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RFID TECHNOLOGIES IN INTELLIGENT MEDICAL APPLICATIONS

Master of Science Thesis

Examiner: Professor Jari Nurmi
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ABSTRACT

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This thesis examines RFID-technologies as a part of the development of intelligent medical applications. In this context the intelligence is interpreted as a property of a system that is more automatic, safe or efficient due to solutions achieved by information technology. RFID-technologies offer a wide range of possibilities for both containing and acquiring information. With the help of RFID-systems information such as the count, location, or status of hospital equipment can be obtained and monitored without the need for line of sight. In this thesis the task of applying RFID-technologies to achieve more intelligent medical applications is approached by researching the compatibility of all the known RFID-technologies at the moment of writing. However researches presented in this thesis are generally related to systems operating within the UHF-frequency band.

The thesis describes the main characteristics of the four main RFID-technology standards. As this research is concentrated on the solutions specialized in hospital environments, the compliances to such a setting are highlighted from the research papers undergone in this thesis. Functionalities that are considered to be useful in an intelligent hospital setting are presented in the literature study. Such functionalities include RFID-tags that are aware of their location and orientation, tags that carry user updatable data and even tags that update their data by themselves.

After revising the RFID-technologies, a case-related research conducted for this thesis is presented. The research analyzes and estimates the saturation times of the carbon dioxide absorbers that are used in anesthesia machines. The measurements are conducted by multiple tests where environmental variables are changed to different known values and the results are recorded. The goal of the research is to find out if it is possible to predict the absorber behavior, and whether saving the information needed or the prediction can be done directly to the absorbers themselves. To predict saturation, lifetime and usability of the absorbers a formula is calculated, and the formula is evaluated based on the values measured. As a conclusion UHF-RFID-technology is evaluated to be most compatible to be used in the prototype for the case. In this thesis the RFID-technologies are evaluated to be an economical and functional solution for the monitoring of absorber state, and the case is agreed to be a convenient solution to begin the transformation to intelligent hospitals.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Sähkötekniikan koulutusohjelma
PYNNÖNEN, LAURI: RFID-teknologiat osana älykkäitä lääketieteellisiä sovelluksia
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Tämä diplomityö käsittelee ja tutkii RFID-teknologioita osana älykkäiden lääketieteellisten sovellusten kehittämistä. Älykkyys tulkitaan tässä sellaisten järjestelmien ominaisuudeksi, jotka ovat joko automaattisempia, turvallisempia tai tehokkaampia tietoteknisten ratkaisujen ansiosta. RFID-teknologiat tarjoavat mahdollisuuksia sekä tiedon säilytykseen että sen hankkimiseen. RFID-laitteistojen avulla voidaan esimerkiksi tuotteiden lukumäärää, sijaintia tai tilaa tarkkailla ilman näköyhteyttä. Tässä diplomityössä RFID-teknologioiden soveltamista älykkäisiin lääketieteellisiin sovelluksiin lähestytään kaikkien tunnettujen RFID-teknologioiden kannalta. Aiheeseen liittyviä tutkimuksia esitellään suurimmaksi osaksi UHF-taajuusalueilla toimivista järjestelmistä.

Työssä kuvaillaan neljä tunnetuinta RFID-teknologiaa ja kuhunkin niistä liittyviä teknisiä yksityiskohtia ja erityispiirteitä. Radiotaajuustunnistuksen etuja ja heikkouksia käsitellään eri aineistojen perusteella, ja eri menetelmistä tuodaan esille sekä niiden heikkoudet että vahvuudet. Työssä tarkastellaan useita aiheeseen liittyviä tutkimuksia ja niistä korostetaan juuri sairaalaympäristöihin soveltuvia ratkaisuja. Tutkimukset tuovat esiin monia hyödyllisiä toiminnallisuuksia, kuten laitteiden sijainnin ja asennon tunnistuksen, mahdollisuuden tallentaa tietoa suoraan tuotteisiin ja jopa itsenäisesti omia tietojaan muokkaavat laitteet.

Diplomityössä käsitellään myös työhön liittyvää tutkimusta. Tutkimuksessa analysoidaan anestesiakoneissa käytettäviä hiilidioksidiabsorbereita ja niiden saturoitumisen ennakointia. Mittauksissa muutetaan eri ympäristömuuttujien arvoja, joiden seurauksena muuttuvaa absorberin saturoitumisnopeutta pyritään ennakoimaan. Ennakointia varten määritellään yhtälöitä, jotka arvioivat absorberin kokonaiskapasiteettia ja käyttöaikaa. UHF-RFID todetaan parhaiten kyseiseen käyttötarkoitukseen soveltuvaksi teknologiaksi. Lopputuloksena RFID-teknologia todetaan taloudelliseksi ja toimivaksi ratkaisuksi absorberin tilan seurantaan ja sovellus hyväksytään helposti lähestyttäväksi ensiaskeleeksi älykkäisiin sairaalaympäristöihin siirryttäessä.

PREFACE

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Science adjusts its beliefs based on what's observed. Faith is the denial of observation so that belief can be preserved.
-Tim Minchin

ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AM	Amplitude modulation
CRC	Cyclic Redundancy Check
CO_2	Carbon Dioxide
DC	Direct Current
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPC	Electronic Product Code
ERP	Effective Radiative Power
$EtCO_2$	End Tidal Carbon Dioxide
$FiCO_2$	Fractional Inspired Carbon Dioxide
FHSS	Frequency Hopping Spread Spectrum
FSK	Frequency Shift Keying
Gen2	Class 1 Generation 2 RFID standard
HF	High Frequency
IC	Integrated Circuit
LF	Low Frequency
LFSR	Linear Feedback Shift Registers
NF	Near Field
pH	Pondus Hydrogenii
PLM	Periodic Limb Movements
PSK	Phase-Shift Keying
RF	Radio Frequency
RFID	Radio Frequency Identification
RHCP	Right Hand Circular Polarization
RLS	Restless Legs Syndrome
TOA	Time Of Arrival
QAM	Quadrature Amplitude Modulation
UHF	Ultra High Frequency

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1. INTRODUCTION

In anesthesia machines the closed circuit breathing air is guided through a carbon dioxide absorber. The CO_2 absorber is a filter that, with the use of a chemical compound, filters out nearly all of the CO_2 from the air that passes through it until the chemical, or absorbent, is saturated. When the inspired CO_2 level begins to differ from zero, it continues to rise exponentially. Clinically the absorber is considered to be expired once the CO_2 concentration of the filtered air rises up to 0.5 percent. In an average environment the type of absorber under examination lasts eight to twelve hours, after which it must be replaced.

Before initiating the airflow through the system the absorber is in unknown state, and even during the air circulation the absorber state is known only during the last two to three hours of the absorber lifetime when the inspired CO_2 levels differ from zero. The continuous usage of an absorber allows the user to observe the absorber saturation level through a color change visible from the used absorbent. The problems arise when the absorber is left unused for a longer period of time, because the color change is the result of a chemical reaction that reverses by time.

Changing the absorber during the anesthesia greatly increases the risk of patient complications. In a situation where the absorber lifetime would be known not to be sufficient for the entire operation, the hospital staff could change the absorber before the operation would begin. This is the original motivator of this research; the need to save and load information from hospital equipment to know the status of the devices and therefore increase the safety and efficiency of their usage. The desire to use RFID-technologies as a solution for the task at hand brings up another question which this research pursues an answer for: Besides acknowledging the device status, what other medical applications would there be for the technology under examination?

RF-identification is a set of technologies where the item under examination does not need to be optically visible to the reader – only within the range of the reader. With the ability to identify objects without line of sight we are able to obtain vast amounts of information from our surroundings quickly and automatically. But the idea can be developed further. The potential benefit does not lay in just identifying the items but saving new information directly to them. This would at least partly free us from the need to have a connection to an external database to access the up-to-date information, as we could just read and write the information from and to the items themselves. But what if the idea would be taken even further? What if the technology would not only be able to host information, but if it could manipulate the information by itself? It might be aware of its surroundings: its temperature, humidity and pressure. It could observe its own characteristics: concentration, pH and weight. The location of the item could be automatically defined, and in most advanced cases even the orientation of the item.

The applications based on new technologies are tempting due to the potential functionalities they include. Commonly these functions bring benefit not yet seen in the market, but they tend to have their disadvantages. When implementing systems that are not mature, meaning that they have not been tested or used to the level where most of their characteristics would be known, problems and risks occur. Implementations of RFID-technologies are subtle to identity thefts, product counterfeiting, viruses, hackers and a wide range of other threats that must be taken into account.

The scope of this thesis has remained quite well within the original boundaries. The positive findings achieved in the case study ruled out the original plan to present the algorithms used for the absorber lifetime estimation, as it would have jeopardized the potential financial gain attainable through the solution. Multiple innovations utilizing RFID-technologies suitable for hospital were encountered and presented as possible candidates for future development. The ultra-high frequency band provided most interesting solutions, therefore the majority of the implementations presented in this thesis work on that particular set of frequencies.

In this research the first chapter gives the reader a short introduction to the thesis. Chapter two tells about the technology, its trends, possibilities and limitations. Chapter three addresses the current solutions for the ever-so-important privacy and security achievable by the usage of RFID, chapter four lists different types of applications that are either planned or that already exist for RFID. In chapter five we go through a simple case study where RFID tags are used to identify carbon dioxide absorbers in a hospital environment. Chapter six concludes the thesis with an evaluation of the research done and an analysis of the usability of RFID technologies in intelligent medical applications.

2. RFID TECHNOLOGY

People can observe and identify their environments in a generally effortless and instinctive manner. We have five distinct senses that allow us to efficiently collect information about the objects that surround us, and typically our minds quickly associate vast amounts of data with each of the objects observed. We spontaneously understand our environment as being composed of separable things with specific properties and locations. We realize the world in terms of what is where and when. This is where the lack of perception of computers easily dissapoints us. By default the automated world is clueless when it comes to perceiving and recognizing all the discrete physical objects that we so easily detect and categorize.

Because of the incompleteness of the electronic world in the area of object recognition and its lack of networked awareness, a field of study known as automated identification has been created. Auto identification, or Auto-ID, covers all the means required for automating the task of identifying a physical object. Until recently the most common method of Auto-ID has been to tag an item with a special machine-legible code, and then to identify the object by scanning the code using an optical transducer. The ID is then associated with further information of the object, and if needed the information about the characteristics of the current object can be updated and associated with the object ID in a database. This type of identifier is of course known as a barcode.

One-dimensional bar codes are easily deciphered and two-dimensional bar codes fit more information into the same space, but they have somewhat lower reliability. A slightly less popular optical identification method is OCR, or optical character recognition. It is used to acquire information directly from conventional human-readable text. However all optical methods have the same deficiency, which is an outcome of the technologies' optical nature itself; to successfully read the information, a clear line of sight must exist between the sensing device and the identifier of the item under examination. Not only other objects, but dirt, paint, ink, and all other objectionably opaque but relentlessly commonplace substances can distort or deface bar codes and other optical marks, obscuring the information that optical auto-ID techniques require. The data stored in printed marks on a surface cannot be readily modified or extended, save perhaps by entire replacement. [3, pp. 1, 2.]

While optical techniques for object identification are versatile and inexpensive, it is clear that in many cases other approaches might be helpful. To remedy some of the deficiencies of optical identification, the market has turned to an alternative technique; radio-frequency identification (RFID). RFID means the usage of radio communications to identify a physical object. RFID is not in fact one but a suite of identification technologies, because of the differing characteristics of the radio waves varying by the frequency used, and because of the differing approaches used to operate the sensors that serve to identify individual objects. RFID has existed for more than half a century, but its widespread application has had to wait for inexpensive integrated circuits to enable small, low-cost transponders to be fabricated.

Over the last three decades the capability of integrated circuits has doubled and the cost per function halved about every two years, following devotedly the Moore's famous law [40]. This has made the new RFID applications become economically feasible. In particular, for the past quarter of a decade, a great deal of effort has been focused on the application of RFID in the manufacturing and distribution of goods and supply chain management, where until recently the bar code ruled absolutely. To serve the needs of manufacturing, distribution, and shipment functions, RFID tags must be very inexpensive, compact, mechanically robust, and preferably readable from more than a meter away. [3, pp. 3, 4.]

2.1. Inductive RFID

The main components of a wireless identification system are the reader and the tags (Figure 1). In a typical communication sequence, the reader emits a continuous radio frequency carrier sine wave. When a tag enters the RF field of the reader, the tag receives energy from the field. After the tag has received sufficient energy, it modulates the carrier signal according to the data stored on the tag. This modulated carrier signal is resonated from the tag to the reader. The reader detects and decodes the modulated signal. Finally, information is relayed to a host computer. To explain the transaction of information, the sequence of the reader can be divided into the following steps:

2.1.1. Provide energy to the tag with the RF field

The tags are powered by the RF field emitted by the reader. The field is a time-varying electromagnetic field in the kHz, MHz or GHz range depending on the type of the RFID system. When the tag is in the range of the field, it is able to generate a DC (direct current) voltage across its antenna coils. A time-varying magnetic field through a surface bounded by a closed loop (such as the antenna of the tag) induces a voltage around the loop.

The reader generates the magnetic field by passing current through its loop shaped antenna. The field generated is perpendicular to the plane of the loop, and is given by

$$B = \frac{\mu_0 I N a^2}{2(a^2+r^2)^{3/2}} \tag{1}$$

$$= \frac{\mu_0 I N a^2}{2r^3} \; for \; r^2 \gg a^2 \tag{2}$$

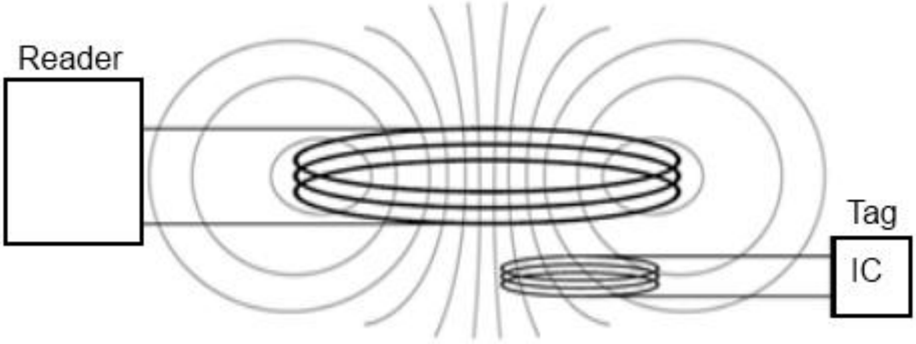


Figure 1 *RFID Induction*

Where μ_0 is the permeability of free space, I is the current through the loop, N is the number of turns in the loop, a is the radius of the loop and r is the perpendicular distance from the center of the loop [7, p. 1.].

According to the formula 2, a larger reader antenna means a stronger B field and thus a longer read range. It’s also possible to increase the range by adding to the number of ampere-turns (IN). A larger antenna increases the size and the expenses of the reader and makes it less portable. The consequence of increasing the number of ampere-turns is a larger inductance in the reader antenna circuit that increases as the square of the number of tums. A high inductance load results in large amounts of reflected power as well as large impedance that varies significantly as a function of frequency.

2.1.2. Provide the carrier signal for the information propagation

The field that energizes the tag also works as a carrier signal used by the tag to perform its functions. Tags that use clocking circuitry also use the carrier as a source for the synchronized clock.

2.1.3. Detect and decode the modulated signal sent by the tag

The group of signals returned to the reader by the tag is called backscatter modulation. Having received the backscatter modulation, the reader must decode the information coded to the signal. There are different ways to modulate the information to the signal, some of the most common being amplitude modulation (AM), phase shift keying (PSK) and frequency shift keying (FSK). The sequence of the tag consists of the steps described in the following three chapters.

2.1.4. Utilize the energy provided by the reader

A passive inductive RFID tag absorbs the power it needs to operate via the antenna coil voltage induced from the field. The reader antenna acts as the primary coil and the tag antenna as the secondary coil, effectively forming a transducer. The maximum magnetic flux flows through the coil when the reader and the tag antenna coils are in parallel.

2.1.5. Resonate the carrier signal

When a capacitor and inductor are placed in parallel, they resonate at certain frequency range. For example if a tag receives a signal with a frequency of 13.56 MHz, it is able to resonate the same signal back to the reader if its antenna is tuned so that $\left[2\pi\sqrt{LC}\right]^{-1} = 13.56MHz$. If the tag is able to change the length of its coil or its capacitance value and thus change the inductance L, it is able to modulate the signal.

2.1.6. Modulate the resonated signal

If the tag is slightly out of tune so that it does not fully resonate the carrier signal it sends a weaker, lower voltage signal back to the reader. By achieving two states, the tuned and the detuned state, the tag is able to send a variation of strong and weak signals. If the sequence of strong and weak signals correlates with the data stored on the tag, then the reader can decode the signal and retrieve the data. [7, pp. 82-85.]

2.2. Radiative RFID

Different RFID technologies use different communication frequencies, as presented in figure 2. Systems that use ultra-high frequencies are usually equipped with an antenna that is comparable in size to the wavelength of the carrier signal. These systems tend to use radiative coupling instead of inductive coupling to communicate between the reader and the tag. The reader antenna launches a traveling electromagnetic wave, whose intensity in the absence of obstacles attenuates as the square of the distance traveled. The wave interacts with the tag antenna at some distinguishably later time much longer than a single RF cycle and a faded copy of the transmitted signal is provided to the tag. A distinct scattered wave returns to the reader such that the total round-trip transit time is much longer than the RF cycle time. [1, p. 25.]

The distinction between inductive and radiative coupling has important consequences for the behavior of RFID tags. The success rate of inductive coupling between the reader and tag falls rapidly as the tag moves away from the reader antenna. Likewise the coupling is uniformly strong when the tag is close to the reader, but the coupling falls rapidly to near zero in all directions for distances that are large compared to the antenna. Insertion of a metallic object near the reader antenna will distort the fields but in a fairly smooth fashion and on a length scale comparable to that of the obstacle. The read range of an inductive tag is roughly comparable to the size of the reader antenna and dependent on the direction of displacement relative to the antenna (and the relative orientation of the tag and reader). To a good approximation, when an

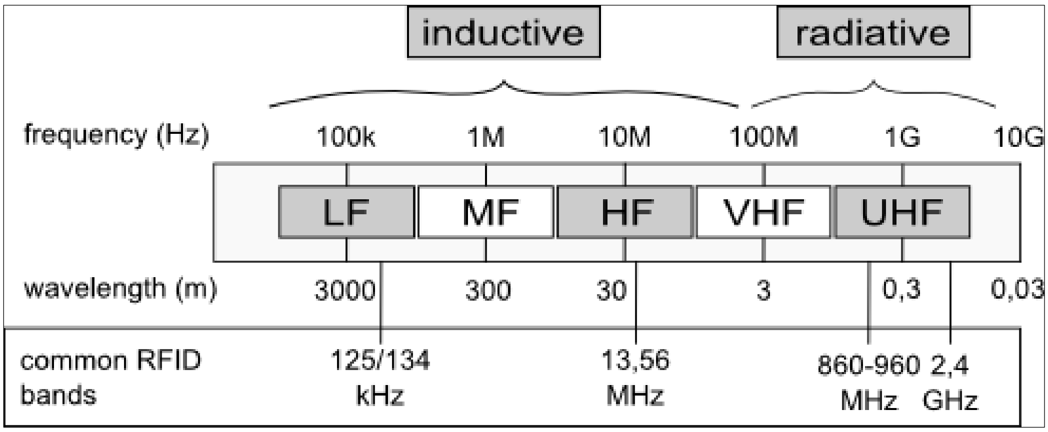


Figure 2 *Frequency bands*

inductive tag is close to the antenna, for example less than tens of centimeters away, it will be reliably read, and when the tag is far from the antenna, it is invisible to the reader. [3, pp. 26-27.]

The circumstances change noticeably when radiative coupling is used. In radiative coupling the power falls slowly with distance, and the wavelength is small compared to the average distances between the tag and the reader, so reflections from distant obstacles can propagate back into the region of interest and interfere with the waves launched by the reader antenna. This is likely to create a very complex dependence between the received power and the location of the tag. The received power falls monotonically near the reader, but for longer distances the propagation environment becomes very complex. Moving a tag away from the reader antenna by distances on the order of half a wavelength may lead to an increase in received power. As a consequence, a radiatively-coupled tag may disappear and then reappear even multiple times to the reader as it travels away from the antenna. Furthermore, this large and complex read zone will overlap with other similarly unpredictable zones when multiple readers are present in close proximity to one another: interference is a lot more likely with long-range ultra-high frequency (UHF) systems than short-range high-frequency (HF) or low-frequency (LF) systems. The read range of a radiatively coupled system can be longer than an inductively coupled system, but at the cost of a much more complex propagation environment, and a discontinuous and unpredictable read zone. [3, pp. 27-31.]

2.3. Performance limitations of passive RFID systems

Passive RFID tags have no internal source of energy but instead they derive their power from the carrier signal of the reader. When compared to active tags, the freedom from integrated energy source is apparent in lower costs, smaller size and longer life cycle. It also is eminent in imminent drops in reading distance and reliability.

Material	*Skin depth at*			
	125 kHz	13,56 MHz	900 MHz	2,4 GHz
Tap water	8 m	2 m	4 cm	8 mm
Animal tissue	2 m	60 cm	2 cm	8 mm
Aluminum	0,23 mm	71 µm	2,7 µm	1,6 µm
Copper	0,18 mm	55 µm	2,1 µm	1,3 µm

Table 1 *Signal skin depth*

In [16], the performance of passive UHF-tags was tested in a medical environment. The test covers the effects of tag movement, reading distance and stacks of multiple tags. In each of the test scenarios the UHF-technology was shown to be somewhat unreliable. Only in optimal environment where there are only a few tags a small distance away from the reader the reliability is close to a hundred percent and the tag movement poses no effect. However, stacks of tens of tags pose a challenge for the reader. As the number of tags increase, the inter-tag distance decreases and the tags interfere with each other. When increasing the distance of the reader and moving the tags with human walking or running speeds, more and more tags disappear from the readers' view.

2.4. Antennas and signal propagation

Different kinds of materials have different effects on the fields created by the reader antenna depending on the frequency of operation. The most important substances are metallic object and water, of which people, plants, and animals are mostly constructed. On impact to a conductive object the electromagnetic wave penetrates the material an extent known as the skin-depth. The skin-depth correlates to the frequency f, as it does to the magnetic permeability µ (or μ_0, except for magnetic materials), and the objects´ electrical conductivity σ

$$\delta = \sqrt{\frac{1}{\pi \mu_0 \sigma f}} \tag{3}$$

The table 1 [3, p. 30] can be used to illustrate the damping effects of materials to the signals and therefore to roughly estimate the propagation of signals at different frequencies. From the table one can clearly see that at 125 kHz water and water-containing materials have little or no effect on the signal propagation, the effects of aluminum and copper prove that a thin sheet of metal is readily tolerated, but a thick metallic sheet acts as an effective shield. At 13.56 MHz, a frequency common to HF systems, penetration into cows or people is considerable but not indefinite, and only thin metal layers can be infiltrated. At UHF frequencies, penetration through water is minimal and practically all metallic obstacles to propagation. [3, pp. 29-31.]

In an ideal environment, electromagnetic waves propagate with the speed of light and attenuate inversely with the distance. In the actual world ideal environments are hard to come by. The difference between the power delivered to the transmitting antenna and that obtained from the receiving antenna is known as the path loss. Antennas that distribute the emitted energy evenly around them in a spherical shape are known as isotropic antennas. Antennas that emit a strong field to certain direction and a lesser field to other directions are called directional antennas. The operation distance of an antenna depends on multiple variables. Shapes, sizes and materials of the objects around the antenna distort the signal propagation. In the case of directional antennas the orientations of both the tag and the reader antennas have an effect. Complex equations have been created to approximate the signal levels, paths and path-losses in different kind of environments.

2.5. EMC and EMI

Electromagnetic compatibility, or EMC, is an important factor in RFID system development, especially in the healthcare industry. If not properly taken into account, the incompatibility of wireless medical devices can cause malfunctions of all severity levels. Low level risks are related to the loss or corruption of non-vital or historical information, medium level risks cover areas such as the transmission of diagnostic information that can withstand degradation. High level risks are the ones that relate to functions like remote control of vital therapy, such as infusion of drugs or blood products, where even momentary lapses in a wireless signal can have serious consequences [22]. Hazardous incidents have occurred, including total switch offs and changes in the ventilation rates of mechanical ventilators, complete stoppage of syringe pumps and malfunctions in external pacemakers.

UHF RFID devices operate in the license free-channels, which are shared among many other users that results in multiple electronic equipment radiating either intentionally or unintentionally in the same band. RFID reader antennas radiate with comparatively intense RF power to energize the passive tags that are within their interrogation zones. This radiation has high probability of interfering with the nearby electronic devices operating in the band of interest. The RFID system designers must be aware of the challenges imposed by the environment and media in question, and of the strict regulations set to avoid incompatibility with local limits.

In Europe, the provision of Listen Before Talk (LBT) imposes a great challenge on both the quality of the RF front-end of the RFID receiver and its antenna placement. The LBT enforces the potential transmitter to observe the channel prior to transmission with a defined listening time for the presence of another signal. Once the band is selected it may be reserved for the maximum duration of 4 seconds. The concept of LBT has been introduced by the European Telecommunications Standards Institute (ETSI) alongside with spectrum management standard EN 302 208-1. The latter allocates the frequency band 865 to 868 MHz for deployment of RFID. This band has been subdivided to 15 channels, each spanning a total of 200 kHz; however when operating the reader with its maximum effective radiative power (ERP) of 2 W, only 10 channels shall be used.

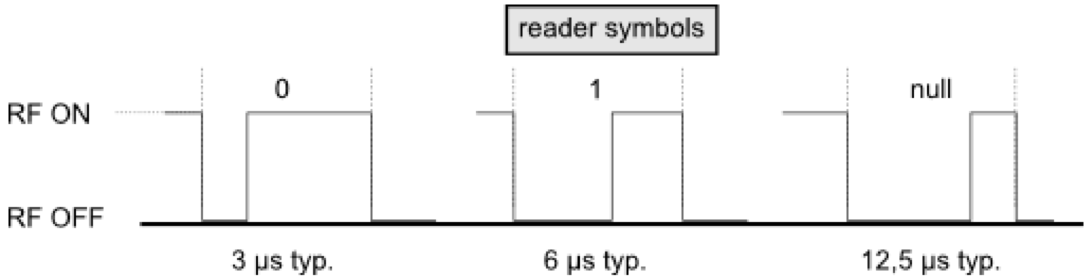


Figure 3 *EPCglobal Class 0 Reader symbols*

In the US, the Federal Communications Commission, or FCC, regulates the use of RFID systems to the range of 902 to 928 MHz, and Frequency Hopping Spread Spectrum (FHSS) must be used. The maximum ERP is limited to 4 W, and due to FHSS at least 50 hopping frequencies of 500 kHz must be used with the average time of occupancy of any frequency kept below 0.4 seconds within a 10-second period. This implies that there is a maximum limit on the power available at a given label distance from a transmitter. Thus, passive labels with size limited by a particular label class or application are receiving power from a stated power flow per unit area. The power available to the label is one factor contributing to the determination of the type of security scheme and the cryptographic hardware used in a label. [23]

2.6. Data transfer protocols and speed

Every communication process is based on agreements about certain conventions, or agreements about how messages are to be sent and received and what they mean. The coding and its interpretation used with the communication are known as the communication protocol. The protocol answers questions like what sort of modulation of the reader signal is used to define a binary one, what is zero, how fast information is transferred, who talks and when and how collisions are resolved.

Passive tags face problems that are not commonly encountered in most other digital radio systems. Because the tags are cheap and hence very limited in the sense of computation power, only changes in the amplitude of the reader signal can be used. Advanced modulations like quadrature-amplitude-modulation (QAM) or phase-shift keying (PSK) are not available. The reader-to-tag modulations used tend to keep the power on most of the time, so that the tags would receive maximum available power. Such modulations waste spectrum, leading to relatively wide channels with low data rates.

The tag can modulate phase or amplitude of the reflection that it creates. As the relatively small tag reflection is combined with large reflections from the reader antenna and the ambient, the resulting signal at the reader may change amplitude when the tag reflection changes phase, and so on. One can only hope to detect changes in state of the tag antenna, but not the type of change. The reader can count edges from the tag but not the absolute or differential phase or amplitude. Generally the tag and reader symbols must be chosen with these constraints in mind. [3, pp.361-381.]

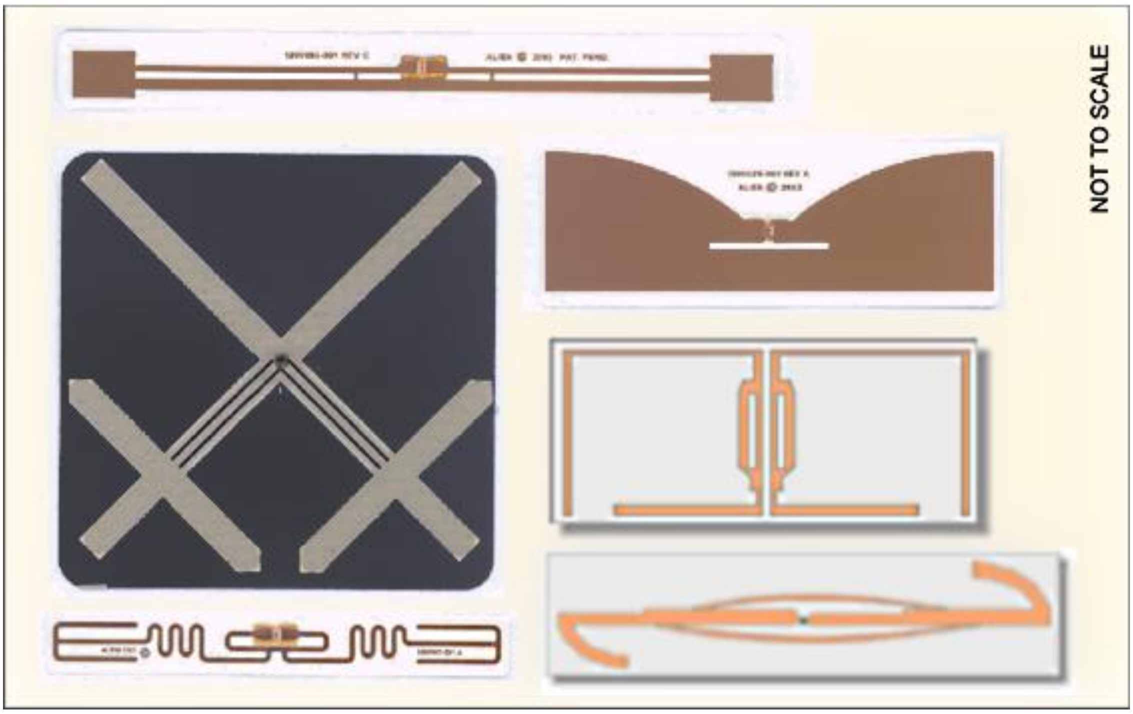


Figure 4 *Examples of dual dipole tags [41]*

2.6.1. EPCglobal Class 0

The class 0 standard describes a family of passive write-once tags. The signals used in the standard consist of binary one, binary zero and a null symbol (Figure 3). They differ from the more recent Class 1 tags primarily by the use of the reader-to-tag subcarrier modulation scheme. The class 0 tags are generally configured to work as dual dipole tags, which mean that the integrated circuit is connected to two distinct antennas that are placed typically orthogonally to one another, as shown in figure 4. Dual dipole tags are necessarily larger than the corresponding single-dipole tag, but in compensation they are much less sensitive to the polarization of the incident radiation than a single dipole.

A specialized approach is employed for the reverse tag-to-reader link. The tag scatters its reply during the high part of each symbol. The symbols themselves use sub-carrier modulated frequency-shift keying. The tag uses relatively high rates of 2.25 MHz for binary zero and 3.25 MHz to send binary one. The use of this sub-carrier modulation has two advantages. First, the demodulator gets to count a lot of edges for each tag transmission, so it is easy to tell which symbol was sent. Secondly, the corruption of a single edge due to the noise or interference doesn't prevent the reader from distinguishing a one from a zero. The relatively high frequency also means that the down-converted baseband signal contains information only in the region 2-4 MHz away from the carrier, where the phase noise of the local oscillator is typically small, which makes high sensitivity easier to achieve. However, the class 0 scheme encounters problems when in the presence of multiple readers, for the tag reply is so far away from the carrier that it may lie right on the frequency transmitted by a neighboring reader. In Europe, even passive tags are regulated as transmitters, and the tag radiation may be centered outside of the fairly narrow bands allocated to RFID operation, causing even more compliance problems.

In class 0 the approach to control access to the medium is rather simple (figure 5). In the beginning of communication the reader sends a command informing all the tags that are in range that it is going to execute a binary tree traversal.

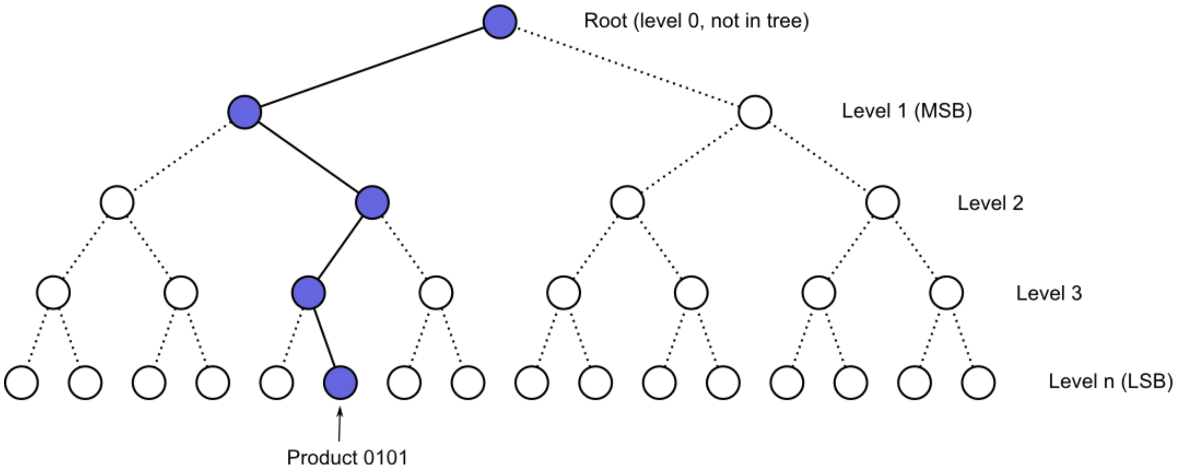


Figure 5 *A binary tree traversal [3 p. 389.]*

The reader then sends a null symbol followed by a binary zero. As a reply all the tags backscatter the first binary bit of their ID. The reader can tell if a one or a zero was received, even though it can't tell if more than one tag transmitted at the same time. If some tags send a binary one and others a binary zero, the reader may detect a collision, or it may simply randomly choose to see either bit. The reader then echoes the bit that it heard. Any tags that hear their bit stay in the traversal and send their next bit. Tags that don't hear their bit fall out of the traversal by transitioning to the mute-state and wait for another null-zero combination. If everything goes well, by the end of the traversal only one tag is still participating, and all its bits have been read. By remembering which branches of the tree had responses, the reader should ideally be able to navigate only the occupied parts of the tree of all possible tags. [38]

2.6.2. EPCglobal Class 1

To address the complications encountered in class 0 protocol, class 1 protocol was defined. The first version of the class 1 protocol is known as the class 1 generation 1 protocol. The major difference between class 1 and class 0 is the packetized interface of the class 1. Where the class 0 reader sends messages to tags one bit at a time, the class 1 reader sends out full commands, to which one or more tags may reply with either a few bits or a complete message. In all the communication situations the reader repeatedly sends the proper command to go through the range of all the IDs. Any tag hearing the sent command replies with a message containing the tags own Cyclic Redundancy Code (CRC) and Electronic Product Code (EPC). This approach is known as the global scroll mode of operation and it is relatively fast; about five hundred tags can be read in one second, even if most of the reads will simply be repeated reads of the same tag.

The reader can optionally add a talk command to the beginning of the message to make sure that tags are all active, and a quiet command directed to a tag after it has been read to make it possible for other tags to talk. Compared to other commands, the quiet command is rather time consuming, since the whole tag ID must be sent as a filter to ensure that only the desired tag stops talking. The whole procedure takes around 4 ms for a 64-bit tag, allowing around 250 tag reads/second.

If only one tag is expected to exist within the read zone of the reader, it is possible to skip the collision resolution entirely. However, when a large number of tags are simultaneously present in the read zone of a reader, a sophisticated anti-collision algorithm can be employed with the use of the filter capability built into reader commands. Each command may contain filter bits, of any length up to the full length of the CRC plus EPC, and starting anywhere in memory. Only tags whose EPC fits the filter will respond to the command. The PING command causes tags whose EPC's match the filter to respond by sending the next 8 bits of their EPC, and doing so within one of 8 reply bins, each marked by a special symbol from the reader, the choice of bin depending on the first three bits of the reply. When the reader believes that only one tag is replying in a bin, it can request the full EPC of the tag.

Soon after the deployment of the first generation protocol multiple complications were acknowledged. The bit depth of generation 1 was condemned insufficient. The use of a 16-bit CRC as the only validation of a tag ID meant that on average one in 64,000 reads of random noise produced an accidentally valid tag read – a phantom or ghost tag. Class 0 tags had problems with large numbers of collocated readers due to the large frequency offset between the tag signal and the reader signal, and it had no standard for field writeable tags. Class 1 singularisation was relatively slow when a large number of tags were present. Both class 0 and class 1 generation 1 had problems with late arrivals: tags that entered the read zone when a tag inventory had already started were likely to cause unpredictable behavior. Finally, class 0 and class 1 were mutually incompatible and approximately equivalent in applications and performance.

Realizing these problems, in early 2004 the EPCglobal Hardware Action Group started to work on a second-generation standard that would fix the problems in the first-generation standards and provide sufficient performance at sufficiently low cost to become the universal protocol for RFID in supply chain applications. The Class 1 Generation 2 standard was ratified in early 2005, and is now also ratified by the International Organization for Standardization (ISO) as ISO 18000-6C. In order to obtain the aforementioned improvements in performance, the Gen 2 committee started anew in many respects; the Gen 2 standard is completely incompatible with first-generation class 0 and class 1 readers and tags.

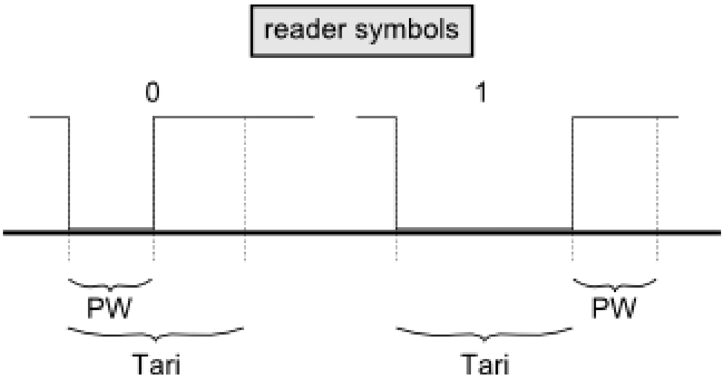


Figure 6 *EPCglobal Class1 Generation 2 Reader symbols*

In generation 2 the reader symbols (figure 6) are distinct from those introduced previously. A binary '0' is a short high level pulse followed by low pulse of equal length; a binary '1' is a longer high pulse followed by the same low pulse width. This symbol set provides a high average RF power delivered to the tag. The length of a binary '0' is defined as Tari, and is used as a reference for several other times in the standard. The data rate can vary from 27 to 128 Kbps (Tari from 25 to 6.5 microseconds). The most significant bit of the most significant word is always sent first. [39]

2.7. Summary

The automotive world is generally unaware of objects that surround it. It depends highly on human interaction or visual connections to create an understanding about its surroundings. RFID systems provide a series of affordable, reliable and even secure solutions for increasing the awareness of systems in need of object recognition.

A RFID system consists of one or more transponders scanners. Transponders, or tags, contain data that can be either readable or re-writable by the user. The tags can be read within the range of the scanner without the need for line of sight. There are three types of tags in the sense of tag powering. Active and semi-passive tags use internal batteries to power their circuits. Active tags also use their batteries for broadcasting messages, whereas semi-passive tags rely on the reader to supply the power for broadcasting. Passive tags rely entirely on the reader as their power source.

The two ways to energize a passive tag are inductive and radiative transfer of power. The inductive systems use coils to transfer the energy in a magnetic field that attenuates as the square of the distance traveled. In radiative coupling the energy is delivered in an electromagnetic field, and the attenuation is inversely proportional to the distance between the tag and the reader. This increases the range, but it also makes it possible for the reflections from distant obstacles to propagate back into the region of interest and therefore interfere with the waves launched by the reader antenna.

All RFID systems are to some degree affected by their surrounding materials. The microwaves of radiative RFID are very susceptible to metal because they are easily reflected. Aqueous materials absorb high and ultra-high frequencies very effectively.

Inductive RFID is less susceptible, but metallic objects may still alter the resonating frequencies.

There are multiple regulations and standards that provide predictability and consistency in the operation methods and protocols of RFID communications. Higher communication frequencies tend to suggest higher data-transfer rates, but the most common radiofrequency-bands are already in use. Ultra high frequencies are less regulated, which promises more freedom in the band selection, but also causes unawareness of the other devices possibly interfering with the RFID signals.

3. RFID SECURITY

Since Second World War radio frequency systems have been used to identify physical objects. However the identity acquired is not guaranteed to be the true identity of the object by the method of identification itself. On the other hand, sometimes we do not even want to our identities or the identities of the objects we possess to be revealed, and thus may want to conceal our identity and deny queries that are directed to us.

The privacy in RFID technologies has been under constant concern from the first moment it was considered as an alternative and successor for bar codes and typographical IDs [5]. In this chapter we analyze why such skeptic approach is justified. In presentation [17] a representative of Philips shows an imaginary scenario of a normal appearing male walking on the street in the year 2020. Outwards there is nothing distinguishing about him, however when scanned with a RFID reader some details of his life are accessible. The nature of information we do not want to be acquired by illicit actors about our personal lives is usually sensitive. In this case the man was identified to carry a wig, a replacement hip, 30 items of lingerie, a communist handbook and 1500 euros of money, with their serial numbers exposed.

Despite the vast array of RFID systems, those that are at the low cost end pose the greatest threat to security and privacy due to the possibility of wide scale deployment and inherent constraints that place severe limitations on the number of possible solutions. The previous exaggerated scenario of privacy exposure could easily be expected to apply in hospital environments as well. A patient labeled with unprotected tags could be monitored by unauthorized readers. The tagged patient card could expose trace of personal location, clinical history and personal health information to any tag reader anywhere.

Other prospect of RFID security is the product authentication. This is desirable to prevent the counterfeiting of items. The primary concern of low cost RFID tags is cloning. Since the authentication is not done directly to the item, but to the RFID tag attached to the item, the risk of authenticating a counterfeit item with cloned valid tag exists.

3.1. Illicit actors

The RFID automates information collection about individuals’ locations and actions wirelessly, sometimes even from a large distance. The freedom from galvanic connections and line of sight greatly simplifies the usage of RFID products, but it also enables multiple different kinds of illicit actors that can be performed on the devices by hackers, retailers, and even the government.

Most of the RFID specific illicit actors are combinations of the techniques previously used with wireless networks and bar codes. Here we list some of the most important and dangerous techniques.

3.1.1. Sniffing and replay attacks

RFID tags are designed to be read by any compliant reading device. Sniffing means the act of listening or eaves-dropping the communication between a RFID tag and a reader. By recording the whole transaction of messages between the devices and analyzing the recording with proper equipment the identification of the protocol and communication pattern is relatively easy. Decrypting of the messages is also generally achievable due to the limited calculation capabilities of the tags and the relatively immersive calculation potential a common computer system.

Sniffing is usually the first step of the attack against a RFID system. It enables the adversary to define the security functions used to protect a specific system and, based on the information achieved, to choose the correct course of action to successfully misuse the system. The simplest approach is to leave the recorded signal as it is and use a replay attack. In a replay attack the adversary records a conversation between trusted parties and then replays a section, or all of the recorded information to essentially achieve the same outcome that a legitimate reader and tag would have achieved even without the need to copy the tag. Basic RFID tags provide no mechanisms to prevent such attacks. [17]

3.1.2. Spoofing

Spoofing, or mimicking the behavior of a genuine label, is related to the concept of authentic RFID tags and the simplicity of cloning of tags’ contents to empty tags. The spoofing of a tag can be done either by cloning or simply just removing and re-applying a tag to another object. A notable spoofing attack was done by the Johns Hopkins University and RSA Security explained in [8]. The researchers cloned a RFID transponder by using a sniffed and decrypted identifier. The transponder was then used to buy gasoline and to unlock an RFID based car immobilization system.

Spoofing presents a serious threat to a RFID system. Spoofing will add a new dimension to thieving. A thief may replace a valid item with a fake label or replace the label of an expensive item with that of a fake label with data obtained from a cheaper item. Thus the lack of a means for authentication allows an adversary to fool a security system into perceiving that the item is still present or this may fool automated checkout counters into charging for a cheaper item. Fake labels may also be used to create imitation items. Thus it is important to be able to authenticate labels to establish their legitimacy.

3.1.3. Denial of Service

A DoS, or denial of service, attack is a way to bypass or avoid security systems. The attack is carried out by placing a large number of labels for identification by a reader. Persons may also have the ability to disturb an RFID system implementation by destroying or corrupting a large set of labels. Labels are also exposed to protocol attacks. Therefore labels may be repeatedly asked to perform an operation, thus making them unavailable to an authorized reader. Labels need to be able to defend against brute force attacks as this raises concerns regarding system availability.

In addition tags may be prevented from being read by using the simple concept of a Faraday cage or by jamming the RFID interrogator signals, for instance by intentionally creating noise in the frequency band in use. For critical applications, a DoS attack may pose devastating effects. [17, p. 16.]

3.1.4. Brute force and Side channel attack

A brute force attack means the intent to break the encryption of data. It consists of going through the whole search space of possible keys until the correct key is found. A side channel attack on the other hand is considered to be any attack based on information gained from the physical implementation of a cryptosystem, such as timing information, power consumption, electromagnetic leaks or even sound can provide an extra source of information which can be exploited to break the system. Many side-channel attacks require considerable technical knowledge of the internal operation of the system on which the cryptography is implemented. [20]

3.1.5. RFID virus

Input data can be used to exploit back-end software systems, such as databases and other information storages. This is old news and generally well taken into account for example in web applications, however it has not prevented RFID designers to implicitly trust the structural integrity of the data provided by RFID tags. RFID attacks are generally known as properly formed but fake or misleading RFID data. No-one currently expects a RFID tag to send a SQL injection attack or a buffer overflow.

In [8] a self-replicating RFID virus is presented. The document shows hard evidence of the RFID technologies’ serious vulnerability to malicious data by providing a long list of weak spots in a RFID system. In the example the self-replicating virus inserts the following clause to the system:

```
Contents = Raspberries;
UPDATE NewContainerContents
       SET ContainerContents = ContainerContents ||
       ‘‘;[SQL Injection]’’;
```

The RFID system expects to receive the data before the semicolon. In this example the data describes the contents of a container, which in this case happen to be raspberries. The semicolon itself however is unexpected. It ends the previous clause and introduces a new one, which in this case adds an Oracle SQL+ clause to the table. If the SQL Injection would be an alias for the whole clause, the injection would allow the clause to multiply recursively through other tags.

3.2. Cryptography and computation

Cryptography provides security for the communication in a mathematical sense. It has been used throughout the human evolution to provide security and to protect the privacy of individuals or organizations. Due to computational constraints of the low resource RFID tags, classical cryptographic primitives such as block ciphers and asymmetric cryptography have been thought to be unrealistic. To this end numerous light weight protocols have been proposed [23, p. 1], but due to their low computational potency they expose multiple serious vulnerabilities that tend to encourage the developers to minimize the already suppressed usage of cryptographic operations.

A research [24] done by a group of scientists from the University of Massachusetts proves that by using maximalist approach to cryptography, RF powered UHF tags can perform strong encryption. The research proposes Tiny Encryption Algorithm (TEA) to be used with the low cost RFID applications, and three different TEA based algorithms have been acknowledged to fit even to the budget of five cents per tag. On the other hand opposing information has been provided in a research [24] done by Iowa State University. The paper clearly states that feasible security solutions are not achievable with the amount of gates provided by an average RFID tag. The latter study does provide examples of methods that are not suitable; however the first study fails to name the technology in question, therefore making it hard to prove the functionality of their theory in one direction or another.

The encryption can be primarily achieved through three different approaches. The approaches are dedicated hardware, adjusted operation frequency and the addition of extra data [26 pp. 1]. The encryption through pure hardware is usually out of the question due to the complexity and high cost of such a system. The adaptive frequency rates combined with the usage of redundant bits has been proved to increase the capability of protecting data in the article [26].

3.3. Product Authentication Techniques

As stated before, the major advantage of RFID technology is the freedom from optical contact between the tag and the reader. The long communication range also enables illicit third parties to attempt to connect with the tags, and if no authentication is used, the exchange of messages is likely to be successful. Eavesdropping and cloning of tags may easily lead to situations like loss of privacy, fake merchandising and unauthorized access privileges. The problem is simple; without any added security, a naive approach to tag identification does not prove the identity of the tag to the reader, nor does it tell the tag that the reader can be trusted. Multiple studies exist [27]-[31] covering different kind of authentication methods. The previously stated studies share the same tendency to favor light weight methods due to the computational limitations and power restrictions of the low cost tags.

As traditional cryptography methods are likely to be too expensive for low cost RFID systems, techniques like Physical Unclonable Function (PUF) and Linear Feedback Shift Register (LFSR) are popular in tag authentications. Most of the passive Gen2 tags provide approximately 2000 gates for security usages. The most desired approaches use mutual authentication, where the idea is that both the reader and the tag must authenticate themselves to one another. An authentication scheme presented in [28] utilizes 784 gates for 64-bit variables and therefore shows great potential in securing the low-cost RFID transactions.

3.3.1. Physical Unclonable Function

A Physical Random Function or Physical Unclonable Function (PUF) is a function that maps a set of challenges to a set of responses based on a complex physical system. The challenge can only be evaluated by a specific instance of the underlying hardware. A PUF computes its output by exploiting the inherent variability of wire and gate delays in manufactured circuits. In short a PUF is a function that is embodied in a physical structure and is easy to evaluate but hard to predict.

The particular advantage in this technique lies in the fact that an adversary cannot construct a model or a device to clone a PUF as there can be a number of possible challenge-response pairs, exponentially dependent on the number of challenges. Hence the system has computations security because a model based on an exhaustive search is impractical. However, the PUF based structure is generally sensitive to noise, especially thermal noise, as wire latencies and gate delays depend on operating temperature of the device. This leads to reliability issues when trying to obtain consistent responses for a given challenge. [4]

3.3.2. Linear Feedback Shift Register

Linear Feedback Shift Registers are used in cryptography as pseudo-random number generators. They are particularly useful in RFID system authentications due to the ease of construction from simple electronic circuits, long periods, and very uniformly distributed output streams. However, an LFSR is a linear system, leading to fairly easy cryptanalysis.

LFSR is a simple circuit that consists of shift registers and XOR gates. The LFSD has a seed value to which every following value is based on. The registers functionality is deterministic and because the register has a limited amount of possible values, it must eventually enter a repeating cycle. If both the transmitter and the receiver have similar LFSR register, the secrets produced by the LFSR can be used to obscure the transmissions between the two ends. [28]

3.4. Summary

The possible lack of privacy in RFID technologies poses great concern when developing applications endowing radio frequency systems. The freedom from the line of sight between the reader and the target makes it a lot easier to acquire information secretly so that the subject of the theft will never know his privacy has been compromised. Product authentication with RFID tags is tempting, but the need to minimize the tags expenses reduces its calculation power, which makes the prevention of tag counterfeiting more challenging.

Different methods of taking advantage of the RFIDs' vulnerabilities include sniffing, spoofing, denial of service, brute force attacks and viruses. Most of these RFID specific illicit actions are modifications or combinations of the techniques previously used with wireless networks and bar codes. The objectives in illicit attempts on RFID systems are to acquire private information, to imitate the behavior of a tag, to prevent the communication between tags and readers or to contaminate the whole system with a virus.

To counterattack the illicit actions taken towards RFID products two clear approaches have been taken; cryptography and authentication. Cryptography means hiding the information of the message behind codes and ciphers. Authentication aims to deny unprivileged tags and readers to take part in the communication. The potential benefits achievable through cryptography are limited and complicated to efficiently realize due to the vastly smaller calculation power of a RFID-tag compared to a modern computer system. However a combination of an unclonable authentication method and simple cryptography would seem feasible and effective enough if not to stop malevolence, then at least to slow it down while better methods are being developed. Progress is being made as the tags get to have more and more power and memory, but impenetrable systems are yet to be found.

4. APPLICATIONS

The core idea behind RFID tags and readers is not just to enable identification without a line of sight, but also the tags’ ability to carry and process other information besides just a unique set of numbers. Modifiable information can even be interpreted as memory, which external observers can manipulate based on their updated knowledge of the environment. The most sophisticated of tags can even measure their surroundings by themselves, extending the range of possible usages even further.

4.1. Identifying items and personalizing systems

RFID systems have been suggested multiple uses outside hospital environments. At home a refrigerator equipped with a RFID reader could be aware of its contents if all the items inside would carry tags. By time the system could produce a history of its contents and thus form trends and predictions, which in turn could inform the user about products that would be about to run out or would have the tendency to expire. Washing machines could identify the clothes they have inside them and wash the items with correct settings. After the wash the machine might update the tags and save the date and details of the wash to the tags.

Identifying items would make automatization of systems a lot simpler. In the previous case the washing machine could separate clothes based on color and washing temperature automatically and that way handle unprocessed piles of laundry without human interference. In hospitals medicines, syringes and other hospital equipment could be identified and sorted automatically according to the item information. As different medical equipment needs to be washed and sterilized in different temperatures and with different chemicals the cleaning process could closely resemble the previous example related to the washing of clothes.

The identification of people, or in the sense of systems, users, would be forever useful, especially in hospital environments. Moving patients from one environment to another would be more secure and less susceptible to humane errors. Working with systems such as respiratory or anesthetic machines and ECG-devices, which need to be personalized for each patient, could be done faster as the equipment could configure itself based on the information the patient would be carrying. The machines could even recognize the hospital personnel attending the operations and prepare the systems to match the preferences of each user.

4.2. Localization and orientation

In hospitals, high-value mobile assets are often misplaced, lost, or stolen. It is not uncommon for hospitals to lose 10 percent of its annual inventory having its employees spending more than one quarter of their time looking for equipment. While traditional approaches such as vision sensor and active sensor based methods are obvious solution candidates for object recognition and localization, realization of a cost effective and robust system has yet to be implemented after several decades of research. Recent deployment of RFID technology for asset tracking and management has made RFID tags and associated devices available with low cost and minimal energy usage. RFID tags provide a cost-effective and energy-efficient approach for solving the environment sensing problem. [9]

Locating RFID tags could be done on a coarse level by simply identifying the stationary reader that is able to read the tag and by locating the tag to exist within the reading distance of the reader. This methodology enables the object to be traced with low level of accuracy, e.g. to exist within a room. However, a large number of applications would benefit from more accurate location information of objects. For example, in an intelligent hospital environment, a low-cost solution of knowing precisely where people are and what objects are close to them would enable personalization of user interfaces, optimization of energy consumption and enhanced convenience. It is not hard to imagine the re-organizing an operation room in a way similar to the children’s game where round, cubical and triangular shapes are to be placed to holes shaped respectively, but thanks to the RFID localization even the current location of the items would be apparent to the user.

The inspection of the characteristics of the tag-sent signal with multiple antennas offers potential solutions for fine-grained object localization. The objects’ location can be approximated by multiple means. The signal strength received from the tag can be read from multiple readers and then compared to the signals received from tags with known locations. The signal characteristics of interest are generally the signal power and phase difference experienced in different readers or antennas. The tag can be traced to exist in the proximity of other known tags with most similarities in the signal properties. It must be noted that even though localization algorithms developed for wireless ad-hoc networks can, in theory, be applied to localization of RFID tags, due to the unique characteristics of RFID technology, such as the limited computational capabilities of the tags and complex indoor operating environments, RFID specific algorithms must be further researched and developed in order to take full advantage of the phase-amplitude based localization. [10]

Ultrawide bandwidth (UWB) technology is a promising solution for next generation RFID localization systems. The employment of wideband signals enables the resolution of multipath, the mitigation of frequency dependent fading, and high localization precision based on time-of-arrival (TOA) estimation of the signal. The prospective advantages of UWB include low power consumption at the transmitter side, extremely accurate positioning capability, robustness to multipath, low detection probability and large numbers of devices operating and coexisting in small areas. [32]

The research done in [35] presents a method that combines RFID technology with external range sensors. The purpose of the research is to propose a solution for the joint process of object identification, localization and discovering the objects orientation. The range sensors are used to acquire 3D information of the scene in question. After recognizing each object through their RFIDs the orientation and localization can be calculated based on the information available from the 3D image. The drawback of the otherwise potential method is the need for line-of-sight between the object and the device that captures the 3D image.

In [37] RFID usability is analyzed in pharmaceutical supply and distribution chain usage. The motivation to apply the benefits of RFID in the pharmaceutical area is high due to the safety and security concerns of the field. By providing better tracking and tracing with a complete electronic system, RFID would not only discourage counterfeiting products but could also provide complete supply chain visibility, which, in turn, would rule out tampered products as well as products with unacceptable status. The research concentrates on testing the performance of HF and UHF systems in situations where the speed, orientation and packaging material of pharmaceutical products on a supply chain varies. The technologies are also tested on reading the contents of crates that have large amounts of different items mixed together. UHF is recognized to show significantly better results in all of the situations, and HF is judged to be too sensitive to speed and materials in the sense of signal propagation. The orientation dependency of HF tags can be eased with the use of multiple antennas; however the solution is not truly cost effective. The research also mentions the recent introduction of near/far field passive UHF tags, which is told to have significantly improved the performance when compared to the previous generations of passive UHF RFID systems

4.3. RFID sensors

RFID sensors provide tempting solutions for healthcare industry with easily accessible up-to-date information about the status of the patients’ health. The wireless monitoring of people and the feasible possibility of constant sensing of their real-time body temperature, heartbeat, glucose content and blood pressure with low costs and near unlimited operation time of the tags has stirred a lot of discussion and motivated multiple researchers to overcome the challenges encountered during the exploration of RFID sensors.

Currently the technology trend popular with RFID development favors the usage of ultra-high frequencies over other RFID types. When considering sensors that would be placed within the body some problems related to the signal propagation might rise. Ultra-high frequency signals have the tendency of reflecting off materials that have high permittivity and electric susceptibility. The human body consists mostly of water, and is therefore apt to discontinue the UHF signals propagation send to and from the body. This could be solved with the usage of a combination of frequencies, where the UHF-tag placed on the surface of the body would communicate with the LF-tag that would be within the body. As no research or material was available at the time of writing, there is no proof that this approach would work or even be possible.

4.3.1. Thermometer

There are already multiple types of thermal RFID sensors available for multiple purposes [12]-[14]. The sensors designed for general temperature measurements can usually measure temperatures from -40 °C to 85 °C at 1 °C accuracy. More convenient sensors for patient surveillance could be adapted from sensors, such as [15], that are designed to measure the temperatures of animals. These sensors can measure temperatures from 30 °C to 50 °C with higher 0.1 °C accuracy. The drawback of the animal specific sensors is the short reading distance of a few centimeters, which is caused by the limited range of LF RFID technology.

The UHF RFID sensor presented in [12] investigates the possibilities of a next-generation wireless body temperature specific application, which operates with an extremely low power consumption (110 nW at ten measurements per second) and high precision (0.1°C) within the range from 35°C to 45°C.

4.3.2. Accelerometer

In a healthcare environment one of the multiple applications of a wireless sensor detecting a tags’ movement could be the surveillance of unconscious or sleeping patients. In a research done by the department of IT in biomedicine of University of Roma [11] feasibility of the technology for the observation of patients with sleeping disorders has been investigated.

In the study the test subjects were expected to suffer from neuromuscular diseases such a restless leg syndrome (RLS) or of periodic limb movement (PLM), hence their limbic movement was observed during the whole period of sleep. The observation was done with the help of UHF RFID sensors that were attached to limbs and thorax of the test subject. A record of movement was saved each time when acceleration that exceeded a predefined limit was detected.

The major problem in the research was to design a UHF RFID tag that could be read from a distance even with the close proximity to a human body. The presence of the human body causes a strong pattern distortion and efficiency degradation due to dissipation and scattering. The solution was to isolate the radiative part of the tag so that it did not have any electric contact with the body. This reduced the radiation losses into the body and thus improved the antenna gain. Special care was also taken with the tag placement-areas such as inner thigh and armpits were avoided to elude the possibility of isolating the whole tag with the body.

4.3.3. Vapor and gas monitors

Research [33] presents a solution for vapor monitoring with the use of RFID technology. The sensor was constructed by coating the fabricated antennas with a dielectric sensing film. The vapors sensed consisted of trichloroethylene, water, and toluene. The presented solution is able to detect vapors down to part-per-billion concentrations. Similar study [34] has been done in Tianjin University, where a vehicle exhaust gas detection system is simulated. The system consists of vehicles, simple passive RFID tags with gas sensors, readers and rather complex computer software. The constructed system is evaluated to be highly experimental, but nevertheless with good potential for future development.

4.3.4. Chemical sensing

RFID sensors can be also used to sense ions and organic solvents in water or toxic vapors in air [36]. In chemical sensing from water, analyte-induced changes affect the complex impedance of the antenna circuit through changes in material resistance and capacitance between the antenna turns. Both polysulfone sensing film and hydrophobic sensing film can be used to analyze different kind of ions in the water.

In air measurements individual measured parameters are affected by relative humidity. However, critical to the sensor performance, sensing material applied onto the RFID antenna responds with the same magnitude to the model analyte vapor at variable relative humidity. RFID sensors developed in [36] were further tested for detection of toxic industrial chemicals. In the research the RFID sensors used are told to deliver unique capability of multianalyte sensing and rejection of environmental interferences with a single sensor, whereas previous known solutions needed multiple sensors to acknowledge and subtract the environmental effects on the signals.

4.4. Summary

If used in all the medical applications, the RFIDs could present an easy way to catalog and monitor all the tagged items. Multiple UHF tags can be read at the same time, even though the tags would be in close contact from each other and many meters away from the reader. This makes it possible for the hospital staff to easily make an inventory of the items they currently possess, scanning one room at a time. Even the status of each item could be read, allowing the greatly simplified categorization of items e.g. by condition or by purchase date.

The RFID-sensors make it possible to monitor the status of many different environmental variables without the need for either cables or sensor specific energy sources. The cables are a big factor when defining the locations of systems that are attached to the patient. Without the need for having these computers close to the patient the operating room could be throughout reorganized, freeing more space for both staff and life sustaining systems.

Four potential sensor types that can easily be implemented in a hospital environment are the temperature sensor, accelerometer, vapor sensor and chemical sensor. The temperature sensor would not only allow to monitor a room temperature, but to follow the body temperatures of a patient in different parts of his body. Accelerometers provide ways to monitor different kinds of movements, from the breathing rate of a newborn child to the movements of an awakening unconscious patient. Vapor and gas sensors placed in different locations within patient tubing make it possible to monitor both the status of the patient and the re-breathing system, and chemical sensors can be used to attain information of concentrations of different medical mixtures.

In theory there are vast amount of potential benefits from employing RFID-sensors in medical environments. The lack of testing and prior experiences proves that the market is rather open for newcomers, but the immaturity of the field puts the risks high.

5. CASE: SMART ABSORBER

During surgical operations or intensive care, patients are most commonly treated under general anesthetics. The anesthesia is usually induced with the help of gases containing anesthetic agents. The circulation of gases to and from a patient is kept within a closed circuit to prevent the medical staff from suffering the dozing effects of the medicines exhaled by the patient. To maintain the patient both unconscious and alive, carbon dioxide must be filtered out from the circulation and replaced by oxygen.

A canister full of soda lime compound is used to absorb the undesired CO_2 from the closed air circulation. A standard sized canister can be used for approximately eight hours in a row, after which the soda lime is saturated with CO_2 and the absorber must be changed. The use of an absorber can be observed easily, for the absorbers' contents change color based on the saturation level. However the color neutralizes after a certain period of time, and after a few days even a fully saturated absorber starts to closely resemble absorbers that haven't been used at all. To avoid the usage of depleted absorbers new means must be found to enable better observation of the absorber use.

5.1. Background

Anesthesia has been described to mean a pharmacologically induced reversible state of amnesia and analgesia, loss of responsiveness and skeletal muscle reflexes and decreased stress response. During anesthesia patients' respiration is artificially induced, and carbon dioxide must be absorbed from the exhaled air. If the CO_2 is left to the circulation and its percentage in the air allowed grow, the anesthesia is likely to be interrupted by the patients' automatic response to the CO_2 caused feeling similar to downing.

In 1916 Dennis Jackson of the University of Cincinnati proved that by absorbing exhaled carbon dioxide in alkali, confined animals could survive in a closed space containing an anesthetic mixture. Only oxygen needed to be added to replace the part diffused into the blood from the animals' alveoli. Soda lime was discovered to absorb CO_2 during test conducted for gas masks in World War 1. Since 1921 it has been used as an absorbent in closed circuit breathing systems in hospitals. The soda lime is an alkali able to absorb large quantities of CO_2 with only small side effects; some water is absorbed and some heat results from the chemical reaction. [1]

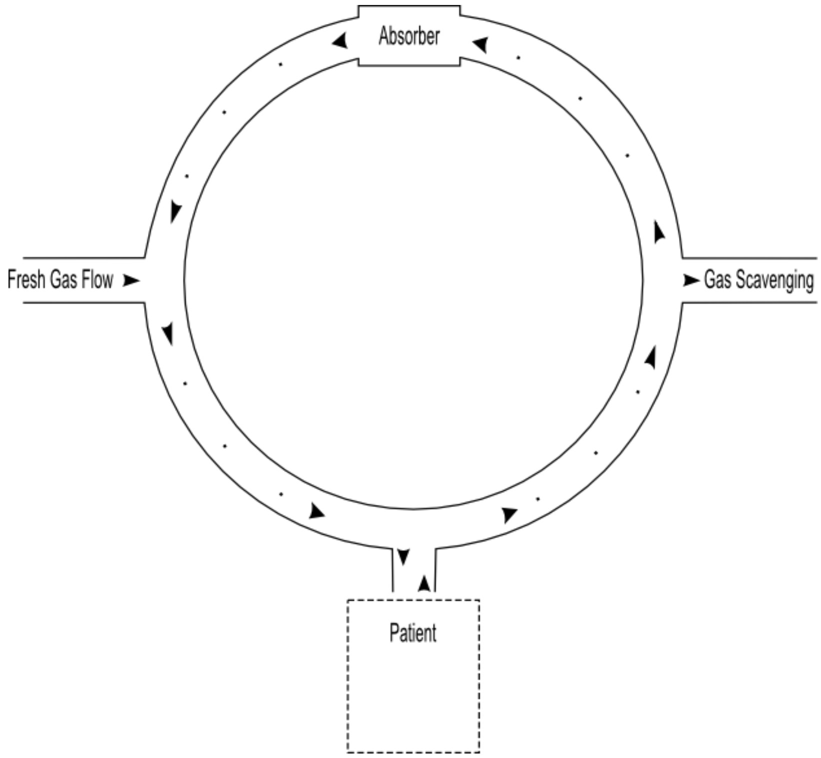


Figure 7 *Simple anesthesia machine gas flow*

A common anesthesia setup consists of fresh gas and anesthetics flows, gas scavenging, patient and the absorber. The absorber (on top in the figure 7) can only absorb a limited quantity of carbon dioxide. The absorption is not linear, as virtually all carbon dioxide is absorbed from the air until the absorber is saturated. If the absorber discontinues working the patient is likely to start to show symptoms of respiratory acidosis. [2]

5.2. Problem

The absorbers have a limited lifespan. At the moment it is virtually impossible to keep track of their usage and their level of saturation. The time each absorber has been in active use could be marked manually to the side of each can; however this approach would rely heavily on the activity of each individual using them, and thus would be quite prone to human errors. The next approach would be to automatically log the usage of the absorbers. Each absorber should have an ID of some sort that would distinguish it from the other absorber cans. The ID could be printed to the side of the can – however, using letters is inefficient for automated systems. The next intuitive approach would be to use bar codes to ease up the absorber identification. However, since the same absorber can be used in multiple care stations, the log of each the absorber could not be maintained in the station itself, and an external database would be used. The care stations cannot be expected to be connected to an external database, which makes the need to find new solutions more pressing.

During the patient anesthesia the CO_2 levels are closely observed. However the operation environment is usually prepared before the patient is connected to the device. This renders the CO_2 monitoring impossible when trying to avoid dysfunctional absorbers in the first place. The monitoring equipment could be made more useful if the system would be aware of the saturation of the absorbers. The staff could be advised to pay closer attention to the CO_2 monitoring system during the operation if the absorbers saturation would start to go to the critical area.

The other issue with the absorbers also solvable by logging its usage is desiccation, or in other words drying up. Approximately one fifth of the soda lime compound used in absorbers is water. The container is sealed before first usage, allowing the container to be stored for up to two years without losing the great quantities of the humidity inside. Water plays an important role in the chemical reaction of the absorption of carbon dioxide. In the rare case of storing an opened container for longer periods of time the soda lime inside can be desiccated until the point where the absorber would render impaired. This could be avoided by acknowledging the date when the absorber was created and the time of first usage. Based on these records the user could be informed when about to use a possibly expired piece of equipment.

The ability to read tags from longer distances might cause errors in situations where the anesthesia machine reads and updates the wrong absorber e.g. an absorber that just happens to be in the same room. Hence the absorber in use should be identified either by locating the absorber to be close to the reader or by using galvanic connection as an identifier.

5.3. Goal

The goal of the project is to come up with a solution that can be used with the future models of care stations. The care stations currently under examination use the same physical framework, which should not be modified any further at this point of development. This forces the absorber identification solution to be post mountable. It must be possible to easily attach the system to any of the new care station models, and the system must use the existing connections for both communication and attaining the energy required for it to function. The solution used should not interfere with any of the other electronic devices used in the hospital environment. In other words the solution should be electromagnetically compatible.

The other main goal of the solution is to add additional value to the absorber, thus attracting the client to use smart absorbers instead of normal ones. Currently only one tenth of the absorbers used are the ones designed for the care stations by GE. This is due to the fact that the only parts of the absorber that are care station specific are the input and output connections for air. These are easy to imitate, letting competitors to take advantage of the market. As the quality of the competitor produced absorbers cannot be guaranteed, the clients should be encouraged to use the original GE produced absorbers. The cloning of the smart absorbers could be made more challenging by adding security to the identification method.

The additional goal for the solution would be re-usability. The technology should be usable in other similar applications and participate in the development of intelligent medical applications. Identification of other medical items for logging purposes could have multiple possible usages. The identification could be extended to cover also the personnel and clients, enabling quick and easy access to further information related to each ID.

5.4. Possible Solutions

5.4.1. Bar code

Bar codes are cheap and reliable. The scanning is done with infrared light, which is completely EMC safe. The codes can be printed to stickers or directly to the absorbers. The readers are light and use only small amounts of energy, which makes them easy to mount to the existing care stations. Obviously the bar codes cannot be changed after the printing, which limits their information to static ID numbers. This limits the usability, for data related to each ID has to be saved to an external database as the same absorber can be used in multiple care stations. To successfully track the usage and alarm the user of almost saturated absorbers a connection to the database is needed during the usage of the care station.

There are no cryptographic services available for bar codes at the moment. To suppress smart absorber cloning valid IDs could be selected from a predefined list. This would allow the denial of unknown IDs limiting the usage of unsupported absorbers. However existing IDs from bar codes could be copied and reused, making the tracking process unreliable.

5.4.2. LF RFID

The RFID systems consist of RFID readers/writers and of RFID tags. The tags are usually really small microcontrollers with a relatively large antenna. LF RFID equipment uses low frequency signals to communicate. The most common frequencies used are 125 kHz and 134 kHz. Because of the low frequency the signals are quite unaffected by the presence of substances such as water or salt. The communication range tends to be one meter or less. LF RFID is particularly appropriate for identifying living organisms. The tags are rather costly (a few US dollars), but this is not a major impediment to the indented usage, such as the identification of livestock, pets, or people. It is usually straightforward to arrange for only one tag to be in the read zone at any given time. Generally several seconds are needed to read a single tag, and a low data rate disables the usage of cryptography.

LF tags and readers are popular in access control. Short-range LF readers can be implemented at very low cost since signal frequencies of 100 kHz present very little challenge to modern digital circuitry. Tags can be implemented in a credit card form factor, with a several turn coil antenna, and used as identification badges allowing entry into secured facilities. Near-contact ranges of a few centimeters are acceptable, and ensure that only one badge is presented to the reader at any given time. LF tags are useful in e.g. robust identification of metal compressed gas cylinders.

5.4.3. HF RFID

The high frequency RFIDs commonly use communication signals of frequency 13,56MHz. The energy for the tag is transmitted in the signal itself; as in the LF tags, the HF tag absorbs energy from the electromagnetic waves through induction. The communication distance is roughly comparable to the size of the reader antenna and dependent on the related orientation between the tag and the antenna. The data rate of HF is usually tens of kbps.

HF tags are widely used for noncontact smart cards, credit-card-like transponders that contain an IC (Integrated Circuit) and antenna and support secure financial transactions. At close ranges the power absorbed by the tag is high enough to provide the means for cryptographic operations, so HF tags can readily carry out secure communications with a reader. Short range also helps ensure against interception and inadvertent activation of the cards when they are not supposed to be accessed. High data rates can support a relatively complex exchange to allow a sophisticated transaction to occur. Like LF systems, HF-equipped badges can also be used for access control. HF tags are also increasingly used in items like RFID equipped passports and travel documents.

HF tags have ample ID space to support unique identification of a considerable quantity of items. The availability of high power at short range means that HF tags can support large memory spaces, up to several thousand bytes, allowing a user to record a substantial amount of unique information on a tag in the field. This capability is very useful when users need to interact with the tags when out of reach of networks or relevant databases. [3]

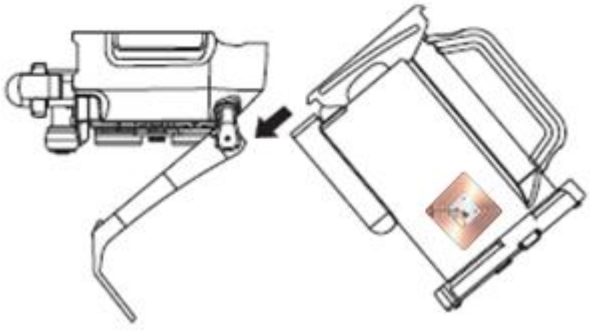
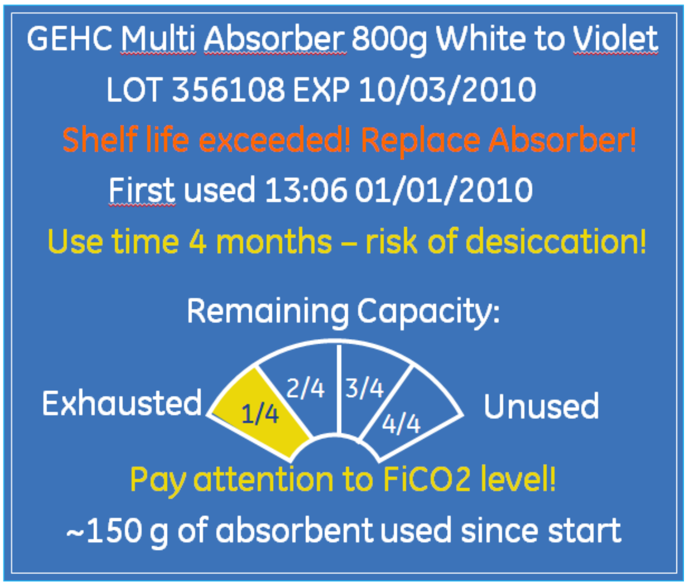


Figure 8 *An example of a RFID tagged absorber*

5.4.4. UHF RFID

UHF RFID technology is can be considered as the most futuristic and modern of the RFID technologies. Unlike HF with the transmit distance limited by antenna size, UHF operation provides range limited only by transmit power, which makes the UHF tags benefit from the potential of long range. The relative simplicity of UHF antenna designs, which involve only a few features with no critical dimensions and no need for crossovers or multiple layers, help reduce the cost of fabrication. At least one component in the tag’s circuitry must operate at very high frequencies, which in the past added significantly to the cost of the circuitry. Today the UHF tags match the price range of HF tags. Due to the high frequency of communication signal materials with high permeability easily disturbs the propagation and makes reflections more common. This forces the tags to be placed on the surface of items that contain conducting materials, such as metal or water.

UHF tags are widely used in automobile tolling and rail-car tracking, where ranges of several meters add considerable installation flexibility. They are increasingly used in supply chain management, transport baggage tracking, and asset tracking, where the future potential for very low-cost tags is important, and relatively long range adds flexibility in applications (at the cost of some ambiguity in locating the tags that are read). The tags can be easily attached to the absorbers (figure 8) with glue or similar substance. UHF tags equipped with batteries can have ranges of tens or hundreds of meters, and are used for tracking shipping containers and locating expensive individual assets in large facilities. [3]



GEHC Multi Absorber 800g White to Violet

LOT 356108 EXP 10/03/2010

Shelf life exceeded! Replace Absorber!

First used 13:06 01/01/2010

Use time 4 months – risk of desiccation!

Remaining Capacity:

Pay attention to FiCO2 level!

~150 g of absorbent used since start

Figure 9 *Example of an UI implementation*

5.5. Software and implementation

This thesis does not go deep into details when describing the software that is to be implemented to the anesthesia machine for the RFID-system. However some details related to the case can be listed even when the actual implementation of the software might be far in the future.

The RFID-reader needs a driver to run in the anesthesia machine. As the expenses of the reader are to be held rather low, the actual hardware is likely to have low computing power. Therefore the possible encryption and other manipulation of the data should be implemented to the driver. There are many generations of anesthesia machines available on the market, and they run different operating systems, which increases the value of a multi-platform driver that runs on different versions of Windows (CE 5.0, CE 6.0, Embedded) and possibly even on Linux. The presentation of the remaining absorber lifetime depends on the resolution and reliability of the estimation the algorithm is able to produce. If the absorber lifetime can be estimated with an error of only a few minutes the user can be presented with an accurate estimate of the lifetime in hours and minutes. On the other hand if the algorithm provides unstable results that need to be re-adjusted during the absorber usage, the usage of a user interface such as in figure 9 should be considered. If the absorber lifetime drops for example from three hours to half an hour during the operation, the user is likely to lose trust in the reliability of the device. However in a situation where the user is presented the information so that the updates in the remaining absorber capacity are not so apparent, the user is more prone to feel confident about the information the software presents to him.

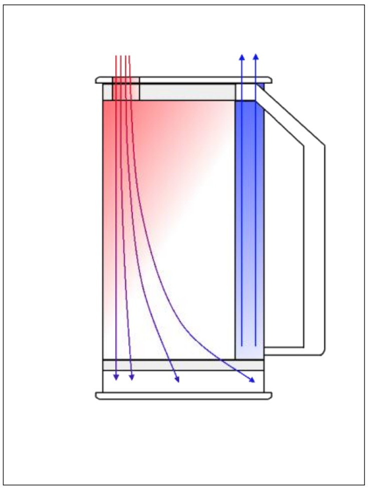


Figure 10 *Normal airflow through an absorber*

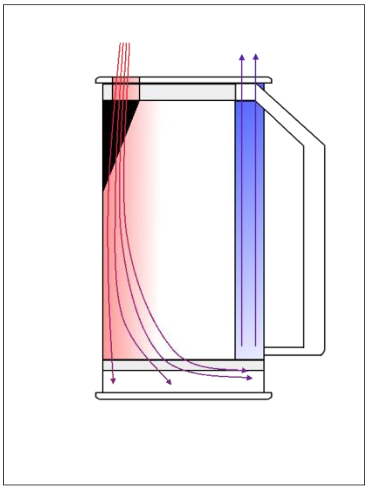


Figure 11 *Channeled air-flow via empty space through an absorber*

5.6. Absorber lifetime

One of the project goals is to successfully estimate the absorbers' remaining lifetime. As mentioned in the previous chapter, the absorber state cannot be defined by the CO_2 levels before the patient is attached to the operating system. However, if the remaining capacity of the absorber would have been defined when the absorber was in use we would have information about the absorbers state even before the operation. The remaining lifetime could be estimated from the capacity, and adjusted according to the settings defined to the anesthesia machine. This information could be presented to the user so that when creating the operation environment depleted or too much used absorbers could be identified and changed to new ones when needed.

5.6.1. Absorber saturation

Even when receiving information from the air flow during the operation the remaining lifetime of an absorber must be estimated, for the current system does not offer the possibility of getting an exact value to present the absorbers' usage. The absorbers are used in different circumstances. The ones we are concentrating on in this study are emergency room and anesthesia environments. Both of the environments use different modules for the management and observation of the respiratory system. The absorber state depends on multiple variables, and the information available depends on the module that is currently in use.

The amount an absorber can absorb carbon dioxide depends the compound used and the amount of compound within the absorber. As these are commonly known values we are able to use them in our approximations. As the gas flows through the absorber it tends to form channels (Figures 10 and 11). The compound closest to these channels gets saturated first, and the compound that is further from the channels might not absorb carbon dioxide at all. The channels effects depends on the flow speed through the absorber, for the longer the air stays in the absorber the more CO_2 gets absorbed. Absorbers that are not full of the compound might have surprisingly low total lifetimes. If the empty sector of the absorber is oriented vertically the airflow only needs to pass a thin layer of compound, leaving most of the absorbent unused.

The end tidal carbon dioxide ($ETCO_2$) is either the partial pressure or maximal concentration of carbon dioxide at the end of patients’ exhaled breath, which is expressed as a proportional percentage of CO_2 or mmHg. During normal anesthesia the values range from 5% to 6% CO_2, which is equivalent to 35-45 mmHg. CO_2 reflects cardiac output (CO) and pulmonary blood flow as the gas is transported by the venous system to the right side of the heart and then pumped to the lungs by the right ventricles. When CO_2 diffuses out of the lungs into the exhaled air, a device called capnometer measures the partial pressure or maximal concentration of CO_2 at the end of exhalation. During anesthesia, the amount of CO_2 excreted by the lungs is proportional to the amount of pulmonary blood flow.

5.6.2. Mathematical approach

The flow of air through the absorber F_{abs} equals the subtraction of fresh gas flow F_{FG} from the minute volume V_{min}

$$F_{abs} = V_{min} - F_{FG} \tag{4}$$

When using the compact airway module E-CAIOVX, the concentration of carbon dioxide in the absorber C_{abs}, or in other words the mixed expired CO_2 ME_{CO2}, can be defined by subtracting the product of dead space volume percentage $V_{DS\%}$ and the top value of the end tidal CO_2 concentration Et_{CO2} from one

$$C_{abs} = ME_{CO2} = (1 - V_{DS\%} * Et_{CO2}) \tag{5}$$

The dead space is the sum of space of volume external to lung (both physical and anatomic spaces) and the space in lung that is inefficiently mixing gas to blood. The dead space volume percentage $V_{DS\%}$ can be solved by integrating the product of gas flow and the amount of carbon dioxide and by dividing the result with the product of the top value of the end tidal CO_2 concentration Et_{CO2} and the tidal volume V_T

$$V_{DS\%} = \int_t^T \frac{F(t) * CO_2(t - dT)}{Et_{CO2} * V_T} \tag{6}$$

When using an E-CAIOV module, the estimation of the dead space volume percentage $V_{DS\%}(est)$ can be solved by first integrating the gas flow F_{tot} from time t to time T. Time t equals the moment of expiratory time exceeding zero, and time T equals the moment when the carbon dioxide level of the output exceeds the fractional concentration of inspired CO_2 plus 0.2. Next the integral must be divided by the expired volume V_{ExpTot}

$$V_{DS\%}(est) = \frac{\int_t^T F_{tot}}{V_{ExpTot}} \tag{7}$$

The carbon dioxide absorbed V_{absCO2} equals the product of the gas flow through the absorber F_{abs}, the CO_2 concentration of the absorber C_{abs} and the absorber efficiency E_{abs}

$$V_{absCO2} = F_{abs} * C_{abs} * E_{abs} \tag{8}$$

The absorber efficiency E_{Abs} equals the subtraction of the bypassed flow F_{BP} from the absorber flow F_{Abs} divided by the absorber flow F_{Abs}, with the product of the subtraction of the average container time t_{cont} from the time needed for absorption t_{abs} divided by the time needed for absorption t_{abs}

$$E_{Abs} = \frac{F_{Abs} - F_{BP}}{F_{Abs}} * \frac{(t_{abs} - t_{cont})}{t_{abs}} \tag{9}$$

The average container time t_{cont} is the product of a constant k (depends of the flow path) and the volume of the absorber, divided by absorber flow F_{Abs}

$$t_{cont} = \frac{\mathrm{k} * V_{abs}}{F_{Abs}} \tag{10}$$

The estimated absorption efficiency $E_{Abs}(est)$ follows the function of the fractional concentration of inspired CO_2 F_{iCO2} and the relation of the minute volume V_{min} to the flow of fresh gas F_{FG}

$$E_{Abs}(est) = F(F_{iCO2}, \frac{V_{min}}{F_{FG}}) \tag{11}$$

The fractional concentration of inspired CO_2 F_{iCO2} equals the carbon dioxide of the fresh gas flow multiplied by the amount of carbon dioxide in the fresh gas (which is always zero) $F_{FG} * 0\%$ minus the subtraction of fresh gas flow F_{FG} from the minute volume V_{min} multiplied by the volume of the absorbed CO_2 and divided by the minute volume V_{min}

$$F_{iCO2} = F_{FG} * 0\% - \frac{(V_{min} - F_{FG}) * V_{absCO2}}{V_{min}} \tag{13}$$

The dead space $V_{DS\%}$ can be calculated by subtracting the carbon dioxide flow C_{abs}^{in} divided by the multiplication of minute volume V_{min} and corrected end tidal carbon dioxide $(Et_{CO2\_\mathrm{k}} - F_{iCO2_{\mathrm{k}}})$ from one

$$V_{DS\%} = 1 - \left(\frac{C_{abs}^{in}}{V_{min} * (Et_{CO2\_\mathrm{k}} - F_{iCO2\_\mathrm{k}})} \right) \tag{14}$$

If we combine the formulas (8), (13) and (14), we can solve the amount of CO₂ absorbed to the absorber

$$V_{abs}^{CO2} = \int_t^T (V_{min} - F_{FG}) * ((1 - V_{DS\%}) * Et_{CO2}(\mathrm{t})) * \left(1 - \frac{F_{iCO2}(\mathrm{t}) * \frac{V_{min}}{V_{min} - F_{FG}}}{C_{abs}^{in}} \right) dt \tag{15}$$

In a normal test setup the values are discrete, so the integral can be replaced with a sum equation

$$V_{abs}^{CO2} = \sum_{k=0}^{n} (V_{min} - F_{FG}) * \left((1 - V_{DS\%}) * Et_{CO2\_\mathrm{k}} \right) * \left(1 - \frac{F_{iCO2\_\mathrm{k}} * \frac{V_{min}}{V_{min} - F_{FG}}}{C_{abs}^{in}} \right) \tag{16}$$

The sum equation (16) gives us the amount of carbon dioxide absorbed until the moment of time n. By running multiple tests with different kind of test setups and absorbers the amounts of carbon dioxide can be calculated and statistics can be formed to acquire knowledge whether the amount of carbon dioxide varies within reasonable limits and if it is therefore predictable based on statistic averages.

5.7. Test setups

The tests were run on an anesthesia machine that allowed the user to change the respiration rate, tidal volume and fresh gas flow. Only air was used for the fresh gas flow and the effects of anesthesia drugs, dioxide nor nitric oxide were not tested. The professional opinion of the people that defined the test setup parameters was that the type of gas used for fresh gas flow had no effect on the test results. The inspiration/expiration rates were kept at default values and multi absorbers were used. The artificial lungs were so called water lungs, where water moved from one tube to another to simulate the expansion and contraction of human lungs and the mixing of gases. The tubing was inserted about one centimeter away from the surface of the water, and more water was added to keep the level equal. The D-fend water trap used in the monitoring system was always the model designed for adults even when smaller tidal volumes were used. After each measurement the tubes and all the water traps were emptied from the concentrated water and the system was recalibrated. No leaks or other similar abnormalities were detected during the measurements. The results were collected through the monitor to S5Collect-software and then exported to Microsoft Excel. The sampling frequency used was one measurement per minute. Two of the measurements had to be done twice due to problems with data transfer issues, and one test run (no. 10) was discarded as it was considered exceedingly unrealistic and therefore interfering unnecessarily with the test results, as average values were commonly used in the estimation algorithms. The test setup no. 10 is not presented in the results or figures, but in can be found from the appendix A.

Multiple tests were designed to discover the effects of different variables to the absorption speeds of the absorbers (table 2). Average values for the variables were defined by experienced anesthesia machine users, and the tests were started by running a normal setup, which simulated the usage of the anesthesia machine with a regular sized person that breathed normal amount of carbon dioxide with average speed through an absorber that was filled evenly. The test was run continuously through the night, and in the morning the results were collected and new test environment was set up. The tests continued by first changing one variable at a time and later by modifying multiple values per setup.

Test Setup	Vmin l/min	Vtidal ml	FGF l/min	Vds %	Filling	Cin ml/min
01 Normal Setup	6	500	1	avg	avg	190
02 High Deadspace	6	500	1	high	avg	190
03 Low Minutevolume	3,6	300	1	avg	avg	190
04 High Minutevolume	10,2	850	1	avg	avg	190
05 High FGF	6	500	2	avg	avg	190
06 Low FGF	6	500	0,5	avg	avg	190
07 High Cin	6	500	1	avg	avg	250
08 Low Cin	6	500	1	avg	avg	150
09 Small tunnel	6	500	1	avg	small tunnel	190
10 Big tunnel	6	500	1	avg	big tunnel	190
11 Small Tunnel High FGF	6	500	2	avg	small tunnel	190
12 Small Tunnel High Minutevolume	10,2	850	1	avg	small tunnel	190
13 Small Deadspace	6	500	1	low	avg	190
14 Small tunnel 2	6	500	1	avg	small tunnel	190
15 Small Tunnel Modified FGF	6	500	1(2)	avg	small tunnel	250

Table 2 *Test setups*

In the later tests approximately one fifth of the filling of the absorber was removed in order to examine the effect of tunnels that may form in poorly filled absorbers. In the last test the effect of modifying a value during the test was examined by increasing the fresh gas flow from one to two liters per minute once a change in the fractional concentrated carbon dioxide percentage was observed.

One of the most interesting values measured is the $FiCO_2$. As long as the absorber is able to filter out all of the CO_2, $FiCO_2$ stays at zero. However, when the carbon dioxide starts to pass through the absorber the $FiCO_2$ levels start to rise. This means that part of the carbon dioxide exhaled by the patient is also inhaled by the patient. The $FiCO_2$ is the most precise pointer that indicates the absorber state. The next interesting value measured is the $EtCO_2$, which is the partial pressure or maximal concentration of carbon dioxide at the end of an exhaled breath, which is expressed as a percentage of CO_2. The two values are related, for when more CO_2 is inhaled, more is also exhaled.

5.8. Test results

In Figure 12 the $FiCO_2$ levels of 14 different test setups is presented. There are three valuable types of information available from the figure. First and most observed information is the moment in time when the $FiCO_2$ reaches 0.5 percent. The second data under close examination is the moment when $FiCO_2$ starts to rise, and how long it takes to it to rise to 0.5 percent. The third interesting setting was the last measurement where the fresh gas flow (FGF) was doubled after $FiCO_2$ started to rise.

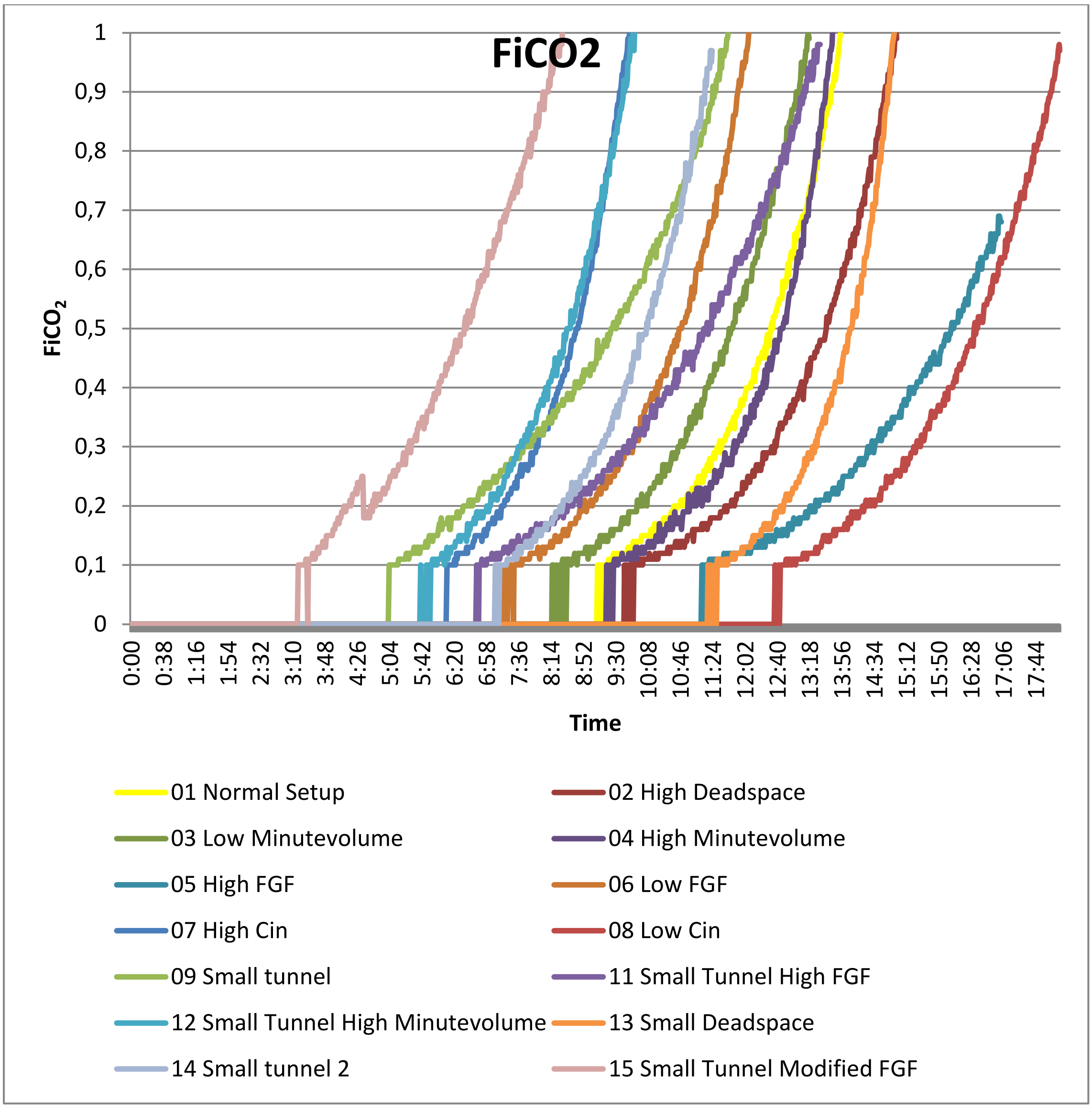


Figure 12 *FiCO$_2$ at different test setups*

The moment when the fractional inspired CO$_2$ reached 0.5% varied a lot depending on the test parameters. The only apparent value that had a big effect and that is not presented in our estimation formulas is the amount of filling of the absorbers and the possible channels formed inside the absorbers due to the uneven filling.

Test setup	**FiCO$_2$ 0,1 (hh:mm)**	**FiCO$_2$ 0,5 (hh:mm)**	**FiCO$_2$ 0,1 to 0,5 (hh:mm)**
01 Normal Setup	9:09	12:33	3:24
02 High Deadspace	9:41	13:38	3:57
03 Low Minutevolume	8:16	11:44	3:28
04 High Minutevolume	9:20	12:44	3:24
05 High FGF	11:12	16:05	4:53
06 Low FGF	7:20	10:45	3:25
07 High Cin	6:12	8:44	2:32
08 Low Cin	12:38	16:32	3:54
09 Small tunnel	5:04	9:25	4:21
11 Small Tunnel High FGF	6:47	11:14	4:27
12 Small Tunnel High Minutevolume	5:41	8:33	2:52
13 Small Deadspace	11:19	14:06	2:47
14 Small tunnel 2	7:09	10:07	2:58
15 Small Tunnel Modified FGF	3:17	6:33	3:16
Average	**8:04**	**11:37**	**3:32**

Table 3 *Durations between different FiCO$_2$ values*

The absorber lifetime variation is roughly between 6.5 hours and 16.5 hours (as shown in the third column in table 3). According to our tests the average deviation in total absorber lifetime is a lot bigger in proportion when compared to the average deviation in the remaining lifetime after the first peak in FiCO2 is observed. On average the first change in the FiCO2 value happens approximately three and a half hours before the absorber is considered to be saturated, with the minimal value of 2 hours 32 minutes and maximum value of 4 hours 53 minutes.

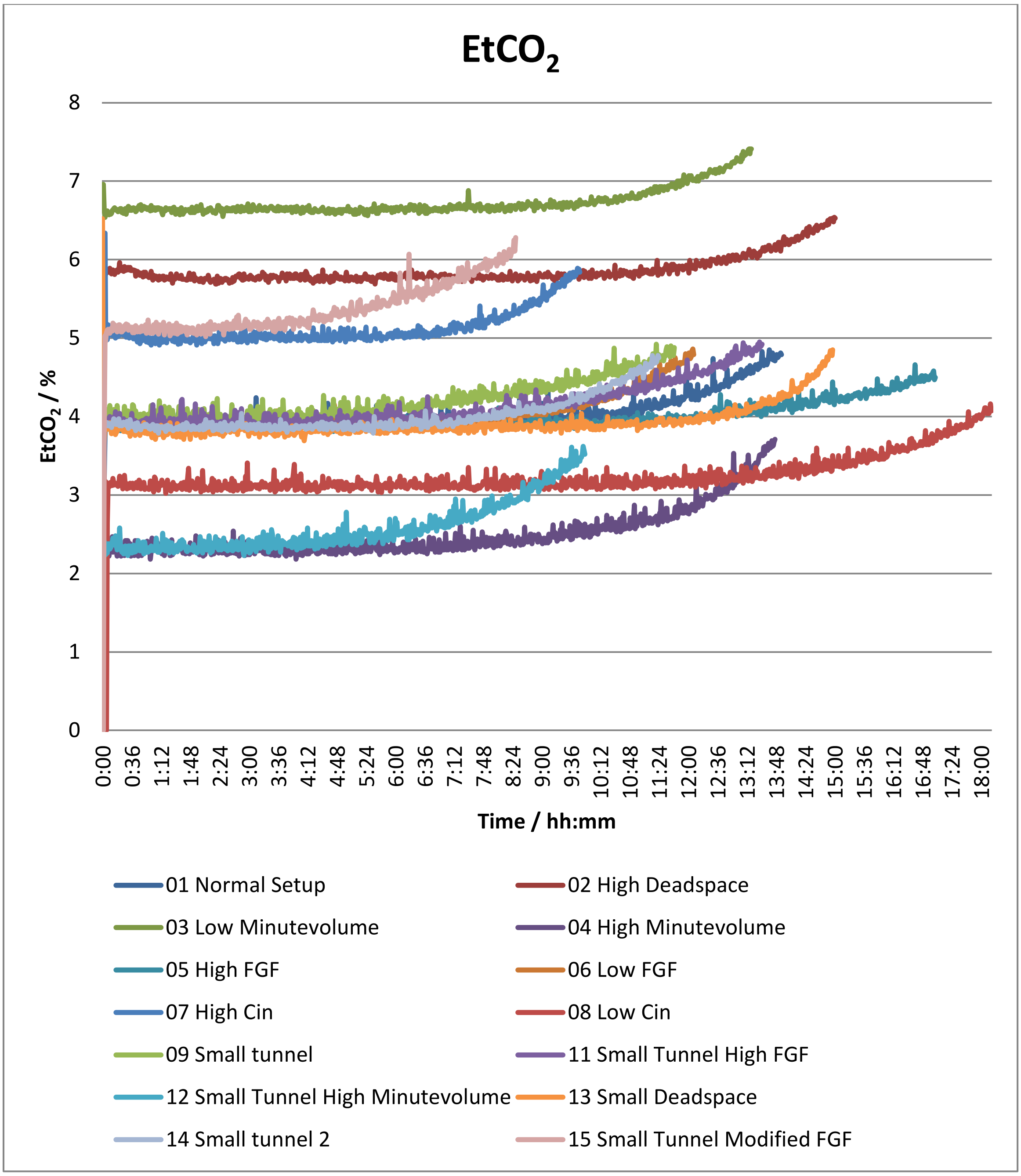


Figure 13 *$EtCO_2$ at different test setups*

The amount of carbon dioxide exhaled by the patient is presented in Figure 13. The $EtCO_2$ is measured because it is used to compensate the effect of increased $FiCO_2$ to the absorption speed *VCO2(t)*. The possibility of observing the absorber status from the $EtCO_2$ has not been evaluated. However as it is apparent from these figures, the $EtCO_2$ rises over time as a consequence of the saturation level of the absorber a question arises. Could the $EtCO_2$ values be used in the evaluation of the remaining absorber lifetime more easily than the $FiCO_2$?

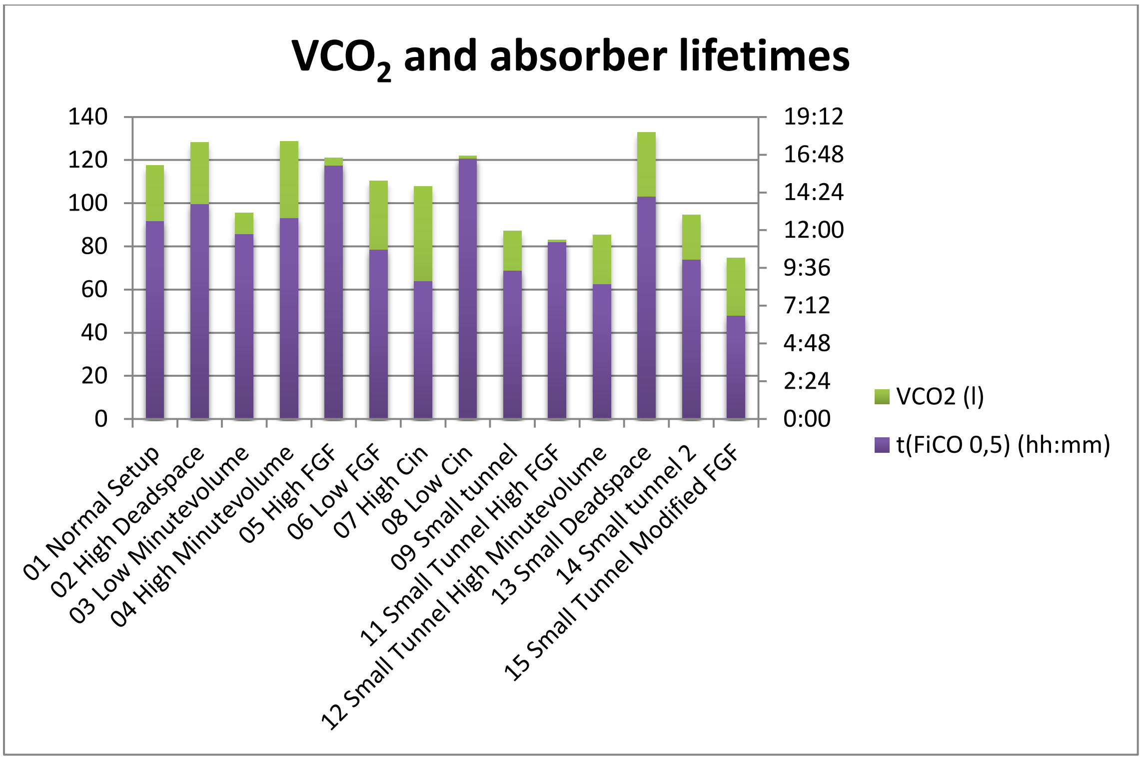


Figure 14 *Total absorbed CO2 amounts and absorber lifetimes*

The EtCO2 clearly has a value that differs from zero during the whole measurement cycle. However due to the static error apparent in the measurements the moment when the $EtCO_2$ starts to rise is a lot more complicated to observe compared to the change in $FiCO_2$. There is no $EtCO_2$ value that is defined to be the limit in the lifetime due to the fact that the $EtCO_2$ base level is affected by the amount of CO_2 exhaled by the patient. It does however seem to present statistical similarities in the amount it increases, so removing the initial value of $EtCO_2$ from the latter bring out more clearly the information related to the absorber saturation. The modification of the fresh gas flow however does not seem to have an effect on the $EtCO_2$, so it is likely that the $EtCO_2$ is not directly affected by the changes in the test setup variables done during the test run.

Based on the formula 16, the amount of carbon dioxide absorbed by the time the $FiCO_2$ reaches 0.5 percent varies between 75 and 132 liters, as presented in figure 14. The average amount is approximately 106 liters. The lifetime t does not seem to correlate directly to the VCO_2, which presents the amount of CO_2 the absorber is able to absorb. As one can assume, the absorbers with tunnels tend to last less time and absorb less carbon dioxide than the absorbers with no tunnels and more filling.

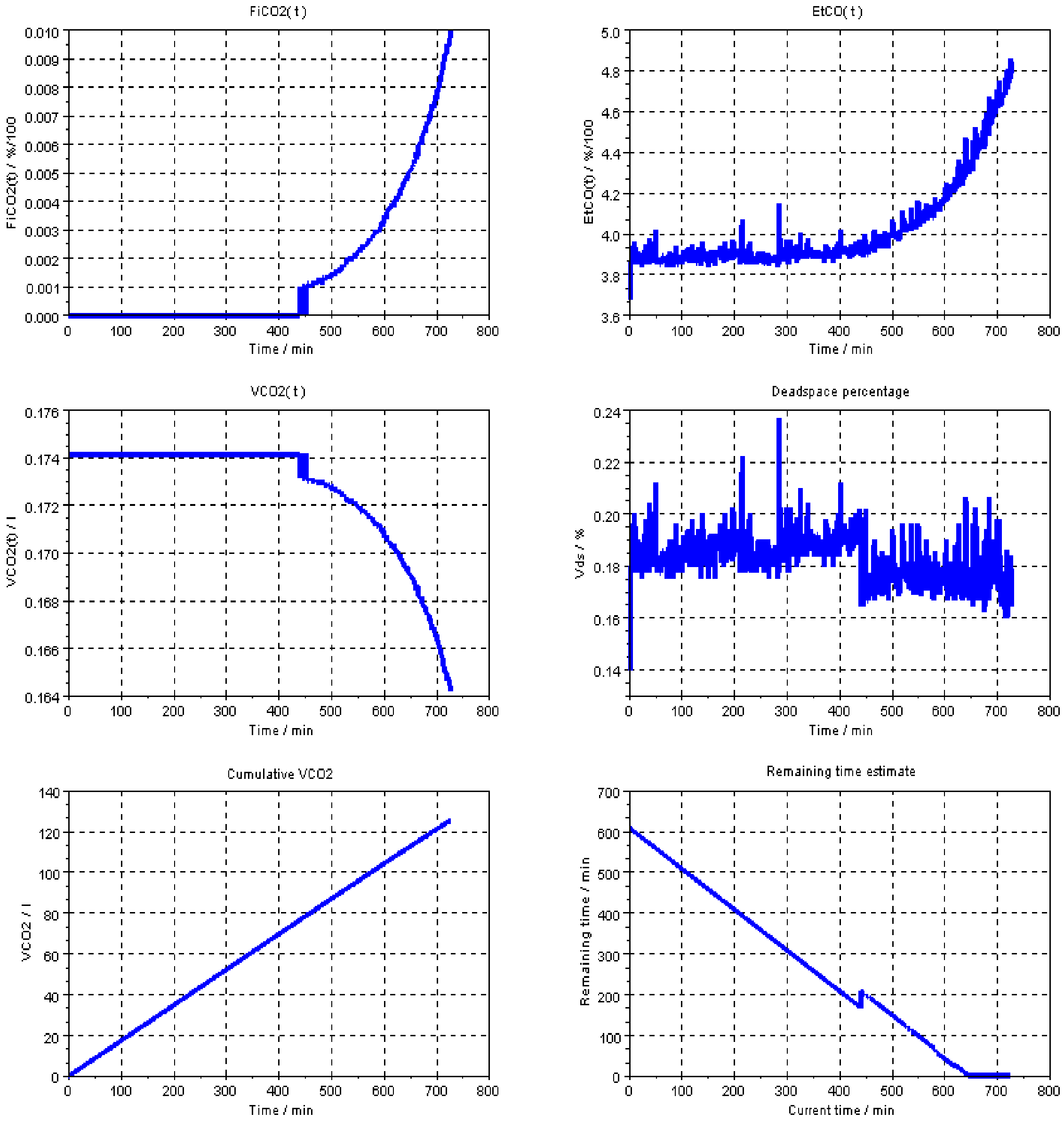


***Figure 15** Example of result analysis data. Test setup 6 - low fresh gas flow*

The test setup number three, where the minute volume is a lot lower than normally showed interesting results. The low minute volume occurs in situations where the patient produces a lot less gas flow to the system by either breathing more slowly, more superficially or both. In such a setup the gas has more time to stay in the absorber and thus could be expected that the carbon dioxide would be absorbed better, i.e. more absorbent could be used to absorb the CO_2, as we evaluate in the formula 15. However as it is apparent from our measurement this seems not to be the case. To further evaluate the subject more measurements with similar test setup values would be needed. With more measurements with different C_{in} values we could find out if the speed of C_{in} actually has an effect on the total amount of CO_2 the absorber can absorb.

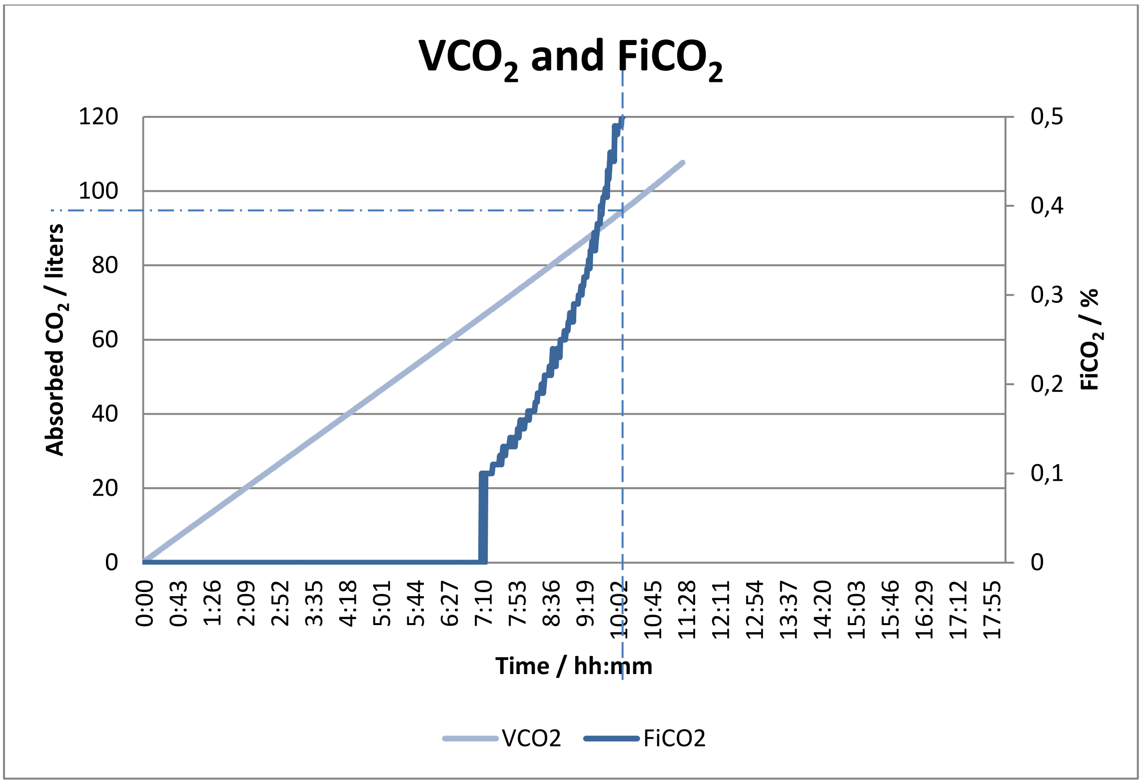


Figure 16 *Defining the absorber capacity with VCO2 and FiCO2*

The general result analysis is done by drawing all the measurements and estimations of each test setup on the same timescale as presented in figure 15. Here the first important facts observable are the correct directions of the curves, as it is observable from the figure of $VCO_2(t)$, where the curve goes down when $FiCO_2$ curve goes up. An important nudge can be seen in Remaining time estimate at the moment of the first measurement of non-zero $FiCO_2$.

The Figure 20 shows how the absorber maximum capacity is defined. As mentioned before, the absorber is considered to be saturated when the $FiCO_2$ level reaches 0.5 percent. At that moment of time the cumulative amount of absorbed CO_2 is defined. In fact the absorber would be able to absorb a lot more carbon dioxide, but the patient would not, as the increased CO_2 levels in a human body are likely to cause complications and therefore bother the anesthesia or even the vital functions of the human body. Therefore the absorber saturation limit is set within levels that are safe for the patient.

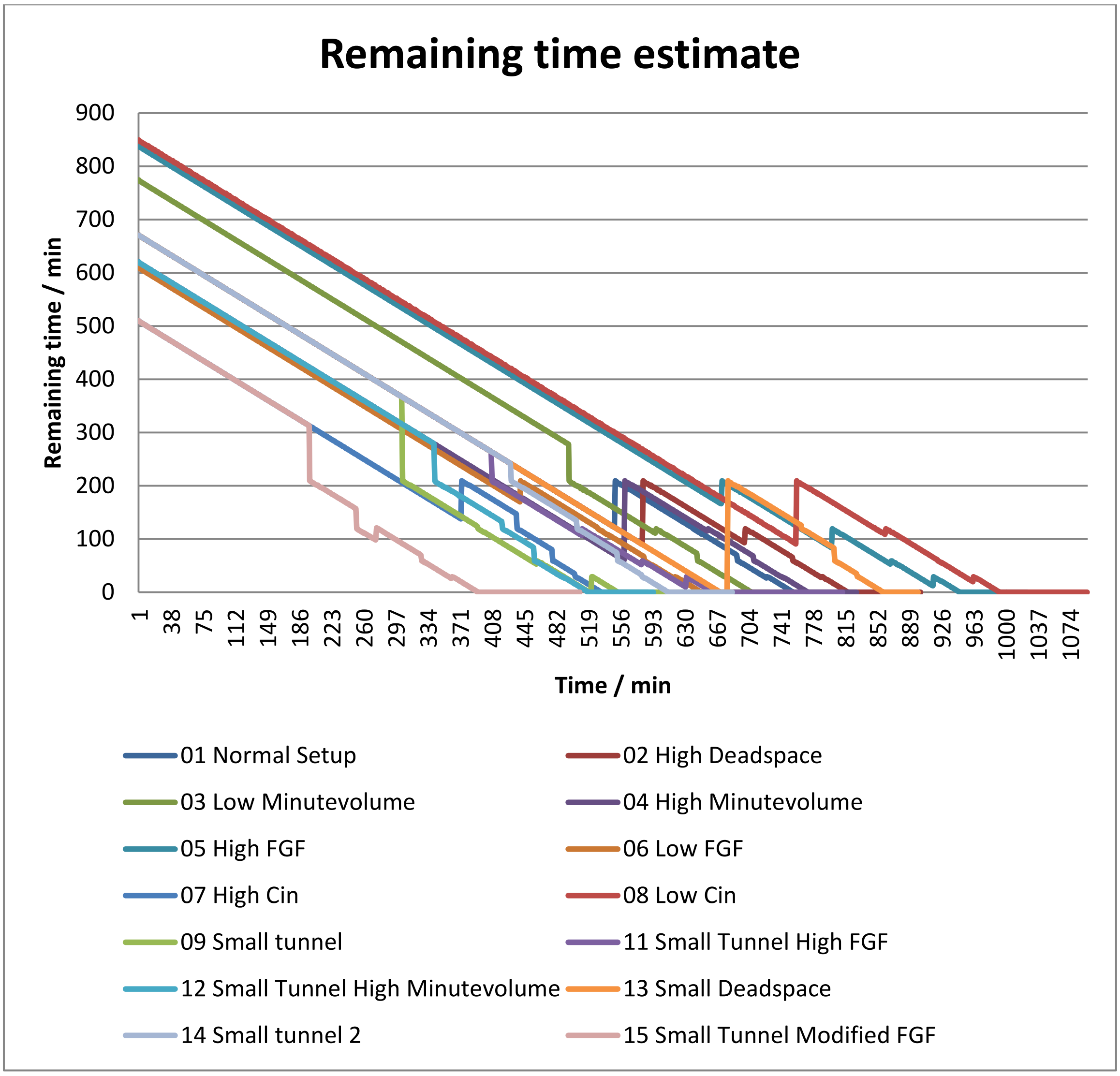


***Figure 17** Remaining time estimate*

The absorber remaining lifetime estimates are based on the formula 16. When a change in $FiCO_2$ is observed the estimation is re-evaluated based on the statistical average of the remaining lifetime of absorbers after the first change. The time value is then used to calculate how much the absorber under examination would be able to absorb carbon dioxide with the current settings, which is then used to continuously evaluate the remaining lifetime based on the current test setup values. The time based absorber capacity is calculated and used as a basis for the remaining time, because using the capacity makes it possible take in to account changes in the test setup parameters, for example the change in fresh gas flow done in test setup 15.

Test setup	FiCO2 times (hh:mm)				
FiCO2 value	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
01 Normal Setup	9:09	10:42	11:30	12:04	12:33
02 High Deadspace	9:41	11:39	12:34	13:04	13:38
03 Low Minutevolume	8:16	9:56	10:44	11:16	11:44
04 High Minutevolume	9:20	10:56	11:49	12:21	12:44
05 High FGF	11:12	13:19	14:27	15:16	16:05
06 Low FGF	7:20	8:49	9:43	10:18	10:45
07 High Cin	6:12	7:16	7:57	8:23	8:44
08 Low Cin	12:38	14:21	15:21	16:02	16:32
09 Small tunnel	5:04	6:31	7:39	8:42	9:25
11 Small Tunnel High FGF	6:47	8:31	9:40	10:31	11:14
12 Small Tunnel High Minutevolume	5:41	6:59	7:36	8:08	8:33
13 Small Deadspace	11:19	12:44	13:22	13:48	14:06
14 Small tunnel 2	7:09	8:25	9:12	9:40	10:07
15 Small Tunnel Modified FGF	3:17	4:11	5:26	6:01	6:33
Average	**8:26**	**10:00**	**10:53**	**11:30**	**12:00**
Average Deviation	**2:01**	**2:13**	**2:11**	**2:10**	**2:09**

Table 4 *FiCO$_2$ times*

After the FiCO$_2$ starts to rise, it raises exponentially. That is to be expected as the more of the absorber contents get saturated, the less there is to absorb CO$_2$, which then cumulates to the output of the absorber. The duration of reaching the first measurable value, 0.1%, varies greatly and therefore seems a poor starting point for the statistics based absorber lifetime estimation. The average deviation, which tells us the average difference between the observed values, varies only little from the original deviation of approximately two hours (shown in table 4).

The previously shown FiCO$_2$ values of different measurements (Figure 12) imply that even though the first changes in FiCO$_2$ spread on a wide range in the timescale, the values tend to rise at the same speed. This in turn implies that the time needed for FiCO$_2$ to rise from 0.1% to 0.5% would be somewhat similar in all the test cases, and the statistics based average remaining lifetime estimate would be more precise at each moment in time after the 0.1% has been reached.

Test setup	**FiCO2 duration (hh:mm)**				
FiCO2 change	**0.0→0.1**	**0.1→0.5**	**0.2→0.5**	**0.3→0.5**	**0.4→0.5**
01 Normal Setup	9:09	3:24	1:51	1:03	0:29
02 High Deadspace	9:41	3:57	1:59	1:04	0:34
03 Low Minutevolume	8:16	3:28	1:48	1:00	0:28
04 High Minutevolume	9:20	3:24	1:48	0:55	0:23
05 High FGF	11:12	4:53	2:46	1:38	0:49
06 Low FGF	7:20	3:25	1:56	1:02	0:27
07 High Cin	6:12	2:32	1:28	0:47	0:21
08 Low Cin	12:38	3:54	2:11	1:11	0:30
09 Small tunnel	5:04	4:21	2:54	1:46	0:43
11 Small Tunnel High FGF	6:47	4:27	2:43	1:34	0:43
12 Small Tunnel High Minutevolume	5:41	2:52	1:34	0:57	0:25
13 Small Deadspace	11:19	2:47	1:22	0:44	0:18
14 Small tunnel 2	7:09	2:58	1:42	0:55	0:27
15 Small Tunnel Modified FGF	3:17	3:16	2:22	1:07	0:32
Average	**8:26**	**3:34**	**2:00**	**1:07**	**0:30**
Average Deviation	**2:01**	**0:30**	**0:22**	**0:13**	**0:06**

Table 5 *FiCO$_2$ durations and deviations*

The remaining capacity is re-evaluated in points where FiCO$_2$ equals 0.2, 0.3 and 0.4 respectively. The re-evaluation is used in this manner to take advantage of the fact that the average deviation from the mean value of the remaining lifetime at each of these points decreases, as seen in table 5. This means that on average the error in each of these points decreases as the remaining lifetime of the absorber grows shorter.

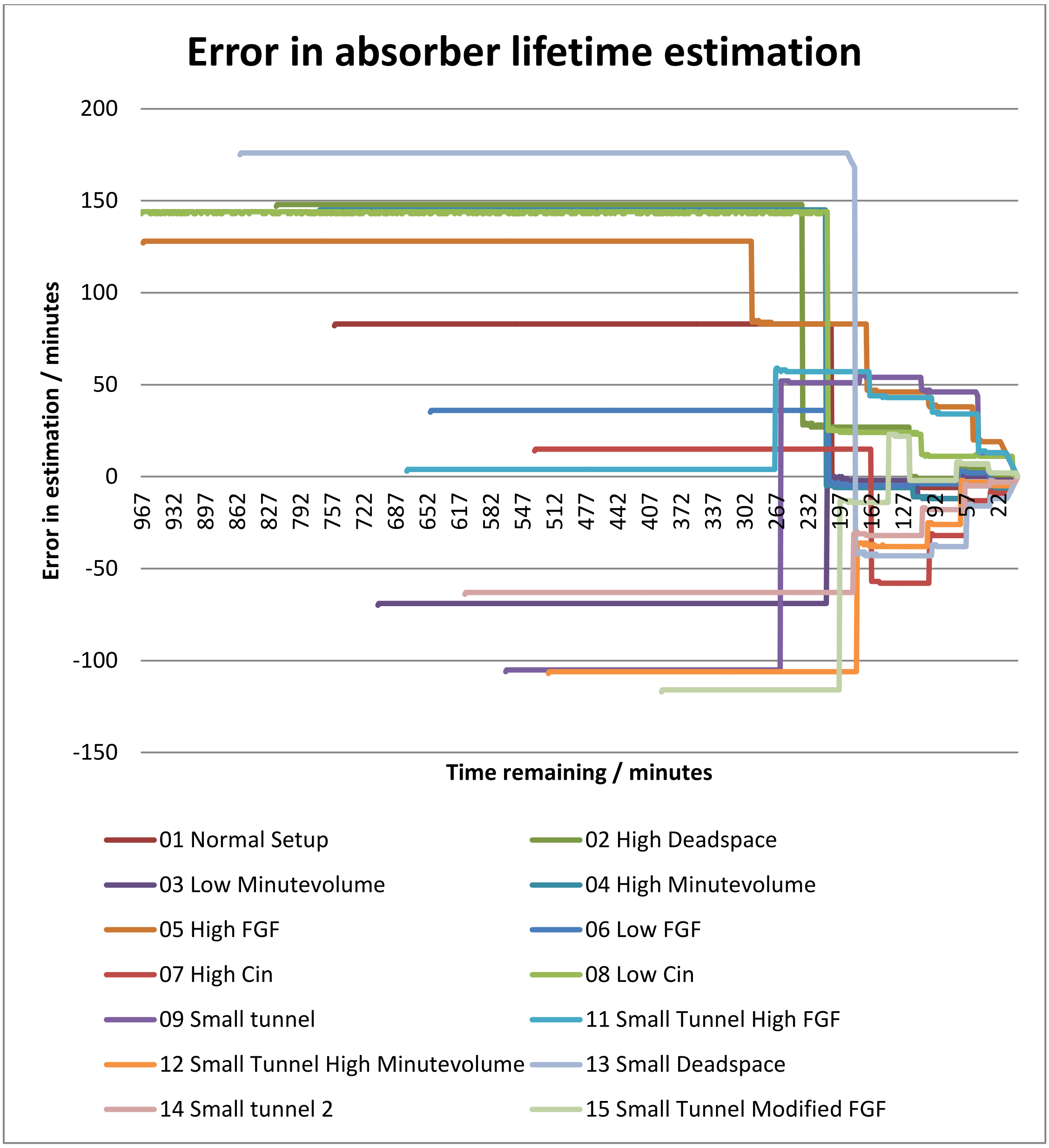


Figure 18 *Errors in absorber lifetime estimates*

Figure 18 presents the errors in the estimations of the remaining absorber lifetimes compared to the actual absorber remaining lifetime. The figure shows that within the context of our measurements the maximum error is 176 minutes, and that in most of the cases the error can be reduced greatly when changes in $FiCO_2$ are measured. It is clear from this figure that when approaching the saturation point of the absorber the estimation gets more and more accurate and thus the re-evaluation can be rendered successful. However it is not apparent why the error increases in the cases of low carbon dioxide flow (test setup no. 6) and small tunnel with modified fresh gas flow (test setup no. 15). As in the previous case where low minute volume produced a significantly lowered absorber capacity (test setup no. 3), unexpected results like these should be analyzed by repeating the tests multiple times with similar test setups.

5.9. Suggestions and further development

The care station framework is made out of either condense polymers or metal, of which both are likely to have undesired effects on the signal propagation, for the RF antenna should be attached to the side of the station. In theory this could be avoided by using either foam space or by using ferrite core sheets as isolators between the antenna and the metal surface, however no sustainable evidence was found from the material undergone in this thesis. The assumption is based on the hypothesis that the absorption of signal energy from the direction of reflection cancels out the interference, leaving the desired signal less corrupted.

The possible problem of reading the wrong tag, i.e. not recognizing which absorber is attached to the anesthesia must be addressed. The localization methods mentioned in the previous chapter could be implemented in the later versions of the product, but the initial solution must be simpler. The problem could be addressed by acknowledging the attached absorber through a galvanic connection that would change the state of the RFID to be “connected”. The disadvantage is that this could require expensive modifications to the anesthesia machine, to the absorbers or even to the tags. In the future a more cost-effective solution could be implemented, for example a system where the anesthesia machine would have a fixed location tag close to the location of attached absorber. When scanning for absorbers, the absorber with the signal power and phase closest to the respective values of the fixed location tag could be identified to be attached to the anesthesia machine, as described in chapter 4.2.

One of the highly desirable outcomes of the RFID based absorber state monitoring is that visual connection to the absorber would no longer be needed. The digital identification of the absorber state renders the usage based color change trivial, for much more accurate information is available through the absorber log. This might change the whole concept of the absorber as we know it; for example the containers would not need to be transparent, and as the contents would not need to be maintained stationary in order to present the color change, the contents of the absorber could be mixed during usage to achieve longer usability. The absorber could be fitted further away from its current position and thus valuable space could be freed for other more important functionalities. Even the chemical reaction that produces the absorbent color would become unimportant, which would free us to use different chemicals for the absorption process. Previously only soda lime has been used for CO_2 absorption, but as the absorbent would not need to support the dying process, alternative chemicals could be considered. Possible alternatives include lithium hydroxide that creates a lot less water during the removal of carbon dioxide, and even metal-oxides, of which some are regenerative, so that the already saturated absorbent would in time become re-usable.

The graphical presentation of the absorber state is everything but unimportant. The goal of the UI presentation is to give valuable information to the user quickly and easily, but also to gain the users’ trust by not giving false values or by changing the estimate of the remaining lifetime in an unpredicted manner. The measurements and estimations presented in this thesis imply that it is not yet wise to give straightforward precise values for the remaining lifetime, for the saturation of the absorber depends on environmental variables such as the level of filling of the absorber, the tunneling or the absorbent moisture, which all cannot be observed at the same time without a large effort. There are many ways to present the values. One promising approach could be to present the absorber state in zones, telling the user for example that the absorber is likely to have three fourth of its usability left, and that it can be safely used for at least six hours more. If critical zones are achieved during an operation the doctor in charge could be advised to increase the fresh gas flow to the system, which directs some of the carbon dioxide to the gas scavenging and therefore gives more lifetime for the absorber. As the estimation for the remaining absorber lifetime becomes more exact the longer the absorber is used, also the scale could become more and more precise.

The estimations of the remaining absorber lifetimes are based on test setups created under professional anesthesia machine users and developers. However at the time of actually implementing the tests no professional staff was available. The test setups were easily later confirmed to have been successfully built by superficial evaluation of the test values. However it was not possible to confirm whether or not the modifications in the absorber fillings were realistic. It is likely that too much filling was removed from the absorbers and therefore the statistical absorber capacities are too low, which means that until the first changes in the $FiCO_2$ values are observed the remaining absorber lifetime is underestimated. More measurements should be implemented and the levels of absorber fillings should be recorded and evaluated.

The five different statistical values used to estimate the remaining lifetime based on the flow speeds of different gases give a good approximation in the precision levels of how many fifths of the absorber have been used. It is likely possible to create more precise estimations for the last four estimations that instead of using statistical averages would follow a second degree equation could be used. The monitor which is used to attain the $FiCO_2$ values caps the changes between 0.0% and 0.1% to hide the static caused by interferences to the system. However even small changes could be useful when defining the absorber state. It is possible to inspect the first small changes in $FiCO_2$, but this must be done through the actual carbon dioxide readings acquirable through the monitor, from which the $FiCO_2$ must be calculated. This was not done in this thesis due to the late discovery of this information; however it is something worth looking into in the future development of the system.

It is quite easy to rethink a whole operating room just by implementing different RFID-enhanced functionalities presented in this paper. The room could be prepared quickly as all the locations and status of all the items would be known. Misplacing an item could cause a warning sound and supplying i.e. an intravenous system with a medicine that the patient is allergic to could trigger a bigger alarm. The patient could have all the necessary sensors attached when he would be brought to the operating room, and the equipment in the room would start to monitor the patients’ status based on the sensors as soon as he entered. At the same time all the relevant information about the patient could automatically be shown on a computer screen. The anesthesia machine and other devices could be configured to present the information most valuable to the operation in question. Operation logs could have information of what staff was present at each moment of time. After the operation all reusable material could be placed into a sorting facility that could identify all the items based on their tags and choose the proper actions to be taken accordingly.

6. CONCLUSIONS

The three main goals the identification technology used should fulfill are affordability, security and usability. Price of the hardware should be relatively low, especially in the tags. Security is needed to rule out piracy of the products and to protect the privacy of the data associated with each product. Usability covers the ease of use and both the coverage of the solutions offered by the technology and the possibility of using the same technology to cover more similar cases.

Security in RFIDs is achievable through high computational power, which in turn needs a considerable amount of energy to exist and operate. With passive tags there seems to be always a shortage of sufficient energy. Tags that are close to the reader, such as LF and HF tags are able to absorb larger amounts energy, as are UHF tags when they operate in near field mode. Fortunately the algorithms used for RFID-security are constantly under development

In general bar code is a perfectly good automatic identification technology, which after more than twenty years of evolution can be considered mature and well established. A commonly encountered attitude is that bar code should always be used in preference to RFID if it does the job required, as it is invariably a cheaper solution. Printing an RFID IC only seems cheap if we assume that the IC complexity is comparable to the complexity of printing a bar code. RFID is a relatively new and quite different automatic identification technology that provides much greater functionality than bar code but also costs a great deal more. However in the case of a smart absorber bar code does not offer the functionalities needed for the planned product. Bar code offers no security and it needs visual connection from the reader to the bar code. As the bar code cannot be modified the usability suffers because no new information can be added directly to the code. Outdated as it is, bar code as a technology offers little or no new possibilities in the development of new intelligent medical applications.

Low frequency tags are the most expensive and they require long reading times and offer only short communication distances. Due to the penetrating properties of the frequency used and the quick dampening of the signal power the signals rarely suffer from propagation complications caused by the environment. The cost, distance or speed requirements are not fulfilled in the case of smart absorber, however the technology might offer some promise in the more general field of making the medical applications more intelligent.

High and ultra-high frequency RFID technologies are very similar in the sense of tag and reader costs, short distance signal propagation models and data rates. They are cheap, relatively secure and quickly readable from a distance; HF tags from up to one and a half meters, UHF from even tens of meters. The tags themselves can be made out of self-adhesive paper containing the antenna and the microprocessor. The relatively short operating distance of HF-tags will not cause an issue in the smart absorber development, as the item is assumed to be within rather close distance from the reader and always with the same orientation.

UHF RFID technology is gaining more and more attention from developers and investors. HF RFID has been used for more than a dozen years now, and it has matured in the sense of providing a noticeably long history of reliability and efficiency. The reading distance of HF RFIDs is limited due to the inductive powering of the tags, which constantly forces the investors to turn again and again to the direction of UHF technologies. Even if the HF and UHF technologies provide equal solutions to the case in question, UHF RFID has the advantage of being the latest joiner. As a cutting edge technology could be used in a project that has its release date in further distance, UHF RFID technologies seem to provide more promise in the case of a smart absorber system, and it seems definitely have more to offer in the field of more complicated intelligent medical applications.

In the case study the absorber tests covered simplified basic use cases, but situations further resembling real-life operations where more variables change during the absorber lifetime and multiple values change at same time have not yet been tested. Tempering with the absorber contents affected many of the tests, which was somewhat uncalled for, as the absorber contents cannot be taken in to account in the algorithm design. The created absorber algorithm is rather simple and the multiple re-evaluations of the absorber lifetime imply that in the future more complex algorithm should be calculated. However even with the current version of the algorithm valuable information can be given to the user, and the algorithm is at least equally informative as the saturation-related color change of the absorbent.

In the future a prototype of the smart absorber RFID-system should be constructed to the anesthesia machine and the functionality of UHF-RFID should be tested. The algorithm should be re-evaluated and a second and third degree functions ought to be considered as a replacement for the current linear equation. If the UHF-technology proves to be reliable, a study about the absorber relocation should be conducted. Furthermore if the absorber can be monitored from a distance, a valuable and a lot more complex subject to investigate could be considered, such as the complete implementation of a wireless sensor operating room, of which the smart absorber would implement only a minor part.

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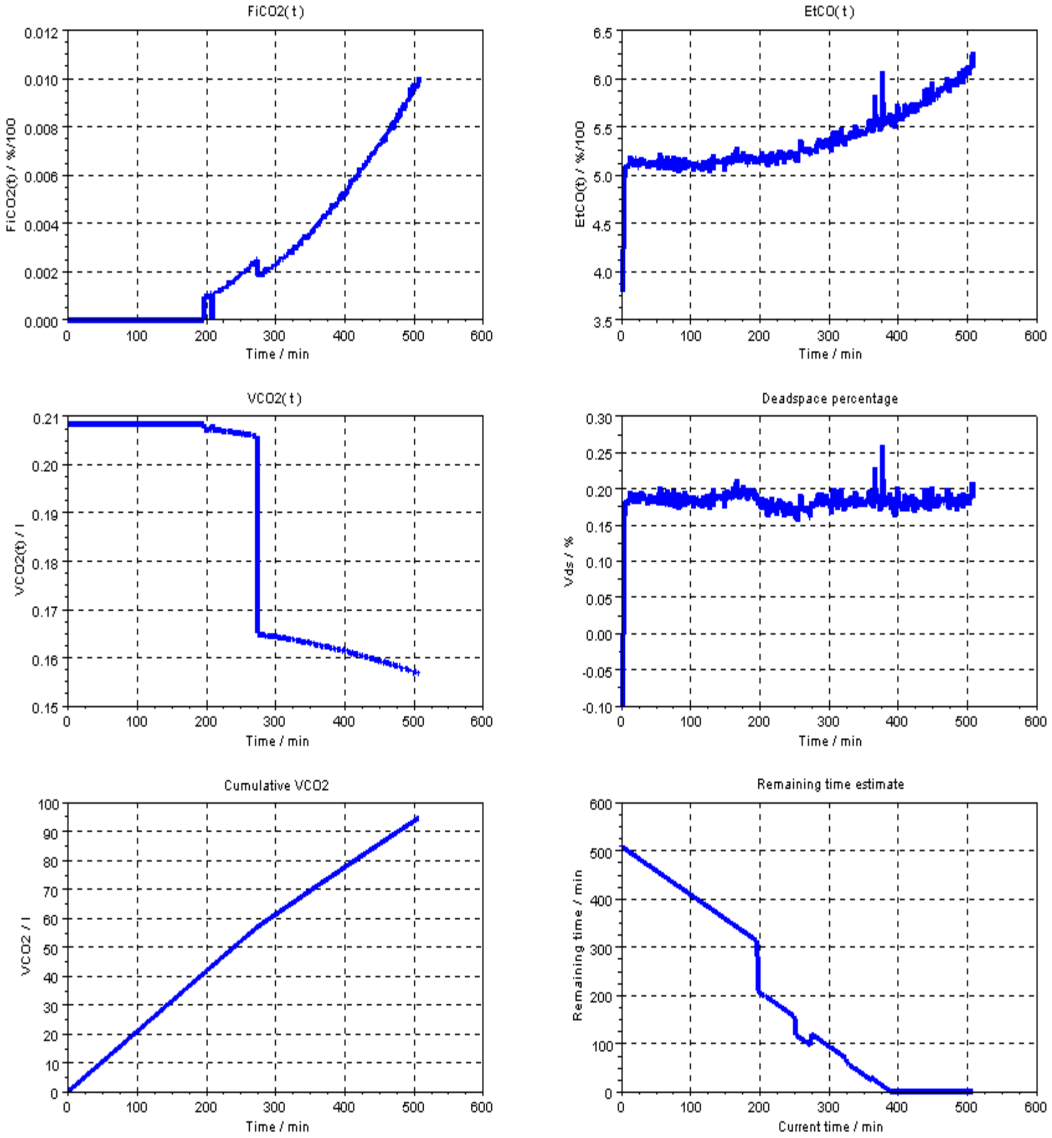
APPENDIX A


FiCO2(t)

EtCO(t)

VCO2(t)

Deadspace percentage

Cumulative VCO2

Remaining time estimate

Figure 19 *The effect of modifying FGF during the test (Test setup no. 15)*

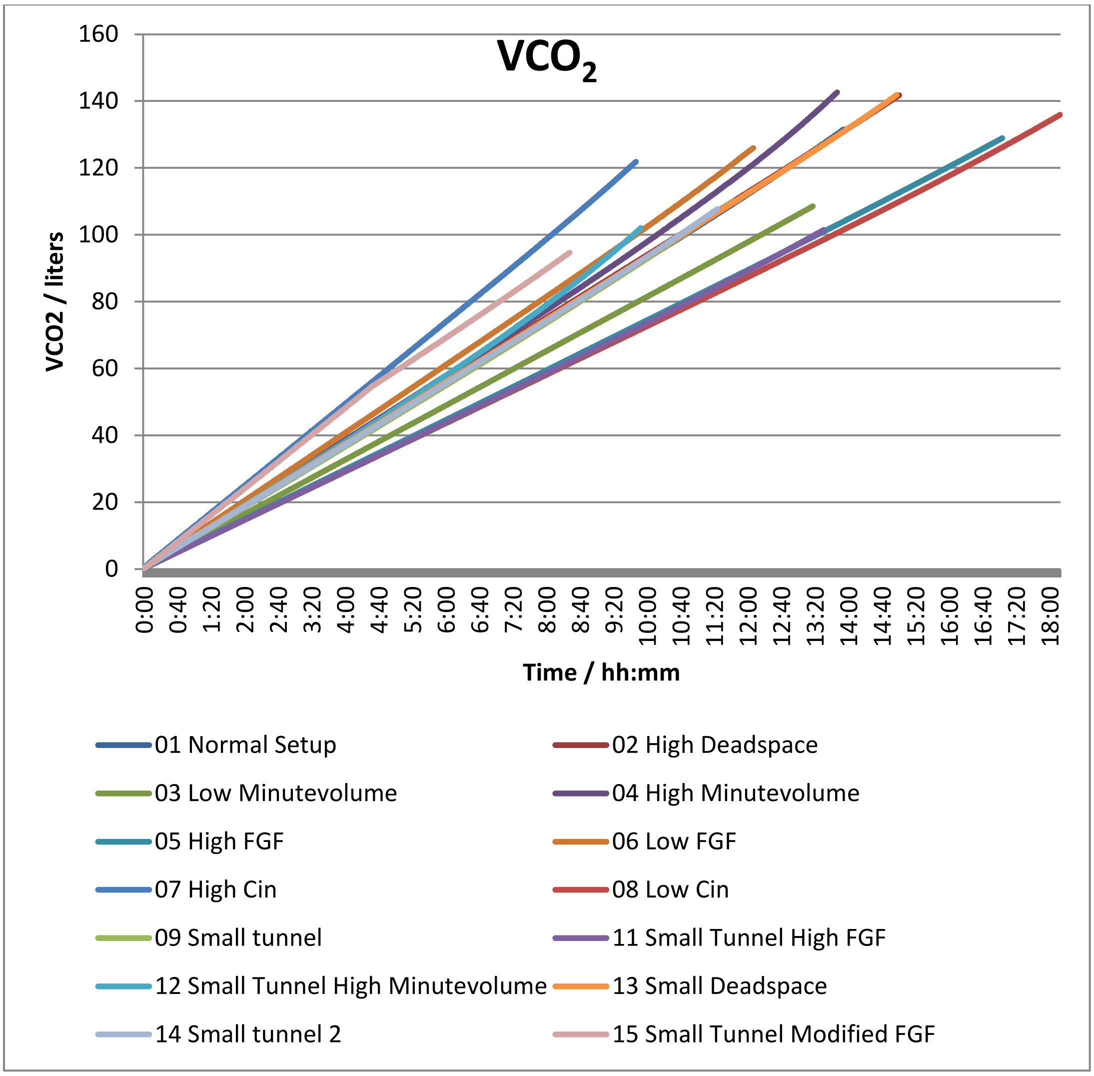


Figure 20 *VCO$_2$ estimations*