Possibilities for UHF RFID labels as an element of a Densor

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***Abstract*—Interest lies in the application for a dental sensor, shortly *densor*, which retrieves information from the oral environment that can be used to draw several conclusions about someones health. This paper investigates whether Ultra High Frequency (UHF) RFID can be used as element of such a densor as the solution for the communication channel. To this extent, we review the basics of RFID and known RFID applications which are in use today. Deployment of UHF RFID brings some extra challenges, especially when we want to look into the special requirements for the densor application, such as size and proper functionality while the tag is surrounded by human tissue. To get a better insight in the possibility of deploying current RFID tags, not only theory is reviewed but also some experiments are done using a MINI ME reader. Using all observations, recommendations are done in which way UHF RIFD needs to be improved to get a reliable communication channel between a sensor residing inside the mouth and a (mobile) RFID reader.**

I. Introduction

The Internet of Things (IoT) is an emerging paradigm which becomes increasingly popular. Researchers and companies are looking for new ways to work with identifiable objects and their virtual representations in an Internet-like structure. Many popular IoT research topics involve us human beings, where we want to retrieve as many information about our bodies and health as possibly. Not only has it entertainment value, health care could also benefit a lot from this.

In line with this interest lies the deployment of a system which retrieves information from inside the mouth. Studies show that the environment of the oral cavity can give information about the overall health of a person [1]. Two proposed solutions to retrieve this information are the usage of special *mouthguards* or the fabrication and use of a dental sensor, shortly *densor*.

To research possible *densor* implementation, this research can be split in two distinct parts. Firstly, the sensor must be able to collect the correct information from the oral environment and convert this to (usable) digital data. This is mostly an micro-electronics problem. Secondly, virtually all IoT applications require a data connection between the physical and digital worlds. Thus also for the densor, we must be able to achieve a reliable communication channel such that the sensor can send its data to the device which relies outside of the mouth.

For the implementation of this data connection, Radio Frequency Identification (RFID) is very popular. RFID is used in applications for amongst other Item Management, Animal Identification and Smart Cards [2], [3]. In an Item Management application for example, items such as pallets are equipped with a identification tag - a RFID tag - which can be read by a reader using radiowaves. This application can be compared with a Barcode System. But, RFID tags are much more powerful than barcode labels because a typical RFID tag can hold 2KB of data, far more than a typical barcode, which represents just 10-12 digits.

This report investigates whether existing RFID technologies can be used for the implementation of the communication channel in a densor application. RFID can be deployed on different frequencies. Reviewing existing RFID technologies, observation is that Ultra High Frequency where systems operate mostly at 860-930 MHz, is an interesting field to investigate further. Namely, currently a global alliance called RAIN RFID [4] is promoting the universal adoption of Ultra High Frequency (UHF) RFID technology into IoT applications. Also other studies state that the biggest future in the usage RFID lies in using UHF RFID, for example because the production costs of tags are very low. Investigation is needed, because UHF RFID systems come with some difficulties that do not arise in systems which work on lower frequencies. Besides this, we also need to consider what application related challenges are.

To be able to give proper recommendations for usage of UHF RFID in a dental sensor application, this report is setup as follows. Firstly, we review the basics for (UHF) RFID and discuss some known RFID applications in Section II and Section III. In these sections, we also treat other used frequency bands than UHF. Secondly, in Section IV we look into the desirable properties of the densor application and challenges which come with them, such that we can define the research area. Here, we also mention international standards which the application should meet. Equiped with good knowledge of RFID systems and its challenges, we then look into the performance of UHF RFID at a theoretical level in Section V. Besides this, we present some experiments with RFID labels in Section VI. Using these sections, this report ends with a conclusion, some discussion and recommendations for one who is interested to use UHF RFID in a densor application.

II. Differentiation Features of RFID Systems

An archetypal RFID system consists of an *interrogator*, more often known as a reader, a *transponder* or tag and *antennas* to mediate between voltages on wires and waves in air [2]. The reader antenna or antennas may be integrated with the reader or physically separated and connected with a cable; the tag antenna is generally physically integrated with the tag. Besides this integrated antenna, each tag contains a Integrated Circuit (IC). A tag is called *passive* when they have no independent source of electrical power to drive this IC and have no radio transmitter of their own. A tag is called *semipassive* when there is a battery incorporated in the tag IC. *Passive* tags depend on rectification of the received power from the reader to support operation of their circuitry, and modify their interaction with the transmitted power from the reader in order to send information back to the reader.

How the communication between the reader and tag works [2] depends on several differentiation features of RFID systems such as the type of tag (active or (semi)passive), but also the operating frequency and used communication protocol (not discussed in this report). The four most common used frequencies for RFID are operating in:

- the Low Frequency (LF) band, 125/134 kHz;
- the High Frequency (HF) band, 13.56 MHz;
- the UHF band, 860-930 MHz and 2.4 GHz. Waves at 2.4 GHz are also called microwaves.

Given the operating frequency, we can see what the wavelength of an electromagnetic wave is:

$$\lambda = \frac{c}{f} \tag{1}$$

Using Eq. (1) we find that the wavelength at 13.56 MHz is around 22 meters and the wavelength at 900 MHz 30 cm.

RFID systems can be categorized by whether the wavelength is comparable in size to the antenna or vastly larger than the antenna [2]. Systems where the wavelength is much larger than the antenna are typically inductively coupled and systems where the wavelength is comparable in size to the wavelength usually use radiative coupling. We will elaborate a little on radiative coupling since this is used at UHF. For more information about inductively coupled systems, one should advice [2], [5].

Radiative coupling is illustrated in Fig. 1. As can be seen, we have a so-called *backscatter* communication channel, where the transmitted wave is modulated and send back (reflected) towards the reader. The performance of backscatter channels can be expressed using *link budget*, which we will elaborate on in Section V. Until around 2007, the radiative coupling was implemented using active tags [5]. Recent advances in technology have made it feasible to use both active and passive in the higher frequency bands. This has been the trend in the industry. The used antennas of these RFID tags have a dipole design.

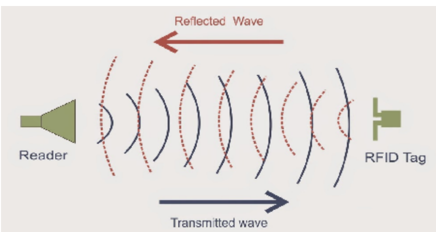


Figure 1: Illustration of Radiative Coupling [2]

A. Frequency Considerations

The operating frequency influences what kind of coupling is used, what kind of antenna is needed in the tag, what size the tag needs to be, how the antennas are produced and how many the tag costs. Results of these considerations will be clear from Section III, but an elaboration on this topic is outside of the scope of this report. An interested reader should advice [2], [3], [5].

We do elaborate on specific frequency considerations, because this will also be of great value when looking at the performance of the UHF RFID tags. The most important differences due to operating frequency are stated below [2], [3], [5]. Note that when we speak of *lower* frequency, we mean operation at 125/134 kHz and 13.56 MHz (LF and HF).

- Antenna gain is directly proportional to antenna size relative to wavelength. This means that tags working at a lower frequency need a larger antenna to achieve a comparable antenna gain. Because antenna gain plays a major role in read range, read ranges at lower frequency are smaller.
- As a consequence of the larger (directive) antenna gain at UHF, correct communication with tags operating in this frequency band is more orientation dependent.
- At lower frequencies there is less pathloss. Although this benefits operation at these frequencies, also more interference from other systems can occur.
- Operation at UHF is very sensitive to the presence of conductive materials such as metals, metal films and aqueous solutions. When dealing with microwaves (2.4 GHz), water absorbs all energy. These problems occur at lower frequency at a lower extent. Radiowaves at 125/134 kHz can successfully penetrate mud, blood and water.
- High frequency bands pose health concerns to humans. As a consequence, international standards put several (power) limits systems operating in the UHF and microwave bands. These limits will be discussed in Section IV-B. This will have a directly influence on the performance of those system. Reports show that, given these international standards, the adverse affect on human health is negligible [6].
- At higher frequencies, a higher data rate can be achieved. For example, UHF tags can supply tens of hundreds of kbps.

III. RFID Applications

Having discussed the major properties of RFID, we shortly review different kind of applications for the three different frequency bands (omitting application operating at 2.4 GHz). As we will see, at the UHF band, different kind of tags are used to suit best for different applications. We will elaborate more on UHF applications than on LF and HF applications, because this information is of most value in this research.

As a start, Fig. 2 show different RFID tags for the different frequencies. Interesting is to note that, although the RFID tag for LF is the smallest one, it has the largest antenna (which should indeed be the case following from Section II-A).

A. LF: Animal Identification

One of the most popular and oldest applications of RFID is in the field of livestock management and pet (or lab animal) identification. To this extent, very small coil tags that are embedded in biocompatible glass are used, making them harmless to animals when they are implanted [7], [8].

Because the tags are implanted, the waves must penetrate animal tissue. This makes operation at LF suitable, because from Section II-A it follows that tags and readers operating on LF are quite unaffected by the presence of water or tissue. Downside of this system is the small read range (< 1 meter), but for this application this is acceptable and often desirable.

B. HF: Smart Cards

Fig. 2 shows as second tag the inside of a smart card. A well-known example of Smart Cards is the Dutch *OV-Chipkaart* (Public Transport Card), which is used as the payment system for public transport [9]. Communication is done with fixed readers (which are located at the entrance of a train station or inside a bus) where a traveler checks in or out. The read range of this system is around 10 cm, which is desirable for this application.

Note that most of the RFID chip smart cards are replaced with systems which work with *Near Field Communication* (NFC), an extension of RFID which also uses the 13.56 MHz operating frequency.

C. UHF: Tracking Systems and Item Management

Currently, almost all applications use RFID tags which operate on UHF. Most of these systems are tracking systems or item management systems. The best-known UHF RFID tags are printable labels, of which one is shown in Fig. 2. The major part of this label is the dipole antenna which can be clearly seen. Every UHF tag has such a dipole antenna, but how this antenna is embedded in the complete tag differs. UHF tags come in different types and shapes, from inflexible hard bars to printable (flexible) RFID labels [7]. This is to tackle the challenges which come with operation at UHF.

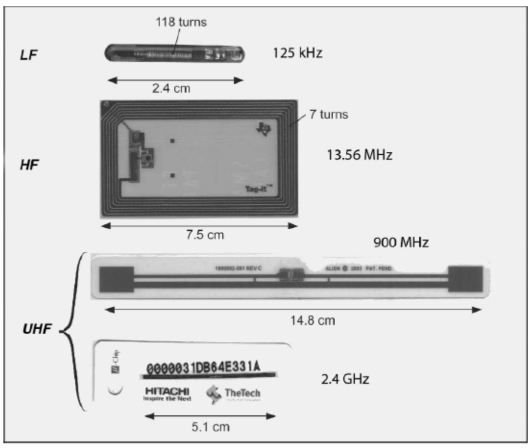


Figure 2: RFID tags operating on different frequencies [2]

For example, special tags are needed when the trackable items contain (or are made of) metal, because from Section II-A it followed that UHF is sensitive to the presence of metal. To solve this problem, RFID tags that use the fact that radiowaves are reflected by metal are produced, which operate best when glued to metal.

Other tracking systems need to track washable objects such as T-shirts. There, so-called laundry tags can be used, which are are flexible tags that are relatively small [7]. Possible dimensions are $68 \times 9 \times 1.2$ mm and $56 \times 12 \times 2$ mm. Their base material is silicon, which ensures that the operating temperature is between -40°C and 85°C and that the tag survives over 100 washing cycles.

At the other hand, tags can be embedded in completely different objects. For systems that track patients in a hospital, RFID tags are embedded in wristbands or key rings.

D. Health Care

In the health care branch, different UHF RFID applications exist which use RFID tags which are presented above [10]. Patients can be tracked in a hospital using wristbands, clothing of medical staff can be identified using laundry tags and the management of all medicines rely on the usage of RFID labels.

Besides this, also research has been done towards a human implantable RFID tag, the VeriChip [11], [12]. This chip is about the size of uncooked grain of rice and operates at 134 kHz (LF) and is thus comparable with RFID tags used for Animal Identification. Also here, all components of the tag are sealed in a capsule of medical-grade glass, coated in Biobond in an effort to prevent the device from migrating within the body.

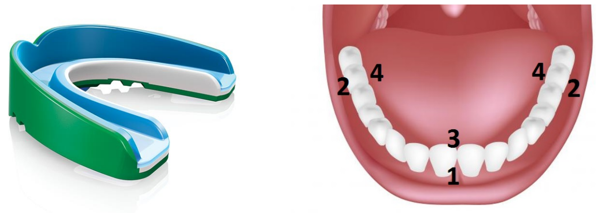
Possible health care applications of the VeriChip are emergency access to patient-supplied health information and in-hospital patient identification; the VeriChip could potentially replace wristbands. However, although its potentials, the VeriChip is not ruled as a regulated device. This is because of health problems that (can) arise when such a microchip is implanted [12].

IV. Application Considerations

A. Densor requirements

The main purpose of a dental sensor is to collect information from the oral environment and send this information to a (mobile) device which can use this information to draw some important conclusions about someone's health. Here, we focus on some unique requirements which comes with this particular system.

The first important property is the dimension (size) and material of the RFID tag which will be used in the system, as the oral cavity does not provide unlimited space. For most diagnoses information collected over a longer time interval is



(a) Mouthguard [from https://www.shockdoctor.com/] (b) Densor locations [adapted from https://www.wisegeek.com/]

Figure 3: Possible designs and locations of a densor

needed, thus it is desirable that the densor can reside inside the oral cavity over a longer period. Ultimately, the densor can be placed along someones teeth such that this person does not actively perceive the presence of this tag. In this case, the tag should be remarkably small. Another solution is the usage of mouthguards (Fig. 3a), where the RFID tag is embedded in this mouthguards. Using this solution, the RFID tag could be larger. Also, when the RFID tag is embedded in a mouthguard, it can better be protected to the moist environment of the mouth.

A second important property is the performance of the system. The RFID tag should have a proper read range such that the tag can be seen by a (mobile) reader outside of the mouth. As we have seen in Section II, different properties influence performance of RFID systems. Here, the extra requirement is that the radiowaves should be able to successfully penetrate human tissue and maybe also teeth. The performance challenges depend on the location of the tag inside the mouth. As can be seen in Fig. 3b ,when using sensor residing alongside teeth, four different locations are possible. At location 1 and 2, radiowaves only need to penetrate through the tissue of the skin, while at location 3 and 4, the radiowaves sometimes also need to penetrate through teeth. *For the reminder of this report, we will assume we search for a solution where the densor is placed at location 1 or 2, or that the tag is embedded in a mouthguard along side the outer edge, such that we only have to consider penetration through human tissue.*

Last, the densor should not have any effect on human health. This relates both to the used frequency in the system as to the material the densor is made of.

B. International Standards

As mentioned, the usage of UHF RFID is becoming increasingly popular in the area of Internet of Things. For the usage of UHF RFID, several international organizations exist which control the way the 860-930 MHz frequencies can be used. These organizations not only try to divide the spectrum equally - namely, GSM also uses this UHF band - but they also pose some restrictions to ensure human health, because radiowaves do pose health concerns to humans.

Different rules for the usage of UHF exist for different continents. For the United States, the FCC (Federal Communications Commission) state the limitations for UHF application, which operate around 915 MHz (902-928 MHz). The allocation of frequency ranges and limitations in Europe is done by CEPT (Conference Europene des Postes et Telecommunications) [3]. In Europe, the 865-686 MHz frequency range is reserved for RFID systems. Besides the frequency allocations, rules are set that define limitations on the transmitting power. For RFID applications in Europe, these requirements are stated in Table I. The *listen-before-talk* protocol is always followed when using passive tags, because in this case, tags can only talk using the energy from the reader.

As will be clear from later sections, the limitations on the transmit power of the reader influences the read range (and thus performance) of a UHF RFID system. This is thus something to keep in mind when choosing applicable tags for the densor system.

Several UHF Standards have been created to give engineers the correct guidelines to follow the international limitations. The two major standards for 860-930 MHz, which are also called *air interface protocols*, are *ISO 18000-6* and EPC Global's *UHF Class 1 Gen-1/2*. Gen 2 is moving towards ISO 18000-6C. In tag specifications, it is always given which protocol the tags operate with [7].

V. Performance Considerations using UHF RFID

So far we have reviewed the basics of RFID, elaborated on some well-known RFID applications and looked into the requirements and challenges which apply when deploying RFID in a mouthguard or densor. Now, we will elaborate on the theoretical performance of UHF RFID systems and factors which needs to be investigated when one wants to see what the possibilities in a densor are.

When investigating the performance of UHF RFID in a densor situation, we assume we use printable tags following the description in Section III-C. Ultimately, these tags could be glued against the teeth or embedded in a mouthguard. In this section, we now only focus on the performance of the communication channel. Considerations with respect the to size and material of the tags are discussed in Section VII.

The interrogation (or read) range has been considered as the most important feature representing the performance of a UHF RFID system [13]. We elaborate on this in the link budget analysis. *Link budget* is known as the amount of power that

Frequency Range	Power Limitations (Reader)	Extra Limitations
865 - 868 MHz	100 mW EIRP	Listen-before-Talk Protocol, 200 kHz Channel Spacing
865.6 - 867.6 MHz	2W EIRP	
865.6 - 868 MHz	500 mW EIRP	
2446 - 2454 MHz	500 mW EIRP	100% Duty Cycle
2446 - 2454 MHz	4W EIRP	Only indoors, having $< 15\%$ Duty Cycle

Table I: CEPT regulations for UHF RFID applications around 868 MHz and 2.45 GHz one needs to deliver to a receiver across a wireless link such that the transmitted data is successfully received.

For a backscatter communication channel, this link budget can be expressed mathematically. As said before, passive RFID tags do not use a radio transmitter; they use modulation of the reflected power from the tag antenna. This way, a reflected (*backscattered*) signal will be send back to the reader which can detect this signal. From Fig. 1 it can be seen tag both the reader and tag 'talk'. Therefor, a RFID system has two separate link budgets, one associated with the reader-to-tag communications (the *forward* link) and one with the tag reply to the reader (the *reverse* link). [2].

The link budget analysis can be mathematically be expressed with use of *Friss equation*:

$$P_{RX}\ (\mathrm{W})\ = P_{TX}G_{TX}G_{RX}\left(\frac{\lambda}{4\pi d}\right)^2 \tag{2}$$

Here, P is the resp. transmit and received power, G is the gain of the reader and tag antenna and we state the *pathloss* for free space. Using Eq. (2) we can state equations for the tag's transmit power (only taking the forward link into account) and for the received power back at the reader. For the densor application, we need to keep in mind that the tag will reside inside a mouth, such that the pathloss description will be more complex. We come to the following equations [2]:

$$P_{TX,\mathrm{tag}} = P_{TX,\mathrm{rdr}}G_{\mathrm{rdr}}G_{\mathrm{tag}}T_b\left(\frac{\lambda}{4\pi d}\right)^2 \tag{3}$$

$$P_{RX,\mathrm{rdr}} = P_{TX,\mathrm{rdr}}G^2_{\mathrm{rdr}}G^2_{\mathrm{tag}}T_b\left(\frac{\lambda}{4\pi d}\right)^4 \tag{4}$$

Here, $T_b(< 1)$ is the backscatter transmission loss at the tag. This can also been seen as power loss due to backscatter modulation or a way to express the modulation efficiency [13], [14].

Eq. (4) is the equation that gives the received power back at the receiver after a round-trip via the tag. As soon as this received power is above the reading threshold of the reader, we have a successful connection between reader and tag. Besides this, the result of Eq. (3) needs to be higher than the power needed for the tag's IC. Tag IC power requirements of tens of hundred of microwatts are actually monstrously large compared to the tiny signal powers that can be detected by a good-quality radio receiver [13], [15]. Such a receiver is generally available in a stationary reader, but not directly when using a mobile reader. For the densor application, ultimately one wants to use a mobile reader (phone).

One should note that Eq. (4) is a simplified equation, which does not elaborate on extra influences on the link budget. These extra influences [15], [16], [17] are possible *polarization mismatch*, an *on-object gain penalty*, *path blockage loss* and *fade margin*, or losses due to *impedance mismatches*. For the densor application, a very important extra influence is the fading due the addition of human tissue. For simplicity, we assume that only the on-object gain penalty and fading due to the addition of human tissue play a major role, but one must keep in mind that polarization does play a role at UHF as mentioned in Section II-A.

It is common to treat link budget in decibel (dB). When converting Eq. (4) to an equation which used dB and adding the influences due to on-object gain penalty and the human tissue, we arrive at:

$$\begin{aligned} P_{RX,\mathrm{rdr}}\ (\mathrm{dB})\ =& P_{TX,\mathrm{rdr}} + 2G_{\mathrm{rdr}} + 2G_{\mathrm{tag}} - T_b - G_{obj} \\ &- 2L^{d-t}_{FS} - 2L^{t}_{HT} \end{aligned} \tag{5}$$

where G_{obj} is the on-object gain penalty, L^t_{HT} is the pathloss due to human tissue of thickness t and L^d_{FS} is the freespace pathloss at distance d, where:

$$L^d_{FS} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2 \tag{6}$$

We have assumed that the tag will reside at the outside of the teeth. In a simplified scenario where little space between the human tissue and the tag is neglected, the distance of free space is reduced by the thickness t of the tissue, leading to $d - t$. In this scenario, the radiowave will first travel through air, then through the tissue, reach the tag immediately and travel back through the tissue and then the air.

Given Eq. (5), we will now elaborate on some terms of this equation. Note that the last four terms represent *losses*.

A. Transmit Power and Antenna Gains

It is clear that the tag's transmit power is determined by the reader's transmit power and thus that the reader's transmit power is a mayor factor that determines the interrogation range of the system. For UHF RFID application, regulations presented in Section IV-B determine the maximum transmit power that can be used. Although Table I and other regulations mostly name the $EIRP$ and ERP ([14]), using the following equation we can directly see how this relate to the maximum transmit power:

$$EIRP(dB) = P_{TX} + G_{rdr} \tag{7}$$

$$ERP(dB) = EIRP - 2.15 \tag{8}$$

The antenna of the reader always amplifies the signal and is also on the way back a positive influence for the received signal. The other possible positive influence in Eq. (5) is the antenna gain of the tag, but one should not except to much from this. [13], [15] state that -0.5 dBi $\leq G_{tag} \leq 2$ dBI, where most of the literature state $G_{tag} = 0$ dB.

B. Modulation loss

The term T_b is used to express the modulation losses in different ways [13], [15], [14]. In RFID systems the signal received at the tag can be modulated using Amplitude Shift Keying (ASK) or Phase Shift Keying (PSK). In simplified calculation, this term could be set to 1 (= 0 dB), when assuming there are no losses due to the backscatter modulation. An interested reader is adviced to look into [13], [14], where equations are presented for both ASK and PSK modulation, where this loss depend on the modulation index $0 < m < 1$.

To get an insight of regular values for T_b, having $m = 0.5$ will resolve in $T_b = 3.8$ dB for ASK and $T_b = 1.25$ dB for PSK. Besides this, [2] gives T_b an example value of 5 dB.

C. On-Object Penalty

For the densor application, an RFID tag will be placed against teeth or embedded in or placed on a mouthguard. Although no concrete values for on-object gain penalty is known for this, influences of performance due to the fact that an RFID tag resides against an object is well-known and something that should be considered to be existing for this application.

D. The Influence of Human Tissue

Many future Internet of Things application these days research towards possibilities to use the human body. Examples of such future systems are wireless body area networks [18], body centric communications [19], wireless implants [16], [20], biomedical apps [21] and body worn anetnna systems [22]. In all these situations, radiowaves need to penetrate different kinds of human tissue.

Results of researches towards the electromagnetic properties of different tissues can be found in [23], [24], [25]. For radiowaves (electromagnetic waves), human tissue such as skin forms a conductive environment, mostly because of the presence of blood vessels. Radiowaves will not penetrate here easily and will die out. Another conductive environment is salt water, where radiowaves propagate badly. Expectation is that the performance in human tissue is slightly better, because human tissue also contains fat, which is less conductive. For example, the analysis in [26] show that the attenuation and delay in the small intestine and muscle tissues are larger than in fat tissue.

The absorption of the radiowaves can be predicted using the penetration depth δ of the tissue:

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{9}$$

where $\omega = 2\pi f$ is the angular frequency, σ is the conductivity and μ is the permeability of the material. In free space, we have $\sigma = 0$ Sm^{-1} and $\mu = \mu_0$. In salt water, $\sigma = 4.8$ Sm^{-1}. From Eq. (9) see that skin depth decreases for higher frequencies and larger conductivity.

The signal strength A at a distance x in the material can then be expressed as:

$$A = A \text{ exp}\left[-\frac{1}{\delta}x\right] \tag{10}$$

Using these equations, one can check that the penetration depth δ represents the distance at with the signal strength has reduced to 0.3678 times the original signal strength.

Human skin in the face (around the mouth) does not contain much fat. To predict the influence of the tissue for the densor application, we therefor focus on muscle (and skin) tissue. From [23] we can read that $0.6 \le \sigma_{muscle} \le 1$ Sm^{-1} at $f = 900$ MHz, which is indeed larger than $\sigma_{fat} \approx 0.4$ Sm^{-1}. Also mentionable is that [24] gives $\sigma_{tongue} = 0.63$ Sm^{-1}.

When we assume that in tissue only the conductivity is different (thus $\mu = \mu_0$)[1], we find that at $f = 900$ MHz the penetration depth of muscle δ_{muscle} is at worst 1.7 cm. At the other hand, [21] states $\delta_{muscle} = 4.2$ cm and $\delta_{skin} = 3.9$ cm, also using [23] but not mentioning the used value for μ. [22] also states $\delta_{muscle} = 4.2$ cm, and $\delta_{fat} = 250$ mm.

Combining these results, we use $1.7 \le \delta_{muscle} \le 4.2$ cm, to see what direct influence this is on remained signal strength after penetrating the tissue around the mouth twice (towards the tag and back towards the receiver). Estimating the thickness of the skin there ~ 1 cm, we find:

$$\begin{aligned} A &= A\left(\text{exp}\left[-\frac{1}{1.7}\right]\right)^2 = 0.31A \\ A &= A\left(\text{exp}\left[-\frac{1}{4.2}\right]\right)^2 = 0.62A \end{aligned} \tag{11}$$

Conclusion is that, although the tissue we need to penetrate is very thin (~ 1 cm), this has a significant influence on the signal strength. Following from Eq. (11) an estimation for $2L_{HT}^{0.01}$ lies between 2 and 5 dB.

VI. Experiments with UHF RFID labels

In the previous section, we looked into performance of UHF RFID on a theoretical level, where we stated which are the major influences on this performance. To get a more practical insight on the performance of RFID labels, this section presents some basic experiments to investigate the maximum reading distance and read rates for three different labels. Using our observations, we can then look into the possibilities of using RFID labels in the densor application.

A. Experiment Resources

The tags used for these experiments can be seen in Fig. 4. All tags are RFID labels with dipole antennas which differ in size. For each tag, the antenna gain is unknown. From now on, we will refer to these tags using A, B, C.

[1]This was adviced by dhr. Remus, Eletromagnetics teacher at TU Delft

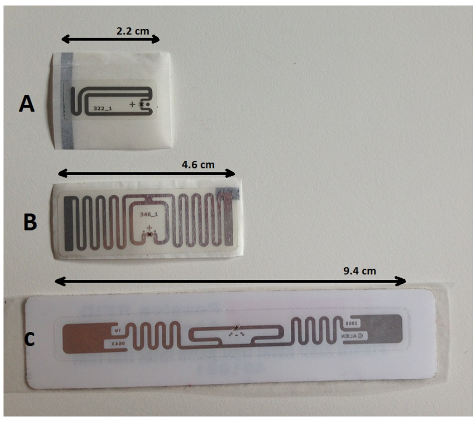


Figure 4: Used RFID Labels

The RFID tags can be read using the `MINI ME` application [27], which can be installed on any mobile phone having the Android operating system. The application used the `MINI ME` reader that is attached via the micro-usb port of the phone.

The core functionality of the application is the *inventory* function, where the application returns the ID's of the RFID labels it has found in an interval of 25 ms. For the first experiments, we used the application without any adaption of the code. Then, for each successful reading in the 25 ms interval, only a 'beep' was given. In this scenario, the exact number of readings in the interval was not extract able, but one is capable to conclude whether there were more or less than 5 readings. In the experiments concerning the read rates, the code of the application was edited to return the exact number of reads per interval - given that there is only one tag present. This number of reads has a maximum of 25, because the application only sends a signal every millisecond.

The `MINI ME` application works with $f = 900$ MHz. One can set the *output power* and *reading sensitivity*. The reading sensitivity was set to the default value of -84 dBm. The output power was changed during the experiments, having the values of 5, 8, 11, 14 and 17 dBm - every time doubling the output power. Note that 17 dBm $\equiv$ 50 mW, which is an output power that fits inside the regulations stated in Table I.

B. Measurement Approach

If not stated differently, both the labels and the phone with reader were positioned in a horizontal way during the experiments. This mimics a scenario where the label resides inside the mouth and one uses the phone to make a call. When the phone is held vertically, one can see this as a scenario where the phone is used for texting or browsing.

The tag and reader are aligned in direct line of sight. During the experiments, the distance between the reader and tag is increased in a regular manner, starting at a distance of 0 cm and increasing this distance with 0.5 cm (tag A), 1 cm (tag B) or 2 cm (tag C). For all measurements, each run where distance is increased to significantly further than the maximum reading range is performed 5 times.

All measurements were done indoors in a regular living room. The experiments focusing on the maximum reading distance were done on a different day than the experiments focusing on the read rates.

C. Finding the Maximum Reading Distance

First we focused on finding the maximum reading distance of all three tags with respect to the output power. Besides this, we shifted the center of tags B and C from the center of the reader to see what the influence on the maximum reading distance is.

Results of the experiment can be found in Fig. 5. We state the maximum reading distance as the largest distance where there were more than 5 readings in the interval for all (5) runs of the experiment, as explained above. Observations from Fig. 5 are:

- As expected, the maximum reading distance increases with tag size. A larger tag brings larger antenna gain which increases the received power at the reader (Eq. (4)). Another explanation for this is that it is more difficult for a radiowave to miss a larger object, such that the probability that tag C is hit by the signal of the reader is larger than the probability that tag A is hit.
- A larger output power also gives a larger maximum reading distance, which is expected looking at Eq. (4). However, the behavior of this growth differs between tags and location w.r.t. the center of the reader.
- With a maximum reading range of 4.5 cm at 17 dBm, tag A will most centainly be unsuitable for the densor application because the reading distance will be reduced even further when adding the influence of human tissue (Eq. (5)).
- When the tags are moved to the left w.r.t. the center of the reader, performance decreased, especially at lower output powers. This is probably due to the gain figure of the reader.

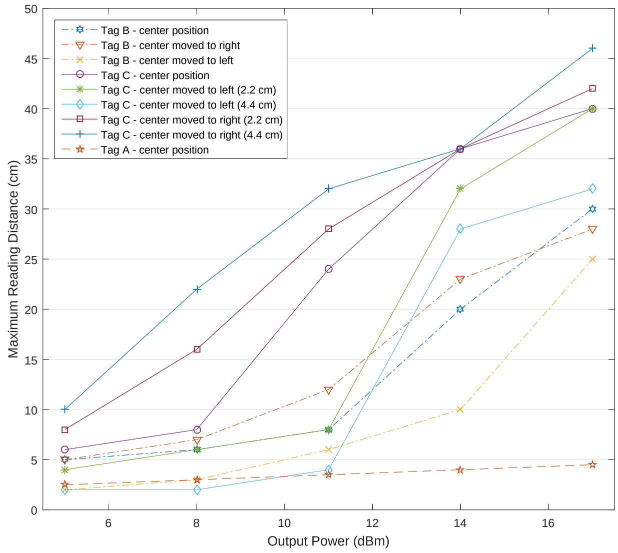
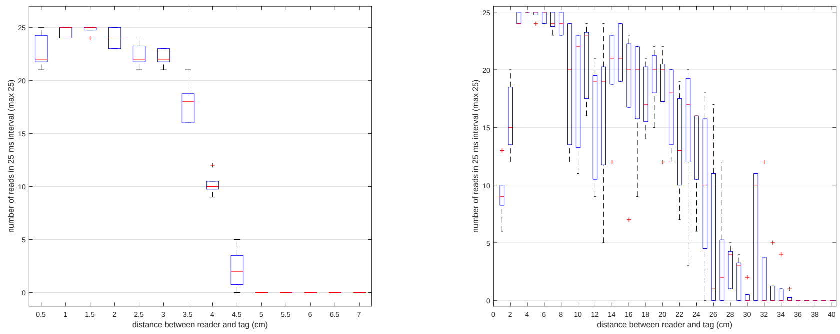


Figure 5: Maximum Reading distances for tag B and C with respect to the output power.

D. Read Rates behavior

A second experiment focuses on the behavior of the read rates at the maximum output power of 17 dBm, where all tags are placed with their center in front of the center of the reader. Results for all tags can be seen in Fig. 6.

We see that if we use the same approach to find the maximum reading distance as in the previous experiment, the performance during this experiment is worse. The performance at distances smaller than the maximum reading distance can be seen as somewhat constant and cogent. The variation in the number of readings is the largest for tag B, having a drop in the number of read rates around 12-13 cm. Also for this tag, the performance is relatively poor when the tag is really close to the reader.



(a) Tag A

(b) Tag B

(c) Tag C

Figure 6: Read Rates behavior for all tags at an output power of 17 dBm

Around the maximum reading distance, the performance shows a steep drop. But, we can see that even that although there are not a lot of readings, the tags are still being read at larger distances than this maximum reading distance. There, the number of readings in the interval gradually dies out at increasing distance.

E. Changing orientation and shape

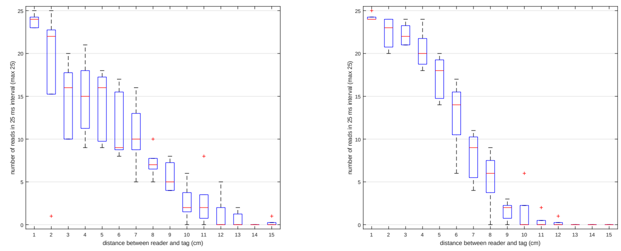
Thirdly, we focused on the performance of the system while changing the tag orientation and tag shape. First considering orientation, in Section V we stated that *polarization mismatch* does have a role in the link budget calculation. Although this was not included in Eq. (5), we did look into the behavior for tag C.

As can be seen in Table II, the maximum reading distance at an output power of 17 dBm does significantly variate when orienting the tag different. This behavior depends not only on the antenna of the used tag, but also on the antenna from of the reader. Namely, we also saw in Section VI-C that the maximum read range depends on the alignment of the label were this is due to the gain figure of the reader.

Secondly, for the densor application probably the shape of the antenna will be an influence on performance. Namely, tag C is too large to directly fit along someones teeth. Thus using such a tag is only possible when this is bend along the teeth (or mouthguard). To predict how this influence performance, we investigated the read rates for tag C while it is residing in a curved shape. We did this while the reader was placed horizontally (as in all other experiments) and vertically. When the reader was placed horizontally, the center of the reader was aligned with the outside of the label, simulating a scenario where the user uses his phone for calling. When the reader was placed vertically, the center of the reader was aligned with the center of the tag, simulating the texting / browsing scenario.

Orientation	Max Reading dist (17 dBm)
Horizontal, upside up	31 cm
Horizontal, upside down	24 cm
Vertical, upside up	2 cm
Vertical, upside down	11 cm

Table II: Reading Distances for tag C w.r.t. orientation



(a) Reader vertically oriented

(b) Reader horizontally oriented

Figure 7: Read Rates for tag C which has a curved shape

Results are shown in Fig. 7. From this, we can directly see that the performance is significantly worse when comparing it to Fig. 6c. The decrease in the number of read rates follows a more linear line and the maximum reading distance in this case will be around 10 cm, which is over 20 cm smaller than in the original case. From this, we can conclude that the shape has a huge influence on the performance of the system.

VII. UHF RFID Densor Possibilities & Discussion

When we want to use UHF RFID labels as an element of a densor, the labels have to meet three main requirements: The label should be readable at a significant distance from the reader, they should be small enough to fit inside a mouth and the labels should not pose a problem for human health.

From the experiments in Section VI we can directly state that labels having a comparable size with tag A are too small to achieve a reading range which is large enough. We have also seen that in regular shape tag C performs the best, which is an expected outcome. Also, tag C is the largest tag which makes it more robust against fluctuations in the gain figure of the reader - in other words, it is more difficult for a radiowave to miss a large object. On the other hand is its size also a disadvantage. To fit tag C inside a mouth, it should be bend along the teeth. Experiments show that the read range of the label in a curved shape is significantly smaller,

In the experiments, we did not take extra influences into account which we mentioned when talking about the link budget. To see whether we can still use tag C when we would reside the tag in the mouth, we can look back at the theoretical link budget calculation presented in Section V. When we look at Eq. (5) and state for simplicity that all factors stay the same but only the loss due to human tissue increases, we can find the new maximum reading distance using Eq. (6) and

$$2L^{d}_{FS} = 2L^{d-t}_{FS} - 2L^{t}_{HT} \tag{12}$$

Consider the curved tag C. At a distance of 10 cm, we find that $2L^{10}_{FS} = 11.5$ dB when we operate at 900 MHz. This would mean that when we have a loss due to human tissue of $2L^{0.01}_{HT}$ between 2 and 5 dB (Section V-D), this significantly reduces the allowable loss due to regular path loss. In the worst-case this would lead to a maximum reading distance around 4.5 cm, which is too small to be useful.

There is more perspective for tag B. Because this tag is slightly smaller, there is a change that this tag could reside inside the mouth along the molars such that bending is not needed (location 2 in Fig. 3b). In this case, following from the experiments, the maximum reading range without the presence of human tissue is 28.5 cm. Using Eq. (6) and Eq. (12) we find for the best- and worst-case loss due to the tissue a new maximum reading range of $14.8 \leq d \leq 22.3$ cm, which is considerable better than we had using tag C.

From the calculations above it is clear that the most perspective in using UHF RFID labels lies in using labels that are like tag B. Tags that are too small don't have the appropriate performance and tags that are too large need to be bend to fit inside the mouth and this influences the performance significantly such that these tags also can not be used. Still, we didn't look into all characterizations which can influence the performance for the densor application. We have noticed that polarization mismatch can play a role even as a on-object gain penalty, but did not find concrete behavior for this. For the on-object gain penalty, this surely depends on how the label is used in the system. Also, in Section IV we stated that in this research the tag would always reside outside of the teeth. Putting the tag inside the teeth would mean even more influences from tissues (i.e. teeth or bone tissue).

Besides this, we have only looked into the changes in maximum read range when the label is residing in a curved shape. When the label would be embedded in a mouthguard, surely the tag should be reformed (i.e. be folded) to fit along the mouthguard. As curving a label has a significant influence on the performace, probably folding the label will also be a significant influence. Although tag B is smaller, it is still too high to fit along only the upper or lower jaw. A second disadvantage of a smaller tag is that it only spans one place in the mouth and not both the middle, right or left side altogether, which a larger tag (such as C) would do.

The third requirement that followed from Section IV was that the system should not pose any threat to human health. In this report, we did not investigate this. In our experiments we used a maximum output power of 17 dBm $\equiv$ 50 mW, which fits inside the regulations we elaborated on in Section IV-B. These regulations are set up to ensure human health, so as long as one follows these rules, the last requirement is fulfilled.

VIII. Conclusion & Recommendations

From this report one can conclude that UHF RFID labels how they currently exist are not a suitable solution for the densor application in the near future. Firstly, the performance (read range) of the system is too much influenced by the presence of human tissue, a problem which we can not directly solve be increasing the output power of the reader due to regulations. Secondly, for tags for which there is a perspective, it is still the case that they are too large to fit inside the human mouth.

If one wants to investigate how UHF RFID can be made more suitable for an application such as the densor, there are two problems one should look into: It turns out that not only the presence of tissue but also the form of the label (and thus the dipole antenna) plays a major role. If RFID labels are going to be used, they will most probable be embedded in mouthguards (due to their size). To see whether this is doable, research needs to be done towards the behavior of UHF antenna's given certain form factors. In a best-case scenario, the antenna will be bend alongside the outer bound of the mouthguard, but it is given that this deteriorates the performance of the system.

Secondly, one should also focus more on the reader-side of the system, something which lied outside of the scope of this report. From this report it has become clear that the read range not only depends on the tag, but also on the reader characteristics. One could increase the output power towards the upper bounds given by the regulation to increase the maximum reading distance, but one could also try to develop and antenna for the reader which is specialized in finding curved tags, such that the deterioration of the read range for bend tags is counteracted.

Besides this, time will tell what kind of development UHF RFID will know in the near future, given that is seen as the future of Internet of Things. Also perhaps the usage of UHF RFID laundry tags can be a promising alternative for the regular UHF RFID labels which are considered here.

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