1 Introduction

Ever since prehistoric times, the idea of flying has fascinated mankind. Yet it took quite some time until the Wright brothers could show the powered flight for the first time in 1903 [She83]. Even over a hundred years later, the fascination of flying has not stopped yet. The Aircraft (AC) industry has developed many revolutionary ideas from the introduction of fly-by-wire in 1943 to the introduction of supersonic airliners in 1969 [She83]. Most recently, building an AC using newly developed materials such as the carbon fiber reinforced polymer, has continued the ongoing innovation process.
As technologies change the customer demand changes as well. Today's customers search for cheap tickets and more comfort onboard the AC. Furthermore, people are more and more conscious of their carbon footprint. AC manufacturers and AC carriers have found fuel reduction to be one solution in order to reduce prices and carbon footprints at the same time.
Less fuel consumption can be achieved by a lighter AC. The focus has already been set towards this development with the first mainly carbon fiber-built ACs such as the Boeing 787 or the Airbus 350. By considering the AC interior as well there is even more potential to reduce the overall weight.
The area with the highest potential is reducing the number of cables inside the AC. An Airbus 380 today has about 10000 wires accounting for a weight of almost 6000 kg [Ins15]. By responding to the passenger request of more comfort, this number can increase significantly. More comfort is usually achieved not only by advanced entertainment systems but also by more intelligent sensor and actor technologies. The latter includes improved temperature sensing as well as elaborated lighting zones, for example.

The use of a self-organizing Wireless Sensor Network (WSN), which still fulfills the required functional safety, is the next revolutionary idea for an AC. This network has the high potential of reducing weight and increasing comfort at the same time [HMR11, MHR11].

1.1 Wireless Communication

Wireless communication had its first breakthrough even before the first civil AC was invented. In 1901 Guglielmo Marconi provided the first wireless communication across the Atlantic ocean [Gol05]. This breakthrough was soon further rewarded by the joint award of the Nobel prize of physics in 1909 to Marconi and Karl Ferdinand Braun [Nob09]. Today, wireless communication has found its way into almost every aspect of our daily life.
Nevertheless, the AC industry has avoided any wireless communications inside the AC for a long time. The slow introduction of some wireless communication inside the AC has only started about a decade ago. Non-AC-related communication such as cellular and Wireless Local Area Network (WLAN) have since started to be available for passengers.
There are some good reasons why wireless communication has been avoided for such a long time: due to its probabilistic behavior, it does not offer the required functional safety as the existing wired systems do. All onboard systems have to be nearly 100% deterministic. Each system is secured by other redundant systems. This redundancy plays an important role. Therefore, an onboard WSN has to provide the same reliable services as the wired system.
A WSN is a network consisting of many nodes each equipped with a sensor. The communication is wireless.
WSNs are considered low-cost, small in size and easy to install devices with a low energy consumption. The use of WSN, which offers unchanged functional safety inside the AC bears many advantages and corresponds well to the demand of less weight and more comfort. An AC has already many sensors inside. However, they are all wired, adding to the overall weight of the AC.

Replacing these wires through wireless connections can lead to a significant reduction of its weight.
The use of a WSN also has another important advantage: the reduction of maintenance costs and efforts by using some sensors for structural health monitoring. The sensors can be placed at hard to reach places and can deliver its structural state precisely. Today, each part of an AC has a certain predefined lifecycle after which it has to be tested or even replaced. Having more precise knowledge about the state of each part can lead to longer life cycles which reduce maintenance costs. This can also lead to cheaper ticket prices for the customer since an AC is most cost-efficient the less time it spends on the ground. Additionally, multiple new and innovative systems are also more feasible by the use of wireless communications due to reduced installation costs and small additional weight compared to the gained comfort for passengers and maintenance crews.
Even though the WSN bears many advantages, one has to consider the main challenge of achieving a reliable network, which fulfills the requirements of the regulatory certification. Up to 1000 wireless sensor nodes have to form a stable network. Furthermore, the network has to be built and exist in an energy efficient way since not all nodes are going to have direct connection to the onboard power supply system.
In addition to the new aspect of wireless communication, self-organization is introduced. A self-organizing system is a system, which reaches its goal without a central control function. This is a contrast to the strongly hierarchical structure of existing AC control systems. In order to achieve a reliable and flexible system design, self-organization plays an important role. For one due to its structure, as it does not have a single point of failure, which makes it more reliable than a hierarchical system. Furthermore, it automatically includes the demanded redundancy. Finally, in most cases of interference it can react quicker and more stable than a master-controlled system. Interference is an issue, which has to be considered in a wireless system. Even though a Medium Access Control (MAC) protocol can organize exclusive access to the channel for each node, other systems can still cause interference.

Research shows that self-organization can provide reliable communication [Ann98, Ras01, Ebn05]. Nevertheless, this self-organizing WSN inside an AC has different requirements and therefore remains a challenging task.

1.2 Contributions

This thesis provides an overview of a WSN inside an AC, which does provide functional safety. It discusses the details for an implementation. Moreover, it develops and evaluates a fully self-organizing system design including a feasible self-organizing MAC and synchronization protocol.
The MAC protocol organizes the channel access in a reliable self-organizing structure, which allows full flexibility for the entire system. Each sensor node has its own slot for its exclusive use of the channel, allowing a reliable and deterministic transmission of data. The exclusive transmission slot is very energy efficient, as the node can remain in a less energy consuming state for the rest of the time. Furthermore, possible interference detection is discussed and an interference avoidance protocol is developed and evaluated. For the slotted structure of the MAC protocol, synchronization is required. The synchronization is also self-organized by all participating nodes.
This system design allows a fully flexible, reliable configuration and operation of the WSN in the dedicated environment of an AC, while also considering the typical requirements of a WSN such as low energy consumption and low complexity.

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Wireless Sensor Networks

Research on WSN began in the early 2000s and then started to increase rapidly with the passing of the Institute of Electrical and Electronics Engineers (IEEE) standard 802.15.4 in 2003 [Kri05]. Ever since, there have been more and more WSNs implemented in actual running applications. They are considered to fulfill two major tasks: monitoring as well as tracking [YMG08]. A WSN is a wireless network, which consists of many low-cost, low-power multi-functional sensor and actuator nodes with a small overall size. The nodes are organized in a network structure. These systems are applied in multiple use-case scenarios and offer much flexibility to the system designer. Compared to the widely used cellular networks or WLAN, the nodes in a WSN are comparatively small in size and use significantly lower data rates.

WSNs are not standardized in a way which could be compared to WLAN or cellular network systems. This is due to the fact that WSNs offer many possibilities when it comes to the final implementation. They are mostly defined by their use-cases, as they are very flexible in use and nothing is fixed.

2.1 WSN Definition

For a more common understanding of the term WSN the following definition will be used, based on [KW05, Dre07]:

WSN is a network consisting of sensor nodes, which have limited energy supply, work independently, and are typically placed in remote areas. The *nodes observe their environment and spread their measurements through the wireless radio channel. This is enabled through the transmission of small data packages over short physical distances.*

With this broad definition in mind, it becomes clear that these networks offer a large range of applications. One key property of these networks is their simplicity. This offers many use cases where the networks are applied to observe things in new environments, which were not easily accessible before.

The common sensor node consists of a microcontroller (µC), a memory, a transceiver, a battery and of course of one or multiple sensors depending on the use case, as shown in Figure 2.1, [Dre07, Kri05]. Subsequently whenever the term 'node' or 'sensor node' is used, it refers to a device following this structure. The transceiver is usually used for the communication from the node to the sink, as most WSNs are organized in a star like structure, where all communication is pointed towards the sink [KW05], [Dre07]. This corresponds to the idea of having simple and therefore cheap nodes inside the network, which mainly measure and collect the data. The evaluation of all this data is then done at the centralized sink. In other words, the network follows the principle of first collecting data and then evaluating it. The collected data or measured sensor data can be temperature, light, motion, humidity, pressure, for example, or basically any kind of physical value [Dre07].

For a complete definition of the term WSN the term Sensor and Actor Network (SANET) also has to be described briefly:

SANET is very similar to a WSN except for the required existence of actors. The term SANET is usually used when a WSN has at least one actor in addition to its sensors. In many cases, this actor is a mobile robot. Sensors measure the environment and act in a more passive manner, while actors can process sensor data and can react accordingly on the environment [Dre07, AK04]. SANET applications can be e.g. temperature control (measure and react accordingly), or fire and smoke detection [Dre07].

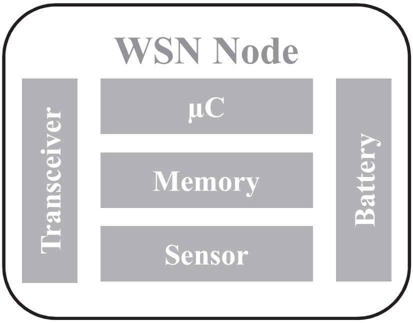

Figure 2.1: Block diagram of a WSN sensor node, adapted from [KW05, AK04, Dre07].

In general the term WSN is more frequently used and is not always precise since a WSN can also include actors [KW05].

In this tesis, the term WSN is used in the broader sense, which can include actors as well.

2.2 WSN Examples

Many WSN approaches include research networks but more and more the focus of the industry is set on WSN. One example for a research based network is the 'Selbstorganisierende mobile Sensor- und Datenfunknetze (SomSeD)' network, which is implemented at the Hamburg University of Technology (TUHH) [GWS+08].
The network mainly measures and monitors temperature and humidity. In addition it was used to determine network factors such as link quality and energy consumption. The energy consumption as well as energy harvesting was researched by using solar modules.

For the industrial market, the monitoring of solar fields, so-called smart grids, is becoming more and more interesting [EKM11]. WSNs are also capturing interest for everyday life application as they are used in smart homes. More generally speaking they are part of the growing market of the Internet of Things (IoT). Regulatory entities demand the installation of WSN in all homes in Great Britain by 2020 [GB15]. These WSNs consists of multiple sensor nodes, which measure and monitor the status of gas and electricity in the households.

2.3 WSN Properties and Requirements

Even though WSNs are quite flexible when it comes to the use-cases, they all have to follow certain constraints, which cannot be varied too much as they define the main properties of a WSN. These properties are explained below, in accordance to [Dre07, Kri05, YMG08, KW05]:
First of all there is the low energy consumption. The nodes have to be designed to be very energy efficient in order to allow their placement in areas/locations difficult to reach. The sensors must be able to rely solely on battery power. Additionally, the battery has to last for a long time, as some of the nodes cannot be accessed easily when a battery exchange is required due to their location. Thus battery exchanges have to be kept to a minimum. These demanding energy constraints make WSNs also look into the topic of energy harvesting e.g. through solar energy [YMG08]. Such a solution then allows more freedom in applications and use-cases.

Secondly there is the requirement of a simple node, which covers multiple aspects. There is the limited processing and computing power, which comes along with a simple and small memory. Reduced memory availability also leads to the fact that the data has to be transmitted continuously to a sink where it can be stored and processed better.
The transceiver also has to be very energy efficient. On the one hand, this is usually realized through small data packets and on the other hand through efficient transmission protocols. These protocols focus on the fact that the node is only consuming energy when actually transmitting or receiving. When the transceiver is doing neither one of those tasks, it shall be in a

sleep mode and reduce energy consumption to a minimum. This further extends the requirements also to the software as well as the protocols used for communication.
Additionally, the overall size of the node has to be small in order to still guarantee its flexibility in physical placement.
This small size also goes along with the constraint of low financial costs per device allowing the placement of a large number of nodes, since one of the strengths of a WSN is that the collected data originates from generous amounts of sources (nodes). All this has to come at low cost in order to allow the implementation of many nodes. Finally, the term ‘simple’ also refers to the deployment and maintenance of such a network. It has to be easily set up and maintained.

As an operating system TinyOs is commonly used [Dre07]. It is a software developed specifically for these type of networks, which is optimized to run under the conditions described. The software was first developed by Berkeley University [KW05].

The protocols for WSN require a low complexity level due to the simple hardware and software architecture which is used. In order to give a general understanding of this low computational power, a device typically used for a sensor node is the µC of Atmel, ATmega128, which is an 8-bit low-power system with a 16 MHz clock with 128 kByte flash and 4 kByte SRAM. The device is combined with a Chipcon/TI transceiver. Depending on the frequency either the CC1000, which covers the sub-GHz domain or the CC2420, which covers the 2.4 GHz domain [Dre07], is used. Atmel also offers a combined µC and transceiver solution: ATmega128RFA1 [Atm12].

Summarized the following constraints come with the use of WSN:

- Energy efficiency
- Limited processing and computing power

- Small node size
- Low node cost
- Energy consumption optimized protocols
- Small range
- Small memory storage thus a sink required

As a result of these constraints, a WSN has the following properties [Dre07, Kri05, YMG08, KW05]:

- Energy consumption: low
- Processing/computing power: low
- Overall node size: small
- Overall financial cost per node : low
- Scalability: high
- Required infrastructure: low
- Use-case optimization: high
- Deployment effort: low
- Flexibility of monitoring hard to reach areas: high

2.4 WSN for an Aircraft

The requirements for a WSN in general conform with the requirements of a WSN inside an AC. There is one additional condition: reliability, also referred to as functional safety. Moreover, there are special properties of a high node density and a large variety of network environments. The high node density