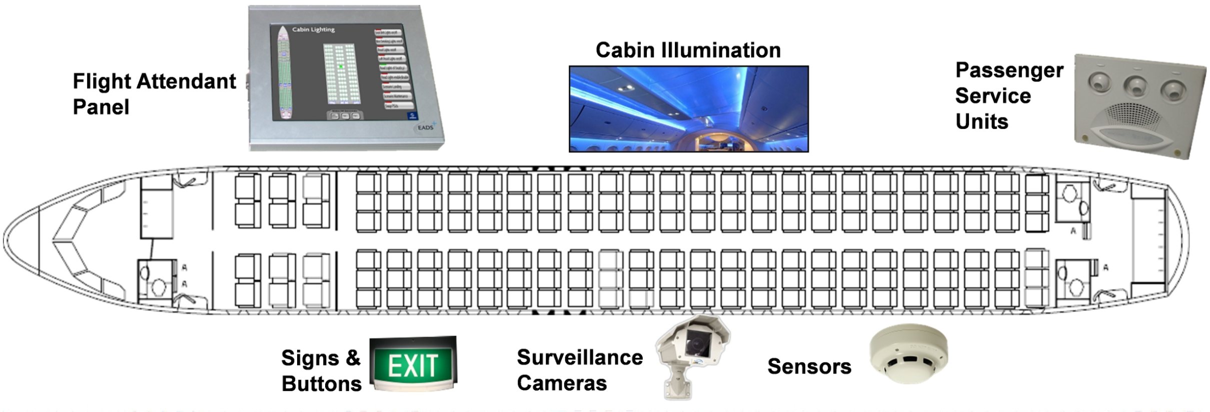


Figure 2.1: CMS application

Function	DAL
Cargo Smoke Detection	B
Cabin Smoke Detection	C
Passenger Address	C
Cabin Interphone	C
Air Conditioning	C
Crew Signalling	C
Emergency Evacuation Signalling	C
Passenger Lighted Signs	C
Passenger Call	C
Lavatory Smoke Detection	C
Cabin to Cockpit Alerting System	C
Cockpit to Cabin Alerting System	C
2nd Power Supply Distrib. Box	C
IFE Interface Functions	C
Slides related Indication	C
Doors related Indication	C
Waste indication	C

Function	DAL
Electrical Load Management	D
Service Interphone	D
Pre-recorded Announc. & Boarding Music	D
Vacuum System Control Function	D
Lavatory Occupied Function	D
Cabin Illumination	D
Reading Lights	D
Software Loading	D
Emerg. Power Supply Unit (Test)	D
Trolley Lift	D
BITE	D
Ice Protection Control Unit	D
Portable Water Indication & Pre-Selection	D
Waste indication	D
Galley cooling	D
Control of Window Shades	D
Therapeutic Oxygen Control & Indication	D

Table 2.1: Function list of the CMS

DAL	Possible system anomalous behaviour consequences
A	Catastrophic failure condition for the aircraft
B	Hazardous/severe-major failure condition for the aircraft
C	Major failure condition for the aircraft
D	Minor failure condition for the aircraft
E	No effect on aircraft operational capability or pilot workload

Table 2.2: Design Assurance Level definitions [RTC92]

The classification of the aircraft systems in DALs is solely based on the safety aspects. The higher the DAL (A is highest level), the more effort and attention is given to the development and certification process of the system. For example the certification process for DAL-A software requires line by line checking with the authorities.

2.1.1 Existing system

The network topology of a commercial aircraft uses a hierarchical structure. From the CMS server several main lines stretch throughout the cabin. Two types of main lines exists, the Passenger Line [KID05], which serves passenger related services and the Crew Line [AIR05], which only handles crew and aircraft systems. The hardware and software for both lines is nearly identical. Both use 10 Mbit/s Ethernet full-duplex transmissions and a proprietary MAC protocol. The difference lies in the configuration of the MAC protocol parameters. This is due to the variation in expected traffic of the different end device types. The Passenger Line forwards mostly data from the server to the end devices; most significant are the audio channels. The Crew Line is designed to support additional end devices and a greater amount of bidirectional traffic, for instance crew-intercom phones.

Figure 2.2 gives an example of the network topology. There is usually more than one Passenger Line and Crew Line, depending on the aircraft size. A large aircraft can have two Passenger Lines for the left, centre and right cabin area, which is in total six Passenger Lines.

Each line has a number of switching nodes, which are called in this work PAX-SN for the Passenger Line and CREW-SN for the Crew Line. The number of supported switching nodes per line is configurable and depends on the protocol parametrisation. The end devices are connected directly to the switching nodes, which can support a fix number of end devices according to the protocol. The connection point for an end device at the switching node is called a *port*.

The proprietary MAC protocol for the Passenger and Crew Line is fully deterministic and managed by the server. It has two important features. First every devices in the system receives a status update many times per second. The status of each light and

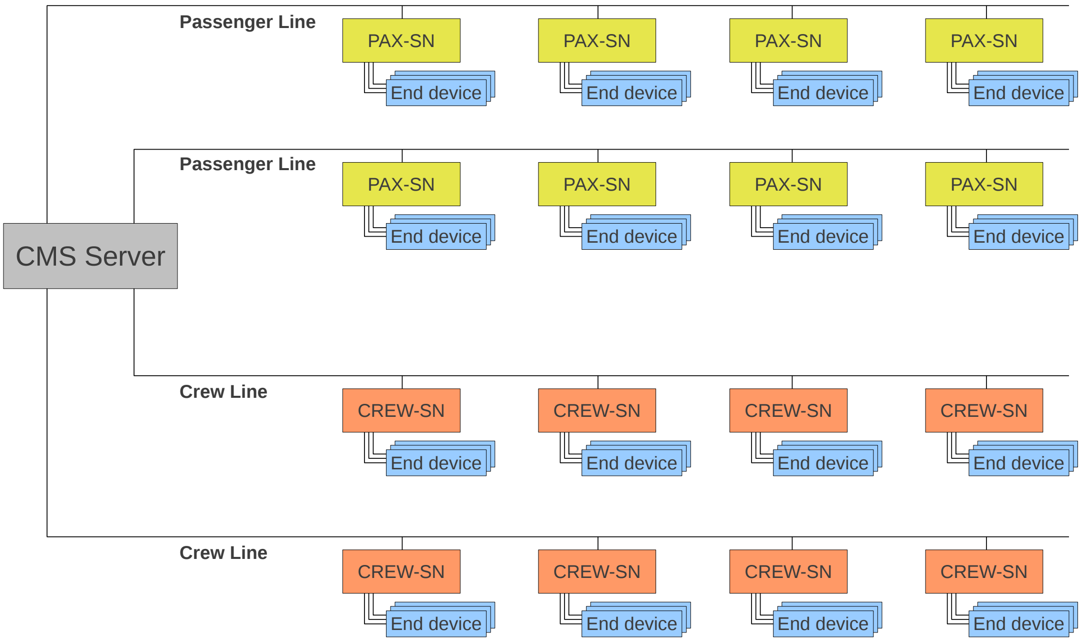


Figure 2.2: CMS topology example. Numbers of lines, switching units and end devices is variable.

button is sent to and from the server in fixed intervals. Thus, the system does not need acknowledgement mechanisms, since the command will be repeated within the next message. The second feature is a binary coding of the functions of the bits and bytes. In the protocol structure the use of every bit is predefined. For example bit N of each message to a Passenger Service Unit (PSU) (the over-head ceiling unit of each bench containing reading lights, signs, speakers and passenger service call) indicates the reading light status of the first seat. These two features have impact on the protocol performance. The binary coding of the functions generates a high configuration effort of the protocol. The continuously resending of the status results in a high network utilisation. Modern protocol designs can increase the system performance and decrease the maintenance effort.

2.1.2 CMS trends

In current aircraft, the electronic equipment in the cabin requires three types of networks: the CMS network, a separate Inflight Entertainment System (IFE) network and the power distribution system. All networks have different DAL categories.

Several research and development projects are ongoing to investigate future cabin networks. The main intentions are to reduce cable harness by combining networks and to operate more services on the network. Various projects address the following approaches:

Full-IP: The possibility of using Ethernet and Internet Protocol (IP) communication with an event based application protocol is being investigated. An event driven approach requires much less network utilisation and additional services can be included in the network.

Hybrid: The hybrid approach is an extension of the existing implementation to support IP packets. Instead of using a 10 Mbits/s interface, a 100 Mbits/s will be used. The gained data rate is used to include IP packets, in addition to the retained deterministic data.

Power-over-data: Combining the communication network and power distribution network reduces the complexity, maintenance effort and weight of an aircraft.

Data-over-power: Same reasons as for power-over-data, but it is technologically more challenging.

Wireless communication: Reduction of cable harness, flexibility of cabin design and device localisation are only some advantages of wireless communication. A detailed discussion follows in Section 2.1.3.

The different approaches can be combined, especially the full-IP and wireless concept with power-over-data or data-over-power.

All approaches, including the existing system, have in common a server at one end of the aircraft and several main communication lines along the aircraft. A number of switching nodes are placed along each line, which connects to the end devices. For a wireless enhancement this basic infrastructure with a server, backbone lines and switching units can be assumed.

2.1.3 Benefits of wireless communication in the cabin

There are several reasons why aircraft manufacturers should consider wireless technology in the aircraft cabin. The first and most obvious one is the reduced weight. With wireless data transmissions the communication network cabling is eliminated. Thus, the aircraft becomes less heavy and less aviation fuel is required. This in turn reduces the operational costs of the aircraft and finally saves money for the airline or the passenger.

The second benefit to the airline operator is the reduced time for maintenance work. The currently used SUB-D connectors require a lot of time to connect, as they are fixed with screws. To avoid rattling of the cables when the aircraft is airborne, they are fixed every few centimetres with cable ties. Wireless devices have no data cables and connectors, thus the maintenance of the devices requires less time. This is a huge bonus during the aircraft periodic safety checks, where the cabin is completely disassembled. Furthermore, mistakes by interchanging cable pairs or not correctly connected connectors are eliminated.

The unique selling point of wireless over wired is the increase in cabin layout flexibility. Future aircraft shall have a very flexible cabin architecture. The seating layout shall match the number of sold tickets and not the ticket number per category has to match the seating layout, as it is currently the case. Hence, the seats shall be rearranged within the turnaround time of an aircraft. The turnaround time is the minimal required time for an aircraft located at an airport between arriving at the gate and leaving the gate. Currently the turn around time of an aircraft is thirty minutes. The ambitious goal is to allow rearranging the seating within these thirty minutes. For instance some rows of economy class seats shall be replaced by business class seats. Many projects are focused on solving this problem: fast and easy mounting of seat rows, spacing of interior and doors to let complete rows be carried out of the aircraft and also fast changes for the electrical devices. Wireless technology would speed up the work on the electrical equipment. With a simplified power distribution system, such as power rails for fast mounting and a click-in system, new devices can be attached very quickly. Cable connectors must not be plugged in and out and the cable ties must also not be fixed.

In current implementations the configuration and network settings need to be preconfigured and transferred to the CMS server. Also the network device ID of communication nodes are set mechanically by hand with small wheels. So not only the installation, but also the configuration of existing systems is very time consuming. Future enhancements of the CMS shall support fully automatic integration of new network nodes into the system.

One disadvantage of wired systems there is still the problem that cables, connectors on switching boxes or certain device IDs are assigned to fix locations, such as *above seat 23A*. Wireless technology has the advantage of supporting the localisation of devices. With wireless localisation the CMS can determine without any help where the device is located. Replacing devices or installing new ones becomes as easy as snapping it in to rails with integrated power contacts and that is it. Network configuration, device identification and localisation can all be done automatically. No additional work to the mounting process is required.

2.1.4 Wireless system requirements, criteria and policies

Details on requirements, criteria and policies of the wireless CMS system are very vague.

As the use of wireless networks on-board aircraft is a new field, the capabilities and risks of the technology still need to be worked out. No strict requirements catalogue exists. The research is done in close cooperation with Airbus and the requirements definitions are part of the project.

However, the project has two fundamental objectives. The first one is to get the certification for the wireless system. This is a must. It has however proven to be very difficult to get details on the requirements that make a system certifiable. In the past, systems with at least DAL-C classification were completely deterministic, at least for the cabin communication. It had to be shown that for a worst case scenario the system will not fail.

There is a strong tendency from aircraft designers and airlines to use standard products and components, for example IP protocols or standard Ethernet devices. This often is in direct conflict with the determinism demands from the certification. The strategy of this work is to use as many standard components as possible to create a reliable and robust wireless communication system. Since determinism cannot be guaranteed for wireless systems, new strategies for the certification will be necessary. However, these are not part of this work.

The second target is to have the same performance for the wireless system, as for existing wired CMS. So the design goal of the wireless performance is to match the existing systems. In some cases this demand will be hard to fulfil, due to network protocol related issues.

In the following several important facts from existing CMS are listed:

Address space

In the current CMS with a proprietary time deterministic protocol each single sign or button is seen as a *port*. In an mid-size aircraft with about 190 PSUs with 16 ports each and 15,118 light modules and a some extra devices, the system support more than 18,400 ports.

However, for the new CMS a new application protocol and an IP protocol is assumed. Thus, many components will be grouped with a common address. A rough estimation for this case can be seen in Table 2.3.

From Table 2.3 one can clearly see that the number of wireless devices becomes very large. An A380 or A350 cabin has dimensions of about 60 $\times$ 6 m. Even without IFE there would still be 1000 nodes on 360 m^2. The A380 has two decks, thus the node density and interference become even worse.

Delays

There are strict constraints on the delays in the CMS. This is due to two reasons: undistracted passenger announcements and synchronised playback. The first reason requires a short delay between speaking into the microphone and the actual playback in the speakers. The second reason requires a synchronised playback of the speakers in the cabin to obtain a clear voice and no hall effect. Table 2.4 shows requirements on timing delays specified in [AIR].

Unit type	**Number**	**Description**
PSU	190	170 seat groups, 20 additional for crew rest, galley, lavatory, etc.
Cabin sensors	200	Estimation; currently an aircraft has seventy smoke detectors
Cabin illumination	400	Estimation; single deck aircraft has about 300 illumination units for the cabin without door area and galley lighting
Video surveillance cameras	25	
Crew adapters	20	Crew related devices
FAPs and mobile devices	20	
Extra devices	50	Various signs, buttons, etc.
In-flight entertainment	555	One per seat
Total:	**1460**	

Table 2.3: Number of devices for an A350 like aircraft

Type	**Definition**	**Max. delay**
Speakers	Maximum playback time difference between any speaker in the system for audio announcements and audio playback	< 1 ms
Signs & video	Maximum visual appearance difference between any display and indicator	< 10 ms
Illumination	Maximum visual appearance difference between any light group	< 10 ms
Buttons	Maximum delay between pressing a button and the required action	< 100 ms
Announcements	Maximum delay between speaking into the microphone and the playback on the speaker	< 100 ms

Table 2.4: Delay requirements for the CMS

The listed types can be categorised in two groups. First the *synchronised action*, which requires the event to be effective simultaneously. These can be easily handled with a time synchronisation protocol. The second group addresses the maximum delay between *cause and effect*. These depend on the processing time and packet delivery times and should be below 100ms. This short delay can be a problem for wireless protocols, as we can see later.

Backbone network

The wireless system must be connected to the wired network of the aircraft. Also a mixed mode with wired and wireless end devices can be possible. This requires compatible connectors, device addressing, communication protocols, routing, etc.

Since the future wired CMS is also under development many aspects are open for modifications. Thus, the task is not to define a wireless system, that can be included in an existing wired system, but to create a holistic wired/wireless CMS architecture.

Transparent wireless communication

As pointed out in the previous paragraph, the wireless components need to be compatible with wired components. The additional devices or protocols from the wireless system shall not effect the application layers. No differences for the system or users must be perceptible.

Fail-safe and redundant

Since the speakers are DAL-C components, the wireless system must be *fail-safe and redundant*. The exact requirements are not defined, but the maximum possible reliability shall be implemented.

2.2 Wireless enhancements

There are a number of wireless technologies in existence, such as the IEEE 802.11 family, Bluetooth or the range of cellular network standards. Which one is the best suitable for the wireless CMS? A number of studies have been completed to evaluate this question.

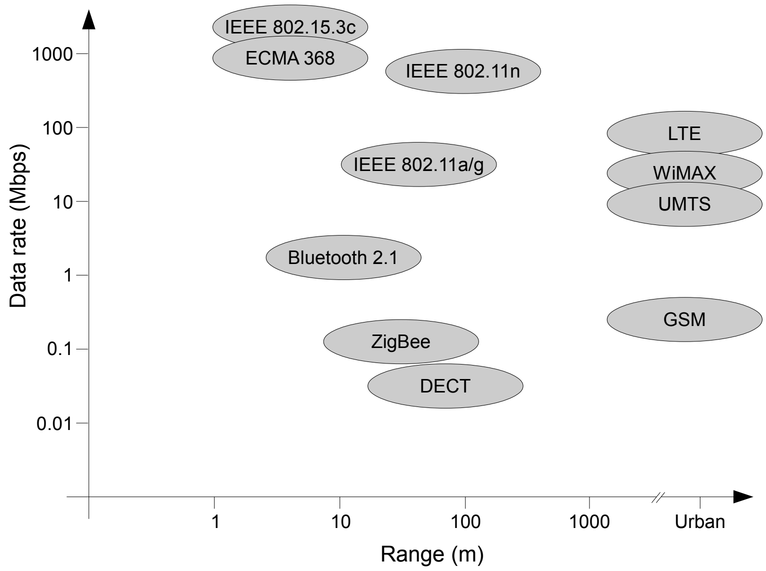


Figure 2.3: Wireless communication protocols compared by range over data rate

2.2.1 Overview of wireless communication standards

Figure 2.3 shows many common standards with respect to their transmission range and maximum data rate. As the standards exist in many variations, a clear categorisation is not easy. The most common range and data rate parameters of common systems are shown. The planned audio and video content requires a standard with moderate data rates. The low data rate technologies, such as Bluetooth, DECT, ZigBee or other wireless sensor network protocols do not provide capabilities for several video and audio channels in the aircraft scenario. The remaining technologies are summarised in the following, with focus on the aircraft related environment:

ECMA-368

The ECMA-368 standard, defined by the WiMedia alliance, is an UWB technology supporting up to 1024 Mbit/s. It has 14 non-overlapping channels and uses a Time Division Multiple Access (TDMA) channel access. The transmit range is about 10 m and no infrastructure is required to operate the network. Due to the low power emission it is free of licensing costs.

UMTS and LTE

The modern cellular phone networks can also provide good data rates. The maximum transmission range of the technologies is larger than needed, but pico or femto cells have shown, that they can also be used in small areas. One problem with this technology is the frequency management, since it requires dedicated bands for the aircraft usage. Furthermore, interference with other aircraft can occur, which must also be handled. Currently LTE technology is also discussed for small private area networks, thus this might be a worthwhile technology to look at today.

IEEE 802.11a/g

The Wi-Fi technology, commonly known from wireless networking with laptops, achieves up to 54 Mbit/s in the 2.4 GHz and 5 GHz ISM bands; hence it is free of any frequency regulation. The infrastructure and ad-hoc modes allow easy and flexible usage with transmit ranges of 40 m indoor and 140 m outdoor. Originally IEEE 802.11a/g had 11-13 channels (depending on the country), but for IEEE 802.11g the channels are overlapping with only three non-overlapping channels available. The disadvantage of this technology is that it uses the ISM bands. These are available for everybody and also many different technologies. On the aircraft a passenger device will very likely transmit on these bands, which will interrupt the CMS system.

IEEE 802.11n

The most recent Wi-Fi standard is IEEE 802.11n. It uses Multiple Input, Multiple Output (MIMO) techniques and achieves up to 600 Mbit/s, thus it has similar data rates as WiMedia. But still it works in the ISM bands and requires a large amount of the total available resources when operated with 600 Mbit/s.

IEEE 802.15.3c

The IEEE 802.15.3c protocol is one of the first 60 GHz standards. It achieves up to 3 Gbit/s and has a transmit range of 10 m. The disadvantage of 60 GHz communication is that it is strictly Line of Sight (LOS). Obstacles and moving objects can heavily influence the signal quality.

WiMAX

WiMAX is an emerging technology that has similar capabilities as cellular phone networks in terms of range and data rate; but the focus is on data packets, not phone calls. For the

	ECMA-368	IEEE 802.11n	IEEE 802.15.3c
Traffic density ($Mbit/s/m^2$)	2.4	1.4	16
Product availability in about 3 years time (from 2006)	Good	Very good	Products are likely
Signal characteristics	Good propagation in aircraft; many resources available	Good propagation in aircraft; few resources	Requires LOS
Expected interference	Little interference due to spatial containment	Many interference from other systems on ISM bands	Little interference due to spatial containment

Table 2.5: Study of wireless protocols for aircraft

aircraft scenario it suffers from the same problems as UMTS or LTE. Furthermore, the availability of this technology and the availability of any future mass market production was hard to estimate at the beginning of this thesis.

2.2.2 Technology survey

In 2006 a survey was initiated to evaluate various technologies for the deployment of wireless technology in aircraft. The most promising technologically suitable products were analysed in detail and a summary of the results is shown in Table 2.5. The final technologies were ECMA-368, IEEE 802.11n and IEEE 802.15.3c. The first criteria analysed was *traffic density*. This is defined as the available data rate per end device. This value depends on the technology data rate, transmit range and node density. The studies assume an aircraft like environment. The *product availability in three years time* describes the situation as seen in 2006. *Signal characteristics* address the propagation of the RF waves in the aircraft and the associated problems. The last criteria, *Expected interference*, address the problems of radio resources availability and utilisation.

One criteria all listed technologies have in common is the free usage in most countries of the world; no licensing requirements exist. This is very important for an aircraft that travels around the world. It is a very challenging task (if not impossible) to find a frequency range that can be used all around the globe in aircraft. There have been attempts by single companies in the past to obtain such a worldwide frequency band, but with no success. Currently several large companies are planning to reuse old, no longer used, aeronautic application frequencies for on-board WSN applications in aircraft. This will be promoted at the next world radio conference.

The study showed that ECMA-368 is the best candidate, because of the moderate data rate and good expected product availability and frequency availability. As a result it was selected for pre-development work on a wireless CMS system.

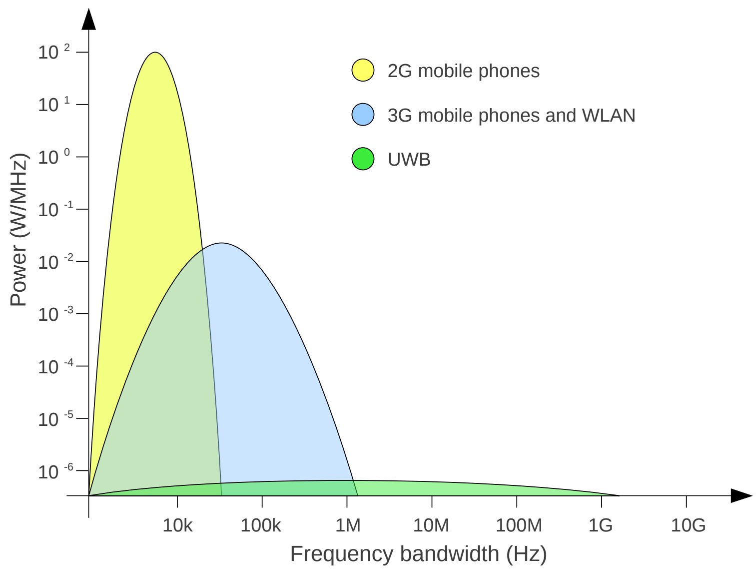


Figure 2.4: Signal bandwidth from UWB and other technologies

2.2.3 Ultra-wideband technology

UWB is a signal form first used for radar applications in the late 1960's [Bar00]. At that time there was work done on UWB communication systems, but they did not become widely used until some years ago. In 2002 the Federal Communications Commission (FCC) (regulatory agency in the US) has specified the signal characteristics and power limits of UWB for communication [Fed02]. By definition an UWB signal has an emitted signal bandwidth of at least 500 MHz or 20% of the centre frequency. Compared to other systems, such as Wi-Fi or mobile phone networks, which usually have cohesive bandwidth of less than 100 MHz, UWB has much more frequency resources but also brings with it new challenges. Figure 2.4 shows the signal width of UWB and other small band systems.

While communication systems such as mobile phone networks, TV transmissions and Wi-Fi have dedicated frequency ranges, there is no band available for UWB communication in the range below 10 GHz. The reason for this is the lack of remaining bandwidth in the frequency spectrum; 500 MHz and more is a huge amount in an already highly competitive area. However, the FCC has allowed UWB transmissions in the range from 3.1 - 10.6 GHz for a very low power spectral density emission limit of -41.3 dBm/MHz (see Figures 2.5 and 2.6). This low power signal will not affect existing wireless systems in the same frequency range since the UWB signals will be seen as background noise. The European frequency regulation agency ETSI and other agencies worldwide have also allowed UWB communication, but with some slightly different emission masks [The07].

Even though the European emission mask has only limited frequency ranges where the

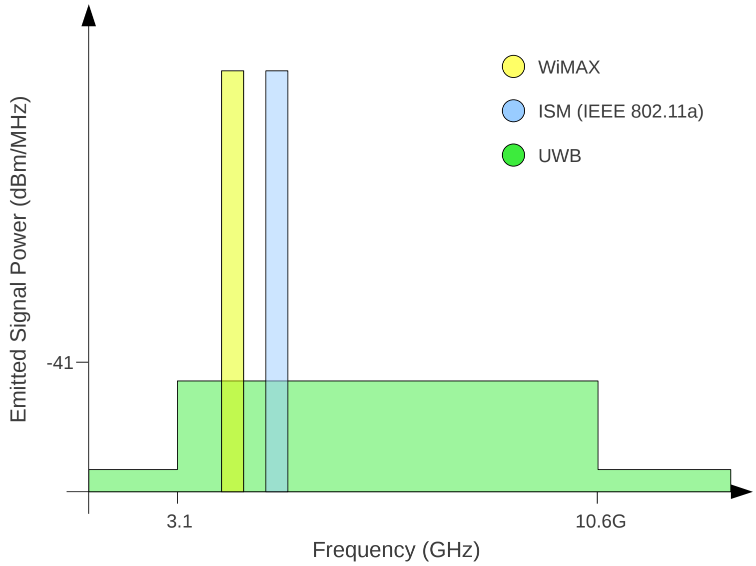


Figure 2.5: Frequency range and power levels from UWB and other technologies

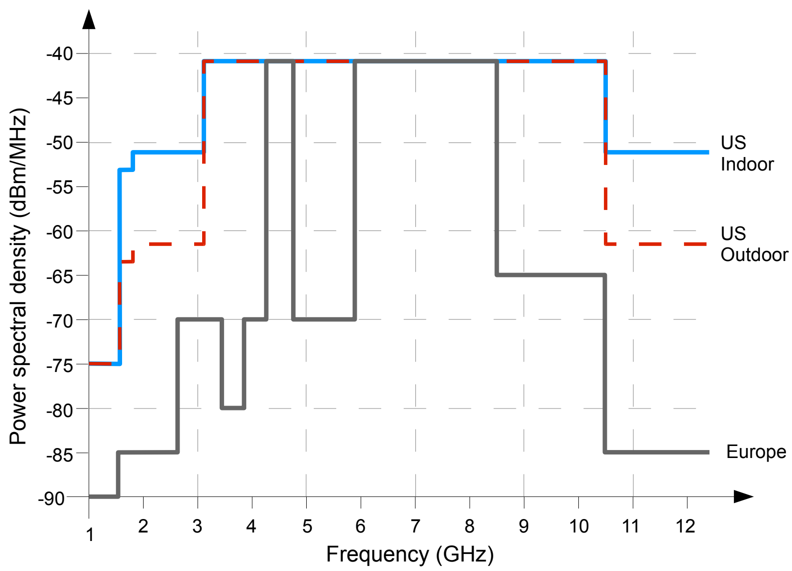


Figure 2.6: UWB essission masks for US and Europe

maximum of -41 dBm/MHz can be used, UWB can still be operated efficiently for wireless communication networks. Emerging techniques like cognitive radio might also enable the use of more bandwidth.

UWB based communication can be implemented in two ways: DS and MB-OFDM

DS UWB

Direct Sequence UWB, also called impulse-based UWB, uses the available signal bandwidth and creates high frequency pulses. The advantage is a very robust signal which is in addition hard to detect. Military applications prefer this approach. Also low data rate communication can be achieved with this technology. The IEEE standard 802.15.4a uses DS UWB and achieves up to 10 Mbps. For higher data rates the transceiver costs become too expensive.

MB-OFDM UWB

In multi-band Orthogonal Frequency Division Multiplex (OFDM) the available signal bandwidth is divided in a number of orthogonal sub-bands. The number of carriers is multiplied and very large data rates of up to 1 Gbps are possible. One protocol using this approach is ECMA-368 from the WiMedia alliance. Historically the MB-OFDM development started with work on the IEE 802.15.3a standard. However, the members could not decide on which technology to choose from DS UWB and MB-OFDT UWB. The group split up and reorganised in the WiMedia alliance on the one side and IEEE 802.15.4a on the other.

2.2.4 Distributed beacon based UWB protocol

The WiMedia alliance released a number of standards, most known the ECMA-368 [ECM08]. It is a physical and MAC definition for an OFDM based UWB protocol. The idea is to have a common radio platform for different higher layer protocols. Figure 2.7 displays the concept. Intentionally it should be used for Wireless USB, Bluetooth, direct IP communication and other scenarios; all using the same physical and MAC level protocol.

The WiMedia alliance and the associated products have undergone some turbulent times in the past. WiMedia chip development was first driven by Intel. In 2008 Intel cancelled all WiMedia activities and left the field to a hand full of smaller companies. The companies currently focus solely on Wireless USB (WUSB) products. However, the business is very delicate, since the market success is still not guaranteed. It is a *chicken-or-egg* situation. The chip producers do not provide a larger range of products and capabilities,

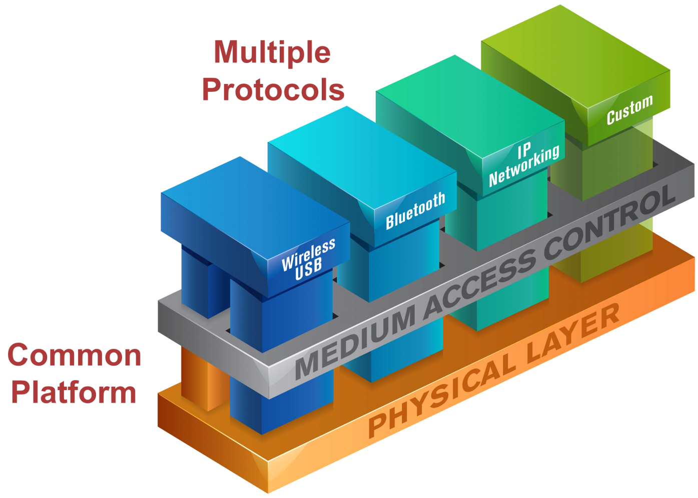


Figure 2.7: WiMedia as a common radio platform (Source: www.wimedia.org)

since they have no real end customer that is willing to order a large number. On the other hand the consumer electronics industry is very reserved in terms of WiMedia since they are uncertain if it will become a mass market product. This leaves the WiMedia market currently to WUSB and some wireless video streaming applications. In 2010 Samsung announced that it will produce its own WiMedia and WUSB chip, which they plan to use in cameras and other products. This could revive the WiMedia standard. The activities of WiMedia for Bluetooth and direct IP communication have currently stopped or are not publicly visible. The company CSR, a well known player in Bluetooth development, tried to establish a WiMedia-Bluetooth product. But the Bluetooth interest group rather focused a Wi-Fi based Bluetooth 3.0 standard and an independently developed Bluetooth 4.0 standard.

On the physical layer the available frequency ranges for indoor UWB are separated to 14 non-overlapping channels of 528 MHz, see Figure 2.8. They are grouped by three bands to one band group (two band only for the last group), which are used for channels with frequency hopping. With both modes, single channel and frequency hopping, is possible. Frequency hopping has the advantage of higher transmit powers, since the emission limitations are given in dBm/MHz. Each band is composed of 110 sub-bands for OFDM signals. Various modulation techniques, spreading techniques and forward error correction provide advanced physical layer features for robust high data rate communication, supporting 53.3 Mb/s, 80 Mb/s, 106.7 Mb/s, 160 Mb/s, 200 Mb/s, 320 Mb/s, 400 Mb/s and 480 Mb/s. The transmit range is up to 10 m. In 2009 an update of the standard was provided, which allows data rates of up to 1024 Mb/s.

As described in Section 2.2.3 UWB technology, and therewith ECMA-368, operates on radio frequencies ranging from 3.1 to 10.6 GHz. Even though ECMA-368 transmits with extreme low power, the danger of interrupting other wireless systems has been of

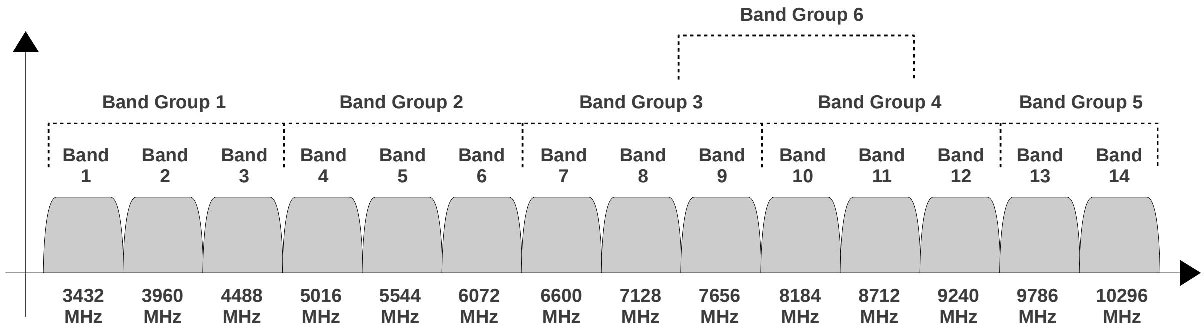


Figure 2.8: WiMedia bands

interest for the regulating authorities and for researchers. In [RZF07] and [PBM+09] the coexistence of ECMA-368 and WiMAX was studied analytically and experimentally. The results show that interference of UWB devices on WiMAX is only a problem, when a high number of nodes transmit. But the interfering area is very limited. Furthermore in ECMA-368 only one node per can transmit at a time. The other way around, WiMAX is a problem for ECMA-368 if the transmitter is closer than 8 m to the ECMA-368 link. The impact of UWB on cellular phone services was studied in [GM05] and [ZCV08]. The research showed that also for cellular phones ECMA-368 poses no risk.

2.3 Wireless CMS architecture

A wireless cabin network can be implemented in different ways. This section describes the design of the UWB network and the design of the complete aircraft cabin network. The aircraft cabin network is a large system composed of multiple sub-networks.

2.3.1 Architecture concepts

With ECMA-368 as the protocol of choice two general approaches for the network topology are possible.

The first approach (*full-wireless*) would have a completely wireless network and infrastructure. Near to the aircraft server one or more gateways provide the access from the server, or wired aircraft network, to the wireless network. The wireless network can either be a fully meshed topology, just composed of the end devices themselves. Transmissions are routed on multiple hops from the gateways to the end devices. Alternatively it would also be possible to create an overlay network with relay nodes that have two UWB transceivers: one to communicate to the end devices and a second to build an overlay network between the relays and gateways.

The second approach (*AP-based*) is a combination of a wired backbone network and several Access Points (APs) throughout the cabin. The APs serve as gateways from the wired backbone to the wireless network. The concept is similar to the usage scenario of Wi-Fi APs for office environments.

The first approach has some drawbacks. First of all it provides a bottleneck close to the gateways. All traffic must be routed over the gateways, which will have the highest traffic density. With the AP-based solution, the APs will serve some wireless end devices and are connected to a high speed wired network, which could be a Gbit/s connection or optical fibre. Thus, the highest data density would be in the wired network, which is assumed to have higher capacities.

Second drawback is the frequency management for the full-wireless concept. The completely meshed topology requires all nodes to operate on the same channel, which results in more nodes per channel and a low bandwidth per end device. With the wireless relay topology frequency diversity can be used, but one channel must be reserved for the relay channel (or wireless backbone). Both solutions are less efficient than the AP-based approach, where neighbouring APs can have different channels. The overall throughput of the network increases; hence the AP-based approach is preferred and used as a foundation of this work.

2.3.2 Backbone based system

Wireless communication systems inside aircraft cabins can be disturbed more easily than wired systems. This can be natural interference from the devices in the environment, blocked frequencies in specific countries, devices with the same technology or even hostile attacks. To increase the availability and reliability of the wireless communication a second independent interface is foreseen. It should use a different physical transmission scheme. Possible candidates are optical or 60 GHz systems. By the time this document was finalised the final decision on this matter has not been made. In this document an optical technology is assumed. Therefore the term *optical transceiver* or *optical network* refers to this alternative communication path.

Figure 2.9 shows the system architecture of the wireless CMS. The server is located in the front of the aircraft. From the server several backbone lines stretch throughout the cabin. Backbone Access Controllers (BACs) are attached to a backbone line. To the BAC various devices can be attached, including APs. These can be UWB or optical. The end devices can then communicate to the APs.

The BACs and APs are embedded computers, where custom applications can be executed. The backbone is capable of IP communication; hence standard protocols can be used. The link between the BAC and the end devices is Ethernet and also is IP capable.

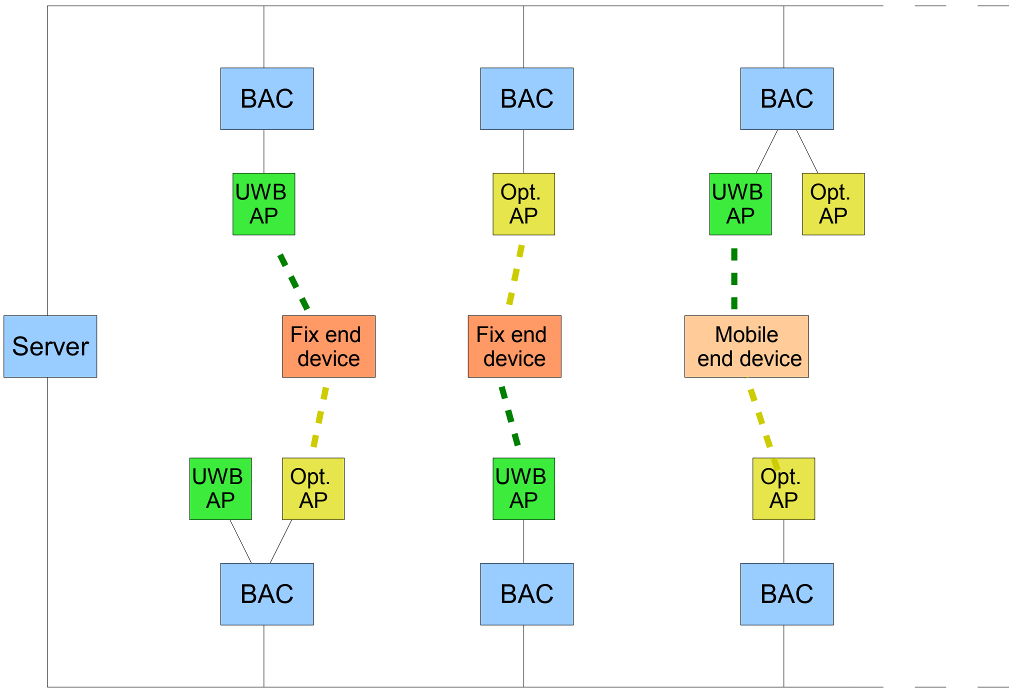


Figure 2.9: Wireless CMS system. The BACs are connected to the server by backbone lines. The UWB and optical APs are linked to the BACs. End devices have an UWB and optical transceiver.

2.3.3 Wireless channel in the aircraft

One question that often arises is the channel quality inside aircraft cabins. For Wi-Fi, GSM, UMTS and Bluetooth several research and commercial tasks have been completed. [Nie03] investigates Wi-Fi, UMTS and Bluetooth for aircraft networks. Boeing has already installed a system called *Connexion by Boeing* [JdLC01] that provides Wi-Fi access to the Internet through a satellite link. The current system *Aircell* uses a terrestrial link for Wi-Fi service, which can only be used in the US. Airbus uses the *OnAir* system to provide Wi-Fi and GSM services via a satellite link. The previous studies and implemented technologies show that there are no severe problems with the propagation of waves and operation of such networks inside aircraft cabins.

There are no safety concerns with operating wireless systems in an aircraft as there is no direct influence of the wireless signals on the aircraft systems. The reason for still prohibiting these services is the possible residual risk no one can eliminate for sure and the influence of mobile networks on the ground. The base station of mobile phone network have problems to cope with nodes with 900 km/h. In the US only wireless services on the ISM band are allowed on board aircraft. In 2008 the European Commission allowed GSM services on the 1800 MHz band to be used in aircraft pico-cells [The08].

However, the characteristics of UWB signals inside the aircraft environment had to be investigated. Several studies for aircraft and cars have been done. [TYY07] analyses the propagation in cars. Several studies investigated the characteristics of the wireless channel of the aircraft cabin with and without passengers for Boeing [CXH+07] [CM10] and for Airbus [SES+08] [JCS+09]. All show that technically the aircraft environment presents no problems for UWB transmissions; it is comparable to the indoor office scenario. To support this research Airbus has carried out tests of UWB signals in aircraft with and without passengers in the cabin.

The regulation issues of allowing low power UWB systems in the range from 3.1 to 10.6 GHz are currently being addressed at the relevant European regulatory bodies. Airbus, Boeing and other companies are addressing these efforts together.

2.4 Challenges of a wireless CMS

To achieve an UWB/WiMedia network inside an aircraft several challenges have been taken into account in this work.

2.4.1 UWB multi-cell network

The choice for the high data rate UWB technology implies transmission ranges for the wireless units of a maximum 10 m. Furthermore, the architecture was said to use a wired backbone network where several APs can be attached. To cover the entire aircraft with wireless access a multi-cell architecture is required. It must be in line with the design from the backbone architecture: namely IP addressing, switching or routing, application layer software and time synchronisation. Protocols for managing the different cell smartly are required.

Until now high data rate UWB protocols are mostly used for small networks, such as a WUSB network for computer peripherals. Recently a number of publications describing the management of larger networks became available, for example [MWH07] shows a ECMA-368 meshed networked. Other research of a network similar to the aircraft cabin network was not found.

2.4.2 Reliability demands

The reliability demands resulting from the inevitable certification of the aircraft require a highly redundant system. Wireless communications are much more susceptible to interruptions, and lost or corrupted packets. Prolonged blackouts are also possible. The system must have the best possible reliability performance to increase the chances of getting certified.

2.4.3 Dense wireless network

The calculations in Table 2.3 show a very high density of wireless nodes. The network and the protocols must be capable of dealing with this number of nodes. Features being most influenced by the node density are the resource management, localisation, tracking and mobility support.

2.4.4 Resource management

The wide frequency ranges of UWB communications and the beacon based protocol with its new features must be included in the resource management. Decisions on the AP positions, frequency allocation and media access times can be optimised to provide the best possible reliability.

2.4.5 Auto configuration

Minimal maintenance and configuration effort is a key requirement for the system. The architecture must be capable of auto configuration for new devices and changed topologies. A major breakthrough is wireless device localisation for this system, since devices can then provide the location and their capabilities automatically to the system.

2.4.6 Interface diversity

The reliability demands mentioned earlier let to the approach with two physically independent interfaces, one with UWB radio and the second on other frequencies, e.g. 60 GHz or optical. This concept introduces new questions for routing and link management. Which link shall be used under what circumstances? How and where are the decisions made and how is the redundant path modelled in the routing or switching?

2.4.7 Mobility

To enable wireless mobile crew equipment, for instance crew intercom, seamless handover must be possible. All audio and video services require seamless mobility. This can be a challenging task, especially for networks that are not tailored for mobility. GSM, UMTS or LTE are by design capable of seamless handover. It is essential for them, otherwise they would not be successful for their application. Other networks, such as the IEEE 802.11 family or ECMA-368, did not have mobility in their main focus during the protocol design. Also the simultaneous management of multiple APs is less efficient than in cellular networks. Handovers require a longer time and especially IP connections take some time for AP switches. Standard protocols are not yet sufficient advanced to cope with seamless mobility in these networks.

Chapter 3

Protocol studies

In the first step towards a wireless CMS concept the ECMA-368 protocol is analysed to identify its general advantages and limitations, and thereby the implied consequences for the aircraft. Of most interest are limitations in the node density, timing behaviour, Quality of Service (QoS), provisioning and impact of malfunctions. Several critical points are identified and solutions are presented. The methods used in the analysis are analytical studies and time discrete simulations.

The foundation of the research is the ECMA-368 protocol. However, some mechanisms used in ECMA-368, like beaconing and resource reservation, are used in other protocols, such as WiMAX, Wi-Fi or ZigBee. The results can therefore be applied to different networks. In some cases the ECMA-368 is new and generates new problems that do not exist in other standards.

3.1 Node density

When defining a new wireless transmission standard there will always be conflicts as parameters have to be agreed and fixed. This will result in hard limitations to the performance. Dynamic parameters will increase the complexity and indeterminism of the protocol. An example of dynamic mechanisms is the use of Carrier Sense Multiple Access (CSMA). The nodes can access the channel when it is free, without any coordination. The disadvantage is the possibility of collisions. In a coordinated Time Division Multiple Access (TDMA) network collisions hardly occur since the access is coordinated. Therefore decisions such as timing the access, number of data slots or number of reservations have to be harmonised.

The ECMA-368 uses a TDMA access with a beaconing mechanism. Several fixed parameters create a strict limitation for the number of nodes in the network. For the aircraft scenario a high node density can be expected, depending on the amount of systems using

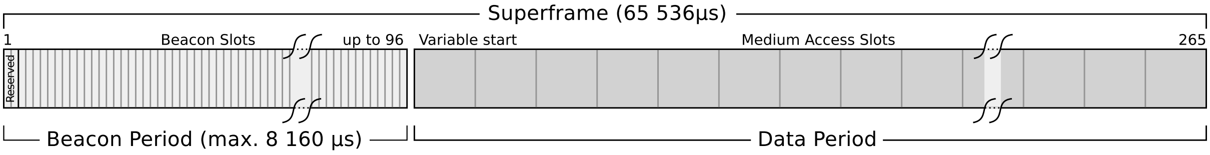


Figure 3.1: ECMA-368 superframe. The superframe has a fixed length of about 65 ms. It is composed of 265 data slots, from which the slots are used for the beacon period. The beacon period is dynamic in size an can have up to 96 beacon slots.

wireless connections. To obtain the information on the capabilities of a wireless CMS, the impact of the node density limitations on the aircraft scenario is investigated.

3.1.1 Density limitation reasons

Figure 3.1 shows a MAC superframe of ECMA-368. The superframe repeats every 65 ms and provides a coordinated access to the channel by all nodes, even when there is only one node. A device being activated listens to the channel for at least the duration of one superframe. If it detects a superframe it synchronises to it and joins the network. If no superframe is detected, it continues to scan for the duration of another superframe length and if no superframe is detected it starts its own, by sending its beacon.

The superframe is composed of a *beacon period* and several Medium Access Slots (MAS), these are the data slots of the superframe. Each node has to select a beacon slot, even when it does not transmit or receive in the current frame. In normal operations the beacon slot position is permanent and only changes on special occasions or when a node leaves the network. Hibernating nodes will still occupy a beacon slot, which is maintained by neighbouring nodes.

The number of beacon slots is variable. After the last used beacon slot, a number of unused slots (the standard recommends eight free slots) are available. These beacon slots, the used and unused, are called beacon period. New devices wishing to join the network have to randomly select one of the free slots at the end of the beacon period. Even if a free slot is detected before the last occupied slot, the nodes still have to select one of the last free slots and can later perform a *beacon slot contraction* operation to select the first unoccupied slot.

For two isolated groups of nodes, this is defined as a situation where there is no communication between nodes in the separate groups, there will be two separate beacon period start times. When these two groups move together, the superframes will not be synchronised. In this state nodes can miss their beacon period because of transmissions from the other group. This state is detected by the nodes and a *beacon period merge* operation synchronises the two groups. The results are one common beacon period start time and collision free transmissions.

The superframe is divided in 256 MASs. The beacon period starts at the beginning of the first MAS and can range over a couple of MASs. After the last beacon slot, the first MAS for data transfer begins.

Beacons are used for various reasons:

Identification of the node. The information consists of the MAC address, vendor information or a device string.

Capabilities and support of protocol features, such as data rates, media access modes, channels and more. Also link feedback can be reported in a beacon.

Node actions to monitor and perform hibernation, channel change, beacon slot relocation or encryption.

Resource reservation of the reservation based media access called Distributed Reservation Protocol (DRP). Within the beacon reservations can be created or confirmed and foreign reservations can be monitored.

PCA availability for the CSMA like media access. Here the node shows which MAS is available for Prioritized Contention Access (PCA) based communication.

Traffic indication summarising the beacon slots, data transfers and communication partner of nodes in range.

From the last item it can be seen that each node is broadcasting the known and expected activities on the channel. This will give every node the information of the activities of its neighbours, called the Beacon Group (BG), and their communication to the neighbour's neighbours, called Extended Beacon Group (EBG). Figure 3.2 illustrates these two groups.

The reason for broadcasting all communication activities lies in the *hidden terminal problem*. This is a fundamental problem of wireless communication and is shown in Figure 3.3. One node (node B) is in range of two or more other nodes (node A and C). A and C are not within transmit range and cannot receive the others transmissions. In CSMA systems it can happen that node A starts a transmission to B. C does not receive the transmission of A and also starts a transmission to B. This causes a collision at B.

To overcome this problem CSMA systems often use Ready-to-send / Clear-to-send (RTS/CTS) mechanisms, which ensure that both nodes broadcast the communication intentions to their neighbour. This however involves two messages before the actual data transfer. In ECMA-368 this problem is solved by broadcasting the Traffic Indication Map Information Element (TIM IE) and Beacon Period Occupation Information Element (BPOIE) in the beacons. All neighbours are aware of planned communication for this superframe and of ongoing DRP reservations. Therewith DRP is collision free.

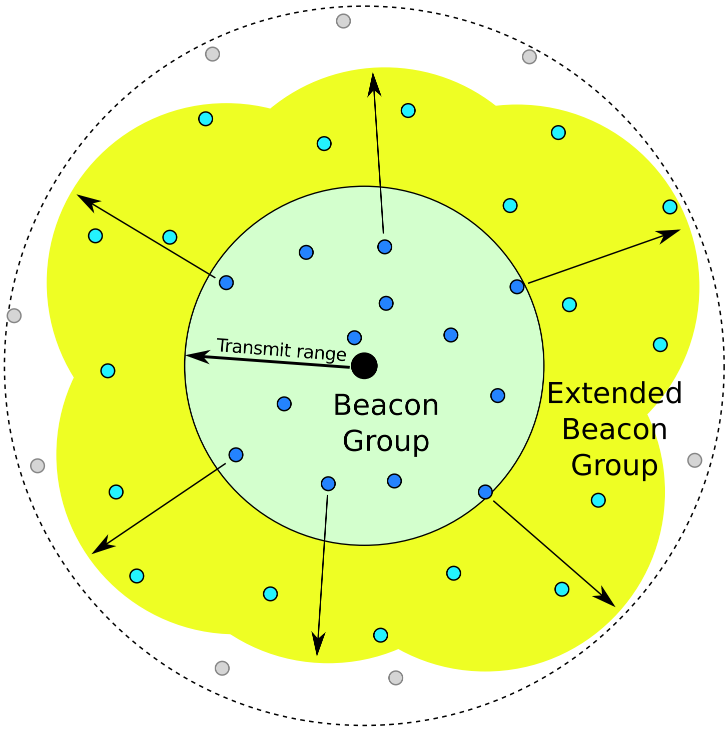


Figure 3.2: BG and EBG of the ECMA-368 standard. The BG is the set of neighbours of a node. The EBG includes the nodes that are exactly in two hops distance.

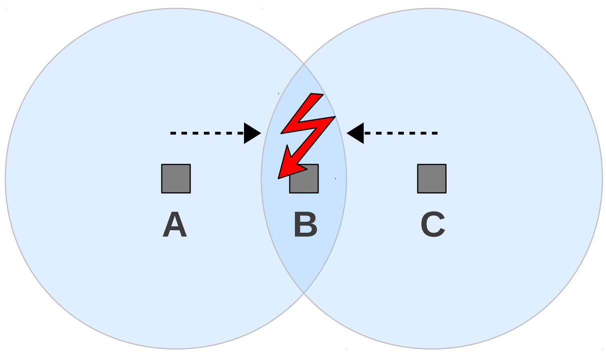


Figure 3.3: Hidden terminal problem in wireless communication systems. Station A transmits to B. C cannot receive the transmission and might also start a transmission to B. This causes a collision at B and neither of the transmissions can be received.

The only occurrence of collisions happens when two or more new nodes join the network and select the same unoccupied beacon slot, or when there is communication in PCA mode.

For the beacon slot selection mechanism the standard defines in section 17.2.1:

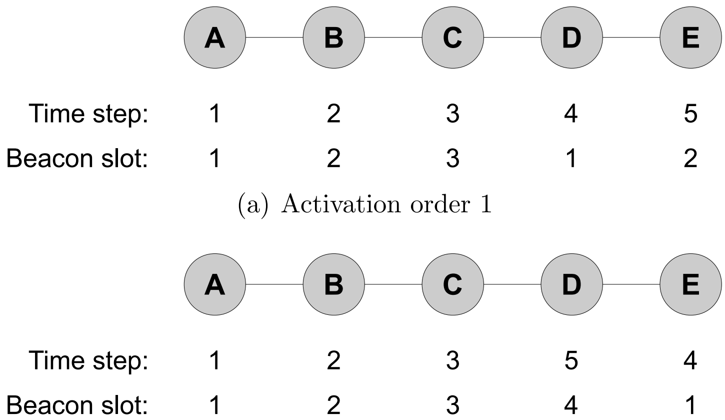
> **Beacon slot state**
> A device shall consider a beacon slot unavailable if in any of the latest mMaxLost-Beacons+1 superframes:
>
> - The beacon slot was considered to be occupied (...); or
> - The beacon slot was encoded as occupied (...) in the BPOIE of any beacon received by the device.
>
> A device shall consider a beacon slot available in all other cases.

Thus, all nodes in a BG must have a unique beacon slot. Nodes in the extended BG can reuse the beacon slot, unless they are in a BG themselves. The members of the BG and EBG need to be viewed from an individual perspective. This means from one node's surrounding status information. Here is an example to further explain the mechanism: A node being activated must select a beacon slot. To do so, it scans the channel and evaluates all received beacons. It is not allowed to select a beacon slot that is occupied by a neighbour, otherwise it would cause collisions. Furthermore, the newly activated node may not select a beacon slot that is occupied by one node of the EBG nodes (the neighbour's neighbours). If this was allowed, then a collision is created at the neighbour node (between the activated node and the EBG node). However, nodes in the EBG can reuse the beacon slot, if they are more than two hops away from each other, so they are not in a BG relation themselves. Furthermore, the protocol identifies a conflict when a newly created node sees two neighbouring nodes on the same channel. When this occurs, for instance the two neighbouring nodes had a 3-hop distance before the new node was activated, and now there is a 2-hop distance, the *beacon slot collision detection* of the ECMA-368 will detect the conflict and a beacon slot relocation takes place for one or both nodes.

The relations of the BG and EBG cause a reuse of the beacon slots. The number of used beacon slots depends on the activation order of the nodes. Figure 3.4 shows two examples that require for the same topology a different amount of beacon slots.

3.1.2 Beacon slot reservation simulation

The beacon period length is related to node density. To obtain the details of the relation the beacon slot selection mechanism was implemented in a discrete Java simulation. The focus is only on the beacon selection; no other MAC features or physical layer influences were included in the simulations.



(a) Activation order 1

(b) Activation order 2

Figure 3.4: Beacon slot selection example. Five nodes being activated in a different order can result in a different number of required beacon slots. In (a) three slots are required, whereas in (b) it are four.

The simulation operates in time discrete rounds. Since the standard uses superframes this approach reflects very much the real operation of the protocol. Furthermore, in the simulation the nodes always select the first available beacon slot. In the real procedure the nodes would have to select a free slot after the last occupied slot and then move to the first free one. This difference does not change the results. Only the convergence time is shortened since no slot relocation takes place.

Also the beacon slot collision detection is implemented. If a collision occurs one of the nodes select another free slot in the next round.

In a first step only the number of nodes belonging to the BG and EBG were calculated. Figure 3.5 shows the result for a random node placement. The left graph illustrates the node placement and highlights the BG and EBG from the node with the most 1-hop and 2-hop neighbours. The right graph shows the node density distribution in the network. Due to the random placement an inhomogeneity in the density exists, that can be seen in the right graph. In Figure 3.6 the configuration complies to an aircraft layout with redundant Access Point (AP) cell coverage, four available channels and a failure of one AP.

To get a direct relation of the density and the beacon period length a set of simulations were done with a constant node density. The nodes were place in grid layout where every node has four neighbours, one in each direction. The transmission range was set to 10 m and the area set to 100x100 m. For each distance multiple simulations were completed, with varying activation order. After each simulation all nodes that are more than 20 m away from the border were evaluated and the maximum beacon period length identified. The results are displayed in Figure 3.7 and Table 3.1. The beacon period length is proportional to the node density. For a density of about 0.19 nodes/m^2 the

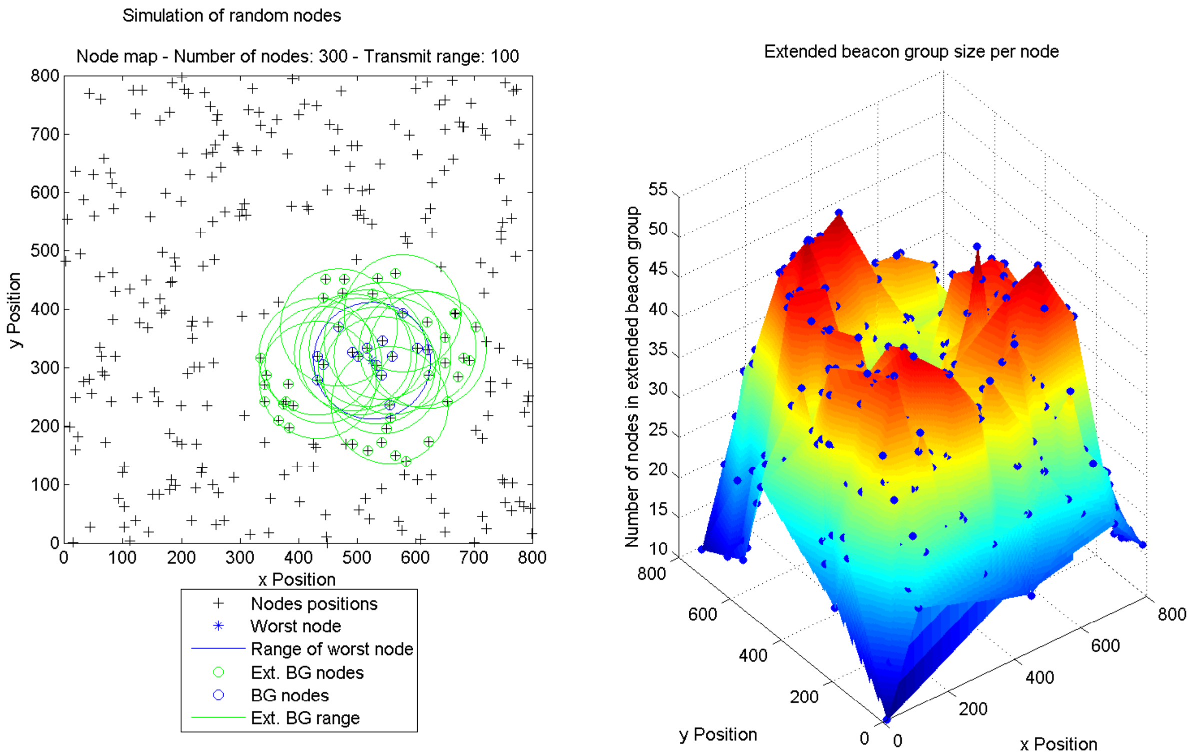


Figure 3.5: The results of the calculation for nodes in a 1-hop and 2-hop distance for a random node placement. The left graph shows the node coordinates; the green circles show the transmit ranges of the EBG nodes of the node with the most nodes in the 1-hop and 2-hop distance. The right graph shows the number of 2-hop neighbours per node.

required beacon period length is longer than what is actually available. Figure 3.8 shows the correlation of the beacon period, BG and EBG.

An approximation of the simulation results is given in Equation 3.1, where r is the transmit radius and D is the node density.

$$N_{Sim} = \pi(1.3r)^2 D. \tag{3.1}$$

3.1.3 Graph colouring problem

The problem of calculating the beacon period length is fundamentally a graph colouring problem. This is a sub section of the mathematical discipline of graph theory. The best known colouring problem is the *four colour theorem* first mentioned in 1850 by a student of De Morgan [Tur04]. The theorem says: For any given map (for instance of countries), only four colours are needed to let all adjacent countries have different colours (assuming

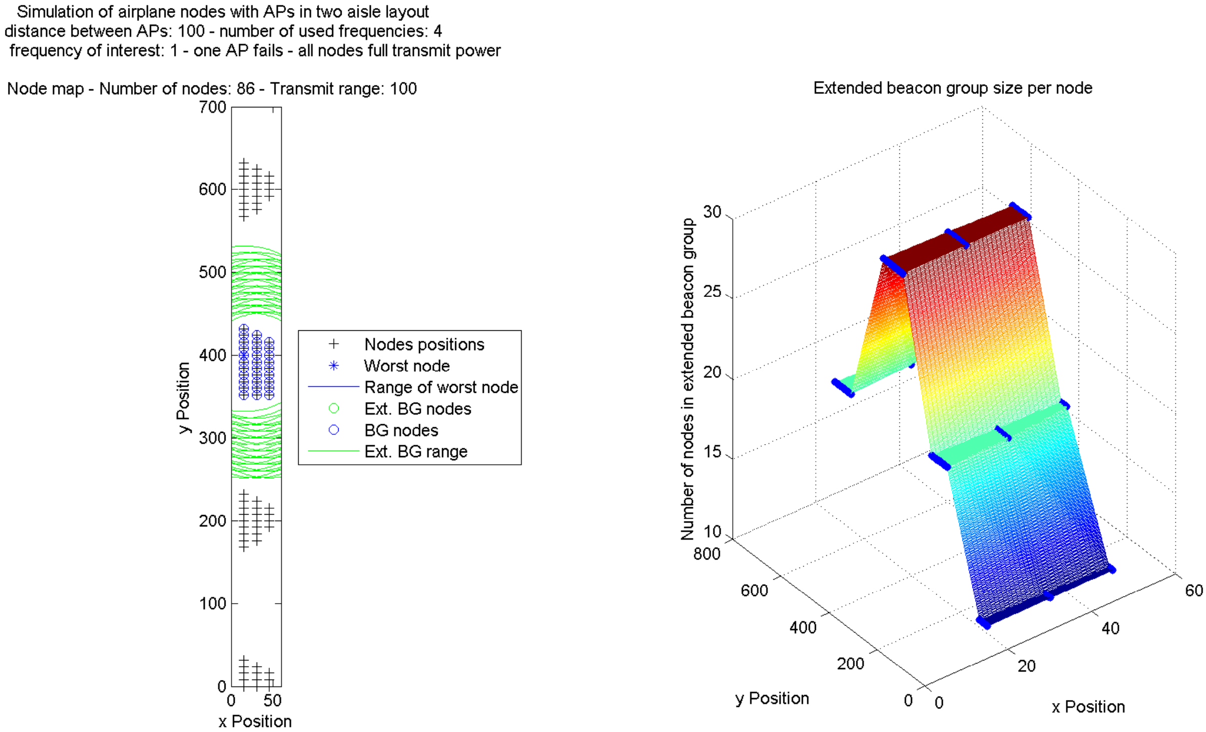


Figure 3.6: The results of the calculation shows the size of the Extended Beacon Group for one possible configuration in the aircraft. The scenario assumes a multi cell network with different channels per APs. Only the nodes from one channel are shown. In the shown configuration an AP failure is simulated. Half of the nodes from the neighbour cell are now registered to the marked AP.

that borders are defined in lines and not points). The problem was unsolved for 125 years until in 1976 K. Appel and W. Haken proved the correctness of this theorem.

In general the colouring problem describes a graph of nodes, which are connected by vertices. Nodes must have assigned a number or colour. The requirement in graph colouring is to have all adjacent nodes to have different colours.

An important attribute of a graph G is the *chromatic number* $\chi(G)$. This is the smallest number of colours required to colour the graph. The upper bound is defined as:

$$\chi(G) \leq 1 + \Delta(G) \tag{3.2}$$

where $\Delta(G)$ is the maximum vertex degree of the graph. The proof for this bound can be found in [Har74]. For most graphs the chromatic number is significantly below the maximum vertex degree.

Determining the lower bound of the chromatic number is difficult. For some special cases the lower bound can be specified:

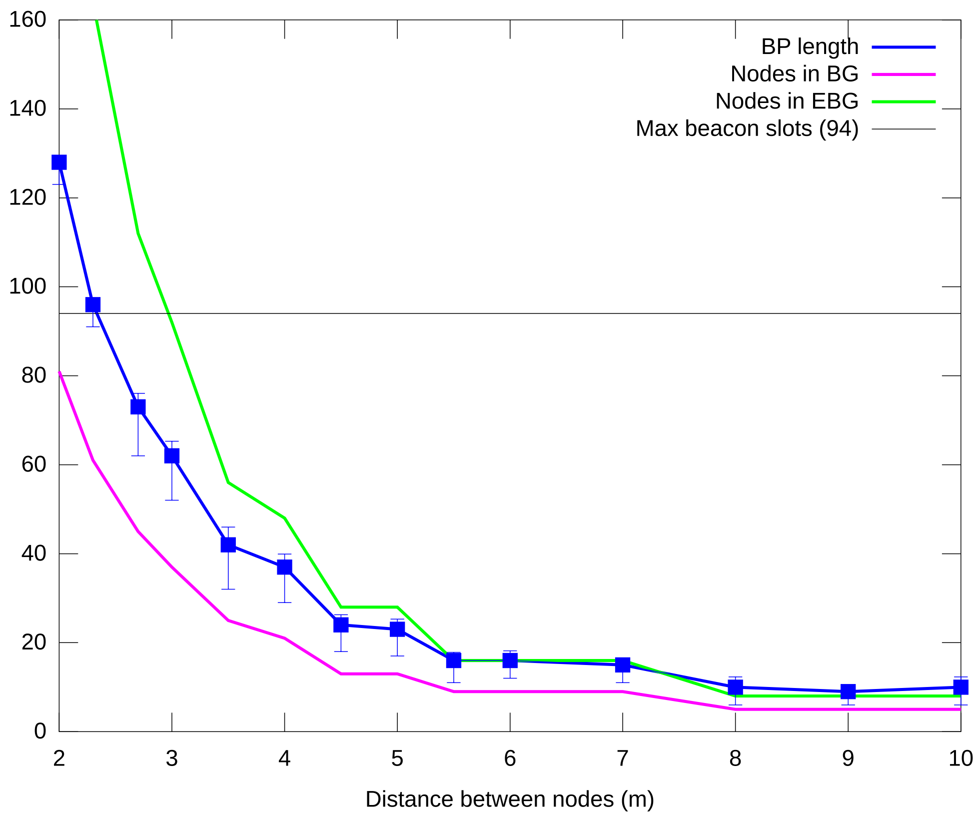


Figure 3.7: Beacon period length simulations

Two-colourable: Any graph is two-colourable if it does not have a closed sub graph with an odd vertex number.

Five-colour-theorem: Any planar graph is five-colourable.

Four-colour-theorem: Any map with border segments (not border points) is four-colourable. The graph of the map is also planar, but has additional constraints on the borders.

The graph colouring problem is NP-complete, so by definition no efficient algorithm exists to calculate the optimal solution within reasonable time for the aircraft scenario. Thus, for complex graphs the calculation of the chromatic number and the colour assignment is not possible. This problem has however been addressed in the past and several approaches exist:

Exact algorithms are those, which will find the best solution. Since it is a NP-complete problem, all possible combinations have to be checked. Even for a relatively small graph this approach can be impractical due to the large number of solutions and the required time for computation. A *brute-force* algorithm will generate and check all possible solutions. Since the algorithm is checking literally the complete solution space, it is highly

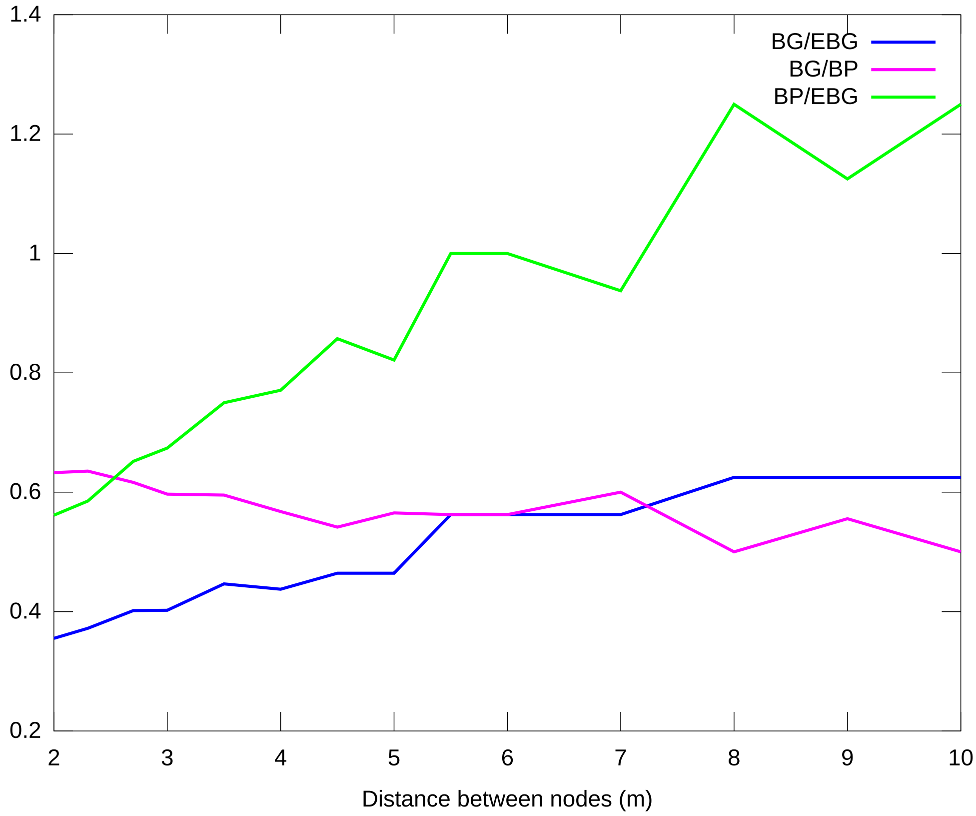


Figure 3.8: Correlation of the BP, BG and EBG

inefficient. Another possibility are *backtracking* algorithms. The objective of the algorithm is to find a solution with n colours. It starts assigning them and as soon as the objective cannot be reached, it goes back and changes the colour of a previous node. Backtracking does not calculate the chromatic solution directly, but can find a solution that is n-colourable. With the termination criterion not the complete sample space is checked, but still very long computation times are required, which make backtracking inefficient.

Since exact algorithms do not compute, a list of *heuristics* has now been developed. Heuristics are algorithms that find very good solutions to a problem, but the solution is possibly not the optimum. Often stated approaches are *greedy* algorithms. These algorithms colour the most suitable node for every step using a given set of constraints. Greedy algorithms may might not lead to a global optimal solution; they may not even find a local optimum. But greedy algorithms often find good solutions in reasonable time. Another possibility are *genetic* algorithms. Here the solution is found by mutating or inheriting valid solutions in hope to find better one.

In wireless networks some problems can be described as a colouring problem. In [MRP04] the channel allocation in WLAN is addressed. And in [QJd10] the TDMA slots of the

Distance (m)	6	5	4	3	2.7	2.3	2
Density (m^{-2})	1/36	1/25	1/16	1/9	0.14	0.19	1/4
BP length	16	23	37	62	73	96	128
Nodes in BG	9	13	21	37	45	61	81
Nodes in EBG	16	28	48	92	112	164	228
BS collisions	13	27	40	52	62	73	102

Table 3.1: Beacon period length simulation results

MAC protocol are assigned by using a colouring algorithm. Characteristics of wireless multi-hop networks are addressed in [Bet02]. This research uses graph theory to investigate the connectivity of a wireless network. On the first view, all these solutions to problems in wireless networks seem to be applicable to ECMA-368. But as shown in the next paragraphs, some fundamental differences exist, that prevent the reuse of the existing algorithms.

The beacon slot selection problem can be formulated as a colouring problem. The colour is the selected beacon slot ID and the vertices are the connections to the 1-hop and 2-hop neighbours. The basic statement is that an activated node cannot select a beacon slot, which is already occupied by any node in the 2-hop distance. This means that the vertex degree of the graph is relatively high and that almost all networks will have a non-planar graph. Note that this requirement also includes the fact that all nodes in transmit range of one node must have exclusive slots (even when they are not in range themselves), since they are now connected by an edge and cannot occupy the same slot.

A second requirement of ECMA-368 is that all nodes select or change to the first available slot. Thus, for a valid solution every node must not have an unoccupied beacon slot before its own. This is a requirement that many solutions for the graph colouring problems do not have.

These two constraints on the selection make the problem complex and unable to be solved with exact algorithms (unless it is a very small network).

3.1.4 Analytical examination of beacon period length

Section 3.1.2 has shown that the beacon period length is variable and depends on the activation order. Of great interest are the shortest possible beacon period and the longest possible.

The shortest beacon period length represents the maximum number of nodes that can be operated for a given density or topology. It is also the solution with the most data transfer capacity in the superframe; hence it is an optimisation for the throughput. How the network will apply the optimal solution is not in the scope of this work, due to two reasons: Firstly, the standard must be modified, since it does not include methods to

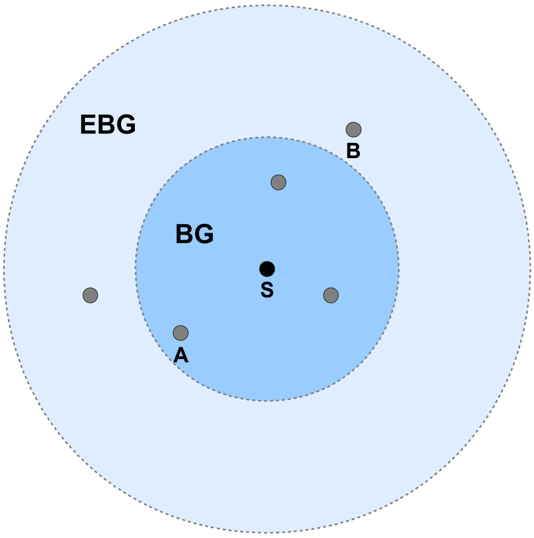


Figure 3.9: Reuse of beacon period slots. Node A and B can use the same slot.

initiate a defined beacon slot change from an application. Secondly the distribution of the optimal solution is not trivial, because if the nodes are being activated without the knowledge of the optimal solution it will cause some nodes not to be able to join the network.

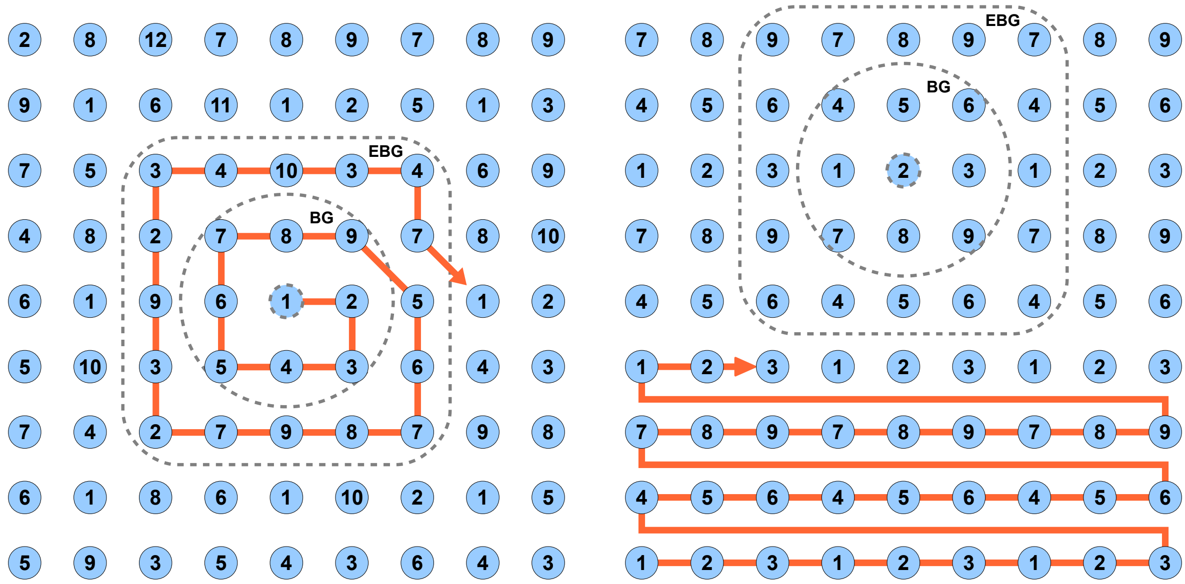
The longest possible beacon period is of greater interest to the aircraft scenario. It is the worst case situation, with the smallest number of nodes where a newly activated node could not join the network. For safety critical systems the network planning should always consider the worst case, as otherwise the system may not be able to include all nodes in the group.

Best case beacon period length

The ideal solution is to have a beacon period length that has the size of the largest BG in the network plus the eight free slots after the last used slot (in accordance with the standard). All nodes in one BG must have exclusive slots, so the length can never be less than that. Figure 3.9 shows that a node of the BG (node A) and a node of the EBG (node B) can reuse the slot, as long as they have a hop-distance of more than two.

The mathematical formula for the best case beacon period length is shown in Formula 3.3, where r is the transmit range and D is the node density. This is only an approximation, as in reality the number of nodes in range is an integer and would cause a curve with steps, rather than a continuous monotone equation.

$$N_{BC} = \pi r^2 D. \tag{3.3}$$



(a) Spiral - requires 12 slots

(b) Line-by-line - requires 9 slots, optimum

Figure 3.10: Two approaches for activating the nodes in a coordinated manner. The line-by-line (b) approach is more efficient and finds the optimal solution.

There are a number of questions that need to be asked, such as: Is this theoretical minimum possible? Can it be achieved in a real scenario? To solve these questions several procedures and heuristics were tested.

The most unfavourable situation occurs when parted groups of the network become connected by activating a node. The simulations in Section 3.1.2 have shown that this causes collisions, relocations and at worst beacon slot reuse. So a coordinated activation that expands the activated area continuously seems to be a good approach.

Figure 3.10 shows two methods of coordinated mode activation. The spiral approach has the longest connected path in the network, without any break. It requires 12 beacon slots for the nodes. In the line-by-line method only nine slots are required. It can immediately be seen that this is the optimal solution, since 9 is the number of nodes in the BG. No better number, except in the border areas, can be achieved, because all nodes in the BG must have an exclusive slot.

The theoretical minimum is shown in Figure 3.10(b). The layout is also a *valid* one, which can be achieved with the standard protocol guidelines.

The grid layout from Figure 3.10 is artificial and will most likely not occur in an aircraft or other application. Can the optimal solution for a larger network with random node placement also be found? As seen in Section 3.1.3, the problem is NP-complete and only heuristics will come up with a solution. Just for curiosity a backtracking algorithm was implemented, but only worked for an extremely small network. For more than 15 nodes

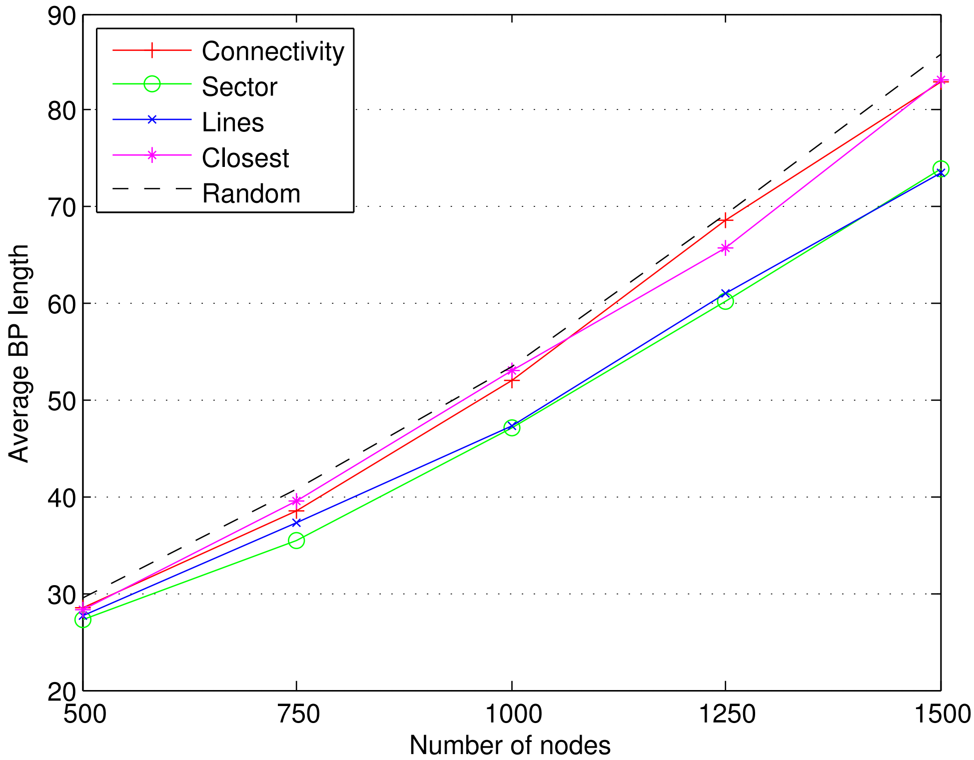


Figure 3.11: Heuristics for average beacon period length of the beacon slot selection for random node placement. Comparison of five different approaches to assign the beacon slot IDs with the goal to have a very short beacon period.

the computation time was too long.

Figure 3.10(b) shows the optimal result. The question therefore becomes: can an optimal or near optimal solution be achieved for any kind of topology. Four heuristics were implemented and tested against random node activation. For the simulations a transmit range of 10 m was selected and the area was 100 m x 100 m. In several steps a number of random nodes were placed in the area and the heuristics started. For each number of nodes the heuristics used the same placement layout. For the evaluation of the results only nodes with 20 m distance to the border were selected. The different approaches were:

Connectivity: This approach activates the nodes according to their connectivity degree (number of neighbours). Nodes with a high connectivity are activated first.

Sections: The area is divided in small squares of one square meter. The sections are processed row by row from left to right and for each section the nodes are activated from south-west to north-east.

Closest: The southernmost node is activated first and then the closest node

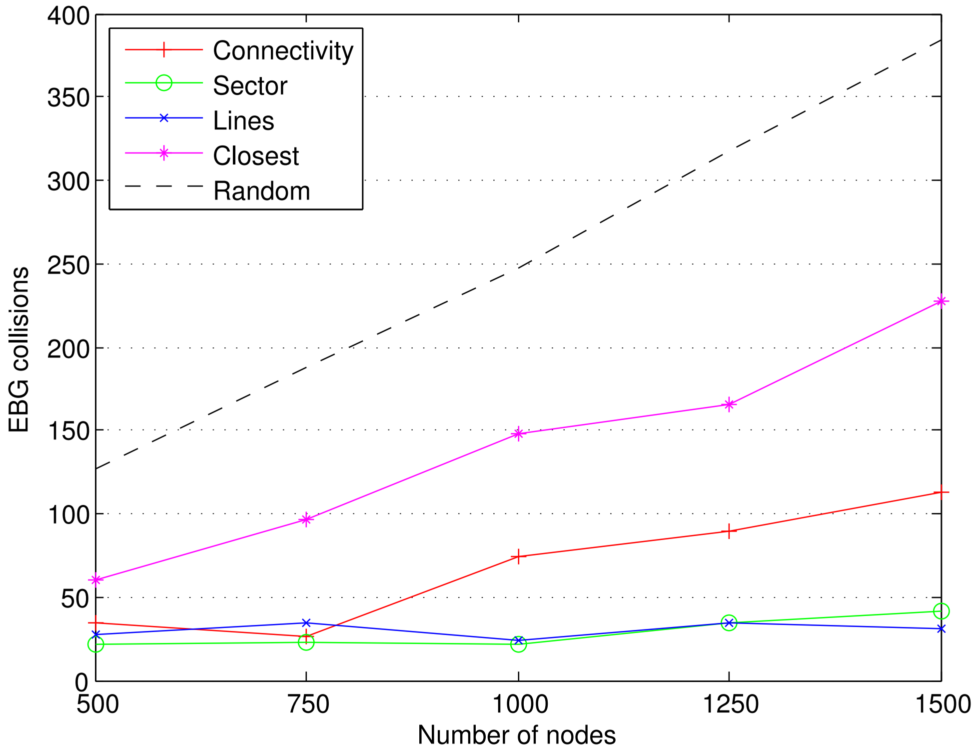


Figure 3.12: Heuristics for average EBG collisions of the beacon slot selection for random node placement. Comparison of five different approaches to assign the beacon slot IDs with the goal of having a very short beacon period.

to the set of already activated nodes is activated.

Lines: First the connected set of westernmost nodes on the field create a *main line*. These are the nodes along the west border that form the edges of the entire node set. The southernmost node of the main line is activated first (which must not be the southernmost node of all nodes) and all nodes south or east of it are activated from west to east, with respect to their connectivity. When the last node in the east is reached, the next node northwards in the main line is activated and again all inactivated nodes south or east of the current main line are activated. The idea is to go through the field in connected rows. While the *Section* approach processes the field in rows based on the coordinates, this approach only adds those nodes, which are in transmit range of the previous node.

Random: In this approach the nodes are being activated randomly, similar to the simulations. This is the reference to compare and evaluate the results.

Figures 3.11 and 3.12 show the results of the different approaches. For the beacon period length the *Sector* and *Lines* heuristics found a solution on average 10 beacon slots shorter than that the *Connectivity* and *Closest* heuristics. This can be explained by the fact that for *Sector* and *Lines* the nodes are sequentially activated with a spatial proximity, while the other approaches can *hop* through the field, depending on the connectivity or distances. The results showed that none of the suggested approaches produced an optimal solution. The number of EBG collisions seen in Figure 3.12 shows a significant less amount of collisions for the *Sector* and *Lines* approaches.

Worst case beacon period length

By analysing the protocol a worst case assumption can be made. As seen in the best case analysis the nodes in the EBG can use slots, which are already taken in the BG. For suboptimal solutions this is not the case and more slots than nodes in the BG are required. It could be possible that all nodes in the BG and EBG require an individual slot. This depends on the locations, the activation order and very much on what slots are used beyond the EBG (since they do have and influence the nodes in the EBG). If this is the case, the mathematical estimation for the number of required slots is given by Equation 3.4, with r being the transmit range and D the node density. As for Equation 3.3 this is an approximation with a continuous function.

$$N_{WC} = \pi(2r)^2 D. \tag{3.4}$$

Calculating the worst case situation is as difficult as calculating the best case. Again the problem is NP-complete and no heuristic could be identified that determines a very inefficient slot allocation, given the rules from the ECMA-368 protocol.

The worst case assumption was analysed for practicability. The goal was to construct a configuration that is achievable (in accordance with the rules from the standard) and that requires at least one node to have for each node in the BG and EBG a unique beacon slot.

An algorithm was implemented that creates a centre node, a BG and an EBG around this centre node. Each node had a unique beacon slot. More nodes were created as needed around the existing nodes, to have each node to fulfil the protocol rules. The rules say that each node must not have a free beacon slot before its own, otherwise the node must change its slot to the free position. A grid placement was chosen to have a uniform node density. Figure 3.13 demonstrates the result for a configuration where the used beacon slots number matches the number of nodes in the BG and EBG. The numbers in the figure represent nodes and show the selected beacon slot IDs of the nodes. Here the connectivity, depending on the node distance and transmit range, was set to have the eight surrounding nodes in transmit range (indicated with the dashed BG and EBG lines). The shown figure gives an example where a node is forced to select a beacon

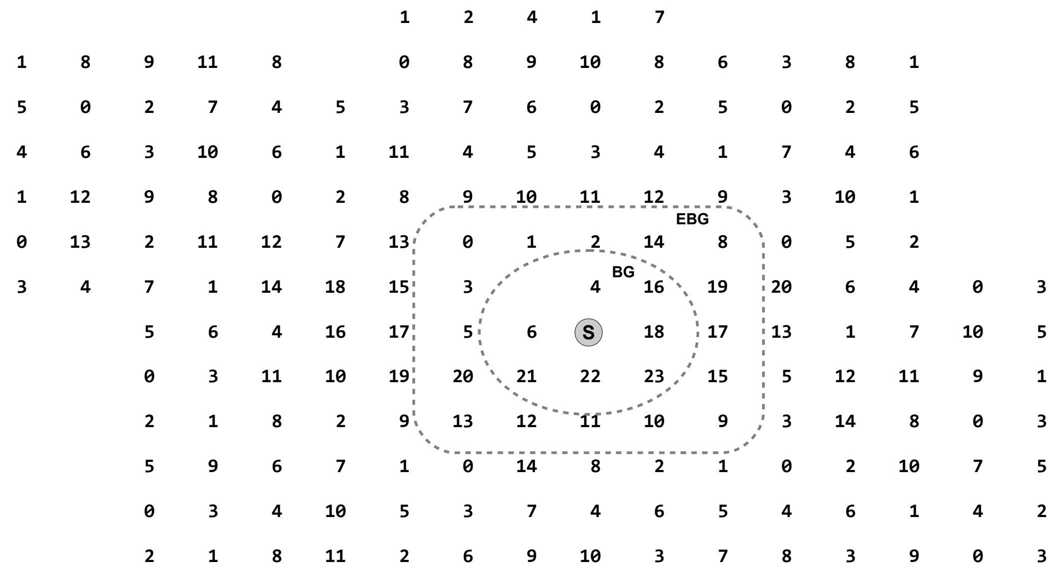


Figure 3.13: Beacon period length - worst case. Each number represents a node and indicates the selected beacon slot (starting at 0). The subject node is activated last and is forced to take slot 24. The number of required slots matches the number of nodes within a 2-hop range.

slot with a slot ID that matches the number of nodes in the 2-hop distance, which is the worst case situation.

The algorithm was also tested in a scenario with doubled node density. In this case the number of nodes in the BG and EBG is larger. A layout was created that has no slot reuse for at least one node in its 2-hop distance.

3.1.5 Node density conclusion

Combining the results from the simulation, best case and worst case analysis will result in the graph shown in Figure 3.14.

The information gained in this section can be used for network planning. It shows the capabilities and limitations of the beaconing mechanism in the ECMA-368 protocol. The scenarios were generic and independent from the aircraft application.

The question is; what can be derived from these results for the aircraft application? Table 3.2 gives some estimates on the number of nodes required for different aircraft types. A three class seating was assumed for the Passenger Service Unit (PSU). The

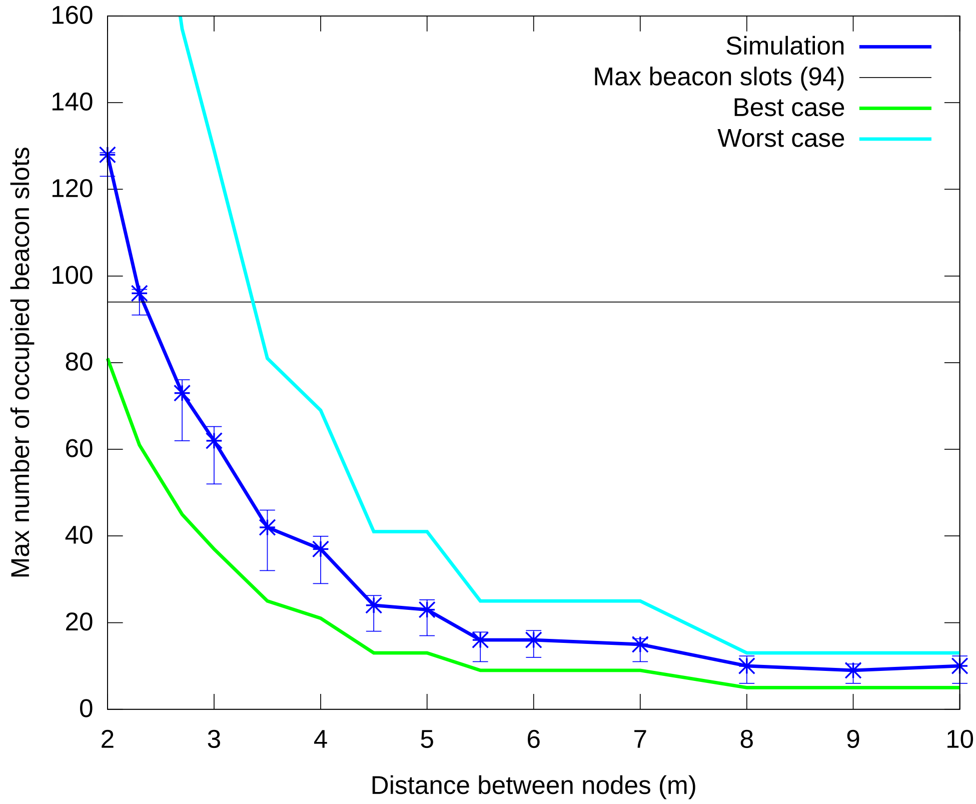


Figure 3.14: Results from the beacon period length simulations for a grid placement, including the best case and worst case bounds.

number of nodes for the illumination, sensors and extra devices are estimates. For the cabin illumination it was assumed that there will be a light control module every 2 m in each aisle and some extra modules at the doors and galleys. The APs are not included, only the end devices are shown.

Aircraft	PSU	Illumination	Sensors	Extra	Sum
A320	55	20	100	50	**225**
A340-600	151	80	200	100	**531**
A380	199	140	320	160	**819**

Table 3.2: Devices per aircraft type

Table 3.3 shows the expected node density in the different aircraft types. It is apparent from the table that the values are far beyond the maximum density calculations. One also has to consider the tube structure of the aircraft fuselage. With 10 m transmit range and a 3.7 m wide fuselage for the A320, parts of the transmit area do not have nodes (the area outside the aircraft). So the effective node density is less than previously calculated. But the density is still too high. A node transmit area has a diameter of 20 m; this is in fact the area covert by the BG. Beyond the BG follows the area of the EBG with 10 m range. This would make an area of 3.7 m x 40 m the approximated area to consider for the beacon slots. The A320 cabin is only 27.5 m of length, so for the centre nodes the remaining 224 nodes are either in the BG or EBG. The same consideration can be done for the other aircraft types. It is obvious, that an aircraft with full wireless services cannot be operated in a single channel set-up. Frequency diversity by using multiple channels simultaneously is a must for this application.

<table>
<tr><th>Aircraft</th><th>Nodes</th><th colspan="2">Area</th><th>Density (nd/m^2)</th></tr>
<tr><td>A320</td><td>225</td><td colspan="2">3.7m x 27.5m
= 101.8m^2</td><td>2.2</td></tr>
<tr><td>A340-600</td><td>531</td><td colspan="2">5.3m x 61.0m
= 323.3m^2</td><td>1.6</td></tr>
<tr><td>A380</td><td>819</td><td>Upper deck
6.5m x 49.9m
= 324.35m^2</td><td>Main deck
5.8m x 44.9m
= 260.42m^2</td><td>2.52 (both decks)
1.4 (separate)</td></tr>
</table>

Table 3.3: Node density per aircraft type

3.2 Network protocol simulation

There are several aspects of the protocol that cannot be investigated with analytical methods or as an isolated problem. To get information about the performance in complex problems the protocol was implemented in the OPNET® simulation environment. The focus is on the MAC protocol and therefore an abstracted model is used for the physical layer. The channel model from [SES+08] was used to derive bit/block error rates and signal strength distribution depending on the distance between two nodes and the desired data rate.

The supported MAC features are: beacon slot selection, including BP contraction, BP merge and beacon collision handling, and the MAS reservation algorithm. Mobility for nodes is supported by establishing the connection to the AP with best Signal to Noise Ratio (SNR). Generated data traffic is transmitted in DRP reservations which are created between client nodes and APs. The reservation scheme is designed to guarantee for each node a predefined maximum access delay to the AP. The access delay is defined as the time interval between two consecutive reserved slots.

3.2.1 Initialization

If many nodes are powered at the same time, it will take a long time for all nodes to join the network. The standard recommends eight free beacon slots after the last occupied slot.

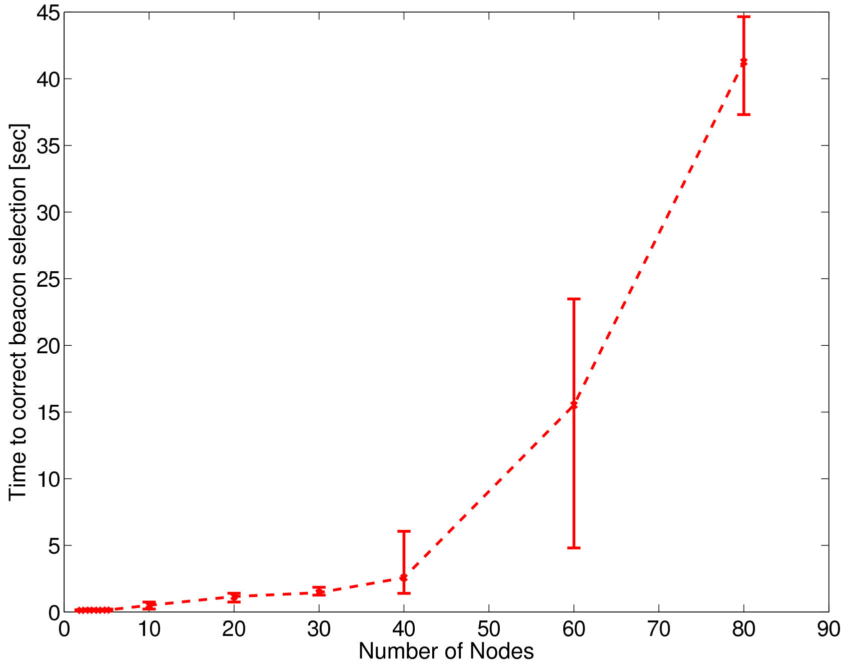


Figure 3.15: Nodes initialisation

The superframe is 65 ms long. If multiple nodes try to join the network simultaneously, they all have to select one of the eight slots randomly and may create a collision. The nodes involved in the collisions will wait a random time and try to access the network again. For a low join rate the protocol can operate efficiently, but for high join rates a high number of collisions will occur. The first nodes in the network will have to create the first superframe; during this time collisions can happen.

The collision probability can be given with:

$$p_{SlotCollision}(N) = 1 - (1 - \frac{1}{mBPExtension})^{N-1} \tag{3.5}$$

where N is the number of nodes and $mBPExtension$ is the number of possible beacon slots for new devices (eight are recommended in the standard). In Figure 3.15, the average time and variance between powering the nodes and correct beacon slot selection of all nodes is shown. The exponential relation shows that for forty nodes or less operating simultaneously within range, the network stabilisation is below three seconds, which is satisfying. Above forty nodes the time takes significantly longer.

The obtained data is in line with results from [VLS$^+$06] that made an analytical analysis of the beaconing mechanism.

There is a statistical variance throughout the runs because of the randomly chosen beacon slot at initialization. Thus, the upper bound of the variance does not represent the worst case, but rather the statistic relevant upper border. Although the theoretical maximum possible number of nodes is 94, it was not possible to get a successful beacon selection in a simulated period of 240 seconds. So it is not reasonable to operate the system at this theoretical limit.

3.2.2 Access point failure

The concept for the aircraft cabin management system contains a redundant AP coverage for the ECMA-368 network. This is due to the high reliability demands. If an AP fails or the channel is blocked, the end devices should register to an alternative AP.

The AP failure was simulated. The standard allows *scan while inactive*. This allows nodes to scan on other channels while they are not communicating in their own BG. The availability of surrounding nodes and APs on different channels is known to the nodes. The simulation assumed three APs in a row and 24 nodes per AP. After the failure of the centre AP 12 nodes will join the first AP and the other 12 nodes join the last AP. A link is considered lost when for mMaxLostBeacons superframes, which is three superframes, the beacon of the AP is missing. Then the node joins the backup AP. Each node has two MASs reserved for communication with the AP and the packet generator creates 188,675 kb/s, which results in an average MASs utilisation of 20%. Figure 3.16 illustrates the simulation results for the correct transmitted data. The y-axis shows the accumulated transfer rate of all nodes.

At time $t_0 = 25s$ the failure appears. There is a slump in the transfer rate because of lost DRP reservations. At this point, the nodes try to set up their Beacon and reservations at the new backup AP. The phase is between $t_0 < t < t_1 \approx 28s$. The overshoot is due to waiting data in the corresponding output queues of the nodes. The system is in steady state at $t_2 \approx 40s$.

3.2.3 Alien Nodes

The final scenario is the existence of unknown nodes in the same frequency spectrum, also called Alien Nodes; for example passengers with WiMedia enabled notebooks. In this case, two nodes reserving all MASs are entering a cell inside the airplane. The result of this simulation is plotted in Figure 3.17. It shows the transfer rate, which is the amount of correctly transmitted data of the airplane nodes.

First, the unsynchronized BP of the Alien Nodes disrupts the communication completely because of conflicting DRP reservations and beacon slots at $t_0 \approx 31s$. Then the *beacon period merge* is executed to synchronise the two networks. After the synchronisation the conflict for the MASs reservations are solved. The chances by the Conflict Tiebreaker bit give a 50% probability to win the conflict. This is done for each MAS individually, so in

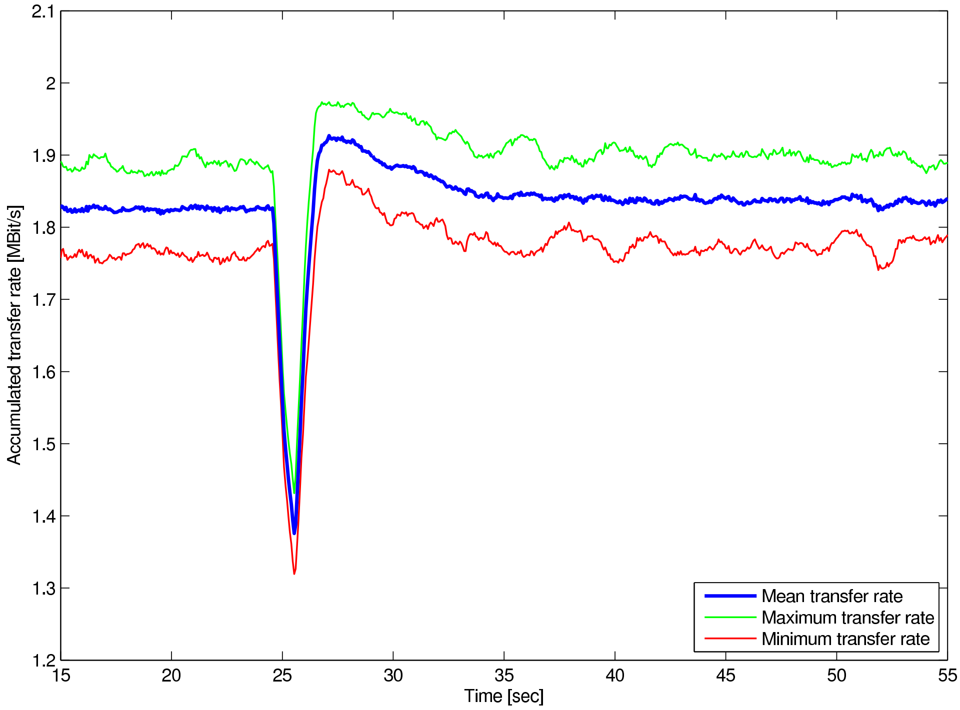


Figure 3.16: Access point failure

extreme cases it could happen that most of the MASs belong to the aircraft or most of the nodes belong to the Alien Node pair.

3.3 WiMedia Logical Link Control Protocol

WiMedia LLC Protocol (WLP) is the Logical Link Control (LLC) protocol of the WiMedia standards. It is not part of ECMA-368 and defined in a separate document [WiM07]. The approved draft 1.0 is publicly available on the WiMedia Alliance website.

The LLC is is part of the Data Link Layer in the seven layer OSI reference model. In the IEEE 802 reference model the LLC protocol creates together with the MAC protocol the Data Link Layer as known from the OSI reference model, see Figure 3.18. An example for the MAC protocol could be Ethernet, defined in the standard IEEE 802.3, and the LLC as defined in IEEE 802.2.

Key responsibility of an LLC is the transparent link to different MAC protocols and thereby allow the Network Layer to access different MAC technologies. It enables the differentiation of Network Layer protocols (such as IP, IPsec or ICMP); thus the network stack can identify which protocol this packet must be handed to. Another feature of a LLC is flow control. Together with wireless networks, for example IEEE 802.11 or

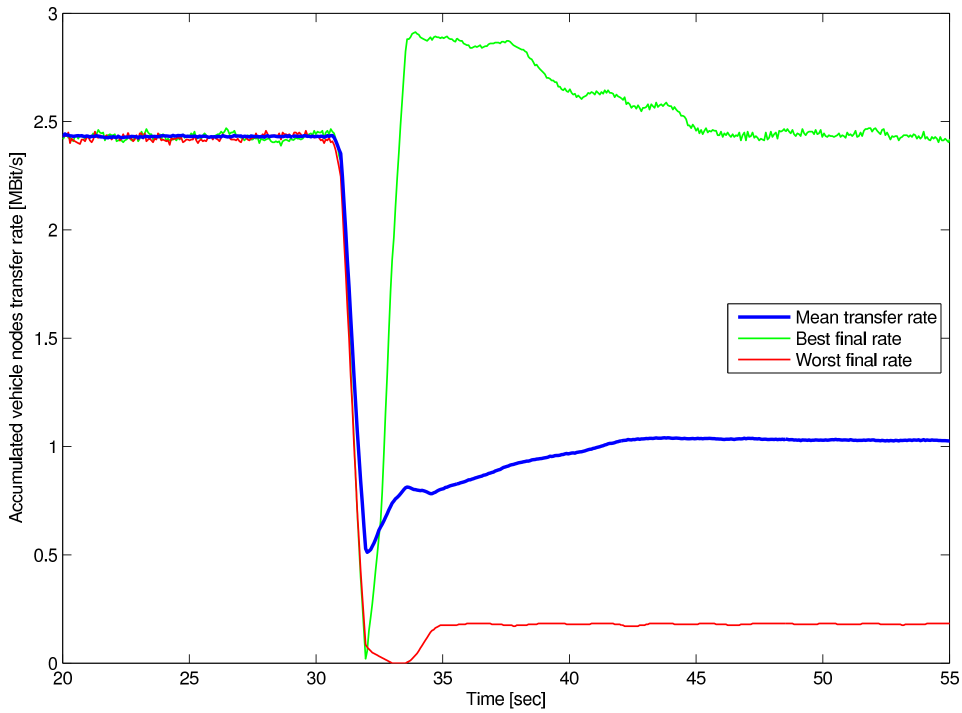


Figure 3.17: Alien Nodes intrusion

ECMA-368, the LLC can also manage encryption and logical segmentation of the network by identifiers, known as Basic Service Set Identifier (BSSID) in IEEE 802.11 and WLP Service Set Identifier (WSSID) in ECMA-368.

The impact of WLP to the network performance was investigated by adding the WLP features to the MAC simulation implementation. Of interest were the start-up times, times on topology changes and protocol overhead. As a results it was identified that the performance of WLP is significantly dependant on the MAC protocol setting. As described in detail in Section 5.2.1 the WLP requires four or six messages to set up an unencrypted connection. The duration of exchanging these messages and processing them in time depends on the channel access, which are PCA or DRP. With PCA the messages can be exchanged in a fraction of a superframe. But for DRP with an awkward MAS reservation this can take up to five superframes. The overhead of WLP is 28 bytes extra per MAC data frame. This is constant over time.

3.4 Summary

In this section several limiting aspects of the ECMA-368 and WLP protocol were addressed. Node density is in principle a limiting parameter for the aircraft scenario if only one channel is used. To provide enough resources in the aircraft a multi-channel archi-

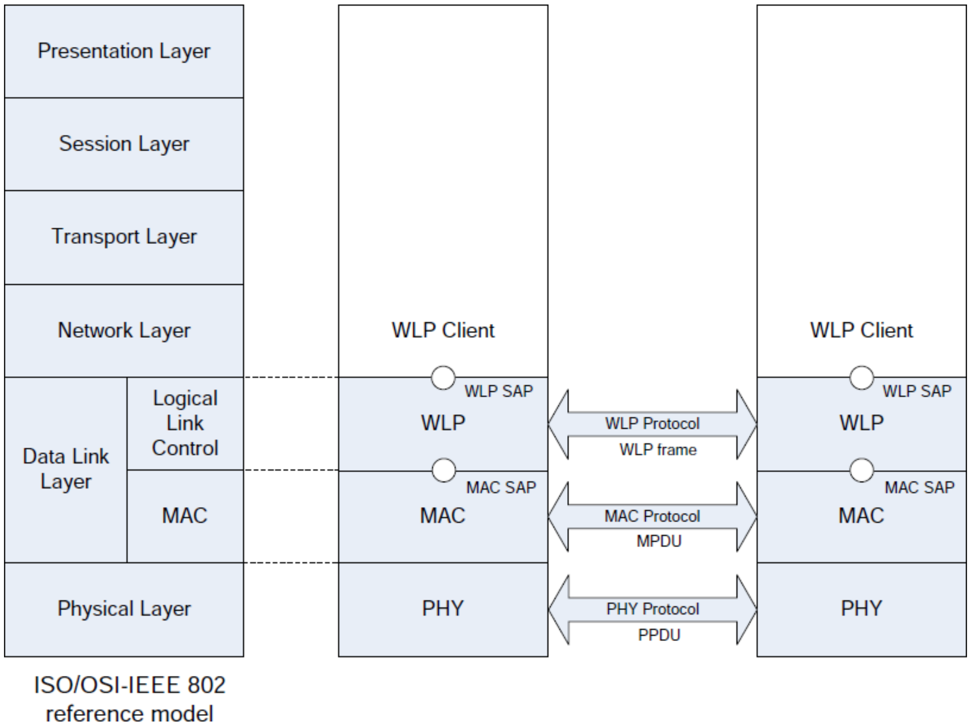


Figure 3.18: WLP architecture (Source: [WiM07])

tecture must be used. ECMA-368 provides up to 14 channels thus this should be less of a problem. The start-up times of the network are also within the tolerances if less than 40 nodes are in a cell. Connection losses or device failures can cause delays or packet losses, but only for up to two seconds. Two seconds connection loss when is transceiver is blocked may create discomfort for the passenger. The result is to use the secondary link in this cases. The added procedures from WLP also require time and resources, but these are not significantly and can be tolerated.

One problem of the ECMA-368 network in the aircraft scenario might still be the Alien Nodes. They can cause huge disruption of the network. One targeted solution was to address this in the WiMedia Alliance and create an extra policy in the standard that does not allow passengers devices to use DRP reservations inside the aircraft. But since the activities of the protocol definitions are currently on hold this approach was not followed. Another solution to this problem is to arrange the reservation scheme in that way, that the end devices hold the reservation to the AP. In this case the Alien Nodes have a smaller chance of winning the reservation conflicts. Another item to consider is that for Alien Nodes the network is not interrupted by collisions. The Alien Nodes and aircraft network would synchronize and a localisation of the nodes is possible. A warning to the flight attendant could be given to provide the location of the devices and request the passenger to turn them off. During the interrupt the secondary link can be used.

Chapter 4

Aircraft radio resource management

As for all wireless access networks the radio resource management question arises for the aircraft scenario. With the choice for ECMA-368 the degree of freedom is limited to Access Point (AP) positions, the channel selection and the Medium Access Slot (MAS) reservations. In this chapter only the resource management of the UWB sub-network is addressed and not the secondary interface.

The AP positions depend on several parameters: signal propagation, number of backup APs per end device, data rate and delay requirements and on the maximum number of devices per AP. The positions for the APs cannot be chosen freely. There will dedicated spots where the installation of an AP is possible.

For the channel selection, 14 non overlapping channels exist. By using frequency hopping two or three channels are combined into one. Five channels therefore exist for frequency hopping; also non overlapping. In general the lower frequencies have a better signal propagation and are preferred. The channel allocation plan depends on the AP and end device locations. The cells should not interfere with each other.

The MAS reservation ensures that each end device has the required minimal data rate and maximal delay. These parameters depend on the application requirements.

For a holistic solution the resource management can be split in two phases. Phase one is done during the configuration of the cabin. It decides where the AP will be mounted and what a default channel allocation can look like. This phase needs to be repeated every time the cabin is reconfigured. This phase is called *network planning* in this work.

The second phase is called *real-time resource management* and handles the resources during the operation of the system. Wireless systems naturally experience interferences, especially UWB technology, since it does not have its own frequencies. The interferences come from other wireless systems, such as from the aircraft, the airport or the environment. Interferences can also originate from other nodes of the system itself. Additionally, different countries have different emission masks for UWB and therefore the system must adapt to them, depending on the aircraft's location. The system must adapt to unintentionally blocked devices, for instance a metal briefcase in front of an AP can cause connection losses. The real-time resource management will continuously monitor the status of the system and adapt to the current situation. While the AP positions cannot be changed, the degree of freedom lies in the frequency allocation and the MAS reservation of the devices.

4.1 Network planning

The network planning solves the question for the optimal AP positioning inside the aircraft cabin. The end device locations are known and a set of Access Point Candidate Sites (APCSs) are given. Additional to the AP positions a valid channel allocation plan is calculated. A technician doing the refitting of the aircraft cabin uses the network planning algorithm to identify if a given layout is possible with the wireless Cabin Management System (CMS) and where the AP should be installed.

4.1.1 Acess point placement and channel allocation problem

The challenges of optimal node placement and channel allocation are known problems and have been an active research field for several decades. It is mostly formulated as a Set Covering Problem (SCP) [CNS97]. In the case of wireless network planning an area is analysed for the most often used end device spots and therefore the potential AP spots. The SCP calculates the locations of the APs that cover all or most of the end device spots by optimizing a predefined cost function. This cost function can consider various parameters, such as installation costs, bandwidths, signal-to-noise ratio, power adaptation and channel selection.

In the beginning the cost function usually targeted the installation costs. The algorithms were used for planning of cellular networks [Tut98], such as GSM networks. The price and installation costs of base stations are very high and the objective is to reduce costs. Figure 4.1 shows an example of the theoretical channel allocation in cellular networks. Seven channels are required to avoid neighbouring cells with the same channel. Over the years sophisticated techniques have been developed to reduce the interferences between the cells. These techniques include sectored antennas and synchronised frame structures between the base stations to avoid multiple transmissions in the same direction. As a result the base stations became complex and expensive.

With the spreading of Wi-Fi networks the situation for the algorithms changed, as APs are relatively cheap. The resource management algorithms were modified and improved for Wi-Fi usage. Also the situation of using one single channel for a large area with multiple

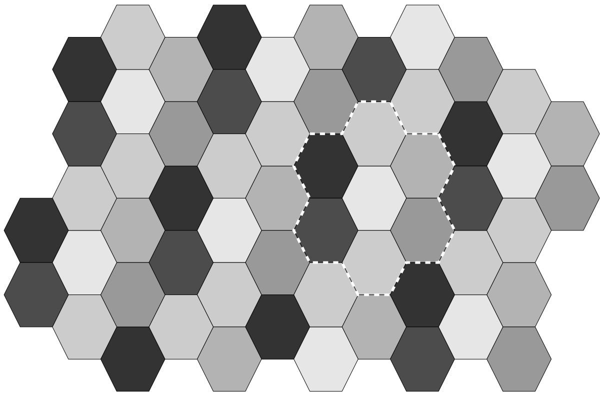


Figure 4.1: Channel allocation of cellular network

APs gained interest and became the focus of the research. This is usually avoided in cellular networks, since it causes interferences.

From the new applications a variety of algorithms emerged with different kinds of cost functions. The authors in [SL05] cover several issues, such as throughput, path loss, transmission power and traffic characteristics.

In [PJKC02] the data rate of each user is maximized. The signal quality is subject of an integer linear programming formulation in [MLR01], which does not require covering all of the area if the costs become too high. The attributes network capacity and coverage are addressed in [Hil01]. In [KU02] the overall and individual path loss is subject to optimization.

The authors of [BCC07] have investigated the AP problem in single and multi channel scenarios for three different methods: the classic SCP, a Minimal-Overlap-Problem and the Maximum-Efficiency-Problem. The SCP produces many overlapping areas, whereas the Minimal-Overlap-Problem avoids them, but still covers the area. The best performance showed the Maximum-Efficiency-Problem, but it also uses the most APs.

Optimization problems for node placement and frequency allocation are often done in two steps. First the placement problem is solved and then the resource allocation is solved. By separating these two problems the optimal solution may not be found. In [EGS07] the authors present an integrated approach solving both problems in one step.

Integer linear programming

Linear programming is a common method for finding the best solutions of optimisation problems. It is used in very different disciplines, such as engineering, mathematics, logistics, economy, and many more. The problem must be expressed in a set of equations, which include one or many variables. There is one cost or utility function that must be

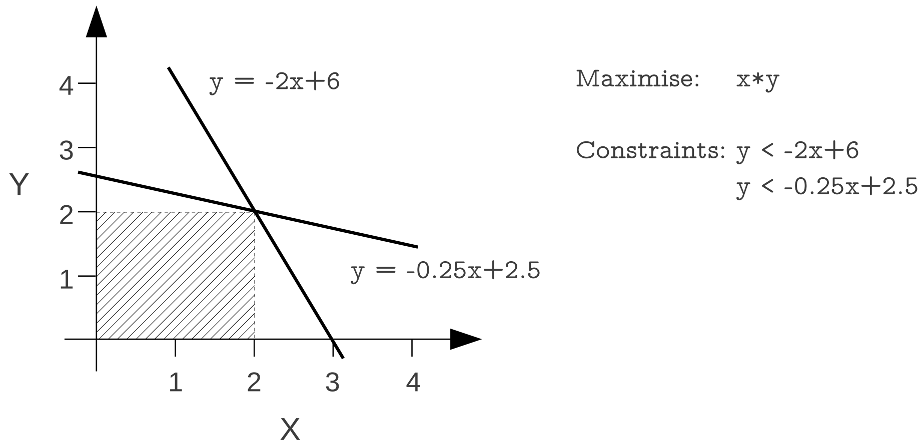


Figure 4.2: Optimisation example

minimised or maximised. Additionally there can be constraints that give extra requirements to find the solutions.

A very basic example of optimization programming is shown in Figure 4.2. The ultimate goal is to minimize a cost function or to maximize a utility function defined by one or more variables. In the example the goal is to maximize the term $x * y$, which can be seen as the goal to maximise the rectangle area of x and y. The constraints are given by $y < -0.25x + 2.5$ and $y < -2x + 6$, thus only results where x and y are within these bound are valid. The optimal results is at $x = 2$ and is shown as the area in the shaded square.

The term *linear* tells us what kind of equations are possible. For *linear programming* only equations, inequations or objectives of a linear nature, for instance $ax + by + cz \leq 0$ are allowed. The algorithms to solve this formula sets are very efficient, since they only have to follow the borders. *Non-linear programming* is also possible, but it is considerably more difficult and complex. For some non-linear equations, like *convex* or *quadratic* problems, efficient solvers exist, but still they are far more complex than linear problems.

The term *integer* implies that only integer variables are allowed in the solutions. This is a requirement for a number of optimisation problems. It has significant impact, since the problem then gets NP-hard in general, as shown in [Wil09]. This means finding the optimum is significantly harder than for a real linear problem. However, for integer linear problems the solution space can be limited efficiently and solving the NP-hard problem in reasonable time is possible. Finally *mixed integer linear programming* allows having real and integer variables in the system. To speed up the solving process every variable that can be a real number, and not integer, should be defined as a real number.

Several exact algorithms to solve mixed integer problems exist. In the *Branch & Bound* approach the solution space is reduced by modifying upper and lower bounds until the optimal solution is found. In the *Branch & Cut* method the equation set is extended by more linear terms to narrow down the solution space. *Branch & Price* is an extension of Branch & Bound, but uses a heuristic for the beginning and a pricing method to prove optimality. A detailed description of the mentioned algorithms is available in [Kal02]. Also more approaches exist, that can be found in the book.

Integer linear programming is used in many practical applications. Logistic problems, such as calculating optimal routes, or also trip information from public transport or car navigation systems use this technique. For wireless networks it can also be used for a number of problems. This section has already given some examples. [HL08] describes the usage of integer linear programming for wireless networks in detail and gives examples for power management, Orthogonal Frequency Division Multiplex Access (OFDMA) optimisation and cooperative routing.

4.1.2 ECMA-368 radio resource optimisation

Despite similar usage of WiMedia and IEEE 802.11 networks there are fundamental differences between the two that have an impact on the resource management strategies.

The WiMedia specifications provide 5 to 14 non-interfering channels, depending on the frequency hopping sequence. In the IEEE 802.11b/g standard 13 channels are defined, which do partly overlap. This allows only a combination of at maximum three non-interfering channels [GBCM07]. This makes area coverage without overlapping cells of the APs very complex. A larger number of channels increases the spatial separation of the AP cells and enables more efficient resource management.

Many networks use managing nodes for the medium access coordination, for instance the AP in IEEE 802.11b/g or the Coordinator in IEEE 802.15.4. Uncoordinated networks usually use Carrier Sense Multiple Access (CSMA) mode, which can result in a large number of collisions for highly utilized networks. Ready-to-send / Clear-to-send (RTS/CTS) messaging can reduce the collisions, but also increase the overhead.

The WiMedia approach is completely infrastructure-less, meaning all nodes have the same physical and MAC layer capabilities. Despite the infrastructure-less architecture, WiMedia is contention free. The protocol uses periodic superframes containing a beacon period and a data period (see Figure 3.1). All nodes allocate a beacon slot in the beacon period, regardless if they have to transmit user data or not. This slot is fixed over time and changes only in rare conditions. For reservation based medium access mode the beacons are used to announce transmissions and reserve parts of the data period. Conflicts are identified early and collisions can be mostly avoided. The only time that collisions occur is in the beacon slot allocation process, which only applies to new nodes joining the network.

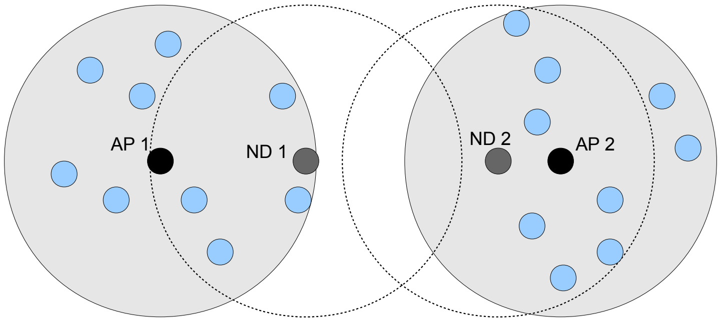
The beacons contain details of all upcoming transmission in the data period. This means a single node knows when a neighbour communicates with another node. This feature makes WiMedia not susceptible to the *hidden terminal problem*, see Figure 3.3. Two adjacent APs on the same channel can have overlapping areas without causing losses. Systems using CSMA, such as Wi-Fi, require eliminating or minimizing overlapping cells with the same frequency, as collisions are expected to increase in the overlapping region.

With the beaconing a hard limitation applies. The beacon period only has 96 beacon slots, including two slots reserved for special functions. This means no more than 94 slots are available and must be shared among the Beacon Group (BG) and Extended Beacon Group (EBG), which has already been described in Section 3.1.1 and shown in Figure 3.2. A newly activated node picks a beacon slot that is not occupied by a node of the BG or by the EBG. This rule implies that for any given node the beacon slot IDs of the BG members must be unique, otherwise they would cause collisions. For the EBG members the IDs can be identical, because the subject node cannot listen to them, but must not transmit at the same time as it would cause collision at the node that has the subject node and the EBG-node in its BG.

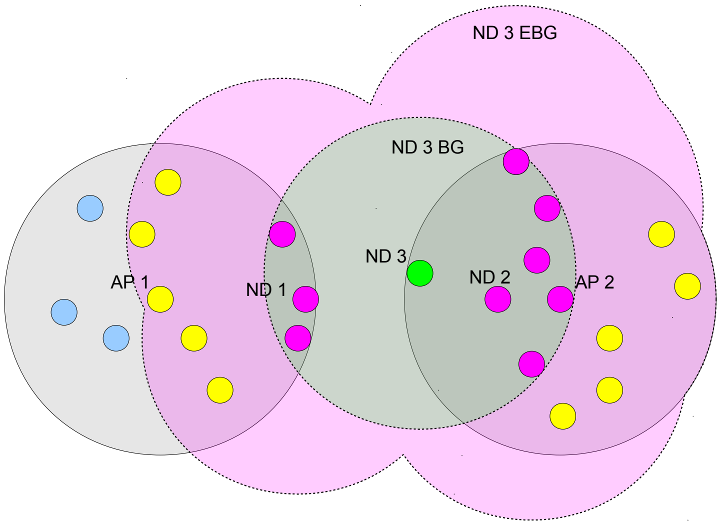
The consequence of overlapping areas in WiMedia is the extension of the EBG. When a border node is within range of two APs, it will add parts of the second AP nodes to its BG, which again appear in the EBG of the first AP. Hence, overlaps increase the EBG size and therewith limit the maximal node density. Figure 4.3 illustrates this relation. The example shows, that by placing one additional node the number of maximal existing BG/EBG nodes in the network rises from 10 to 19.

The BG size is directly related to the node density and transmission range, as slots may only be occupied by one node. The EBG size additionally depends on the activation sequence of the network. A detailed analysis was shown in Section 3.1.1. The beacon period length depends heavily on the node activation order. Including an exact calculation of the beacon period length into the algorithm, would heavily increase the complexity of the optimisation algorithm. The problem is no longer able to be solved using modern computers. Instead the algorithm uses the number of nodes within the EBG and keeps this number under a certain threshold. This bound was investigated in Section 3.1.5 and presented as an upper bound, lower bound and as simulation results. Another result from the protocol analysis was the activation time of the network with respect to the number of nodes in the BG. The result showed that this should be below forty.

Any interference must be addressed in the optimization problem; otherwise the results might not be of any use. Assuming the AP based multi-channel architecture, a situation as shown in Figure 4.4 exists. Each end device calculates the Signal to Interference-plus-Noise Ratio (SINR), using the signal strength from the own AP and the interferences from all neighbouring cells on the same channel. In each cell only one node can transmit at the same time. To calculate the worst case scenario for interference at a *subject* node, the closest nodes in the neighbouring cells must be selected as interference emitters. Implementing this in linear equations is very complex. The solution is to use a virtual node that sits between the subject node and the AP of the interfering cell directly at the

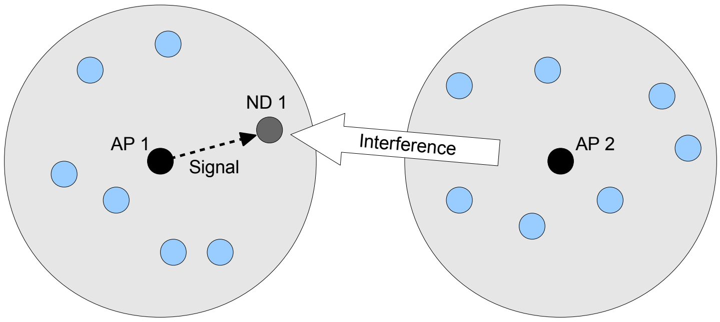


(a) Layout 1

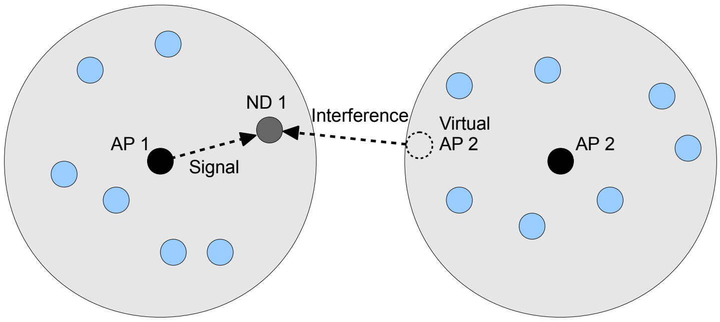


(b) Layout 2

Figure 4.3: Impact of a new node to the EBG size. Both figures show two AP cells with end devices. In layout 1 these two cells are isolated. The number of nodes in the BG and EBG is for all nodes ten. In layout 2 an additional node (ND 3) was placed, which is in range of nodes from both APs. ND 3 has 19 nodes in the BG and EBG.



(a) General interference



(b) Virtual AP

Figure 4.4: Interference model for the optimisation algorithm. Figure (a) shows the general problem. To calculate the interference at ND 1 the signal from AP 1 is interfered from signals of the cell from AP 2. Only one node per AP-cell can transmit. To assume the worst case a virtual node in cell of AP 2 at the cell-border closest to ND 1 is used as an emitter for interference.

border of the interfering cell. This is the worst case and also the strongest signal of a node in this cell. The effort for calculating the interferences with the virtual emitters is significantly smaller. The SNR was taken from the ECMA-368 standard. The free space path loss was taken from the channel model described in [SES+08] and [JCS+09].

In summary the network planning optimisation algorithm has the following features:

- Minimize the number of APs
- Monitoring the BG size
- Monitoring the EBG size
- Interference reduction
- Redundant cell coverage

By limiting the maximal number of nodes in the BG, which corresponds to the maximal number of nodes per AP, it is also possible to indirectly control the throughput per end

Sym.	Element type	Description	Size
A	int	APCSs	No. APCSs
E	int	End devices (EDs)	No. EDs
L	int	All nodes	A+E
I	bin	Nodes in range	L x L
D	float	Node distances	L x L
F	float	Interference strength	L x L
J	float	Signal strength	L x L
M	int	Max BG size	1
G	int	Max EBG size	1
H	int	No. Channels	1
U	int	No. nodes	1
T	int	Transmit range	1
R	int	Redundant APs	1
S	int	SNR	1

Table 4.1: List of parameters

device. Assuming a distributed MAS allocation scheme, it also specifies the delay between to MAS.

4.1.3 Problem formulation

The algorithm consists of an integer linear program solving AP placement and channel allocation in one process. It calculates the assignments of end devices to the APs, monitors the BG and EBG sizes and monitors the interferences.

The setup contains a list of end devices E and list of APCSs A. The coordinates of the end devices and APCSs are known and used to calculate the distances D and the in-range relations I of end devices and APCSs. H is the list of available channels. The parameter M sets the maximum size of the BG and G the maximum size of the EBG. U is the total number of wireless nodes in the network. R specifies the number of APs an end device shall have in range, hence this parameter is the degree of redundancy. The transmit range is given with T. For the interference calculations the parameters F, J and S are used. S defines the required SNR for the devices. J gives the signal strength between each node pair. F defines the to be expected interferences between two nodes, if they are not in the same BG or EBG. Table 4.1 summarizes the parameters in the equations.

The list of variables is shown in Table 4.2. c contains the selected channel of the nodes. s indicates if two nodes are on the same channel. v and w are a helper variables to calculate s. b contains an EBG relations and p shows if an APCS is active, which means that an APCS was selected to install an AP at that position.

Sym.	Element type	Description	Size
c	int	Node channel	L
s	bin	Node same channel	L x L
v	bin	Node s. chan. helper 1	L x L
w	bin	Node s. chan. helper 2	L x L
b	bin	EBG relation	L x L
p	bin	APCS is active	A

Table 4.2: List of variables

The objective of the linear program is to minimize the number of APs and to reduce the distances between the end devices and the active APCSs on the same channel in range. This is done by

$$min(\underbrace{C_1 \sum_{a \in A} p_a}_{\text{Num APs}} + \underbrace{\sum_{a \in A} \sum_{e \in E} s_{ae} D_{ae} I_{ae}}_{\text{Distances to APs}}) \tag{4.1}$$

C_1 is a weighting constant to increase the weight of the first term in the equation. Thus, the number of APs is the primary objective. Even though the costs of WiMedia APs are relatively low, the installation and maintenance costs in the aircraft scenario are not. So the objective is to reduce the number of APs. The values of p and s are affected by the following constraints.

The first constraint requires each end device to allocate a channel.

$$c_e \geq 1, \qquad \forall e \in E \tag{4.2}$$

The channel 0 is only valid for APCSs, indicating that at this location no AP will be installed. Additionally the variable p shows if an APCS is active:

$$-H + 1 \leq c_a - H p_a \leq 0, \qquad \forall a \in A \tag{4.3}$$

In the next steps the goal is to set variable s, which should only be set to 1 for two nodes, if they operate on the same channel, this channel is not 0 and the two nodes are in transmit range. Therefore the two helper variables v and w are defined and a set of node pairs S. The node pairs S describe all *end device - AP* pairs and all pairs of end devices which have a distance smaller than twice the maximal transmit range:

$$\begin{aligned} S := \{(n_1, n_2) | (n_1 \in A \cup E) \wedge (n_2 \in A \cup E) \wedge (n_1 < n_2) \wedge \\ ((D_{n_1 n_2} \leq 2T) \vee (n_1 \in A) \vee (n_2 \in A))\} \end{aligned} \tag{4.4}$$

The equations for s, v and w are shown in Equations 4.5, 4.6 and 4.7. v of two nodes is set to 0, if the difference of two node channels is 0; else it is 1. w then is set to 1 if two nodes have the same channel (including 0), else it is 0. Finally w is used to set s to explicitly be 1 if two nodes are on the same channel and that is not 0, else s must be 0.

$$0 \leq c_{n_1} - c_{n_2} + (H+1)v_{n_1n_2} \leq H, \qquad \forall (n_1, n_2) \in S \tag{4.5}$$

$$1 \leq (c_{n_1} - c_{n_2}) + (H+1)v_{n_1n_2} + H * w_{n_1n_2} \leq H, \qquad \forall (n_1, n_2) \in S \tag{4.6}$$

$$\left.\begin{array}{rl} w_{n_1n_2} = s_{n_1n_2}, & n_1 \in E \wedge n_2 \in E \\ 0 \leq p_{n_1} + p_{n_2} + w_{n_1n_2} - 3s_{n_1n_2} \leq 2, & n_1 \in A \wedge n_2 \in A \\ 0 \leq p_{n_1} + w_{n_1n_2} - 2s_{n_1n_2} \leq 1, & n_1 \in E \wedge n_2 \in A. \end{array}\right\} \forall (n_1, n_2) \in S \tag{4.7}$$

The next constraint defines that each end device must be in range of at least the minimal number of redundant APs:

$$\sum_{a \in A} p_a I_{ae} \geq R, \qquad \forall e \in E \tag{4.8}$$

The channel of the end device must be the same channel as the active APCS that is in range:

$$\sum_{a \in A} s_{ae} I_{ae} \geq 1, \qquad \forall e \in E \tag{4.9}$$

Now all variables are set to calculate the BG. With the following formula the maximal size of the BG is set to be at maximum M. For each node the sum over the same-channel variable of all other nodes in range must be less than or equal to M. The additional added 1 represents the node n_1 itself.

$$1 + \sum_{n_2 \in E \cup A} s_{n_1n_2} I_{n_1n_2} \leq M, \qquad \forall n_1 \in E \cup A \wedge n_1 \neq n_2 \tag{4.10}$$

To calculate the EBG relations a set of node pairs is used:

$$B := \{(n_1, n_2) | (n_1 \in A \cup E) \wedge (n_2 \in A \cup E) \wedge (n_1 < n_2) \wedge (D_{n_1n_2} \leq 2T)\} \tag{4.11}$$

The next variable matrix is the EBG relation b. It indicates if two nodes are in an EBG, which is the case if the subject node n_2 has the same channel as the EBG node n_1 and the BG node n_3, and that n_1 is not in the BG of n_2 (exactly two hops).

$$\begin{gathered} -1 + (1/(U+1)) \leq ((\sum_{n_3 \in E \cup A} s_{n_2n_3} I_{n_2n_3} I_{s_1s_3})/U) + s_{s_1s_2} - 2 * b_{n_1n_2} \leq 1, \\ \forall (n_1, n_2) \in B \wedge n_2 \neq n_3 \wedge n_1 \neq n_3 \end{gathered} \tag{4.12}$$

For each pair of a subject node n_2 and EBG node n_1 that are on the same channel, it is tested if at least one BG node n_3 is on the same channel. If so, b is set to 1, else to 0.

The next constraint limits the EBG size:

$$\sum_{n_2 \in E \cup A} (b_{n_1 n_2} + s_{n_1 n_2}) I_{n_1 n_2} \leq G, \forall n_1 \in E \cup A, n_1 \neq n_2 \tag{4.13}$$

For each node the sum of nodes in the EBG relation should be below G, the maximal size of nodes for the EBG.

Finally the interference is checked by:

$$S \sum_{n_2 \in A} F_{n_1 n_2} s_{n_1 n_2} \leq \sum_{n_3 \in A} J_{n_1 n_2} s_{n_1 n_2}, \forall n_1 \in E \tag{4.14}$$

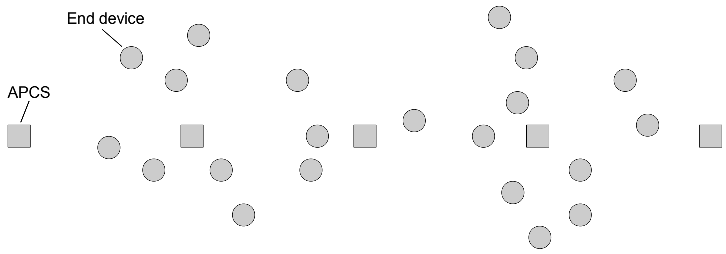
S is the SNR required by the transceivers and defined in the ECMA-368 standard. The left hand sum over F summarises the interferences over all APs out of transmit range and which are on the same channel as node n_1. So this are the interferences from other cells on the same channel. The sum over J returns the signal strength of the connected AP. There will be only one AP in transmit range, so the result of the sum over all APCS only returns one AP.

4.1.4 Verification

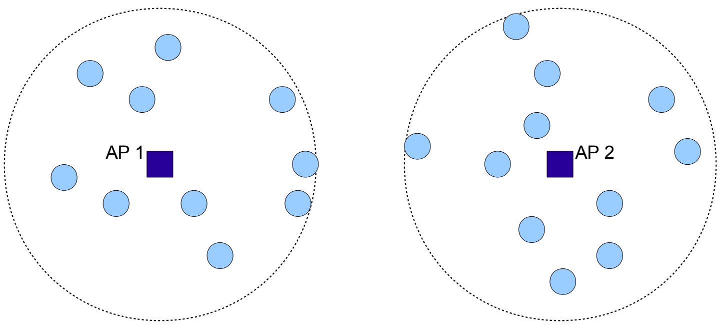
The EBG size calculation and interferences algorithms were extensively tested to prove that they operate correctly and all operational requirements were met. During development the other described constraints from the algorithm were also tested, but the results are not shown here.

Figure 4.5 shows a scenario to demonstrate the EBG calculation. Figure 4.5(a) shows the scenario, which is similar to the example in Figure 4.4. The parameters were maximal two channels, 12 nodes in the BG, 10 nodes in the EBG, one AP per end device and a transmit range of 10 m. In Figure 4.5(b) the algorithm runs without the EBG calculation. The solution is to have all nodes on one channel (indicated by the colour of the nodes). With the EBG calculation the nodes can no longer be all on the same channel, as some nodes will have more than 10 nodes in the EBG. Thus, two channels must be selected, which can be seen in Figure 4.5(c). During the test of the EBG the interferences calculations were deactivated to exclude additional parameters not required to demonstrate the feature.

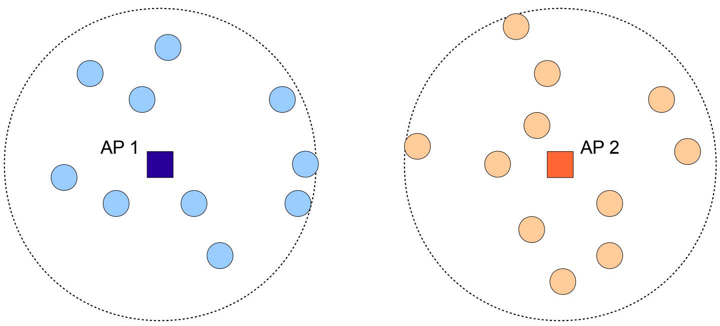
The interferences management can also be shown with Figure 4.5. As already described without interferences management and EBG calculation the result is shown in Figure 4.5(b). If the interferences management in turned on (and not the EBG calculation), the same result as seen in Figure 4.5(c) is generated. Because the two cells are too close,



(a) Setup



(b) Without EBG calculation



(c) With EBG calculation

Figure 4.5: EBG verification

the interference of the other cell is large enough to force the algorithm to choose another channel for AP 2.

4.1.5 Calculation for an aircraft cabin

The described algorithm was implemented using the tools ZIMPL [Koc04] (version 2.08), SCIP [Ach04] (version 1.1.0) and CPLEX [IBM] (version 9.130). CPLEX is a high-performance mathematical programming solver. SCIP is a framework working on top of CPLEX providing control over the solver with focus on linear programming, constraint integer programming and mixed integer programming. ZIMPL is a language to describe mathematical programs and translate them to a SCIP readable format. These three can be used as a tool chain to solve mathematical optimisation problems.

After having tested and verified the correct operation of the algorithm in specific tests it is of interest if the program can also calculate a complete cabin scenario. Therefore the cabin layout of an A321 aircraft was modelled. The left side of Figure 4.6 shows a possible layout of the cabin with a two class configuration. It starts with an exit and a galley, followed by a business class, then a economy class including two emergency exits and finally a rear exit with galley. Each seat bench has an end device. Every 4 m is a cabin illumination module above the aisle. The APCSs are located every 1.5 m alternating above the left and right seats. Each exit and emergency exit is estimated with three end devices. These can be signs, buttons, sensors or hubs to attach multiple wired end devices. The galley areas have an additional six end devices. The node placement and APCS can be seen in the centre of Figure 4.6.

In addition to the placement of the nodes and APCSs the following parameters were specified: two APs in range per end device, four available channels, transmit range of 8 m, maximum forty nodes in the BG per node and maximum 94 nodes in the EBG per node.

The program was run on a workstation with a Dual-Core AMD Opteron(tm) Processor 2218 2.6 GHz and 16 GB RAM. The program, as it can be seen in Appendix A, is translated to be executed by SCIP, which uses a *Branch-Cut-&-Price* method to solve the problem. It took 45.6 hours to calculate the optimal solution. The results are shown in the right picture of Figure 4.6. The dominating parameter for the result is the redundant coverage. Neither the limit of the BG, nor the limit of the EBG were reached.

4.1.6 Optimisation conclusions

The presented algorithm handles the ECMA-368 specific requirement for linear optimisation problems. The key contribution is the calculation of the EBG size, which is essential for a multi-cell architecture. Without this calculation a solution from an existing resource

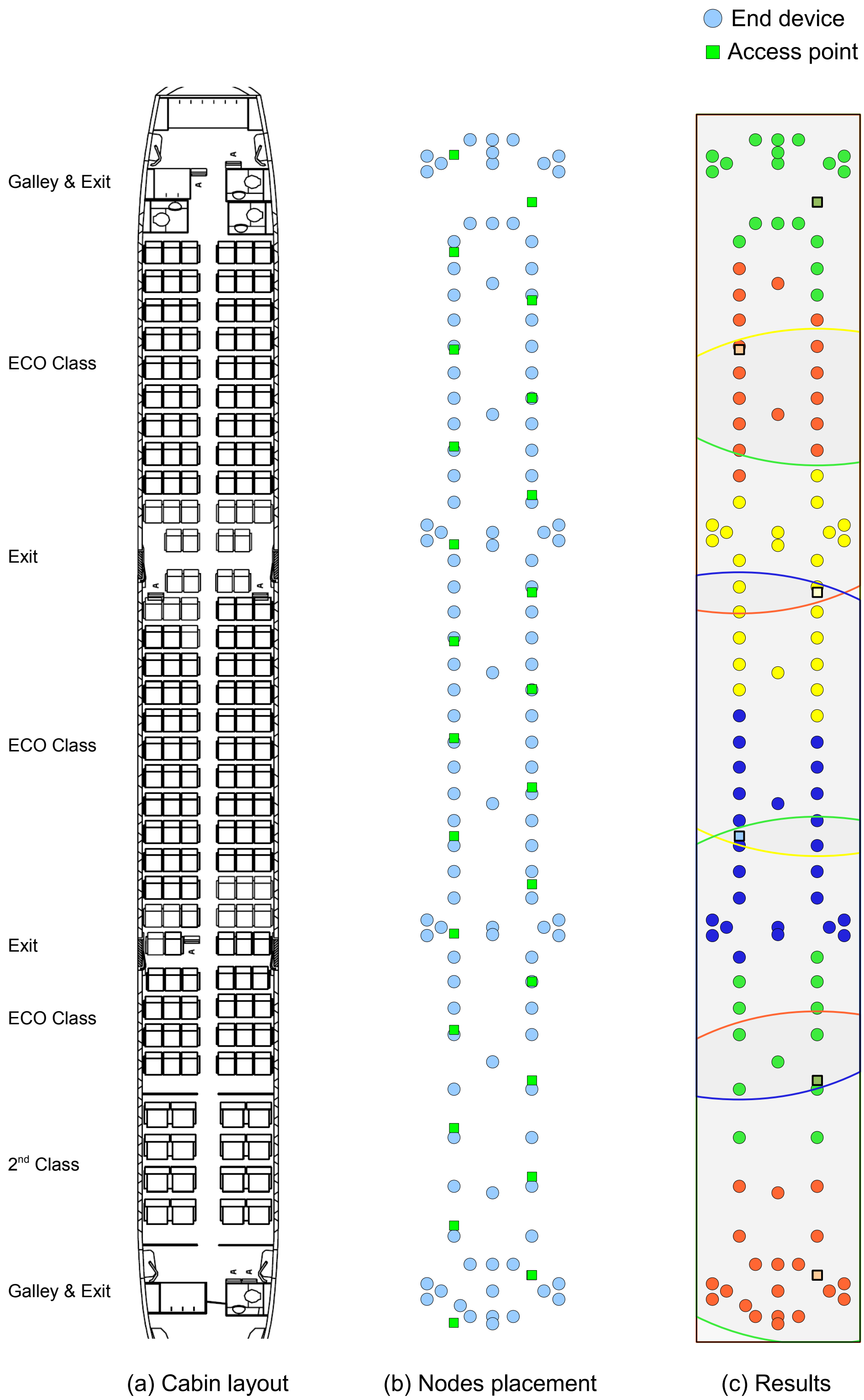


Figure 4.6: Optimisation algorithm results for aircraft cabin

management algorithm might not work in a real setup. The EBG specific constraints can also be included in other algorithms. It is not specific to the aircraft scenario. It is possible to enhance other optimisation problems, which might have a different cost function with these constraints and make it possible to calculate results for ECMA-368 networks.

In the current implementation the algorithm derives the connectivity from the distance between the nodes. This is a simple approach, but it can be improved; for example with an attenuation matrix for the nodes. With this matrix any obstacles, like a dividing wall can be modelled.

The second contribution of the algorithm is the interferences calculation for the aircraft specific environment. A technique was developed to model the strongest interferer from a neighbouring cell. With the path loss model taken from a measurement campaign in an aircraft the result should be close to real setups.

4.2 Real-time resources management

The state of a wireless channel can change on-board the aircraft. Possible reasons can be a blocked device (e.g. a metal brief-case covering the antenna) or even a country where certain frequency ranges in the UWB spectrum are blocked. Failing devices require a reorganisation of the resources among the devices. The results from the optimisation algorithm can be seen as a default resources allocation plan. The real-time resources management presented now monitors the current situation and distributes resources as needed. It is implemented in a distributed procedure to avoid a single point of failure.

The objectives for the real-time resource management can be defined as followed:

- Connect every end device to an AP
- Cause as little interference to other cells as possible
- Meet the data rate requirements of the end devices
- Meet the delay requirements of the end devices

To meet the data rate and delay requirements the MAS reservation plan must also be considered. This was done indirectly in the optimisation algorithm by restricting the number of end devices per AP.

The results presented for the real-time resource management are of theoretical nature. A concept is proposed, which was then tested in a small simulation to demonstrate a proof of concept.

4.2.1 Distributed algorithms for resource management

For the distributed resource management algorithm presented in this work, one key feature is to have a fair resource allocation. Nodes should not act selfishly and occupy available resources. Hence, nodes must not only take their own situation into account, but also those of the surrounding nodes. This feature is often found in game theory based algorithms.

The game theory is capable of defining fair and distributed algorithms. It originates from economics in the 1940s, but has also been applied to biology, engineering, political science, computer science and philosophy. The problem is defined in a strategic game with a set of rational players. Each player tries to maximise its payoff function by choosing the best strategy and also by taking the actions of the other players into account. Usually the players' strategies will result in an equilibrium, for instance the Nash equilibrium, where no player can change its own strategy without decreasing its payoff. Many different types of games have been developed: cooperative or non-cooperative, symmetric or asymmetric, zero-sum or non-zero-sum, simultaneous or sequential, just to name some.

Game theory has been proposed for resource management in wireless networks for many different technologies. For IEEE 802.11 the authors of [BHWM05] present a game to share the available radio channels. The payoff function based on transmission delay, channel access length and throughput. In [HJL04] an algorithm for OFDM based communication is described that minimizes the transmission power, while still achieving the QoS requirements of the system. For IEEE 802.16 networks [NH07] presents a game definition to control the amount of bandwidth given to new connections, with respect to delay, throughput and other QoS parameters in the network.

Even though the amount of available resource management algorithms based on game theory is huge, no one handles a comparable system to that of an ECMA-368 network for a wireless CMS. The distributed beaconing mechanism and Distributed Reservation Protocol (DRP) channel access scheme is unique. The priority for a WiMedia network lies in the efficient MAS allocation. To utilise the WiMedia features a new resource management algorithm is required.

4.2.2 Fair management algorithm

The resource management algorithm assumes APs with fix locations. Furthermore, the network consists of a wired backbone that connects the APs. The APs provide the service for wireless end devices to get access to the wired backbone network.

The MAC mechanism for the WiMedia nodes shall be DRP. For the aircraft scenario DRP is essential, as it provides guaranteed resources to the end devices. The QoS requirements for end devices are defined by required data rate and maximum time delay to and from the server. Assuming only one MAS is reserved per end device and taking into account the 64 ms of a superframe, the delay of an message over the UWB link can be nearly 64 ms. For applications with smaller delay requirements, the resource management algorithm must reserve two or more MASs per end device and per superframe with defined maximum gaps between the MASs.

Despite the mentioned DRP reservation scheme the network may also use the alternative channel access Prioritized Contention Access (PCA) for non-critical applications. MASs that are not completely used by the MAS-owing device can be released and used for PCA, a CSMA like access scheme. This way the unused MAS sections can still be used for applications where collisions can be tolerated. For the following calculations only DRP reservation is assumed.

The following two lists show input and output parameters of the algorithm:

Input parameters
- Link quality
- Devices per AP
- BG/EBG size
- Bandwidth utilisation
- Delay requirements

Output parameters
- Channel allocation
- MAS reservation
- Beacon slot reservation

The link quality is given in Received Signal Strength Indication (RSSI) or Link Quality Estimator (LQE). Both are defined in the WiMedia standard and should be accessible from the application layer. To provide the required information of the surrounding nodes, the QoS requirements, neighbourhood relation and currently superframe structure is exchanged on a two-hop distance. This is already present in the WiMedia protocol and requires only little extra signalling.

Efficiency in a WiMedia network using DRP can be defined as the configuration with the minimal used MAS, which again implies the minimal usage of resources and maximum remaining bandwidth. The straight forward approach would be to choose the AP only by signal quality. A node would therefore always try to connect to the AP with the best signal. But for an badly designed network topology, as in Figure 4.7, this could mean that many nodes try to connect to the same AP while a second AP close by is ignored, because it is further away. If there are too many nodes, the network performance decreases at this AP. The goal of the algorithm is to make some nodes to choose a different AP, if the best AP has a large load.

From the protocol perspective two limiting factors exist. The first one is the number of beacon slots. As described earlier, only 94 slots are available for the BG and the EBG. Therefore, no more than 94 nodes can simultaneously be in transmit range. To allow new nodes to connect to the network, a small amount of slots should always be kept unoccupied.

The second limiting factor is the number of MASs. One superframe has 256 MASs, which

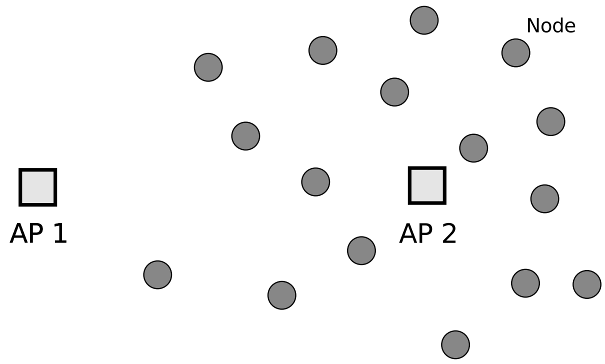


Figure 4.7: Network setup where most nodes would try to connect to the same AP, if the selection is only based on signal quality or distance.

must be shared among the nodes in transmit range. The MASs reservation depends on the data rate and delay requirements. Again some MASs should be constantly available to allow new nodes to make their reservations.

In contrast to the MAS is the data rate between an AP and an end device. An increased data rate requires less MAS reservations and enables more nodes to join the network.

The reservations between an end device and AP are made from the end device. The end device periodically calculates the cost function C_n for all APs in range. It is defined as:

$$C_n = B_n^* + M_n^* + D_n^* \tag{4.15}$$

where B_n^* contains the beacon slot utilisation, M_n^* the MAS utilisation and D_n^* the possible data rate. All three values are normalised to values between 0 and 1, where 0 means the best achievable value and 1 the worst value. Each end device periodically calculates the cost value for each AP and initiates an AP change, if a better solution was found than the one currently in use.

B_n^* is defined as the number of reserved beacon slots b_a at the AP a, divided by the maximal number of beacon slots b_{max} to the power of v:

$$B_n^* = \left(\frac{b_a}{b_{max}}\right)^v \tag{4.16}$$

Analogous to this, M_n^* is defined as:

$$M_n^* = \left(\frac{m_a}{m_{max}}\right)^v \tag{4.17}$$

where m_a are the number of reserved MASs at the AP and m_{max} the number of maximal available MASs. m_a is obtained by calculating the number of required MASs, depending on the delay and data rate requirements, and adding it with the already used MASs by other nodes.

B_n^* or M_n^* describe the utilisation of the beacon slots or MASs. They should only get a value close to 1 if the number of utilised slots becomes close to the maximum. If it is not close to the maximum the protocol can operate efficiently. By modifying v one can control the threshold. In this work it is set to create costs of 0.1, when 90% of the maximum are reached:

$$(0.9)^v := 0.1 \Rightarrow v = 21,85 \tag{4.18}$$

Finally D_n is a linear relation of the possible data rate between the end device and the AP $d_{n,a}$ and the maximal possible data rate d_{max}:

$$D_n^* = \left(1 - \frac{d_{n,a}}{d_{max}}\right) * T \tag{4.19}$$

D_n^* must degrade over time if B_n^* or M_n^* are above the threshold. Therefore T is used; it usually has a value of 1, unless B_n^* or M_n^* are above 0.9. Then T will increase for each round by 10%, when the cost values are recalculated, until the node has changed the AP or B_n^* and M_n^* drop below the threshold, due to other nodes disconnecting from the AP. With this feature enabled the nodes closest to the alternative AP (see in Figure 4.7) will be forced to change. This is because D_n^* will increase for all nodes of the overloaded AP. The nodes close to the other AP will have a relative low D_n^* for the less used AP. For them it generates less costs if they switch to the other AP.

All three addend in Equation 4.15 are influenced by the current reservations of surrounding nodes. The algorithm considers the actions of the other nodes and derives its own actions. After some rounds an equilibrium will be found where each node cannot improve its situation.

For the APs themselves only the channel selection and beacon slot reservation must be done. For them the procedure is to choose a channel that is not used by another AP in its BG or EBG. If no free channel can be found the AP should choose the channel with the least nodes assigned to it.

4.2.3 Procedure

The distributed algorithm runs periodically on every node. All nodes distribute their status. The status includes: signal quality to all APs in range, data rate requirements and delay requirements. From the ECMA-368 beacon information the nodes also know the beacon slot reservations from the BG and the occupied slots by the EBG. The MAS reservations from the BG is also known. With this information ever node has a complete picture of the relevant environment. The details from the beacon data are distributed in every superframe. The remaining status details are distributed on application layer. For fixed devices this can happen every few seconds. Mobile devices must broadcast the APs in range more often. The procedure is different for the APs and end devices.

Access points

By default an AP uses the channel calculated from the network planning optimisation algorithm. If that is not possible the AP chooses a channel not selected by an AP in range or by an AP in range of a neighbouring end device. A channel can become unavailable if there is too much interference on the frequency range or if the channel is not allowed in the country the aircraft currently is operated. If there is no free channel available the AP chooses the channel that has the lowest signal quality or is reported from neighbouring nodes with the lowest signal quality.

End devices

The end devices calculate the cost function as described above. When activated they scan for APs in range. For each AP the cost function is calculated. The current reservation plan from the AP is used as a basis and the nodes calculate the required MAS reservations to meet the data rate and delay requirements. The AP with the lowest cost function is selected to be the current AP.

Calculating the reservation is a challenging task. This is a scheduling problem, which can be found in many areas, for example task scheduling on real-time computer systems, production processes in industries or logistics planning. Many different approaches have been developed over time. A good overview of real time systems scheduling is given in [Kop97]. Commonly used algorithms are Earliest Deadline First (EDF), Deadline Monotonic Scheduling (DMS) and Rate Monotonic Scheduling (RMS). EDF is a dynamic algorithm, which means it can run in a non-static environment, where the sequences are not given and fix. EDF always selects the task with the earliest deadline. DMS and RMS are static algorithms, which must be calculated in advance and prioritise the tasks based on the deadline or repetition rate.

In this work the EDF algorithms is used to select the MAS slots according to the maximal delay requirements. If additional MASs are required to fulfil the data rate requirement, the additional MASs are chosen randomly. The overall performance of the distributed algorithm is influenced by the MASs calculation. EDF was selected since it respects the delay requirements and can act dynamically on changes of the available resources. However, additional research could further investigate the performance of different approaches.

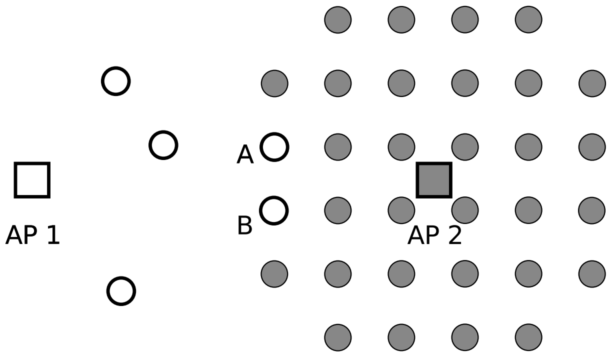


Figure 4.8: Final results of the algorithm, after 9 rounds. The transmit range is larger than the shown field; hence all nodes are in range of each other. The filled nodes are on one channel and the unfilled nodes on another one. Nodes A and B, close to the left AP, initiated an AP change after round eight.

After the node has calculated the MASs reservation, is checks if the beacon slots or MASs cost function terms are above 90%. If this is the case, then the node simulates the stepwise decrease of T from Equation 4.19. This is done until the beacon slot and MASs terms are below 90%.

Finally for each AP the cost function is calculated and compared. The AP with the best cost function wins. A constant requirement is that all nodes are connected to the network.

4.2.4 Results

In Figure 4.8 the results of the algorithm are shown. To demonstrate the results in a smaller scale, the maximal beacon slots number and MAS were set to smaller values as defined in the standard. After the first round of calculating the cost values, each node chose the closest AP. This resulted in a situation where the threshold for the beacon slots was exceeded. Hence, for the following rounds the parameter T, used for calculating the cost value of AP 2 increased, until the cost value of AP 1 for nodes A and B became smaller than the cost value of AP 2. After nodes A and B changed their AP, the threshold is no longer exceeded and the network is in an equilibrium.

Chapter 5

Mobility

One advantage of wireless communication inside the aircraft cabin is the support of mobile devices. These can be crew intercom headsets or mobile touch screen devices with services for flight attendants or maintenance personnel. Due to the targeted system architecture with a multi-cell architecture, mobile devices will transit between the Access Points (APs). This transition is called *handover*. The challenge with handovers for mobile devices is the support of real time data transfer in the wireless network. There is no exact definition for *real time data transfer*, but practically it means in this work, that audio and video transmissions must be possible, without noticeable delays and disruptions for the user application.

To provide a more detailed understanding of the requirements some important use cases, originating from the application description and mobility requirements, are listed below:

Mouth synchronisation: For passenger announcements the delay between speaking into the microphone and the playback in the cabin, shall not have a delay that could cause distractions for the flight attendants. Measurements on personal perception showed that the delay should be around 10 ms and at maximum 100 ms. This must be fulfilled by the fixed devices and mobile devices.

Crew intercom delay: For mobile crew intercoms no delay shall be experienced. The crew intercom will most likely use Voice over IP (VoIP) connections. VoIP systems often have delays between the communicating partners that are longer than for telephone calls. The aircraft crew intercom shall not have a perceptible delay.

Seamless handover: The handovers of mobile devices shall have no effects on the applications. Especially for crew intercom the AP switch shall have no effect on the call. The details are not specified here in this thesis, but comfortable conversations must be supported.

Essential to all mobile devices is the minimised delay and loss of packets in regular operation and during handovers. Next to these fundamental requirements are also the related issues of addressing, routing and route update mechanism. IP network devices have a logical address, the IP address. Each device must have at least one address. They are either predefined by the system administrator or they can be distributed dynamically by network services. Mobile devices moving between unrelated and independent sub networks, with different netmasks or network prefixes, have to obtain a new IP address to communicate with the current gateway or router.

In a relatively small network like in an aircraft all devices are under control of an administrator or maintenance personnel. A common question arises; should mobile devices obtain a new IP address when changing the AP or should mobile devices keep their address permanently. The advantage of changing addresses is that the network can be partitioned in sub networks. For instance all devices connected to one Backbone Access Controller (BAC) (e.g. APs, wireless devices behind an AP, wired end devices, etc.) can be have the same IPv6 network prefix. The IP address of the end device tells the corresponding BAC the approximately position. This can be of great help for operating and maintaining a network. The routing tables in the backbone also become much easier, since the prefix already predicts the next hop; only the bytes of the prefix have to be compared. Also, the update of routing tables for relay nodes is unnecessary, since the prefix already signals the next hop.

With permanent addresses the devices keep their address, even when changing the AP. On AP change the devices must not obtain a new address, which speeds up the AP switching. In this case the IP address does not provide information on the location or topology. The routing tables become more complex, because now the addresses have no common prefix depending on the topology. Also, the BACs and APs must be updated when an end device has completed a handover, to ensure a correct packet routing.

The choice between permanent addresses and dynamic addresses depends on several aspects: the time required for obtaining a new IP address, propagating topology changes throughout the network (for routing and applications) and the need for an easy-to-read addressing scheme (helpful for development and maintenance). Within the pre-development project permanent addressing for wireless devices is used. The addressing scheme is a combination of permanent addresses and segmented sub-networks. The wired devices use segmentation; each BAC and the devices of the BAC use a common prefix. BACs can assign the addresses to their end devices themselves. Wireless devices have their own prefix, thus a dedicated network segment. They permanently possess their IP address and only for the wireless devices the routing tables must be updated and maintained. Therefore proprietary routing table update software was written, to distribute route changes to the BACs. Since this routing software consumed large amounts of time and continuously needed updates, the usefulness of standard mobility protocols was investigated. The actions and results are shown in this chapter.

5.1 Mobility protocols for IP networks

Traditionally the development of the IP protocol evolved from wired networks. Mobility was not an issue at this time, since computers were large and heavy. The IPv4 concept requires the logical address of a device (the IP address) to depend on the subnet of the router; hence the logical address is indirectly location dependant. For example a computer connected via a service provider to the internet will have a different IP address in Germany than it has in another country.

With the progressing miniaturisation of computers, increasing numbers of computers worldwide and advancing technologies like VoIP, the frequently changing IP address of mobile devices has a mobility issue. A solution was required to make devices reachable with constant addresses, independent from their physical location. The Mobile IP protocol (see Section 5.1.1) was developed to accomplish the required demands. Devices were now accessible with the same address, regardless of whether they are located in Munich or in New York.

Since wireless access technologies, like the IEEE 802.11 family, became popular and commonly used a new problem emerged. For wireless network scenarios, where an area is covered by multiple APs, a seamless handover was not possible. The re-establishment of the wireless link took too much time, so that video streaming or VoIP applications were disturbed. The principle of Mobile IP should be sufficient to allow a seamless handover, but the network configuration still takes too much time. Many approaches were and still are developed on this subject to achieve easy wireless handovers in ad-hoc networks. In this work, the Fast Handovers for Mobile IPv6 (FMIPv6) enhancement was selected. It is described in Section 5.1.2. It allows the collection of network information from surrounding APs prior to a possible handover. The handover time becomes dominated by the hardware drivers and not by the network protocols.

Similar to the features of FMIPv6, the authors from [LLM09] have presented procedures of fast forwarding and early buffering for ECMA-368 networks. Since no implementation was available and the goal is to use common protocols, this work focuses on using FMIPv6.

5.1.1 Mobile IP

The objective of Mobile IP was to make the same Internet device accessible regardless of the actual physical location. Every node in the Internet has a logical address, the IP address. In IPv4 networks this address depends of the momentary Internet Service Provider (ISP) or Local Area Network (LAN). So the address of portable devices changes constantly, which makes it impossible for remote services to get reliable access to the device.

One obvious solution would be to register at each network service with the new address.

But this approach has two downsides. First the portable devices must know which remote services and devices might want to connect in the future. If a server-like application runs on the portable unit, it would not know which remote clients this might be. The second concern is the possibility of creating a location profile of the portable device and thus collect sensitive details of the user.

In 2002 The Internet Society published the document *IP Mobility Support for IPv4* [Per02] to provide a discrete solution. It uses a *Home Agent* that acts as a static relay server between the portable and remote devices. In the case of IPv6 the document *Mobility Support in IPv6* [JPA04] describes Mobile IP support, which was later integrated in the IPv6 standard. Mobile IP is for IPv4 and IPv6 very similar. For IPv4 a *Foreign Agent* was defined, that does not exist for IPv6. In the rest of the document the IPv6 mechanism is used, because the aircraft network is based on IPv6.

Figure 5.1 shows the classic example setup. The three units are the Mobile Node (MN), the Home Agent (HA) and the Corresponding Node (CN). The CN wants to transmit a message to the MN. However, the MN's address changes over time, the CN does not know the current address, its Care-off Address (CoAd). The MN has a designated HA with a static Home Address (HAd), which is the actual public known destination address of the MN. Whenever the MN gets a new address, it reports this to the HA. Messages send to the MN must be directed to the HAd (action 1 in the figure). The HA tunnels the message to the CoAd (action 2). The MN can reply to the message by tunnelling an answer to the HA (action 3) which is then forwarded to the CN (action 4).

The CN does not know where the MN is and it does not require Mobile IP support. The process is fully transparent to the CN. In fact the CN does not know that the destination is mobile.

Mobile IP has more modes than the one just explained. For instance the CN can receive the CoAd of the MN and then communicate directly with the MN, without the detour via the HA. This however requires the CN to have some knowledge of Mobile IP. For the scope of this work the basic example explained above is important. More details are available in [Sol04].

5.1.2 Fast Handovers for Mobile IP

Mobile IP has an unfavourable performance in some situations. Imagine two Wi-Fi AP cells, which are close by and have an overlapping area. The cells have different net prefixes. A mobile node can transit from one cell to the other, so it is always in range of at least one of the APs. When the node enters the next AP cell it must create a local IP address for that network. To do so, it uses the Neighbor Discovery Protocol (NDP) to gather information about the network. It must receive the periodic *Router Advertisement* message from the AP. This message contains the prefix of the network. When the mobile node has received the advertisement, it can create a local IP address and connect to

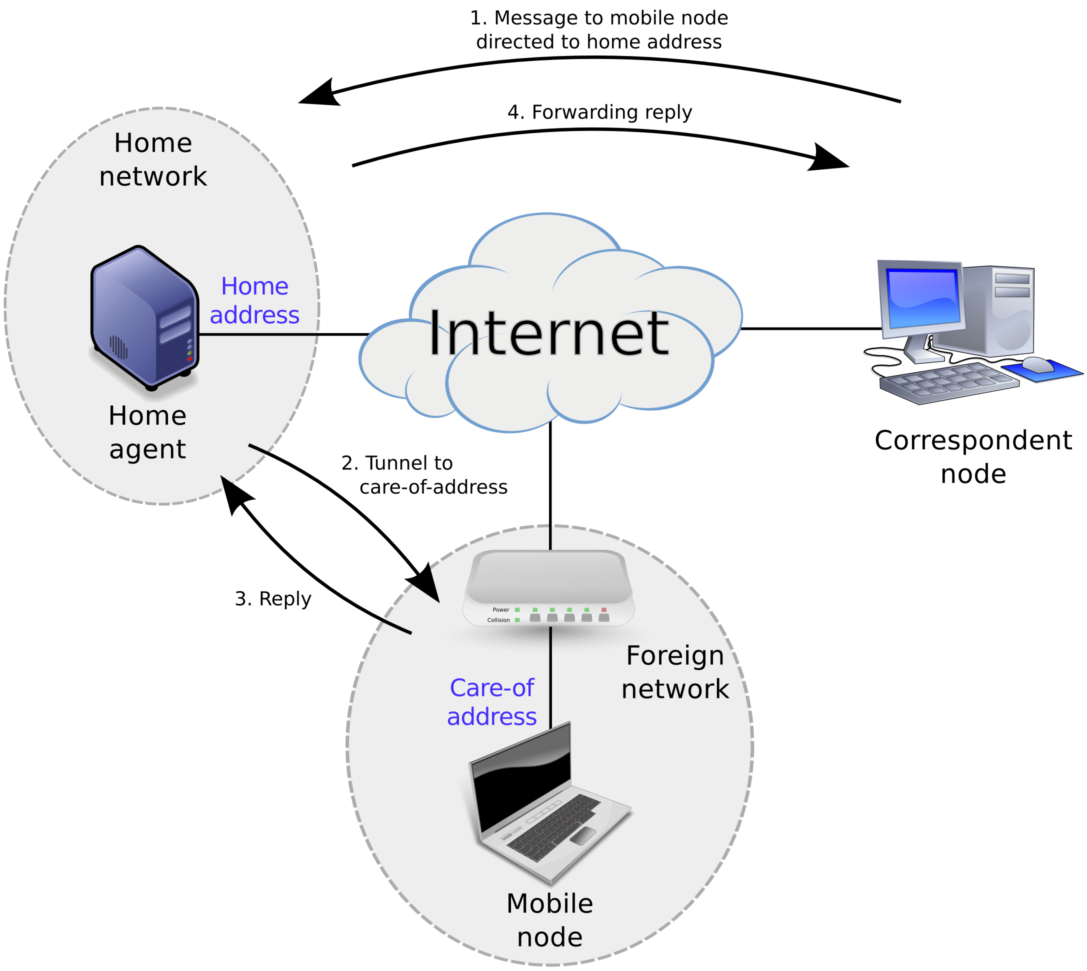


Figure 5.1: Mobile IP scenario

the network. The NDP standard allows a Router Advertisement message to be sent at minimum every three seconds. Hence, the mobile node, entering the new network, must wait up to three seconds, before it can join logically the network. On real systems it was possible to configure the Router Advertisement interval to one second, which is a violation of the standard and it is still classed as a blackout time.

To overcome the problems of Mobile IP several protocols were developed. Hierarchical Mobile IPv6 (HMIPv6) [Cas00] uses an extra agent to manage local mobility, since the authors differentiate between local and global mobility. The reduced paths for managing topology changes increase the performance, with respect to signalling overhead and handover times. In Fast Handovers for Mobile IPv6 (FMIPv6) [Koo05] procedures were developed to prepare time consuming steps to connect to a new AP, while still being connected to the previous AP. This was achieved by identifying the network details of surrounding APs in advance, thereby reducing the reconnect time. The Proxy for Mobile IPv6 (PMIPv6) [UIT+09] standard addresses the problem that HMIPv6 and FMIPv6 require Mobile IPv6 at the host side. This might not be available in some networks, for instance in combination with cellular phone networks. It provides a more generic approach independent of Mobile IPv6. [LF08] and [XCS+02] give a comparison and performance evaluation of the three approaches, which show very good performance for FMIPv6. In this work FMIPv6 was chosen, due to the good performance and the availability of a working Linux implementation.

The basic idea of FMIPv6 is to collect the details, especially the prefixes, of close-by APs while being connected to another AP. A node that is connected to one AP, but also detects another AP in range, can request network details of the detected AP, while still being connected to the active AP. FMIPv6 also has mechanisms to forward packets to the new AP during a handover, which reduces packet losses.

In FMIPv6 the typical AP is named Access Router (AR). The protocol has three use cases: predictive, reactive and network-initiated handover.

Predictive handover

In predictive handovers the mobile node initiates the handover while the Previous Access Router (PAR) is still up and in range. The node might experience a degrading of signal quality and connect to an AR with a stronger signal.

Figure 5.2 shows a sequence diagram of a predictive handover in FMIPv6. The first two messages show the information collection of neighbouring AR. How the MN acquired knowledge of surrounding AR is not part of FMIPv6. One likely method is by scanning for other AR with the wireless interface, provided that the interface supports this action. The aid of location based services could also be possible. With the RtSolPr message the MN transmits the AP identifier and thereby requests details of the corresponding AR. The PAR replies with the PrRtAdv message and provides the information.

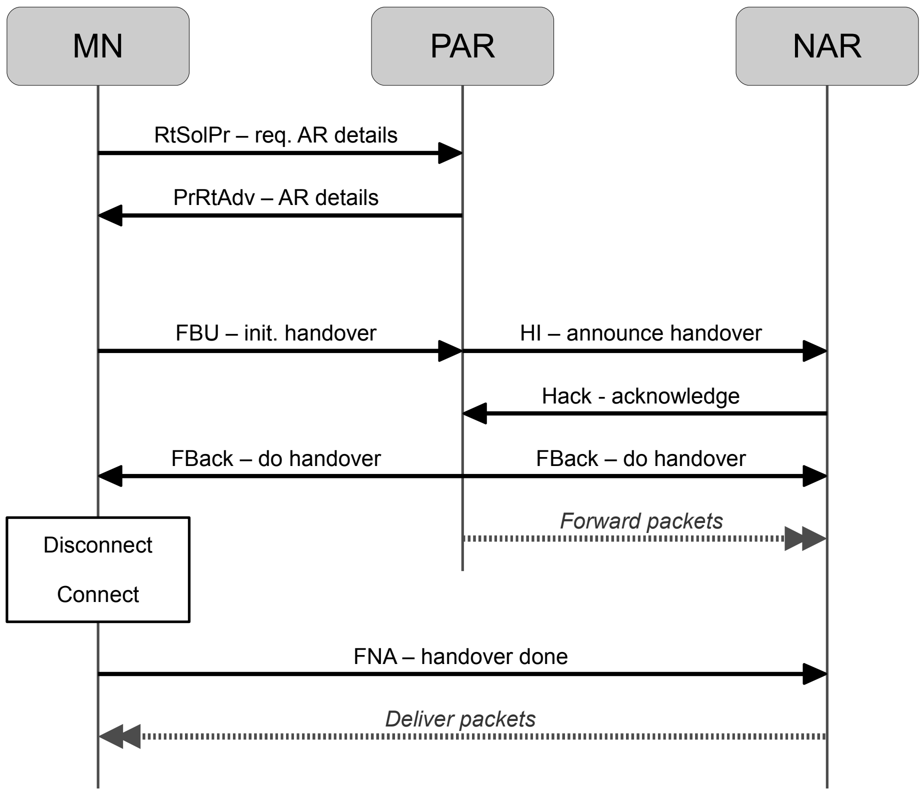


Figure 5.2: Predictive handover in FMIPv6

When the MN wants to initiate the handover it transmits the FBU message to the PAR. The PAR notifies the Next Access Router (NAR) with the HI message, which is confirmed with the Hack message from the NAR to the PAR. After that the PAR sends the FBack message to the MN and the NAR to indicate the actual start of the handover. From this moment onwards the PAR no longer transmits messages to the MN, but forwards them to the NAR. The MN now disconnects from the PAR and connects to the NAR. When done, the NM sends the FNA message to the NAR to announce that the AR switch is complete. The PAR now delivers the packets to the MN.

The main advantages for a predictive handover are the accelerated link switch, due to the no longer required router advertisement message from IPv6, and the elimination of packet losses because of the forwarding of packets. The switch duration is now mainly driven by the interface driver and protocol definitions of the MAC layer.

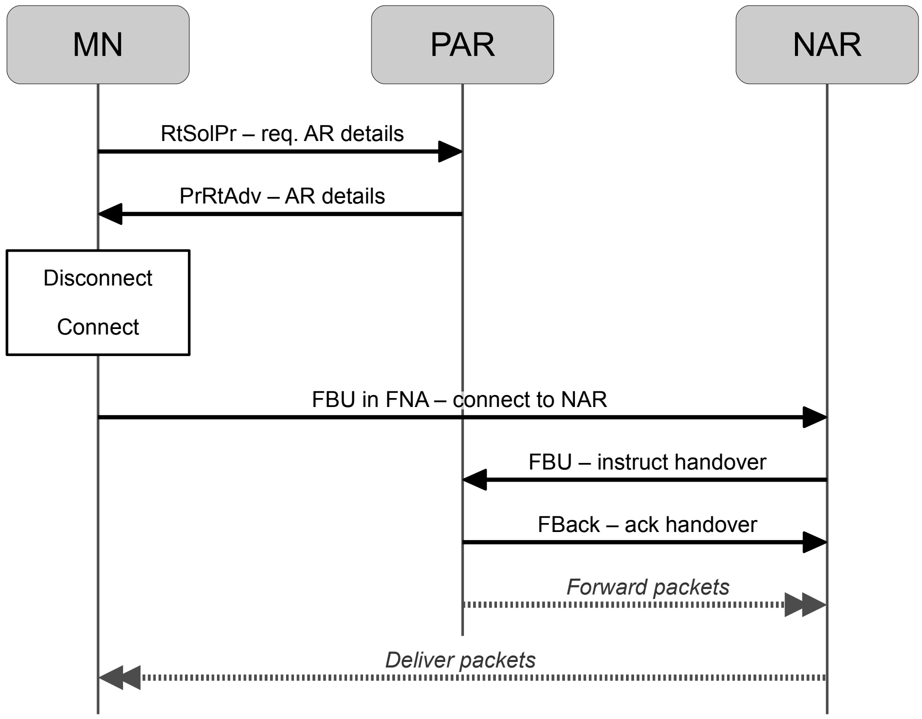


Figure 5.3: Reactive handover in FMIPv6

Reactive handover

A reactive handover occurs, when the link suddenly fails and the initiation of a coordinated handover procedure is not possible. Figure 5.3 shows the sequence diagram for reactive handovers. It is similar to the predictive handover, but no packet forwarding is possible. Thus, FMIPv6 does still provide the fast connection to another AR in this case, but packet loss over time will occur.

Network-initiated handover

The last case, network-initiated handovers, describes the situation when any node of the network except the MN initiated the handover; for example the PAR or a server, triggers the handover. The procedure is similar to the previously described sequences. It is not used in the wireless Cabin Management System (CMS) network.

5.2 Mobile IPv6 and FMIPv6 in ECMA-368 networks

In the first step the performance of the Mobile IPv6 and FMIPv6 standards were investigated. Therefore, predicted results were calculated, according to the standards. The performance of Mobile IPv6 was then measured. To measure the performance of FMIPv6 some modifications to the network interface had to be implemented. They are described in the next section, followed by the measurements.

5.2.1 Theoretical analysis

The theoretical analysis can be grouped in the following phases: ECMA-368 channel change, WiMedia LLC Protocol (WLP) connect, Mobile IPv6 connect and FMIPv6 connect. For most of them the duration depends on a number of situation specific conditions. One can calculate the best case duration, worst case duration and an average duration.

ECMA-368 channel change

The ECMA-368 standard provides means to perform and announce channel leave or channel change. This announcement requires time. So the first consideration addresses the question if an *announced* or *abrupt* channel change should be done. In an abrupt channel change the node immediately stops transmitting on one channel and joins the next channel. This will take the smallest amount of time, but the nodes from the first network will not know that the node is gone. Packets are still being tried to forward. In contrast in an announced channel change all nodes know about the reachability of the channel changing node. In the duration calculations the announced channel change is used.

The procedure for changing a channel is defined as:

- Wait for the next beacon period
- Include the Channel Change Information Element (IE)
- Switch to the new channel at the end of the current superframe
- Include own beacon in the beacon period of the superframe of the new channel

In an equation the steps above will be like this:

$$t_{chanChange} = t_{nextBP} + 2 * mSuperFrameLength + t_{nextBPST} + t_{newBPLength} \quad (5.1)$$

First the node has to wait for the next beacon period start to send the announcement of the channel change. This is called t_{nextBP}. For the best case this is 0 and for the worst case this is the duration of one superframe, which is called mSuperFrameLength in ECMA-368 and is 65.536 ms long.

Then the node will place the Channel Change IE and wait until the end of the superframe. This is exactly mSuperFrameLength long.

Now the node can tune to the new channel. Since it was not possible to find a duration for this process and it is assumed that this duration will be very small, the process of tuning to a new channel was neglected in the calculations.

The standard requires that a node must listen to the channel for at least mSuperFrameLength before joining the channel. Then the start of the next beacon period start time, $t_{nextBPST}$ must be waited for. This can be zero in the optimal case and mSuperFrameLength for the worst case.

Finally the node can place the beacon in the beacon period and is ready for communication at the end of the beacon period. This time is called $t_{newBPLength}$ in the equation above.

$$t_{newBPLength} = (2 + N + mBPExtension) * mBeaconSlotLength \tag{5.2}$$

Equation 5.2 shows the composition of $t_{newBPLength}$. It is assumed that at least one node is already in the Beacon Group (BG). The beacon period has two signalling slots at the beginning. Each slot mBeaconSlotLength is 85 μs long. Then the number of used beacon slots N follows. Then the trailing free $mBPExtension$ slots follow, of which the node will chose one. mBPExtension is variable, but the standard recommends to use eight as a value. The major variable here is N, which can be between 1 and 93. However, the beacon period cannot be larger than 96, so mBPExtension will be reduced in this case. The best case for $t_{newBPLength}$ is

$$\begin{aligned} t^{BC}_{newBPLength} &= (2 + 1 + mBPExtension) * mBeaconSlotLength \\ &= (2 + 1 + 8) * 85\mu s \\ &= 935\mu s \end{aligned} \tag{5.3}$$

and the worst case is

$$\begin{aligned} t^{WC}_{newBPLength} &= (2 + 93 + 1) * mBeaconSlotLength \\ &= (2 + 93 + 1) * 85\mu s \\ &= 8,160\mu s \end{aligned} \tag{5.4}$$

In summary the best case for the channel change is:

$$\begin{aligned} t^{BC}_{chanChange} &= t_{nextBP} + 2 * mSuperFrameLength + t_{nextBPST} + t^{BC}_{newBPLength} \\ &= 0 + 2 * 65.536ms + 0 + 935\mu s \\ &= 132.007ms \end{aligned} \tag{5.5}$$

For the worst case this is

$$\begin{aligned} t^{WC}_{chanChange} &= t_{nextBP} + 2 * mSuperFrameLength + t_{nextBPST} + t^{WC}_{newBPLength} \\ &= mSuperFrameLength + 2 * mSuperFrameLength + \\ &\quad\; mSuperFrameLength + t^{WC}_{newBPLength} \\ &= 4 * mSuperFrameLength + t^{WC}_{newBPLength} \\ &= 4 * 65.536ms + 8.16ms \\ &= 270.304ms \end{aligned} \tag{5.6}$$

The WLP connect time depends on several parameters and can largely vary, due to the MAC mode used, namely Distributed Reservation Protocol (DRP) or Prioritized Contention Access (PCA). In any case it is necessary to exchange four or six messages to set up a WLP connection. The connection process consists of *enrolment*, *activation* and *connection*. A central role is played by the WLP Service Set Identifier (WSSID), which is a logical identifier shared between one or more devices to set up logical communication groups within a larger network. The WSSID is similar to the Basic Service Set Identifier (BSSID) commonly used in IEEE 802.11 networks. *Enrolment* is the process of gathering the WSSID details and can be achieved in a number of ways. First a device can simply create a new WSSID. If a device wants to enrol to an existing WSSID it can use D1/D2 WLP messages to ask remote devices for details; or any other medium to exchange information, such as Wi-Fi, Bluetooth or input by a user if he knows the details. The *activation* is done by adding a WSSID hash value in the WLP IE, which is transmitted in each superframe of the device. Additionally C1/C2 WLP frames can be used to query a device to determine if a neighbour has activated a specific WSSID. The *connection* must be done prior exchanging data frames by using C3/C4 messages. Thus, the creation of a WLP link requires at least the C1/C2 and C3/C4 messages if the WSSID is known a priori and six messages if the D1/D2 messages are used to exchange WSSID details. Figure 5.4 demonstrates the process.

In PCA mode, the theoretical duration for transmitting a pair of messages can be calculated very precisely. It is assumed that all Medium Access Slots (MASs) are available for the PCA transmissions. So no wait time because of occupied MASs exists. Furthermore, the time for processing a message and assembling a reply is also neglected, since it depends very much on the operating system.

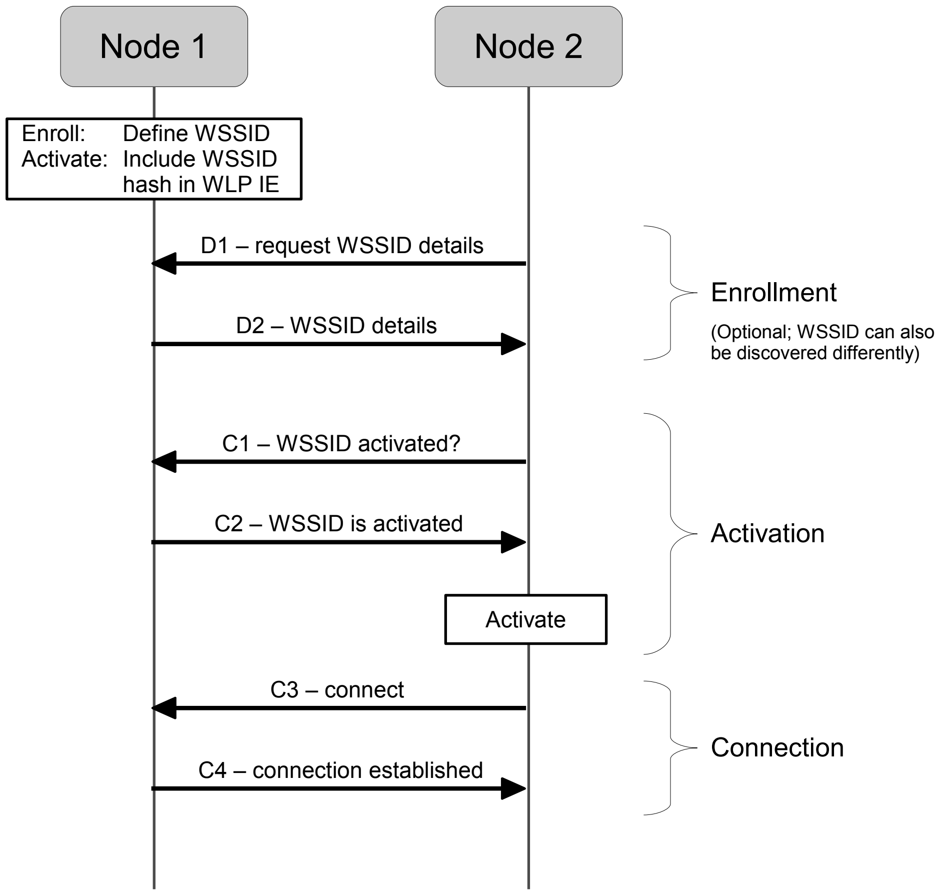


Figure 5.4: Connection process of WLP

The PCA traffic class is assumed to be Best Effort (BE). To access the medium the device needs to obtain a Transmission Opportunity (TXOP); this is an access slot in PCA. The process of obtaining such a TXOP is not described here and can be found in the ECMA-368 standard. Data can only be transmitted within the TXOP, which has a maximal size of

$$mTXOPLimit[AC\_BE] = 512\mu s \tag{5.7}$$

To access the medium and make use of the TXOP the medium has to be unused for a prescribed time, which is called Arbitration Inter-Frame Space (AIFS). This period is composed of several other times $pSIFS$, $mAIFSN[AC\_BE]$ and $pSlotTime$, which are defined in the protocol. For best effort traffic AIFS is

$$\begin{aligned} AIFS[AC\_BE] &= pSIFS + mAIFSN[AC\_BE] \cdot pSlotTime \\ &= 10\mu s + 4 \cdot 9\mu s \\ &= 46\mu s \end{aligned} \tag{5.8}$$

When the medium was unused for AIFS time, a back-off counter, called Contention Window (CW), must expire, before the transmission can start. This counter is set for each transmission to a random value from a defined interval. For the calculations we assume the statistical average of this interval:

$$\begin{aligned} \overline{CW[AC\_BE]} &= \frac{1}{2}(mCWMIN[AC\_BE] + mCWMAX[AC\_BE]) \cdot pSlotTime \\ &= \frac{1}{2}(15 + 1023) \cdot 9\mu s \\ &= 4,671\mu s \end{aligned} \tag{5.9}$$

Finally the time for transmitting one message is:

$$\begin{aligned} t_{wlpPCAMsg}^{AVG} &= AIFS[AC\_BE] + \overline{CW[AC\_BE]} + mTXOPLimit[AC\_BE] \\ &= 46\mu s + 4,671\mu s + 512\mu s \\ &= 5,229\mu s \end{aligned} \tag{5.10}$$

Assuming the best case and worst case for $CW[AC\_BE]$ it is also possible to calculate the maximum and minimum:

$$\begin{aligned} t_{wlpPCAMsg}^{WC} &= AIFS[AC\_BE] + max(CW[AC\_BE]) + mTXOPLimit[AC\_BE] \\ &= 46\mu s + 9,207\mu s + 512\mu s \\ &= 9,765\mu s \end{aligned} \tag{5.11}$$

$$\begin{aligned} t_{wlpPCAMsg}^{BC} &= AIFS[AC\_BE] + mix(CW[AC\_BE]) + mTXOPLimit[AC\_BE] \\ &= 46\mu s + 135\mu s + 512\mu s \\ &= 693\mu s \end{aligned} \tag{5.12}$$

Assuming a consecutive message exchange with an average CW and no interrupting beacon period, the time for exchanging six messages in PCA is:

$$t_{wlpPCAConnect} = 6 \cdot t_{wlpPCAMsg}^{AVG} = 6 \cdot 5,229\mu s = 31.374ms \tag{5.13}$$

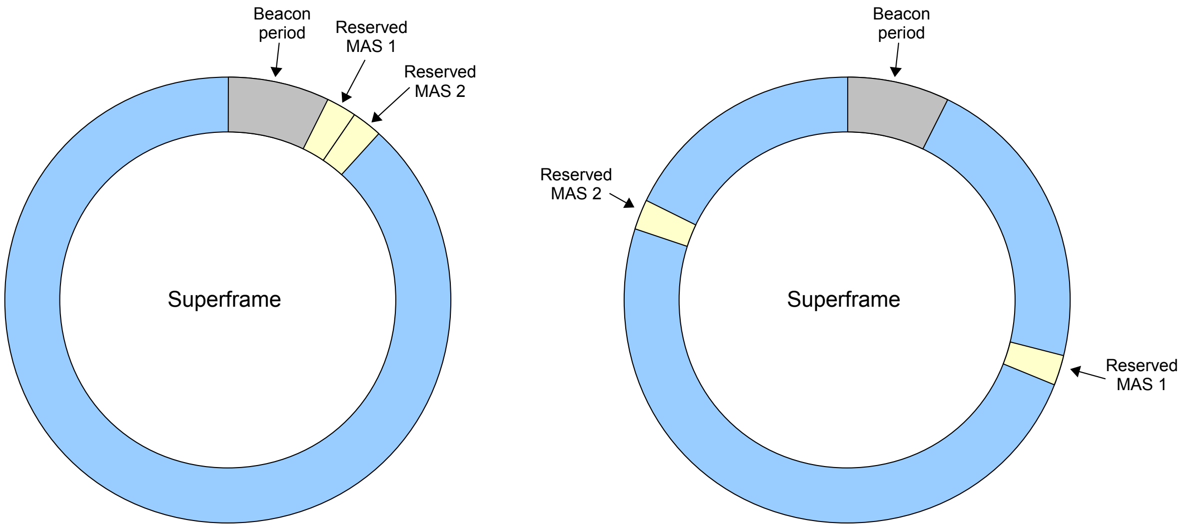
For DRP medium access the duration for establishing a WLP link depends on the MAS reservation of the two devices. Figure 5.5 shows two examples of DRP reservations for a two node network with two MASs reserved for communication between the nodes. In the *compact* assignment example the first two MASs in the superframe are chosen. In the *spread* assignment example the MASs are on opposite sides of the superframe, if it is seen as a circle.

Since one MAS is 256 μs long, it is assumed, that if one node is sending a message, the other node cannot process it and sends a reply within this MAS. Furthermore, it is also assumed that for two MASs located consecutively there is also not enough time to receive one message in the first MAS and transmit a reply in the second MAS. Hence, for exchanging six messages in the compact reservation example it would take six superframes plus the time from the intention to transmit to the first reserved MAS.

$$t_{wlpDRPConnect\_compact} = t_{waitFirstMAS} + 6 \cdot mSuperFrameLength \tag{5.14}$$

For the spread reservation scheme it is possible to process an incoming message and transmit a reply in the next superframe. Six messages are exchanged in about 2.5 superframes.

$$\begin{aligned} t_{wlpDRPConnect\_spread} = &t_{waitFirstMAS} + 2 \cdot mSuperFrameLength + \\ &t_{distReservedMAS} + mMASLength \end{aligned} \tag{5.15}$$



(a) Compact assignment

(b) Spread assignment

Figure 5.5: MAS assignment examples

Mobile IPv6 connect

IPv6 has several operation options. For this work *Stateless Address Autoconfiguration* is assumed. It allows nodes to set up their IP address without a DHCP server or fix IP addresses. The address is derived from a router prefix and the interface EUI-48 hardware address (commonly known as MAC address). In this mode the router periodically broadcasts *Router Advertisements*, which include the network prefix. A new node in the network waits for such an advertisement, then configures the IPv6 address and is ready for transmissions.

For Mobile IPv6 the duration to set up or update the link requires to wait for the router advertisement, then send the *Binding Update* message to the HA and wait for the *Binding Acknowledgement* message. Thus, the Mobile IPv6 connect time is:

$$t_{MIPv6Connect} = t_{MN\_HA\_roundtrip} + t_{RtrAdvIntervalLeft} \tag{5.16}$$

$t_{MN\_HA\_roundtrip}$ is not derived here since the equation is greatly dominated by $t_{RtrAdvIntervalLeft}$. According to [NNSS07] the interval for a router advertisement can be between three and 4 seconds. The average value for the interval is

$$\overline{t_{RtrAdvInterval}} = \frac{1}{2}(MaxRtrAdvInterval + MinRtrAdvInterval) = 3.5s \tag{5.17}$$

And the average remaining interval is

$$\overline{t_{RtrAdvIntervalLeft}} = \frac{1}{2} t_{RtrAdvInterval} = 1.75s \tag{5.18}$$

FMIPv6 connect

With FMIPv6 several messages are exchanged between MN, PAR, NAR and HA to perform a handover. But only two are mainly responsible for re-establishing the communication for predictive handovers. These are the *Fast Binding Acknowledgement* (FBack) and the Fast (Unsolicited) Neighbor Advertisement (FNA/UNA). When the PAR sends the FBack to the MN, it also stops delivering packets to the MN and forwards them to the NAR. This continues, until the NAR has received a FNA from the MN. Only for this time a delay for the transmissions exists. With neglecting the processing time of messages and assuming PCA transmissions (see Equation 5.10), the duration to reconnect a FMIPv6 link is:

$$t_{FMIPv6\_predictive} = 2t^{AVG}_{wlpPCAMsg} \tag{5.19}$$

Summary

It can be seen from the derivations above that the durations depend on a number of parameters and situations. For some numbers it is reasonable to use average values, for instance when a backoff time is used that changes for every transmission. But for other values, for example the DRP reservation where the selected slots are constant over a longer period, the effective values will not be the average and rather depend on the state of the system.

Even though the desired reservation scheme is DRP for the wireless CMS system the available UWB dongles only supported PCA. Thus, for the summary and following work PCA is assumed, to compare the theoretical results with the experiments.

Finally the average values for handovers in Mobile IPv6 are:

$$\begin{aligned} t_{TotalMIP} &= t_{chan} + t_{WLP} + t_{MIP} \\ &= 201.155ms + 26.657ms + 1,750ms \\ &= 1,977.812ms \end{aligned} \tag{5.20}$$

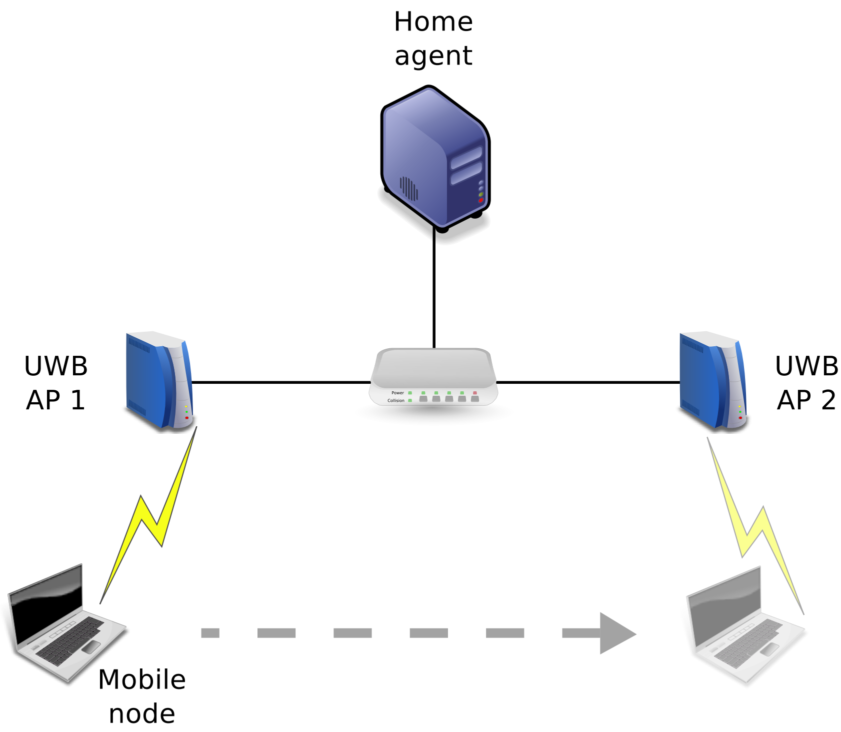


Figure 5.6: Setup configuration for mobility testing

And in FMIPv6:

$$\begin{aligned} t_{TotalFMIP} =& t_{chan} + t_{WLP} + t_{FMIP} \\ &= 201.155ms + 26.657ms + 10.458ms \\ &= 238.27ms \end{aligned} \tag{5.21}$$

5.2.2 Mobile IPv6 experimental results

In a first step Mobile IPv6 was tested with practical experiments. The set-up can be seen in Figure 5.6. All four nodes are x86-computers running Linux Ubuntu with Kernel version 2.6.24 compiled with Mobile IPv6 support. The used Mobile IPv6 implementation is USAGI (UniverSAl playGround for IPv6) UMIP. APs and the MN use IOGear WiMedia dongles with the Intel I1480 MAC chip and an Alereon AL4000 PHY chip. The UWB driver is an experimental Kernel module supporting Intel I1480 and a first WLP implementation. HA and the two APs are connected with a 1Gbit/s Ethernet link.

In each run the MN transits from AP 1 to AP 2. The time from losing the UWB link till registering the new IPv6 address at the HA is measured. Since the Mobile IPv6 depends much on the Router Advertisement message, two measurements with 50 runs

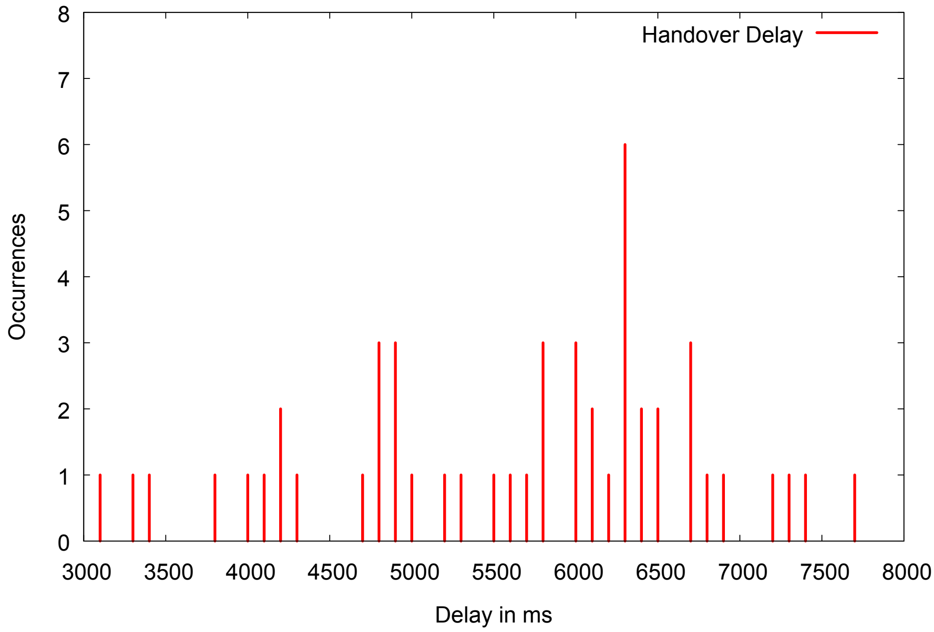


Figure 5.7: Handover delays with Mobile IP; router advertisements messages interval between three and four seconds.

each were executed. Figure 5.7 shows the durations with Router Advertisement messages every three to four seconds, the minimum according to the standard. Noticeable is the large variety of reconnect times, ranging from about 3 to 7.5 seconds. Furthermore, the duration is significantly longer than the theoretical results. The reason for this was a very time consuming UWB driver, which was clearly not designed for fast reactions. The scanning process is also very slow. In Figure 5.8 one run is shown in detail, where the sequence numbers of the packets are displayed over the time.

The second series of runs used a Router Advertisement interval between 0.5 and 1 second. This is actually a violation of the protocol, but still possible. The results are shown in Figures 5.9 and 5.10.

5.2.3 FMIPv6 adaptation and experimental results

The existing FMIPv6 implementation solely depends on WLAN connections. Hence, the first task was to modify the WLAN module of FMIPv6 to handle the I1480 drivers. Changed features involved the scan management and results, connection setup and WLP setup.

Figure 5.11 shows a measurement set of 100 runs with FMIPv6 for disconnect times of predictive handovers. The time from the disconnect to the FMIPv6 reconnect was measured. The performance is much better when compared to the Mobile IPv6 results.

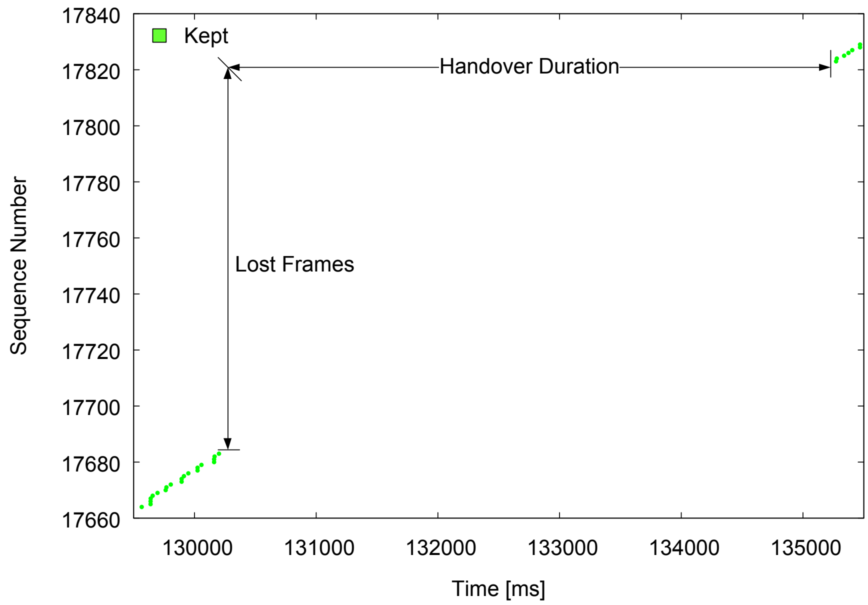


Figure 5.8: Sequence number arrival times for Mobile IP with router advertisements every three to four seconds.

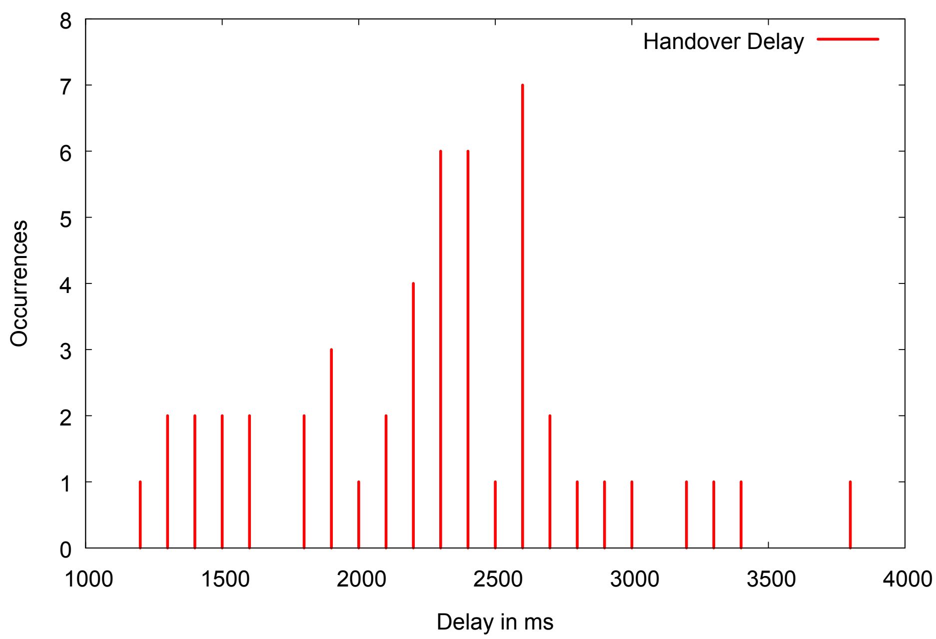


Figure 5.9: Handover delays with Mobile IP; router advertisements messages intervals between 0.5 and one second.

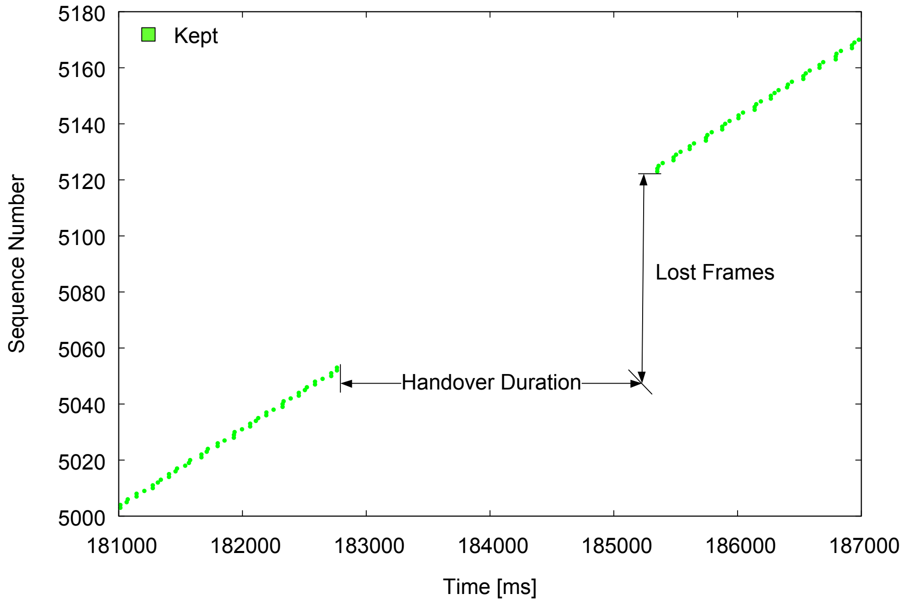


Figure 5.10: Sequence number arrival times for Mobile IP with router advertisements every 0.5 to one second.

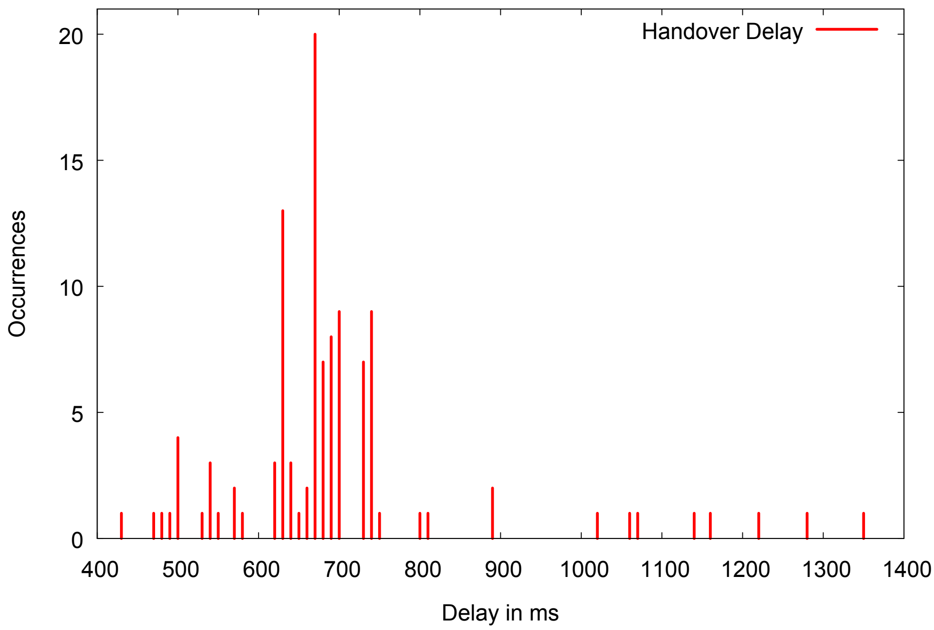


Figure 5.11: Predictive handover delays with FMIPv6

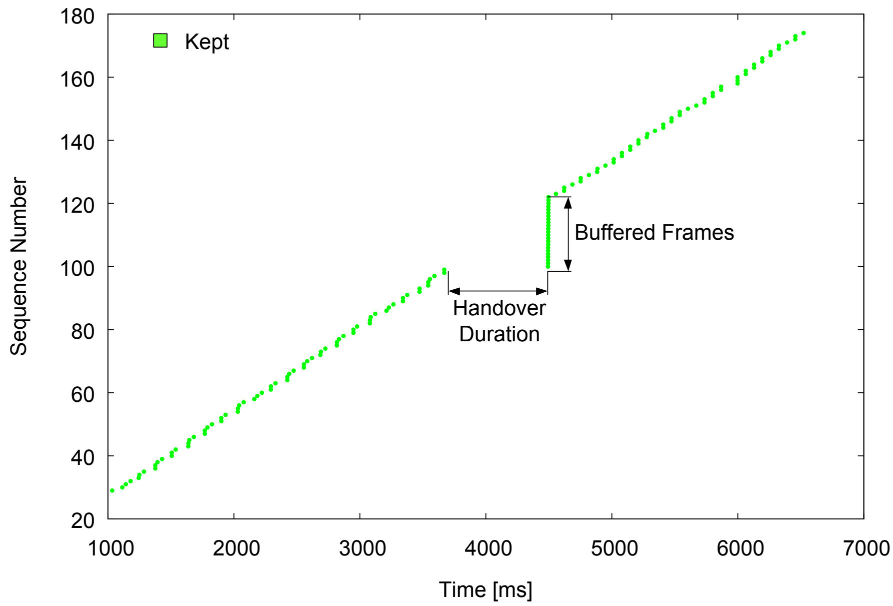


Figure 5.12: Sequence number arrival times for predictive handover in FMIPv6

This has two reasons: Firstly no periodic message must be received before proceeding, and secondly the modified FMIPv6 connection handling is much faster and mostly event driven. The average handover time is now around 700 ms.

Figure 5.12 shows the packets arrival times. When the connection is re-established, the buffered frames are being forwarded to the MN.

The results show a FMIPv6 handover time of about 700 ms in average, which is more than expected from the theoretical results. The most obvious reason is a suboptimal driver. An investigation of the driver performance showed that the *beacon group join* process takes about 300 ms. According to the protocol definition it should take between one and two superframes, which are at most 131 ms. A second issue is that the driver initiates the actions to join a BG and transmit a packet separately. After the join process the host computer is notified and the driver compiles the command to transmit a packet. This is sent to the dongle and the dongle waits until the next superframe. This can cause an extra delay of up to two superframes again. An optimal procedure would be to send the join command and transmit command consecutively and the dongle then knows that directly after joining the network it can transmit the first packet. Also apparent are outliers in Figure 5.11, which show handover times of up to 1.3 seconds. This was tracked down to extra delay time in the dongles, which could not be explained and appeared randomly, since no commonalities between the performed actions could be found.

Another performance issue with the driver is the preparation time for transmitting a packet. According to the standard a node can indicate that it requires for PCA a Traffic Indication Map Information Element (TIM IE), before other nodes can send a PCA packet to it. Thus, one node that wants to transmit messages to another node must include a TIM IE in its beacon first, before it can send the data. Requiring such a TIM IE is marked optional in the standard, however the IOGear dongles have this feature in their firmware as default. The result is that messages with small intervals between the transmits are transmitted faster than consecutive messages with longer intervals. For example the *ping* command that transmits by default every second a packet and measures the round-trip-time returns for a ECMA-368 results between 80 and 130 ms. This is as expected, because the first node has to wait for the next superframe start to include the TIM IE in the beacon and then send the packet. The replying node receives the ping, prepares an acknowledgement message and must also wait for the next superframe start to include the TIM IE, before it can transmit the packet. So the required time is at least one superframe and the time for the first superframe start to begin. Statistically this is between 65 and 130 ms. However, if the ping interval is set to a value below 65 ms the ping result is about 5 ms. In this case more than one ping are sent per superframe and the TIM IE of the previous ping is still present, thus the nodes can send their packets immediately.

Since the firmware on the dongles is not available as source code, there is no way to improve this behaviour with the current driver. Unfortunately the delays explained above cannot be eliminated.

5.3 Protocol enhancements

The performance for FMIPv6 predictive handovers, with values around 700 ms, with the potential to further reduce this delay with sophisticated drivers and firmware is acceptable. It would only affect mobile devices moving through the cabin, such as mobile headsets.

However, a reactive handover still causes packet losses, due to failed packet forwarding that could not be started for an abrupt connection loss. To overcome this problem a new mechanism was developed that permanently assigns a Backup Access Router (BAR) for each end device. It is an extension of FMIPv6 and allows the forwarding and buffering of reactive handovers, similar to the way as known from predictive handovers.

5.3.1 Backup Access Router

The MN can select a current BAR and initiate the transmission of duplicated packets to the BAR. By scanning all channels the MN can tell which ARs are in range and determine the signal strength and link quality. The standard mechanisms from FMIPv6 allow the MN to get the prefix details of the ARs in range. With the prefix details the Backup Care-of Address (BCoA) is known to the MN. Derived from this information an AR is set to be the BAR. Messages from the CMS server sent to the MN are now sent to the current AR and the BAR.

Packets from the MN to the server are not duplicated. In this case the bottleneck is the first hop and the MN can determine itself if the transmission was successful or not.

It would also be possible to use more than one BAR. However, the required memory at the BARs and network load on the backbone will increase. In this work only one BAR per end device is assumed.

5.3.2 Packet duplication

One central question is which node will do the packet duplication; either the CMS server or the current AR. One reason to let the AR do the packet duplication, is that the AR and BAR will most likely be close together and the overall network load will be reduced, if the duplicates are only transmitted between the two nodes. However, the backbone architecture in an aircraft has two or more backbone lines in the cabin. ARs can be attached to all of them, thus the assumption that the current AR and BAR will be close together may not be true when seen from a network topology view. For that reason the CMS server is doing the packet duplication.

When a MN has selected an AR as the BAR, it can generate the possible Care-of Address, even when still connected to the current AR. This address is transmitted to the server, which then transmits all packets to both ARs. The BAR stores the packets in a ring buffer. The size of the ring buffer is at least the size of the maximal expected transmission duration of a handover.

The packets have a sequence number, to track packets and also detect duplicated packets. During a reactive handover the MN connects to the BAR and requests forwarding of the missing packets. Since the MN knows the sequence number of the first missing packet, it can request the packets with larger sequence numbers. If the data stream delivered packets that are out of order, the sequence number can be used to reorder received packets.

One very important feature of the duplication mechanism is to make it transparent to the applications. The applications must not be modified and all existing services can still be used. It is transparent to the physical, data link and network layers, to avoid necessary modifications at all nodes in the communication paths. Since the CMS architecture uses different prefixes, layer 3 partitioned topology, the packet tagging must not disturb network switches or router operations and must not be lost by the packet processing of the switches or routers. On the other hand the tagging must be applicable to all transport layer packets, e.g. TCP, UDP, ICMP, etc. This only allows a tagging of the packets in the network layer, without interfering with network layer procedures. The sequence numbers are added to the end of the IP payload. Only the nodes that support the tagging feature must have modified network drivers to add tags and check if a packet has a sequence number. All other nodes will handle the tagged packets as regular IP packets. Only if a gateway is used this tagging will be lost at the gateway, but this is not the case in the aircraft network.

A modified network driver in the server, ARs and MNs will handle the tagging. The criteria is relative simple for tagging packets, since the IP destination addresses of the MN are known at the server and the server must simply tag and duplicate all packets for the MNs.

5.3.3 Implementation

The implementation of the necessary changes requires definition of new message types, packet duplication and packet tagging. The tagging again contains techniques to tag packets, detect a tagged packets and manage the sequence numbers.

New message types

To implement the features a number of additional FMIPv6 messages are needed:

Backup Care-of Address Registration (BCoAReg): A MN that has found an AR can use the FMIPv6 mechanisms to get details of the detected AR by querying the current AR. With the BCoAReg the detected AR is registered as a BAR at the server. More than one BAR can be defined by one MN.

Backup Care-of Address Deregistration (BCoADereg): Sent from the MN to the server to deregister a BAR.

Backup Care-of Address Registration Ack. (BCoARegAck): Acknowledgement to BCoAReg and BCoADereg.

Buffering Request (BufReq): After the server has received a BCoAReg message, a BufReq is sent to the BAR to start buffering of all messages addressed to the MNs BCoA.

Buffering Stop (BufStop): Stops the buffering at the BAR.

Buffering Acknowledgement (BufAck): Acknowledgement to BufReq and BufStop.

Request Buffered Frames (ReqBufFr): A MN that has done a handover request with the ReqBufFr message the buffered frames from the BAR. The message contains the sequence number of the first frame to be transmitted.

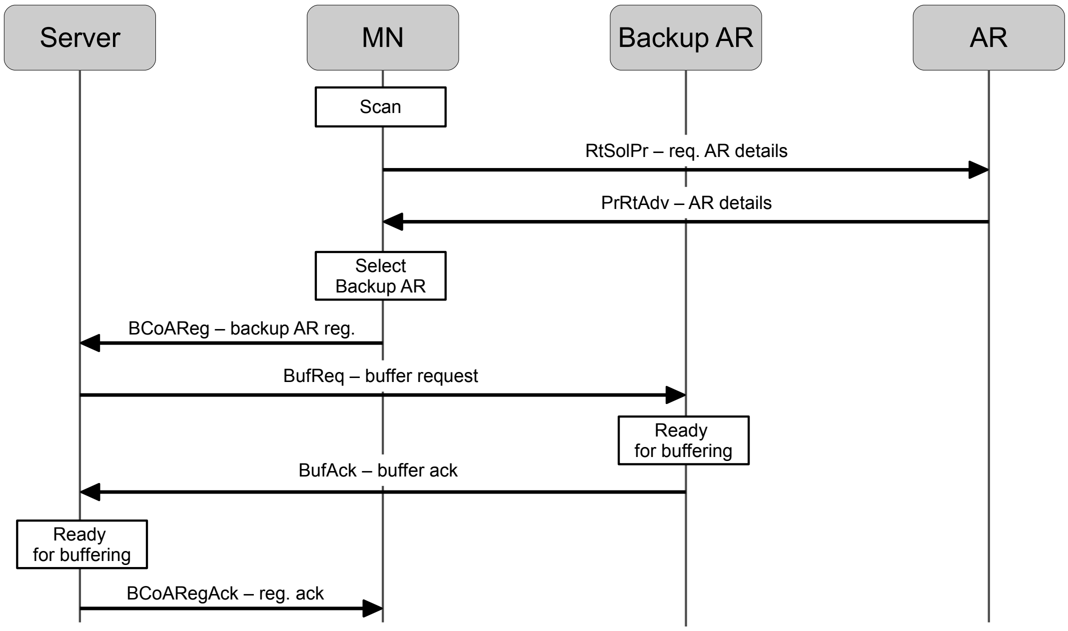


Figure 5.13: Backup Care-of Address registration

Figures 5.13, 5.14 and 5.15 show the new messages with in sequence diagrams to illustrate the new procedures.

Packet duplication

The modified network drivers must be applied in the server, in all ARs and MNs. The server contains a list of all wireless end devices and depending to the destination port the packets are being duplicated or not. For each end device an individual counter for the sequence numbers exist. The ARs know for which destination address the packets should be stored in the ring buffer and for which address the packets can be directly forwarded. The ARs keep track of the sequence numbers currently in their buffers. Only on request, the packets are read from the buffer and sent to the MN, otherwise they become overwritten after some time. The MNs have to identify missing packets and identify duplicated packets. This is explained in the next section, after the tagging mechanism was explained.

Packet tagging

A protocol that has similar ambitions is the Parallel Redundancy Protocol [Wei08]. It also uses redundant paths for communication and handles issues on duplication and tagging. Two significant differences exist between PRP and the network for the aircraft: First

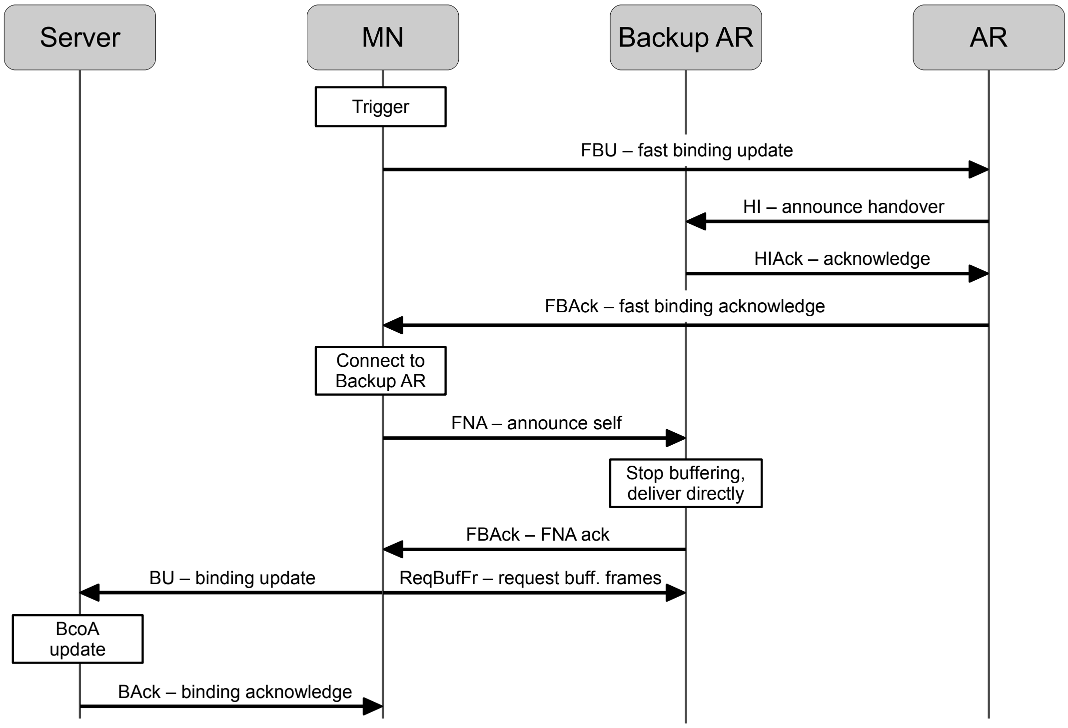


Figure 5.14: Predictive handover with BAR

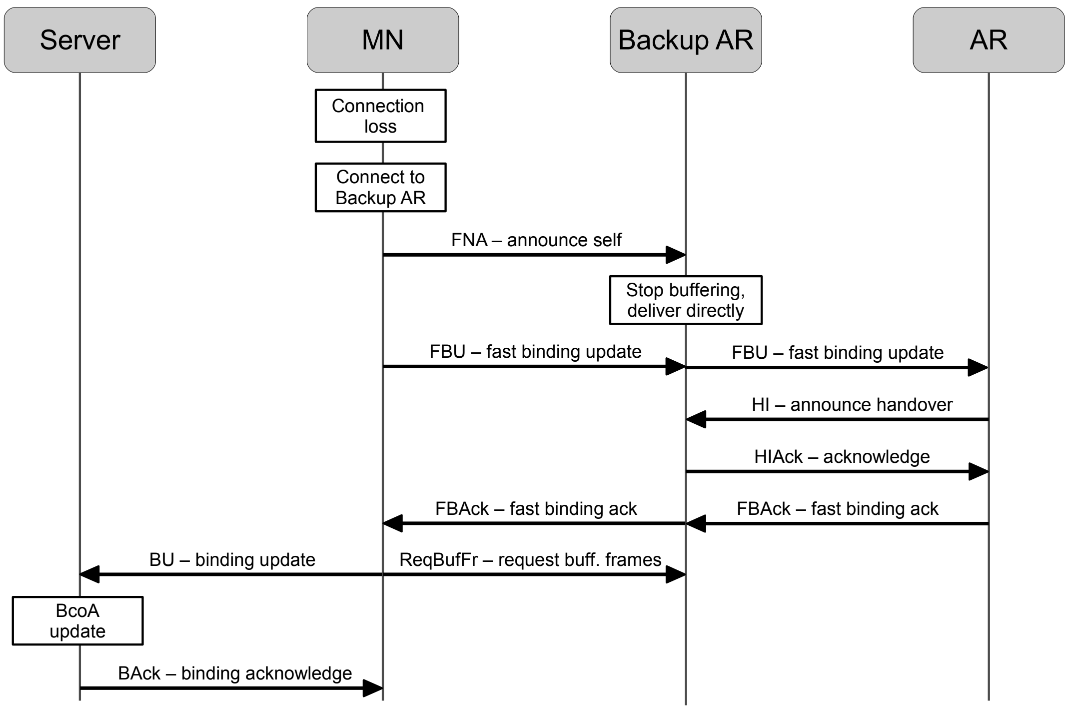


Figure 5.15: Reactive handover with BAR

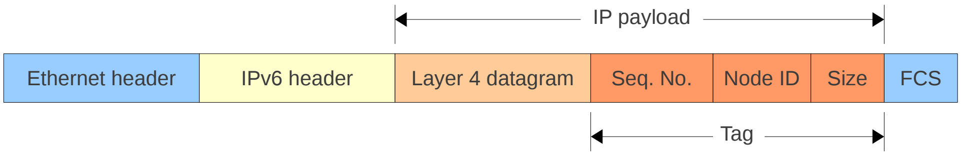


Figure 5.16: Tagged IP packet for duplicate detection

PRP operates on the MAC layer, thus only nodes in the layer 2 network are reached and secondly the redundant paths are completely disjunctive, meaning they are on physically different networks. In the aircraft network the backbone is shared by both paths. One mechanism that can be applied to the CMS is the packet tagging mechanism.

PRP uses additional data that is appended to the MAC payload. With the layer 3 partitioned network the additional data would be lost at gateways. Due to that reason the data is added to the IP payload instead. Figure 5.16 shows the structure of the new packets. A virtual network interface (TAP interface) is used for all transmissions. A packet ready for transmission is checked by the interface driver to see if it satisfies any duplication criteria. If it does, the IP payload field is extended with the tagging fields, then the new packet length fields for the Ethernet and IP headers are updated and a corrected checksum is calculated. The packet can now be transmitted. The tagging fields are as followed:

Sequence number (16 bits): Ascending number for each source and destination address pair.

Node ID (12 bits): Required to support multiple IP addresses for one node.

Size (12 bits): Size of the IP payload.

The BAR and MN check each packet on tagging fields in the packet. This is done by comparing the last 12 bits of the IP payload with the size of the IP payload given in the IPv6 header. If these values are identical, this packet is a tagged packet. A BAR stores this packet in the corresponding ring buffer for that destination address. For the MN the virtual interface will check if the packet was received already and drop it if the check is positive. If not, the driver de-tags the packet, correct the length information and checksum and deliver it to the IP network layer.

Management of the received and non received sequence numbers is done with a shifting list as shown in Figure 5.17. A certain number of sequence numbers before and after the next expected number are stored. The number of a newly arriving packet is compared to the numbers in the list. If it is already marked as received, the packet is dropped. If it is the expected packet number it is accepted and the list is shifted by on number. If it is within the accepted numbers list the packet is accepted and the list is shifted for the number of missed sequence numbers. In all other cases a new list around the received

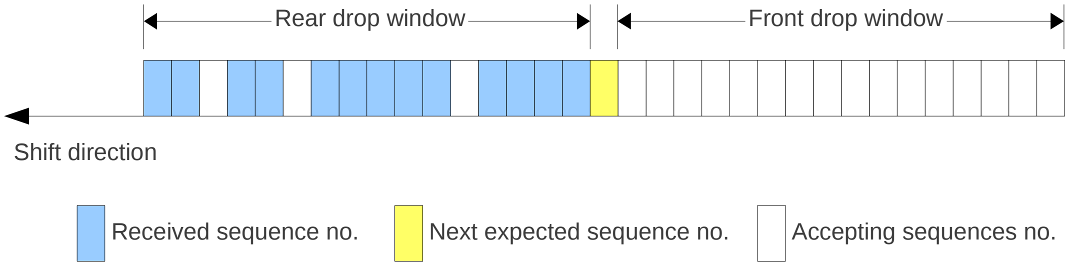


Figure 5.17: Sequence number management

sequence number is started.

5.4 Mobility results

The implemented modifications to FMIPv6 were tested in the described setup as seen in Figure 5.6. A detailed view on one handover can be seen in Figure 5.18 from the perspective of the MN. The sequence numbers of arriving packets are shown for the enhanced reactive handover. It illustrates nicely the forwarding of buffered packets. After the successful connection to the BAR, the packets buffered in the Linux kernel are forwarded immediately and the incoming packets are delivered regularly. After some time the request for buffered packets is handled. The forwarding of the buffered packets uses three superframes. Within these buffered packets are the previously sent packets from the kernel queue. They are dropped by the mobile node. Further optimisations of the algorithm or tweaking the kernel queues could avoid these double transmissions. However, the figure shows the successful behaviour for reactive handovers with the mobility enhancements and the detection of duplicated packets.

For the three variants, Mobile IPv6, FMIPv6 and the enhanced FMIPv6, the duration and packet loss was measured, over a total of 50 runs each. Test messages with sequence numbers were continuously transmitted. The average results are seen in Table 5.1. Mobile IP requires the longest time and has significant losses. The durations for FMIPv6 without BAR and with BAR are nearly identical, which is as expected since the process for establishing the new link is identical. For reactive handover the packet loss with BAR was eliminated.

With the enhanced handover procedure packet loss will no longer occur in the wireless CMS for reactive handovers. With Mobile IPv6, FMIPv6 and the modifications, the delay is reduced to the MAC layer reconnect duration and packet loss is not existent for predictive and reactive handovers. The price for eliminating the packet loss is an increased backbone load and memory usage at the ARs. Since only mobile nodes will cause redundant transmits and buffering, the necessary extra resources are no problem

Type	Handover	Duration	Loss
MobIPv6 (RAI 0.5-1 sec)		2588 ms	70
MobIPv6 (RAI 3-4 sec)		5071 ms	140
FMIPv6	Predictive	823 ms	0
FMIPv6	Reactive	1377 ms	40
Enhanced FMIPv6	Predictive	809 ms	0
Enhanced FMIPv6	Reactive	1381 ms	0

Table 5.1: Results of mobility enhancements

for the wireless CMS.

5.5 Outlook on zero delay handover

The proposed mechanisms of tagging and duplicating the packets can also be extended to the dual interface management. As stated in Section 2.3.1 the architecture foresees devices to have two interfaces: UWB and a second one, which could be optical or 60 GHz technology. With two links to each node, the second link can be used during a handover. This would eliminate a delay for handovers completely.

Two principle techniques for redundant communication paths exist: *hot redundancy* and *cold redundancy*. In hot redundancy packets are always transmitted on both paths. This could be used for critical transmissions, where a packet loss should be avoided. However, hot redundancy also increases the network load. With cold redundancy only one link at a time is used. In this case short delays may occur until the link is switched.

In the aircraft scenario the partly use of hot redundancy is very likely, since some medium critical services will be operated with the network. For hot redundancy the problem of duplication and duplicate detection also exists. The proposed duplication, tagging and FMIPv6 enhancements described in this chapter can also be applied to the dual link hot redundancy. Thus, two levels for the duplications may exist in parallel: first the UWB only duplication and secondly the dual link duplication.

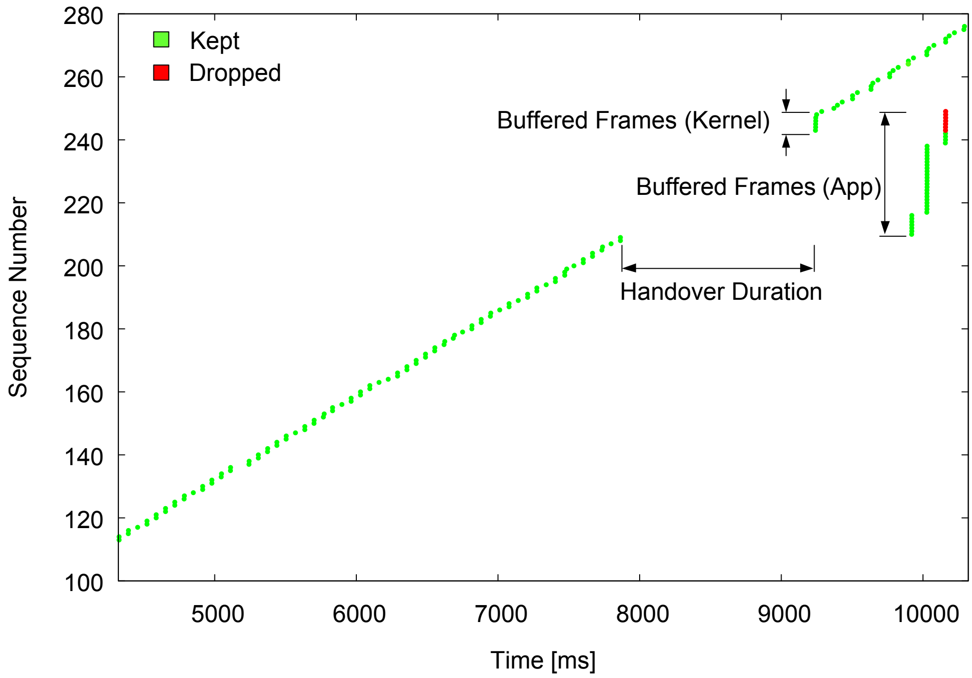


Figure 5.18: Sequence number arrival times for reactive handover in the enhanced FMIPv6

Chapter 6

Redundant interface architecture

As already mentioned in Section 2.3.2 the aircraft network concept foresees two independent wireless interfaces. One is based on ECMA-368 and the other can be based on optical or 60 GHz technology. In this chapter a system architecture is presented to handle these two sub-networks. The second interface is called the optical interface in this chapter.

Figure 2.9 showed the components of the system. The server is connected to several Backbone Access Controllers (BACs) with the backbone network. The backbone is a wired high speed connection, for instance 1 Gbit/s Ethernet. The BACs serve as routers to wired end devices. UWB Access Points (APs) and optical APs are connected to the BACs. For each technology the APs create a full cabin covering network, to provide wireless end devices access to the network. The end devices are equipped with both interface technologies, so they can use both links simultaneously if required.

The APs for each link shall be placed so that for each end device there are two APs in range. If one AP is no longer accessible the end devices have a backup AP. This means there are two types of redundancy. Firstly the devices can connect to the UWB or optical interface and secondly they have two APs per interface. The connection to the UWB and optical AP can run in parallel. With the UWB link (based on ECMA-368), and assuming that neighbouring APs have different channels, only one UWB link can be maintained at a time. For the optical link no details are currently available. It is assumed that the optical APs also operate on different channels and the end devices can only have one optical channel activated at a time.

Based on the described preconditions the following tasks must be handled by the system:

Sub-network: Always connect the end devices to the best possible AP

Interface redundancy: Choose for each end device the *better* interface, which is called the primary interface. Regular transmissions are sent via the primary interface. Safety critical or real-time transmissions are sent via both, the primary and secondary, interfaces.

Addressing: End devices must be addressable by their UWB IP address, optical IP address and interface independent IP address.

Transparency: On application layer the wireless connection with its redundancy must be transparent. The application shall handle a wireless device the same way, as they handle wired devices. Thus, no modifications to the applications are necessary.

Figure 6.1 shows the model for the architecture. At the bottom are the interfaces. They are managed by the UWB Manager or Optical Manager. The task of these managers is to scan for APs and select the best AP. The distributed algorithm of Section 4.2 would be located in the UWB Manager. The managers send signal quality and connection status reports to the IF Redundancy Manager (IF stands for interface). The IF Redundancy Manager evaluates the UWB and optical link of each end device and decides which one has the better performance. The UWB Manager, Optical Manager and IF Redundancy Manager send status updates to the Route Manager, which handles the update of routing entries. The enhanced FMIPv6 protocol from Chapter 5 would be part of the Route Manager. Finally the Route Manager reports the available links and lost links to the applications.

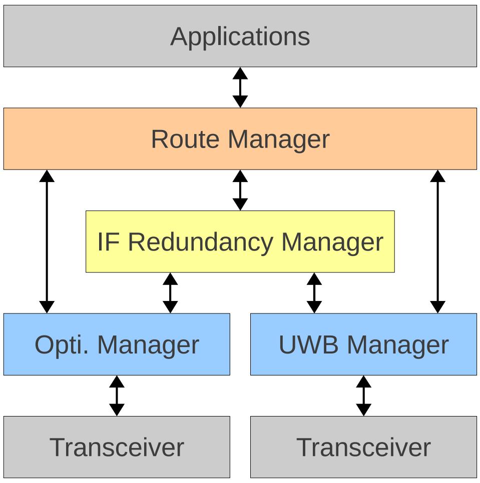


Figure 6.1: Software components and hierarchy of dual interface architecture

The UWB and Optical Managers are located on the end devices and on the APs. The IF Redundancy Managers must be located behind the UWB and Optical Managers. This are then the BACs and the end devices. All devices in the network shall be accessible with IP messages, thus the Route Manager is located on all devices. The actual Cabin Management System (CMS) applications are installed on the server and on the end devices. Figure 6.2 shows a layer model for the different type of devices.

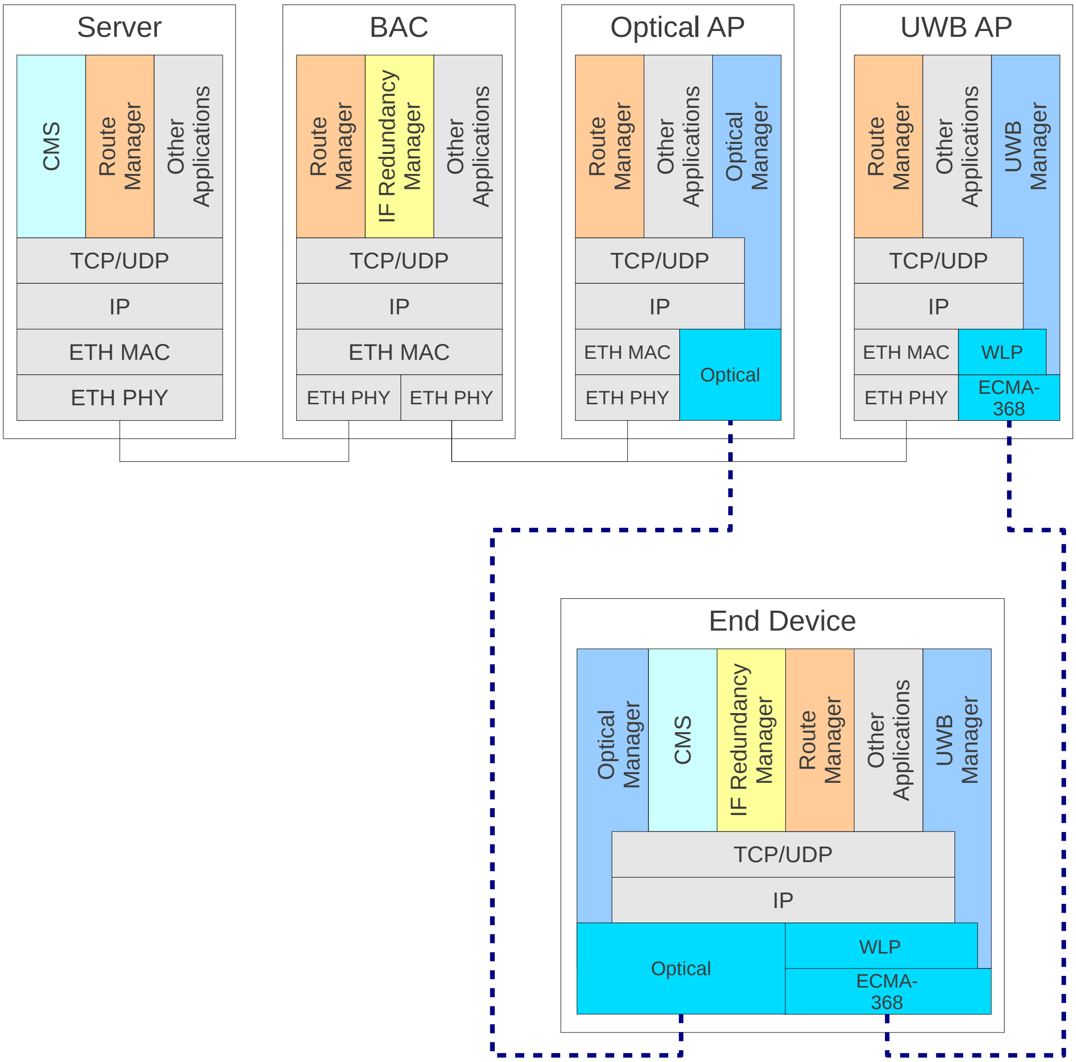


Figure 6.2: Communication layer model of the system concept

Figure 6.3 shows the signalling message flow between the components. The UWB Manager and Optical Manager operates between the end devices and the APs. The goal is to maintain the connection between the end devices and the APs. This task can be done independently. Only the signalling of the link status is done between the UWB/Optical Manager and the IF Redundancy Manager. The IF Redundancy Manager interacts between the end devices and the BACs. Here two cases have to be viewed separately: First the UWB AP and Optical AP are connected to the same BAC. In this case the IF Redundancy Manager on the BAC has both link quality reports available and can decide which link is the primary link. It can also happen that the two APs are not connected to the same BAC. Then the IF Redundancy Managers of the BACs have to exchange the link quality details before calculating the primary link. Finally all links have to be reported to the Route Manager, which is located on every device. The Route Manager updates all routes in the system. With the distribution of the routes the server has all IP addresses of the end device. These include the UWB address, the optical address, the IF independent address and an identifier of the primary route. If a message is sent to the UWB or optical address, the message is forwarded via the route of the technology. If a packet is sent to the independent address, then it will automatically be forwarded on the primary route. So all routing tables in the system must have an entry for the independent addresses of all end devices.

The quality of the links have a generic description. The technology specific parameters may not be comparable. A signal strength from the UWB link might have a different maximum or minimum value and meaning than for the optical link. Hence, the real parameters must not be reported from the UWB/Optical Managers to the IF Redundancy Managers, but a technology independent value. One possibility is to use a scale from one to ten to describe the link quality. The UWB/Optical Managers only report new links with these abstracted link quality descriptions. The algorithm to calculate the abstracted values must be aligned between the UWB and optical parameters.

This system concept was successfully implemented in a project together with other project partners. Appendix B shows details of the developed demonstrator.

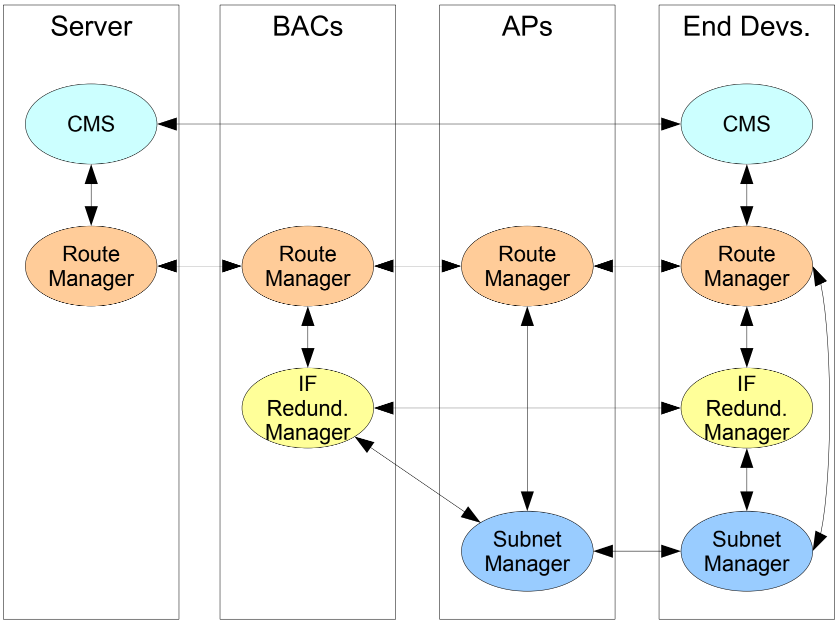


Figure 6.3: Hierarchy and communication directions of the applications

Chapter 7

Conclusions

This work addressed the design and development of a wireless network inside commercial aircraft cabins. The sharp reliability demands in the aircraft environment make the use of wireless technology for aircraft safety critical systems a challenging task.

Despite the large number of existing wireless transceivers technologies, most of them are not suitable for the aircraft application. Shortcomings are mostly the low data rates, sparse resources or frequency regulation issues. The comparison identified ECMA-368 as the most suitable technology. This is a protocol designed for multiple applications and is currently used in Wireless UWB. The nature of wireless technology is burdened by interferences from other systems and is more susceptible to interruptions, when compared to wired networks. As a consequence the system architecture that was developed uses two independent interfaces for wireless transmissions per device. One of them uses ECMA-368 and the second is based on infrared or 60 GHz technology. With redundant interfaces the reliability of a wireless Cabin Management System (CMS) is increased.

The analysis of ECMA-368 identified limitations of the protocol, which must be given special attention for a successful wireless aircraft network. The fixed amount of maximum beacons in the superframe structure gives an upper limit for the number of nodes simultaneously within transmission range. Simulations showed the expected beacon period length, depending on node density (nodes per square meter). Also the upper and lower limits of the beacon period length were deduced. The results showed that the number of nodes in an aircraft are too high for a network operating on one channel. A solution to this problem is a multi-channel architecture, where the end devices are organised in cells, each cell operating on a different channel. To identify the timing behaviour of an ECMA-368 network the protocols were implemented in an event discrete simulator and key situations were examined. The implementation included relevant ECMA-368 and WLP protocol features. The start-up time, when the system is powered up, can become very long, when too many end devices join the channel at the same time. A limit of forty nodes per cell was identified, for which the join process is within a reasonable time.

Simulations of a failing Access Point (AP) showed the duration until the system recovers and the impact on the throughput. Both values are tolerable in the aircraft. Alien Nodes, which are nodes of a foreign network operating on the same channel, can impact the performance of the ECMA-368 network onboard the aircraft. This problem cannot be solved directly. The impact can be reduced if the end devices make the resource reservations and not the APs. Furthermore, the interfering devices can be easily located and a flight attendant can request the deactivation of the devices.

An aircraft cabin can have many different layouts. Future aircraft will have more flexible cabin architectures and the layout will change more frequently. Each time the AP positions must be calculated to support all end devices. An integer linear optimisation algorithm was developed to support unique features of ECMA-368 and to allow optimal positioning of the APs. The algorithm considers the limitations from the beacon period length and the Extended Beacon Group. Interferences from nodes on the same channel are included in the calculation to retain a minimum SNR. In preparation for the cabin changes, the algorithm is given the end device locations and AP candidate sites. The results are the optimal AP positions and channel allocations to provide redundant AP coverage to all end devices and not violating the ECMA-368 standard. The optimisation algorithm is used during the configuration planning of the cabin. However, during operation of the aircraft, interferences or blocked devices can cause connection losses. In this case the calculated optimum is no longer possible. To handle these dynamics a distributed algorithm was developed. The link quality is monitored periodically and an efficient and fair resource reservations calculated to connect all end devices according to their data rate and delay requirements.

With a wireless CMS the possibility of mobile crew devices arises, such as headsets or handhelds. An existing solution for mobility in IP networks that is based on Mobile IPv6 and Fast Handovers for Mobile IPv6 was adopted for ECMA-368 and tested in a real setup. Problems were identified for reactive handovers, where packets are lost for a short period. The protocol was enhanced to support backup access routers in range of an end device, which stored temporary duplicates of sent packets. After a reactive handover the new access router already has the missing packets available and can forward them to the end device. With the modifications the losses were eliminated and the handover time is dominated by the MAC layer duration for registering at a new node, which is dependent on the device driver of the vendor.

The wireless network for the aircraft cabin includes two independent network interfaces to increase the reliability of the connections to the end devices. A hierarchical system design was developed to handle redundancies in the network. Manager modules handle specific tasks in the network and provide a structured partition of the managing functions. The solution is transparent for relay nodes (switches, routers) in the network. Therefore it is flexible enough to be included a wired system, which will be present on modern airliners.

With the results of this work the challenges of a wireless CMS were addressed for several phases of the aircraft. First the network design was handled by protocol studies and mobility enhancements. The optimisation algorithm is used during the layout configuration of the aircraft cabin. This step must be repeated every time the cabin layout changes. Finally the operational phase of the aircraft is supported by a distributed algorithm that reassigns resources given the actual available resources. The operation of a cabin wide wireless CMS should be possible, based on this work. The chances to test such a large system did not exist during the time this research was performed. Smaller demonstrator systems have been developed instead which are described in the appendix.

Appendix A

Optimisation algorithm

```
###########################################
#
# reading files
#
###########################################

# number of channels
param num_chans :=  read "data_num_chans.ltxt" as "1n" comment "#" ;
set num_chans_set := { 1 to num_chans };

# transmit range
param trans_range :=  read "data_trans_range.ltxt" as "1n" comment "#" ;

# ED positions
set ed_index := { read "data_ed_pos.ltxt" as "<1n>" comment "#" };
param ed_x[ed_index] := read "data_ed_pos.ltxt" as "<1n> 2n" comment "#";
param ed_y[ed_index] := read "data_ed_pos.ltxt" as "<1n> 3n" comment "#";

# AP candidate sites positions
set apcs_index := { read "data_ap_cand.ltxt" as "<1n>" comment "#" };
param apcs_x[apcs_index] := read "data_ap_cand.ltxt" as "<1n> 2n" comment "#";
param apcs_y[apcs_index] := read "data_ap_cand.ltxt" as "<1n> 3n" comment "#";

# max BG size
param max_bg_size := read "data_max_bg.ltxt" as "1n" comment "#" ;

# redundant APs
param redu_APs := read "data_redu_aps.ltxt" as "1n" comment "#" ;
```

```
###########################################
#
# calculating parameters
#
###########################################

# num ed, apcs, nodes
param num_ed_nodes := max(ed_index);
param num_apcs_nodes := max(apcs_index);
param num_nodes := num_ed_nodes+num_apcs_nodes;
set num_nodes_set := { 1..num_nodes };

# distances and inrange
defnumb nodes_dists_func(nd1,nd2,num_p) :=
        if (nd1<=num_p) then
            if (nd2<=num_p) then
                sqrt((ed_x[nd1]-ed_x[nd2])^2 + (ed_y[nd1]-ed_y[nd2])^2)
            else
                sqrt((ed_x[nd1]-apcs_x[nd2-num_p])^2 +
                (ed_y[nd1]-apcs_y[nd2-num_ed_nodes])^2)
            end
        else
            if (nd2<=num_ed_nodes) then
                sqrt((apcs_x[nd1-num_ed_nodes]-ed_x[nd2])^2 +
                (apcs_y[nd1-num_ed_nodes]-ed_y[nd2])^2)
            else
                sqrt((apcs_x[nd1-num_ed_nodes]-apcs_x[nd2-num_ed_nodes])^2 +
                     (apcs_y[nd1-num_ed_nodes]-apcs_y[nd2-num_ed_nodes])^2 )
            end
        end ;
param nodes_dists[ <i,j> in num_nodes_set*num_nodes_set] :=
        nodes_dists_func(i,j,num_ed_nodes);
param nodes_inrange[ <i,j> in num_nodes_set*num_nodes_set] :=
        if (nodes_dists[i,j] > trans_range) then 0 else 1 end;

# weights
param weight_num_ap := 10000;

# interferences
defnumb nodes_interf_dist_func(nd1,nd2) :=
        if (nodes_dists[nd1,nd2]<=2*trans_range) then
      0
else
    nodes_dists[nd1,nd2]-trans_range
end ;
```

```
param nodes_interf_dists[ <i,j> in num_nodes_set*num_nodes_set] :=
        nodes_interf_dist_func(i,j);
defnumb ch1_sig(dist) := if (dist==0) then 0 else 1000000000 *
        tenpow( (-10.3 - ( 46 + 10*2.05*log(dist/10)))/10) end ;
param nat_noise := tenpow(-8.5);
param sir_53 := tenpow(0.53);
defnumb nodes_interf_dist_ap_func(nd1,nd2) :=
        if (nodes_dists[nd1,nd2]<=trans_range) then
      nodes_dists[nd1,nd2]
   else
    0
end ;
param nodes_interf_dists_ap[ <i,j> in num_nodes_set*num_nodes_set] :=
        nodes_interf_dist_ap_func(i,j);


###########################################
#
# variables
#
###########################################

# nodes channels
var nd_chn[num_nodes_set] integer >=0 <=num_chans;

# same channel and helper variables
set ndh_set := { <nd1,nd2> in num_nodes_set*num_nodes_set with nd1<nd2
                 and nd1!=nd2 and ( ( nodes_dists[nd1,nd2] <= 2*trans_range )
                 or (nd1>num_ed_nodes) or (nd2>num_ed_nodes) )};
var nd_s_chn[ndh_set] integer >= 0 <= 1;   # node same chan
var nd_h_sgn[ndh_set] integer >= 0 <= 1;  # node helper sign
var nd_h_chn[ndh_set] integer >= 0 <= 1;  # node helper chan

# ebg matrix, is 1 if nodes are in ebg relation (but not bg)
set ebg_set := { <nd1,nd2> in num_nodes_set*num_nodes_set with nd1<nd2 and
                 nd1!=nd2 and nodes_dists[nd1,nd2] <= 2*trans_range };
var ebg[ebg_set] integer >=0 <=1;

# apcs active
var apcs_acti[apcs_index] integer >= 0 <= 1;


###########################################
#
# objective and constraints
```

```
#
###########################################



# objective
minimize costs:
  # num of aps
  weight_num_ap*(sum <apcs> in apcs_index: apcs_acti[apcs]) +

  # short distance between ed and apcs when same chan and inrange
  (sum <ed,apcs> in ed_index*apcs_index with
    nodes_inrange[ed,apcs+num_ed_nodes]==1 :
    nd_s_chn[ed,apcs+num_ed_nodes] * nodes_dists[ed,apcs+num_ed_nodes] ) ;

# every ed must have a channel
subto ed_chan:
  forall <ed> in ed_index do nd_chn[ed] >= 1;

# generate node helper sign
# is 0 when nd_chn1-nd_chn2>=0; is 1 when nd_chn1-nd_chn2<0
subto nd_h_sgn_:
  forall <nd1,nd2> in ndh_set do
    0 <= nd_chn[nd1] - nd_chn[nd2] + (num_chans+1)*nd_h_sgn[nd1,nd2]
      <= num_chans ;

# generate node helper channel
# is 1 when two nodes have the same channel (including 0)
subto nd_h_chn_:
  forall <nd1,nd2> in ndh_set do
    1 <= (nd_chn[nd1] - nd_chn[nd2]) + nd_h_sgn[nd1,nd2]*(num_chans+1) +
          num_chans*nd_h_chn[nd1,nd2] <= num_chans ;

# generate node same channel
# is 1 when two nodes have the same channel and that is not 0
subto nd_s_chn_1:
  forall <nd1,nd2> in ndh_set with nd1<=num_ed_nodes and nd2<=num_ed_nodes do
    nd_h_chn[nd1,nd2] == nd_s_chn[nd1,nd2]  ;
subto nd_s_chn_2:
  forall <nd1,nd2> in ndh_set with nd1>num_ed_nodes and nd2>num_ed_nodes do
    0 <= apcs_acti[nd1-num_ed_nodes] + apcs_acti[nd2-num_ed_nodes] +
         nd_h_chn[nd1,nd2] - 3*nd_s_chn[nd1,nd2] <= 2 ;
subto nd_s_chn_3:
  forall <nd1,nd2> in ndh_set with nd1<=num_ed_nodes and nd2>num_ed_nodes do
    0 <= apcs_acti[nd2-num_ed_nodes] + nd_h_chn[nd1,nd2] -
```

```
        2*nd_s_chn[nd1,nd2] <= 1 ;

# generate ap active
subto apcs_acti_:
  forall <ap> in apcs_index do -1*num_chans +1 <= nd_chn[ap+num_ed_nodes] -
        num_chans*apcs_acti[ap] <= 0;

# every ed must be in range of redu_APs active apcs
subto min_aps:
  forall <ed> in ed_index do
    sum <apcs> in apcs_index with nodes_inrange[ed,apcs+num_ed_nodes]==1 :
        apcs_acti[apcs] >= redu_APs ;


# selected channel of ed must have an active ap in range
subto ed_chan_active_ap:
  forall <ed> in ed_index do
    sum <apcs> in apcs_index with nodes_inrange[ed,apcs+num_ed_nodes]==1 :
        nd_s_chn[ed,apcs+num_ed_nodes] >= 1;

# check bg for max size
subto check_bg:
  forall <nd1> in num_nodes_set do
    (sum <nd2> in num_nodes_set with nd1!=nd2 and nodes_inrange[nd1,nd2]==1 :
      if (nd1<nd2)then nd_s_chn[nd1,nd2]
      else nd_s_chn[nd2,nd1] end
    ) + 1 <= max_bg_size;

# generate ebg
# nd1: the to be checked extended bg node, nd2: the subject node
# nd3: node of the bg
subto gen_ebg_:
  forall  <nd1, nd2> in ebg_set do
    if nodes_inrange[nd1,nd2]==0 then
      -1+(1/(num_nodes+1)) <= ((sum <nd3> in num_nodes_set with nd2!=nd3 and
        nd1!=nd3 and nodes_inrange[nd1,nd3]==1 and nodes_inrange[nd2,nd3]==1 :
            if (nd2<nd3) then nd_s_chn[nd2,nd3]
            else nd_s_chn[nd3,nd2] end
        )/num_nodes) + nd_s_chn[nd1,nd2] - 2*ebg[nd1,nd2] <= 1
    else
      ebg[nd1,nd2] == 0
    end ;

# check ebg for max size
subto check_ebg:
```

```
  forall <nd1> in num_nodes_set do
    (sum <nd2> in num_nodes_set with nd1!=nd2 and nodes_inrange[nd1,nd2]==0 :
          if (nd1<nd2) then ebg[nd1,nd2]+nd_s_chn[nd1,nd2]
       else ebg[nd2,nd1]+nd_s_chn[nd2,nd1] end
        ) <= 1.5*max_bg_size;

# check interferences
subto interf_:
  forall <ed> in ed_index do
    sir_53 * sum <apcs> in apcs_index:
        ch1_sig(nodes_interf_dists[ed,apcs+num_ed_nodes]) *
        nd_s_chn[ed,apcs+num_ed_nodes] <=
    sum <apcs> in apcs_index:
        ch1_sig(nodes_interf_dists_ap[ed,apcs+num_ed_nodes]) *
        nd_s_chn[ed,apcs+num_ed_nodes];
```

Appendix B

Demonstrator

The architecture from Chapter 6 was implemented in a demonstrator. This demonstrator evolved over several years in cooperation with other project partners. Results from multiple projects were deployed. Figure B.1 shows the components of the demonstrator. The wireless part of the system includes two Access Points (APs) operating on different channels, two fix end devices in form of wireless Passenger Service Units (PSUs) and one mobile end device (wireless FAP). The optical interface was not available during the integration. Instead, a pair of infrared transceivers was used, which had no MAC protocol. Without a MAC protocol and with more than two devices, the number of collisions increases. Therefore, only one link used the infrared technology.

The UWB Manager and IF Redundancy Manager from Chapter 6 were implemented. They managed automatically the selection of the best link available. A comparison of the UWB and infrared link qualities was not possible, because the infrared interfaces provided no such information. Instead the algorithm always preferred the UWB link, if it was available. The Route Manager did not use the enhanced protocol from Chapter 5. At the time, a proprietary solution from a different project partner was used.

The demonstrator showed the operation of a wireless Cabin Management System (CMS), including handovers between two cells. These handovers had some seconds delay. The reason for the delay was insufficiency of the available UWB drivers. Many problems of the driver could be solved, since the driver is Open Source. But the dongle firmware was not accessible and could not be enhanced.

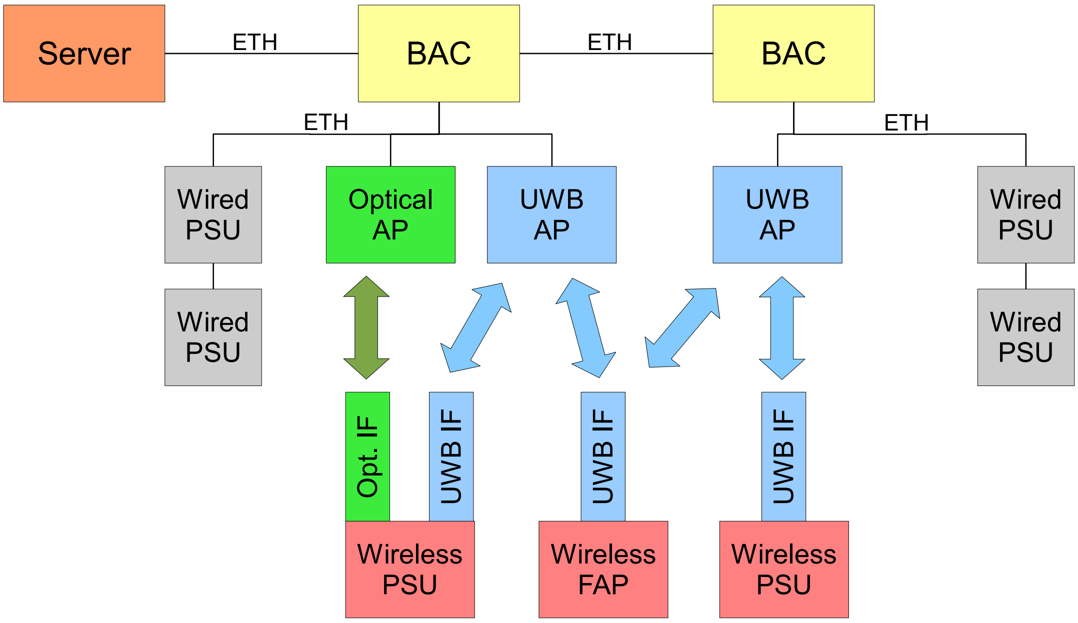


Figure B.1: Demonstrator overview

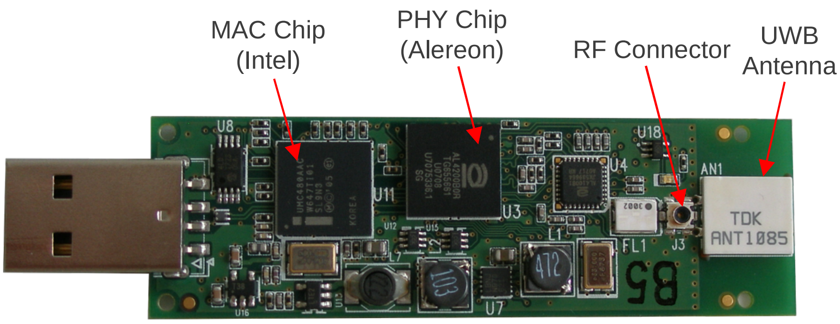


Figure B.2: IOGear WiMedia dongle

Figure B.3: Passenger Service Unit

Figure B.4: Access Point

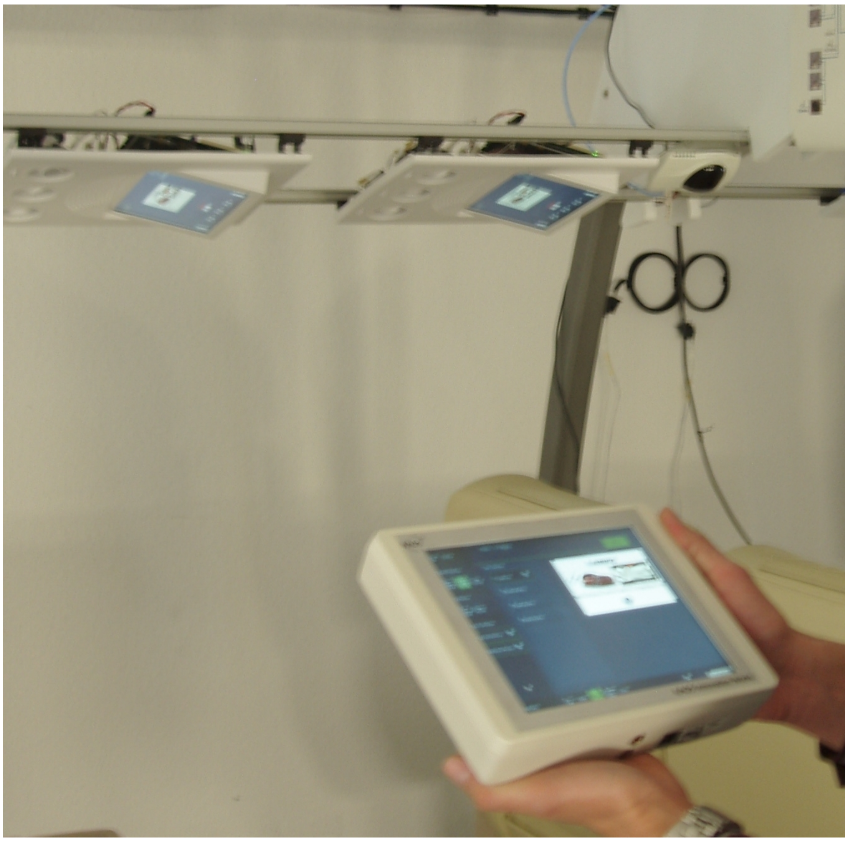


Figure B.5: Picture from the demonstrator showing the wireless FAP, two wireless PSUs and one infrared transceiver

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List of Abbreviations

AIFS	Arbitration Inter-Frame Space
AP	Access Point
APCS	Access Point Candidate Site
AR	Access Router
BAC	Backbone Access Controller
BAR	Backup Access Router
BCoA	Backup Care-of Address
BE	Best Effort
BG	Beacon Group
BITE	Built In Test Equipment
BPOIE	Beacon Period Occupation Information Element
BSSID	Basic Service Set Identifier
CMS	Cabin Management System
CN	Corresponding Node
CoAd	Care-off Address
CSMA	Carrier Sense Multiple Access
CW	Contention Window
DAL	Design Assurance Level
DECT	Digital Enhanced Cordless Telecommunications
DHCP	Dynamic Host Configuration Protocol
DMS	Deadline Monotonic Scheduling
DRP	Distributed Reservation Protocol
DS	Direct Sequence
EBG	Extended Beacon Group
ECMA	European Computer Manufacturers Association
ED	End Device
EDF	Earliest Deadline First
EUI	Extended Unique Identifier
FAP	Flight Attendant Panel
FCC	Federal Communications Commission
FMIPv6	Fast Handovers for Mobile IPv6
GSM	Global System for Mobile Communications

HA	Home Agent
HAd	Home Address
HMIPv6	Hierarchical Mobile IPv6
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IF	Interface
IFE	Inflight Entertainment System
IP	Internet Protocol
IPv4	IP version 4
IPv6	IP version 6
ISM	Industrial, Scientific and Medical
ISP	Internet Service Provider
LAN	Local Area Network
LLC	Logical Link Control
LOS	Line of Sight
LQE	Link Quality Estimator
LQI	Link Quality Indicator
LTE	Long Term Evolution
MAC	Medium Access Control
MAS	Medium Access Slot
MIMO	Multiple Input, Multiple Output
MIPv6	Mobile IPv6
MN	Mobile Node
NAR	Next Access Router
NDP	Neighbor Discovery Protocol
OFDMA	Orthogonal Frequency Division Multiplex Access
PAR	Previous Access Router
PAX	Passenger
PCA	Prioritized Contention Access
PMIPv6	Proxy for Mobile IPv6
PRP	Parallel Redundancy Protocol
PSU	Passenger Service Unit
QoS	Quality of Service
RMS	Rate Monotonic Scheduling
RSSI	Received Signal Strength Indication
RTS/CTS	Ready-to-send / Clear-to-send
SCP	Set Covering Problem
SINR	Signal to Interference-plus-Noise Ratio
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
TDOA	Time Difference of Arrival
TIM IE	Traffic Indication Map Information Element
TXOP	Transmission Opportunity

OFDM	Orthogonal Frequency Division Multiplex
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
UWB	Ultra-wideband
VoIP	Voice over IP
WLAN	Wireless Local Area Network
WLP	WiMedia LLC Protocol
WSS	WLP Service Set
WSSID	WLP Service Set Identifier
WUSB	Wireless USB

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