Communication system for a tooth-mounted RF sensor used for continuous monitoring of nutrient intake

Master Thesis

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ABSTRACT

In this Thesis, the communication system of a wearable device that monitors the user's diet is studied. Based in a novel RF metamaterial-based mouth sensor, different decisions have to be made concerning the system's technologies, such as the power source options for the device, the wireless technology used for communications and the method to obtain data from the sensor. These issues, along with other safety rules and regulations, are reviewed, as the first stage of development of the Food-Intake Monitoring project.

Keywords: wearable device, diet monitoring, RF sensor, food detection, resonance.

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1 Introduction

Technology is constantly evolving and changing human habits. Since the first semiconductors were developed in the 1940s, the complexity and scale of digital and analog electronics has led to a society where computer-based products are of great importance. With the improvements in battery technology [27] and the reduction of form factor and power consumption, personal devices such as phones and personal computers are reimagined to be portable and connected one with each other. Improvements in battery energy density, combined with the increasing number of transistors in the same silicon area (and thus computational power) allow the technology companies to create very powerful and miniaturized products with a number of applications such as phones, media players and activity trackers.

The Internet of Things (IoT) is the concept where nearly every physical device and everyday object can become smart, by being provided with sensors, embedded electronics and Internet connectivity [17]. Thanks to the development of reliable networks, more storage and faster computers, data can be analyzed and monitored in real-time, allowing very quick response to the identified events. Different standards have been stipulated for this purpose, such as Bluetooth (2.4 GHz ISM band) in the transport layer or Message Queuing Telemetry Transport (MQTT) as a data protocol.

In strong relation with these trends, wearable devices related to self-health monitoring [18] have been at the heart of many research discussions, and new products are being released. Moreover, society is becoming more aware of the importance of fitness and health. Wearable devices can play a major role in improving preventive medicine and reducing healthcare costs, and can avoid future problems if anomalies are detected in early stages. The market of Medical IoT (MIoT) has proven to be strong, and is expected to continue growing in the next years.

The best examples of MIoT are the “fitness trackers” wearable devices created by brands such as Fitbit or Misfits. These devices, normally in the form of watches or wristbands, monitor heart rate, physical activity and sleeping quality, and claim to help achieve the users’ health objectives by giving feedback of the daily activity [5].

Figure 1: Fitbit Charge 3 fitness tracker [5].

Although these devices are widely used, one very important part of fitness and health activity is still missing in the wearable devices market: An automatic food monitoring tool. Smartphone applications such as MyFitnessPal already exist, where the users enter the food ingested, and then the calories and macronutrients are calculated using a database. However, this mechanism is inexact and manual, and relies on the user’s motivation to weigh and record everything he/she eats and the database precision for a particular food information.

This thesis is inspired by an academic research project at the University of California, Irvine, where a group of Engineering Professors and students are developing a food intake monitoring system.

1.1 Objectives

Every person has different objectives and problems regarding health and nutrition: lose weight, gain muscle, lower cholesterol, etc. Personalized healthcare is the set of tailored processes that a person follows to reach these objectives. This medical and nutritional attention requires the development of new sensors able to measure the human body metrics. Academic research and industry are trying to acquire a sufficient amount of data related to people's daily routines in order to detect disease or injury, thereby improving the wellness of the users. Motion trackers, vital signs measurement electronics, and other biomedical devices are already being commercialized.

One of the most important physical needs of humans is food. It has an important impact in health, and is currently a growing concern in society. High-Protein or Low-Glycemic index diets help overweight persons lose weight, thus improving their health. Nutritionists, dietitians and tech companies are collaborating to make mobile applications to improve people's diet, by providing recipes or keeping track of what they eat.

Nevertheless, the current methods of keeping track of the food that a person has eaten are slow and require a lot of work, such as weighing every ingredient or introducing the information of the Nutrition Facts in the application. To avoid these problems, a new food intake sensor has been developed based in a combination of a dielectric sensor and RF technology [22]. The project consists of developing a tool based on a novel food sensor; by creating a system able to acquire the data and process the information, the food intake of the user can be monitored.

The main features of the new sensors and bio-IoT systems design are: 1. Biocompatibility, 2. Autonomy, 3. Size [21]. The system is going to be in constant contact with the human body, both externally and internally. This means that the implant has to be proven to be safe for human interaction. In particular, the power consumption is critical because it will determine the autonomy of the device. The distinct parts of the distributed system (sensors, microprocessor) can be powered in different ways (e.g., batteries, wireless power transfer) but the overall consumption must be low to increase the time between charges. These hardware challenges combine with the specific potential problems identified in this project: 4. Wireless communication inside the mouth, 5. Food detection algorithms.

This Thesis addresses the main questions that have arisen at the early stages of the system development, with an emphasis in the communications part. Every issue is analyzed using a simple problem-solving procedure: 1. Definition of the problem, 2. Information gathering, 3. Summary of alternatives, 4. Choice recommendation.

In this early stage of the project, the first objective is to obtain continuous data of the food intake sensor with a wireless and portable method. Once this stage is completed, a system-oriented strategy will be developed to finally have a real product developed. The data from the sensor has to be acquired, and different options and technologies can be used to implement it. Different alternatives will be discussed:

- Vector Network Analyzer (VNA) methodology
- Inductive coupling (Near-Field) or Electromagnetic coupling (Far-Field) technology
- Coupled Inductors
- Wireless power or batteries
- Frequency Modulated Continuous Wave (FMCW)

Before tackling the main problems, a review of the most important technologies discussed in the thesis, along with the actual sensor and desired system explanation are done to have a deep understanding of the global project.

2 Technological review

Different technologies for sensing and communication will be used in the project. In this chapter some of the most important concepts will be reviewed, to understand the goals and challenges of the project.

2.1 Metamaterial-based sensors

Metamaterials are artificially built structures with enhanced electromagnetic properties, normally constituted by periodically organized metallic elements [20]. The size of these elements is less than the incident EM wavelength. The behavior of these materials can be different from any natural component, and the exhibited properties are very different depending on the geometry, shape or size of the structures. For instance, fields can be strongly enhanced or localized, improving the transducer's selectivity and sensitivity. Typical applications of metamaterial-based sensors are, for example, biosensing devices and super lenses for optical engineering.

Nowadays, the research on this topic is intense in both academia and in industry. The submicron and nanometer scales are currently commonplace in both design and fabrication, leading to widespread use in many sectors. The first feature that material-based sensors must have is a strong and measurable resonance, readable from other spectrum analyzer devices. Moreover, the operating frequency must be low enough to avoid absorption by the substrate, a difficult task considering the small size of the transducers. Finally, sensitivity and linearity must be studied to characterize the sensor's response.

The basic units of biosensing metamaterials are the Split Ring Resonators (SRRs). They are formed by a pair of concentric loops, etched in a dielectric substrate with gaps in them at opposite ends. Non-magnetic materials are used for the loops (e.g., copper, gold, etc.) and they can have different shapes, such as circular, square or u-shape. This structure, paired with the right dielectric, allows the generation of a desirable response to electromagnetic fields, specifically in magnetic susceptibility and magnetic coupling [19].

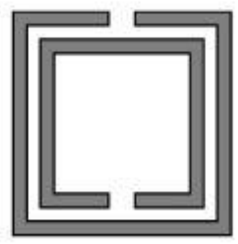

Figure 2: Square Split Ring Resonator [19].

When a time-varying magnetic field penetrates the loop, an electromotive force is induced on the ring and a rotating current appears. This phenomenon is ruled by the Faraday's Law. The ring produces a magnetic field opposed to the changes of the external field, leading to an inductive effect. Moreover, a capacitive effect is also present in the structure, because of the dielectric material gap in the open-loop. This gap acts like a parallel capacitor, leading to an electrical model of an LC tank.

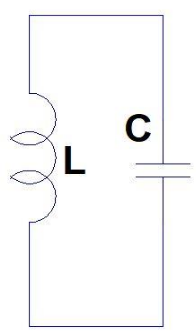

Figure 3: Electrical model of SRR (LC tank) (LT-Spice).

At the resonant frequency, when the inductive and capacitive reactance are equal (X_L=X_C), the total current is at its minimum and the impedance reaches a peak whose height is only limited by the loss in the tank. The resonant frequency is given by:

$$f_R = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

In biosensing metamaterials, the resonant frequency shifts according to a specific measured event. The capacitive part, which is related to the dielectric, changes with the presence of a particular molecule, and the resonant frequency is shifted accordingly. With the right system in place, the SRR acts like a material-based sensor. Using a network analyzer or a Vector Network Analyzer (VNA), the reflection (more specifically the scattering parameter) can be measured and detect the shift of the resonant frequency, thereby finding the cause of the event.

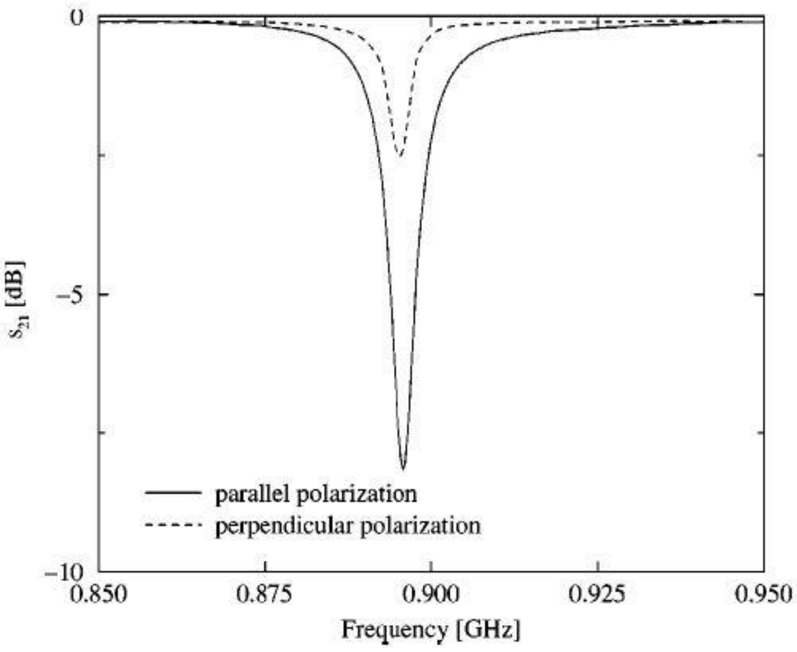

Figure 4: Scattering parameter of an SRR [19].

Reflection:

Many metamaterial-based sensors rely on the reflection measurement to detect a particular event. When a transmission line is not terminated in its characteristic impedance, part of the incident wave returns towards the source, the reflection [27]. The Reflection Coefficient has a relationship with the normalized load impedance, defined by:

$$\Gamma = \frac{\frac{Z_L}{Z_O} - 1}{\frac{Z_L}{Z_O} + 1} \qquad (2)$$

Where Z_L is the load impedance and Z_0 is the characteristic impedance of the transmission line, which is the value of the load that makes the reflection zero.

The characteristic impedance of a transmission line, neglecting the resistive effects, is equal to the square root of the ratio between the line's inductance per unit length to the line's capacitance per unit length:

$$Z_O = \sqrt{\frac{L}{C}} \qquad (3)$$

To define a two-port system as shown in Fig. 5, it can be represented by the voltage and current of each line, as well as the impedances (or admittances) that relate those voltages and currents.

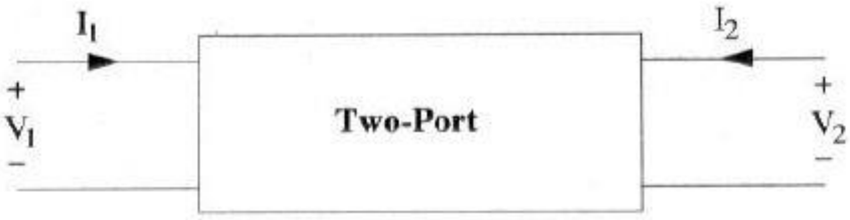

Figure 5: Two-port system defined by impedances [27].

This representation has the following equations, where the parameters can be found by open-circuiting the ports (or short-circuiting if working with admittances) and applying and measuring the voltages and currents, because different terms become zero depending on the open-circuit (or short-circuit) configuration:

$$V_1 = I_1 Z_{11} + I_2 Z_{12} \qquad (4)$$
$$V_2 = I_1 Z_{21} + I_2 Z_{22} \qquad (5)$$

In the same fashion, the system can be expressed in terms of power and Scattering parameters (S-parameters), that are useful to avoid the open/short-circuit concepts in high-frequency applications, and it is most convenient for RF transmission because a line terminated in its characteristic impedance has no reflection.

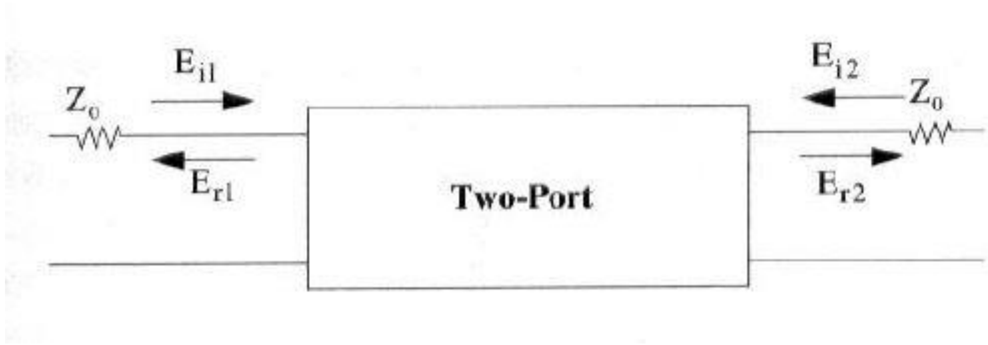

Figure 6: Two-port system defined by S-parameters [27].

In Fig. 6, both ports present the characteristic impedance Z_O and the input and reflected voltage waves E_i and E_r. The equations of the system are given by:

$$b_1 = a_1 s_{11} + a_2 s_{12} \quad (6)$$

$$b_2 = a_1 s_{21} + a_2 s_{22} \quad (7)$$

Where a_n and b_n are normalized by the square root of Z_O, to be equal to the square root of the power of the corresponding incident or reflected wave.

$$a_1 = \frac{E_{i1}}{\sqrt{Z_O}} \quad (8)$$

$$a_2 = \frac{E_{i2}}{\sqrt{Z_O}} \quad (9)$$

$$b_1 = \frac{E_{r1}}{\sqrt{Z_O}} \quad (10)$$

$$b_2 = \frac{E_{r2}}{\sqrt{Z_O}} \quad (11)$$

When the output port load is matched to the characteristic impedance; i.e., $Z_L = Z_0$, and driving the input port, a_2 is zero. This makes it possible to determine that s_{11} is equivalent to the input reflection coefficient.

$$s_{11} = \frac{b_1}{a_1} = \frac{E_{r1}}{E_{i1}} = \Gamma_1 \quad (12)$$

This way of defining two-port systems is important in the Food-intake Monitoring Project; in order to measure the metamaterials-based sensor response in a wireless fashion, it is necessary to detect the impedance changes of the sensor using the power waves approach.

2.2 RF technology

With the spread of wireless technologies in many applications, the field of RF has experienced a growth in the last two decades. New IoT devices utilize more and more of this technology for communication, and different standards and network protocols have been defined based on this hardware [29]. The design of RF circuits is a multidisciplinary science, where knowledge of IC design is needed, but other concepts such as communication theory and signal propagation are also useful.

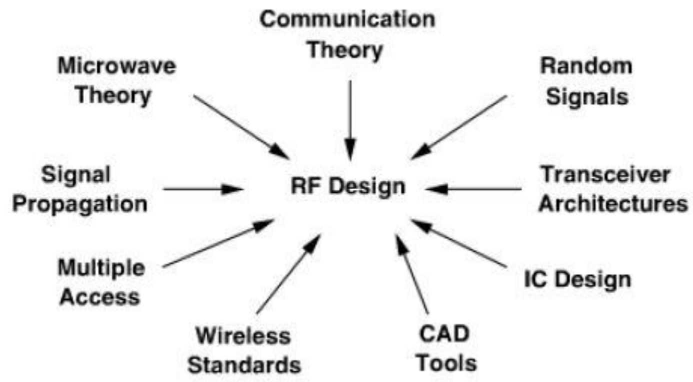

Figure 7: RF technology related fields [29].

RF technology is based on radio waves. The main properties of oscillating waves are the frequency, amplitude and wavelength. The amplitude refers to the peak-to-peak value of the signal. The frequency is the number of cycles of a periodic wave per unit of time. The wavelength is the distance between two equivalent points of two consecutive cycles, given by:

$$\lambda = \frac{c}{f} \quad (13)$$

where λ is the wavelength, f is the frequency and c is the speed of light in free space (300,000,000 m/s).

When referring to RF, the frequency range of the electromagnetic waves is from 20 kHz to 300 GHz. This means the wavelength range is from 15,000 m to 1 mm. In electromagnetic antenna theory, the length of a dipole antenna is half the wavelength of the signal, so this parameter is relevant to the form factor of a transmitting or receiving device.

RFID:

Radio Frequency Identification is a wireless technology that enables automatic identification of distant objects, using a transmitting device (interrogator) and a receiving tag [13]. This approach started as a way of tracking products in industry, substituting the classic barcodes, but in recent years more complex and useful devices have been developed using RFID.

The tags can be classified depending on the power as either passive or active. On the one hand, in passive tags, power and data are transmitted from the interrogator to the tag, and a then the tag is read. On the other hand, active tags have a power source like a battery to power it, and only data is transferred between the interrogator and the tag. In this active approach, the device can be more complex because the extra power allows more processing in the tag, but the size is also bigger because of that portable power source.

The most popular RFID tags are passive devices, due to the small size, the simplicity and the convenience to be incorporated to an adhesive label. This kind of tag has three main components: an antenna, a semiconductor chip and an encapsulation. The reader or interrogator sends power to the antenna, and shortly thereafter the tag transmits the data (e.g., identification) in response. The tag chip is powered by the energy received with the antenna, and it activates the electronics to send the corresponding response to the reader. As it will be studied in the communication system of the RF sensor, two ways of transmitting data and power are possible: near-field or far-field, or in other words, magnetic induction or electromagnetic wave capture.

As the technology is becoming more mature, different communication methods are being used. The modulation is one of the techniques to send digital or analog information using waves, as illustrated in Fig. 8. With Amplitude Shift Keying (ASK) modulation the amplitude is varied to send binary data. However, other types of modulation such as Phase Shift Keying (PSK), where the signal is inverted (180˚) to send 0 or 1; or Frequency Shift Keying (FSK), where the frequency of the wave is increased or decreased to send the digital value.

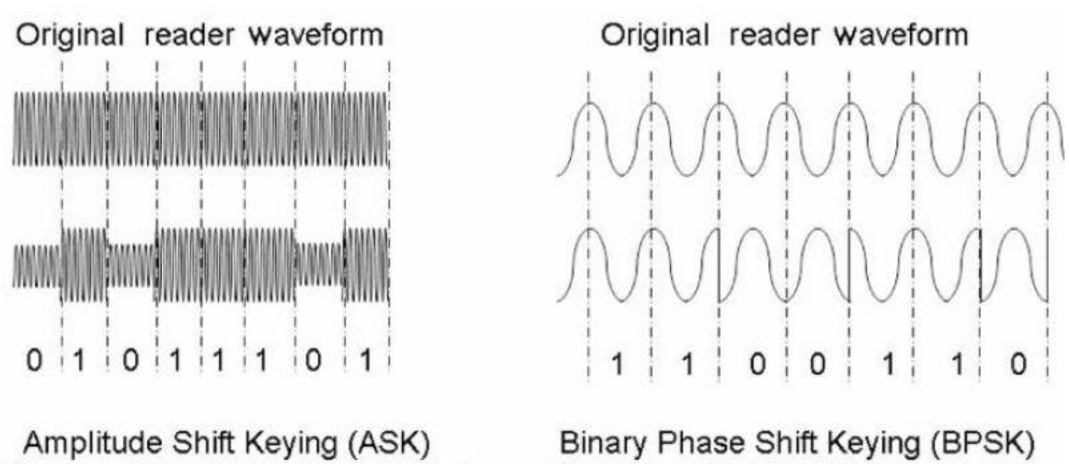

Figure 8: ASK and PSK modulation techniques [13].

Although RFID is one of the most important, it is not the only RF technology developed. Bluetooth is a wireless standard for communication within a range of about 10 m. These devices support two-way communication in the ISM (industrial, scientific and medical) band of 2.4 GHz. The latest update of this technology, the Low Energy version, has less consumption. Thus, devices deliver longer battery life, becoming more convenient for healthcare applications. Moreover, another technology is nowadays very important: the NFC (Near Field Communication). This standard performs as a HF RFID, in the 13.56 MHz frequency, and enables communications between two active or one active-one passive devices.

The applications of RF in implants enables the Body Area Network (BAN) concept [33]. This is a class of networks that includes all the wireless wearable computing devices. Implants and wearable sensors, in combination with wireless technologies based in RF, make possible the development of healthcare monitor applications. One interesting example is the Body Posture Analysis system in [14], where 6 accelerometers and a receiving board are connected using the IEEE Std. 802.15.4 wireless transmission protocol, which enables tracking of the user's body posture and falling detection; this is important, for instance, in older patients.

RFID implants are those tags that are introduced in the human body. The first device approved by the US Food and Drug Administration was the VeriChip in 2004 [28]. This device stores a personal identification number (PIN) that can be read in a range up to 15 cm. An example of such an application using this technology is e-payment or e-signature, which is a way to remotely identify the user, thereby replacing the fingerprint scanners. Moreover, the device is passive, making it easier to become biocompatible.

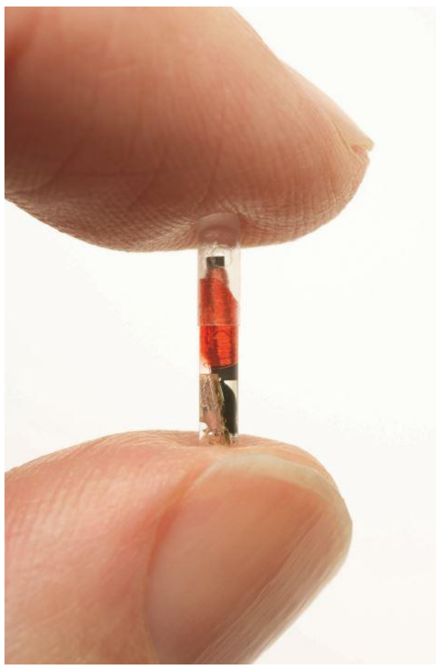

Figure 9: VeriChip implant [28].

Wireless power transfer (WPT) will also be studied in the project. The transmission of energy without wires, using the nonradiative approach (near-field) or the radiative approach (far-field) can be an interesting option to power the RF sensor, minimizing the components inside the mouth.

In conclusion, RF is a critical technology in the Food-Intake Monitoring project, and the communication system will utilize it as a way of transferring data and/or power between the sensor's and the processing computer.

2.3 Wearable devices

Wearable devices include IoT technologies attached to the human body, in the form of implants (such as the VeriChip) or clothing accessories (e.g., Fitbit wristbands). The purpose of these types of devices is very diverse: position tracking, fitness, healthcare, entertainment, identification, etc.

One example of a device that combines many of the wearable devices' applications is the smartwatch. This device primarily provides a digital readout of the time and date. Moreover, it connects to the users' smartphones and is a communication and entertainment device, where users can listen to music or answer phone calls directly from the watch. In addition, a new generation of smartwatches, such as the Apple Watch Series 4, can monitor the user's health parameters (e.g., heart rate), helping to keep track of the calories burned, the daily activity, and the time and quality of sleep [3].

A variety of sensors is necessary to measure the different features that wearable devices track. These transducers need to have some characteristics to be convenient for this purpose: biocompatibility, autonomy and small size.

An Inertial Measurement Unit (IMU) is used to monitor the motion and the body activity. The IMU consists of a set of accelerometers and gyroscopes (the number depends on the axes measured) that enable tracking of the position, velocity and acceleration of the device. In the current wearable devices, the IMU is used to quantify the activity of the user and calculate the calories burned.

Moreover, the advanced devices can perform electrocardiograms (ECG) to measure the heart rate of the users. This is done using different techniques, such as the Photoplethysmography (PPG). The PPG is an optical technique of measuring the heart rate using light to detect blood flow and thus the cardiovascular movements [16]. Keeping track of these vitals enable detection of heart problems such as cardiac arrhythmias, or monitoring of sleep and physical activity, as well as the stress of the user.

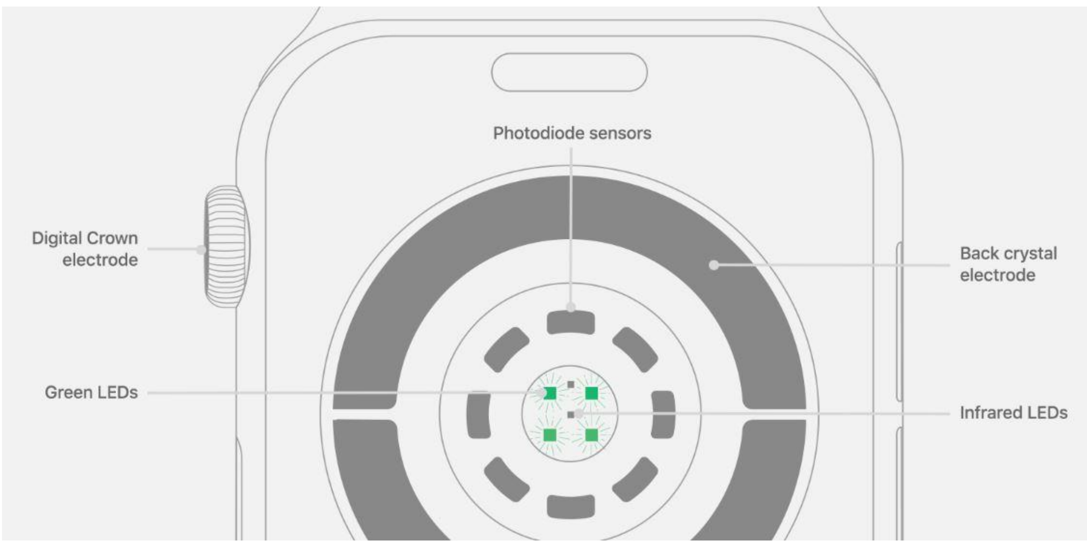

Figure 10: The optical heart sensor in Apple Watch Series 4 [3].

However, a very important part of healthcare and fitness is still not being monitored by these devices: the nutrition. Some smartphone applications have been created for this purpose, but it is a manual method that relies on the user's actions. Therefore, there is not a reliable way of keeping track automatically of the food-intake in commercial products.

In [12], different on-body sensing solutions are studied. By keeping track of the body movements, the intake gestures can be monitored and thus the food intake, distinguishing between food and drinks for example. Another approach is to keep track of the chewing sounds or the swallowing movements, but none of these techniques can differentiate between different kind of foods.

In [10], a mouthguard biosensor is presented. This electrochemical sensor is able to measure the salivary uric acid in a continuous way, while transmitting data with Bluetooth LE to an external device. The sensor has potential applications in healthcare as a wearable device, but it seems difficult to see an expansion of this kind of devices, because the form factor is not convenient for daily use.

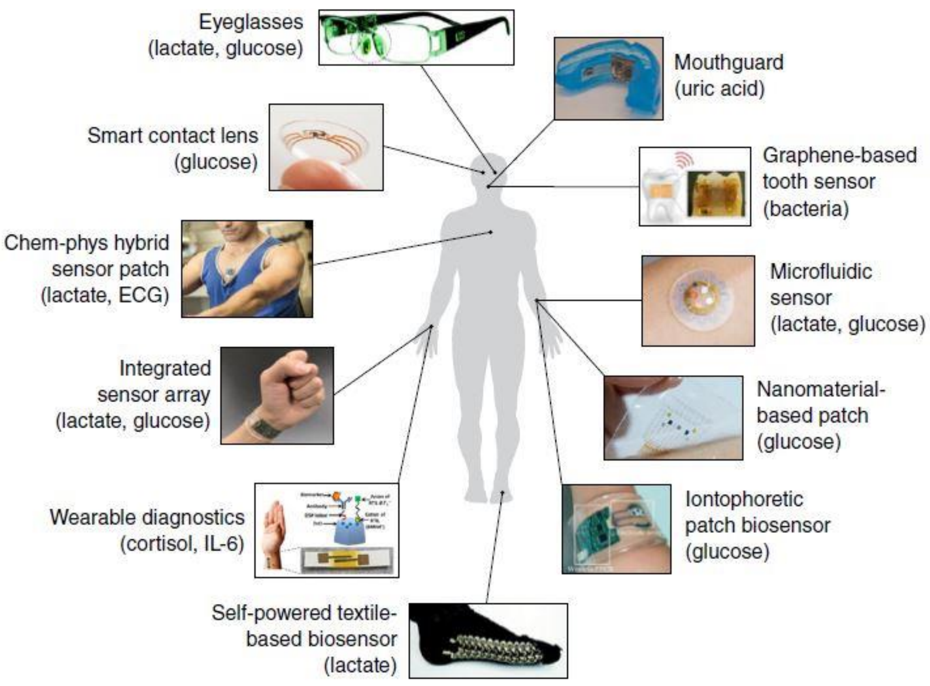

Figure 11: Summary of Wearable Biosensors for healthcare applications [32].

Finally, a summary of different healthcare Wearable Devices is done in [32], where the authors bring together other kinds of MIoT sensors used to monitor health and nutrition: epidermal sensors, for real-time sweat analyses; smart contact lenses, to measure glucose; and other skin and ocular biosensors, as described in Fig. 11.

These achievements in the Biosensors research area will enable researchers to develop tools to improve people's lives, by facilitating the health monitoring, keeping track of the nutrition and adapting the fitness and health strategies to each person based in the analytics that come from this data.

3 Food intake monitoring project

Peter Tseng et al. (2018) [22] is the starting point of this project. In this article, a new passive RF-based sensor is presented as the first step to build a food intake monitoring system.

3.1 RF sensor

The sensor is based in the dielectric layer response to different foods. This active layer is embedded between two Split Ring Resonators (SRR), forming an RF tri-layer sensor. This metamaterial has the SRRs reverse-facing each other, forming a Broadside Coupled SRR (BC-SRR), which has a lower resonant frequency (appropriate for RF instrumentation) and confines the electric field to reduce the external influence, important in an in-vivo biomedical device.

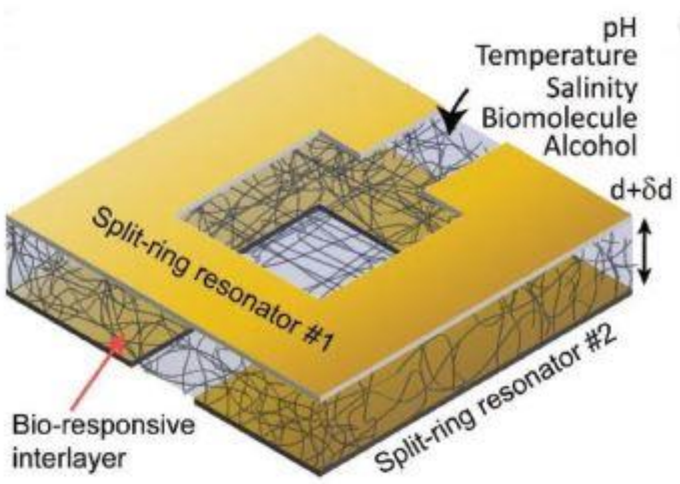

Figure 12: RF tri-layer sensor schematic [22].

Different interlayers have been used, based in porous silk films or modified PNIPAM (poly N-isopropylacrylamide) hydrogels. The sandwiched interlayer changes its properties depending on the solvents where it is immerged. Temperature, pH and nutrient's concentration provoke a geometry shift of the dielectric (thickness), leading to the sensor's response, thus making it possible to differentiate between foods.

The tri-layer structure makes it possible to measure the dielectric response to solvents with RF technology, due to shifts in the resonant frequency. The capacitance changes of the interlayer affect the LC resonator, and thus the quality factor, resonant frequency, and amplitude would be different depending on the solvent, when an impedance spectrum measurement is done. Depending on the thickness of the interlayer and the size of the BC-SRR, the resonant frequency varies from ≈400 MHz to 1 GHz. SRRs with sizes of 3 mm x 3 mm lead to resonant frequencies around 400 MHz. Smaller ones (2 mm x 2 mm) result in higher resonant frequencies. Likewise, thinner interlayers (1.2 μm) exhibited lower resonant frequencies (300-450 MHz), while thicker (2.3 μm) have higher frequencies (525-650 MHz).

The wireless RF solution is less invasive to the human body than other solutions, such as electrochemical sensors and mouth guards. This sensors' form factors and wires make them unsuitable for continuous monitoring, and seem to be rejected by the medical profession and the market. This RF sensor being passive means that no external power source is needed inside the mouth, which is a very convenient approach since such a source can be difficult to embed in a small and bio-compatible device inside the mouth.

The RF transducer has some important challenges, such as size (imposed by the operational band) and measurement inconsistency (misalignment, environmental factors), and thus needs to be calibrated due to fabrication variations. Nevertheless, the flexibility and bio-compatibility of the materials, and the size of the BC-SRR itself (fits in a tooth) make it possibly the best solution for the food intake monitoring.

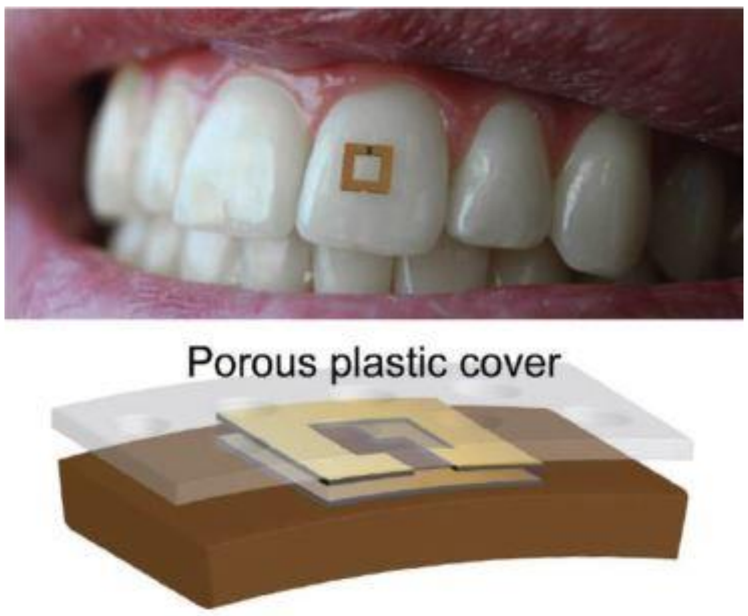

Figure 13: RF sensor adhered to a human's tooth [22].

Several tests have been made to characterize the sensor and are presented in Peter Tseng et al. (2018) [22]. For instance, the authors measured the sensor's response to different solvents and solutions such as deionized water, artificial saliva, 50% alcohol, methanol and high-salinity saliva. As observed in Fig. 14, the amplitude of the reflection and the resonant frequency of the sensor changed depending on the substance.

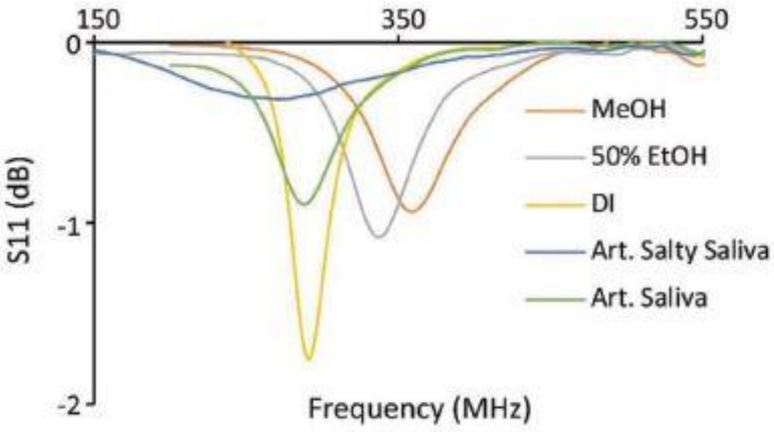

Figure 14: Response of the sensor to different solvents [22].

Another important factor of the sensor is the response speed. The behavior of the sensor depends on the diffusion of the food's molecules. Diffusion time is $t=L^2 \cdot D^{-1}$ (L: length, D: diffusion coefficient), and the detection of food doesn't occur until the biomolecules go into the active interlayer, provoking a change in the sensor's output. This output is transient, because it is dependent on the concentration of the nutrients and the saliva is continuously mixing with the food or drink, so the average solution concentration is a better result to detect the aliment than each instant output. In the existing sensor, it takes around 30 seconds for the food to be detected. The average time of a bite of food in the mouth is around 20 seconds, and less time if it is a liquid.

To improve the performance, in the project proposal [6] two options are considered. The first option is enhancing sensitivity of the transducer by developing porous SRRs. The diffusion length in the material will decrease, and the response time of the sensor will diminish to a more realistic intake-time (e.g., approx. 10 seconds), so the food and drinks can be monitored. The second option is modifying the interlayer properties, engineering the porosity and diffusivity to improve sensitivity, thereby reducing the time response.

In conclusion, the tri-layer sensor enables the discrimination of food based on the concentration of nutrients, thanks to the RF technology detection of the resonant frequency and amplitude of the scattering parameter when performing a network spectrum measurement. The fabrication process of the SRRs and the active interlayers provoke different responses of the sensors, so a calibration procedure needs to be put in place to increase the accuracy. Moreover, some changes need to be made in the sensor, leading to a responsive passive RF tri-layer food sensor.

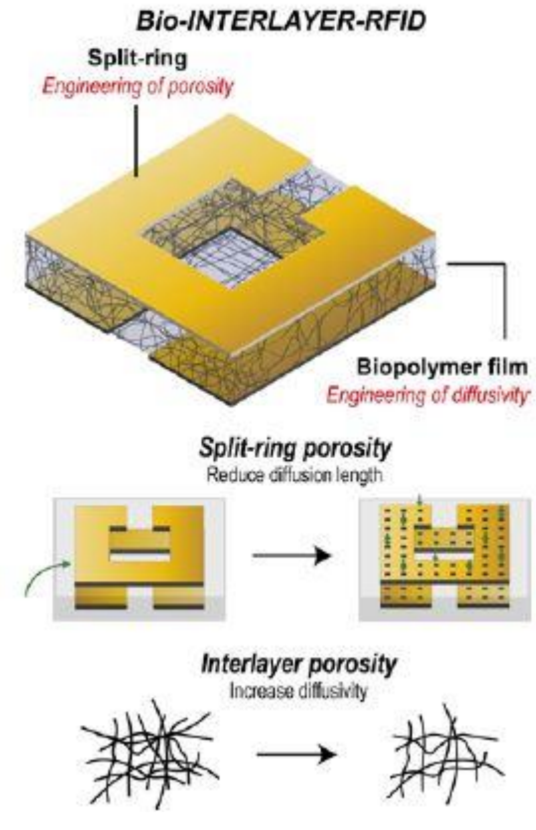

Figure 15: Improvements for the sensor's sensitivity and time response [30].

3.2 System development

Diet and nutrition monitoring are currently self-tracked and inaccurate. Health and food consumption are closely related, and it is difficult to keep track of all of the food and beverages a human takes every day. Moreover, allergic and food-intolerant people can be at risk if they ingest those foods. To monitor diet, a whole system in addition to the novel sensor needs to be developed to be able to record food consumption.

For that purpose, the food intake monitoring project has started [6] [30]. Three different sensors are needed to detect the nutrients and the quantity: 1. The RF tri-layer sensor, to detect the different nutrients of the food in the mouth. 2. A strain gauge, to monitor jaw movements. 3. An acoustic sensor, to measure the swallowing. This first approach can change if during the project other technologies or methodologies appear and are proven to be better than the mentioned ones, but these are expected to work together and become the first food intake monitoring system based in the RF tri-layer sensor.

The data of the transducers will be transmitted to a wearable device, a Medical IoT platform where data can be analyzed. This embedded system, limited by the size, power and battery autonomy, needs to be able to utilize data from the sensors and, using machine learning techniques, identify the type and quantity and record the nutrition of the user.

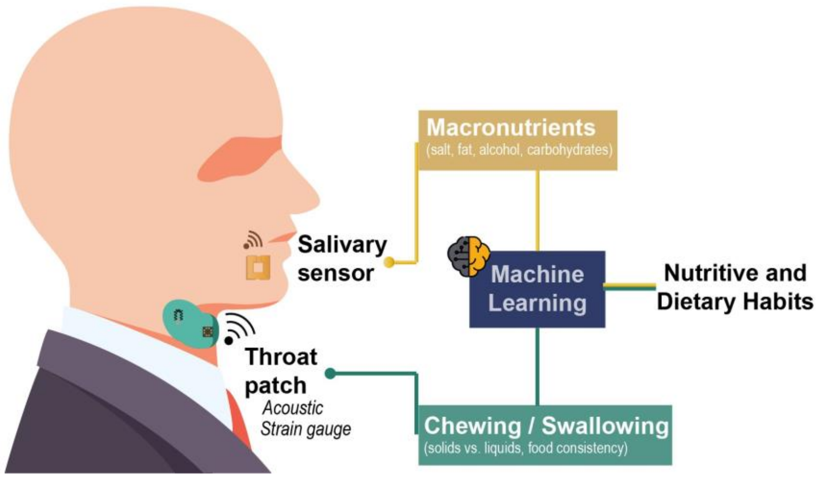

Figure 16: Diagram of the system [6].

A salivary sensor has been presented in [22], but it is interesting to understand how the other two transducers work and the information that it can provide. The first sensor is the strain gauge [11] used to monitor the jaw movements. This piezo-resistive strain sensor is made of wrinkled platinum (wPt) nanostructures and is ultrasensitive and bio-compatible. It has been developed at the University of California, Irvine, and has been proven to detect physiological activity such as chest wall displacement during respiration.

Figure 17: Strain sensor placed to measure chest wall displacement [11].

The second sensor is an acoustic transducer used to collect the sounds generated during eating, and later processed to detect different events. In combination with the previous sensor and a machine learning algorithm, it will provide information about the density of the food (liquid or solid) and help quantify the volume ingested by analyzing the sounds made by swallowing.

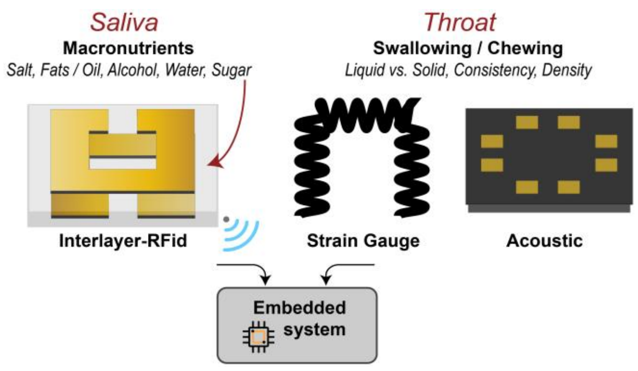

Figure 18: Sensor's and system schematic [6].

Although the project's schedule is not completely developed, as it is at a very early stage, there are some short-term and long-term objectives defined. The first step is to obtain data from the RF tri-layer sensor and transfer it to a wearable device. This step is very important, because it is an in-vivo sensor where size, power and data transmission are challenging. After completing this stage, the rest of the sensors can be implemented. Acquisition, calibration and accuracy have to be studied to ensure the reliability of the data. Finally, the machine learning algorithm embedded in the wearable device will be developed, so the system can detect the different kind of nutrients, and measure the quantity of every ingested food component (e.g., water, glucose, alcohol, etc.). Once this step is done, the nutritional data of the user will be recorded and ready to use in health or fitness applications.

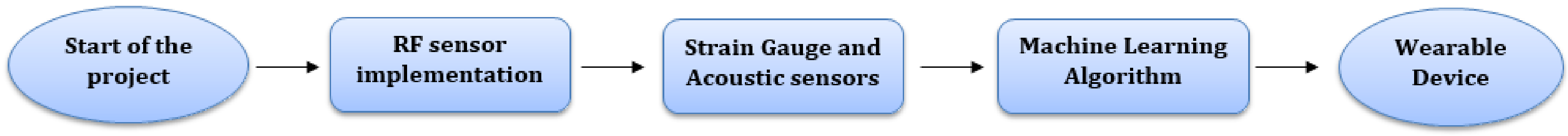

Figure 19: Flow Diagram of the project.

4 Communication system study

In this chapter, the communication system of the RF mouth sensor is studied. To begin with, the VNA measurement method is reviewed. Then, other wireless approaches and technologies will be compared, such as inductive coupling and EM-waves coupling. Moreover, the powering options of the transducer are also discussed, along with the safety regulations concerning the maximum power exposure of human bodies.

4.1 The Vector Network Analyzer method

A Vector Network Analyzer (VNA) is an instrument that determines the network parameters in electrical systems. The VNA differs from a Scalar Network Analyzer (SNA) in the output of the device, because a VNA measures not only the amplitude but also the phase properties of the network. A VNA is also different from a Spectrum Analyzer, because the latter only measures external signals over frequencies, while the VNA generates signals and receives the device's response over a frequency range.

VNAs are normally used in RF and microwave devices to make sure they are matched with input and output impedances. They usually have two ports, enabling the measurement of four S-parameters (s_{11}, s_{12}, s_{22}, s_{21}) and thus characterizing the reflection.

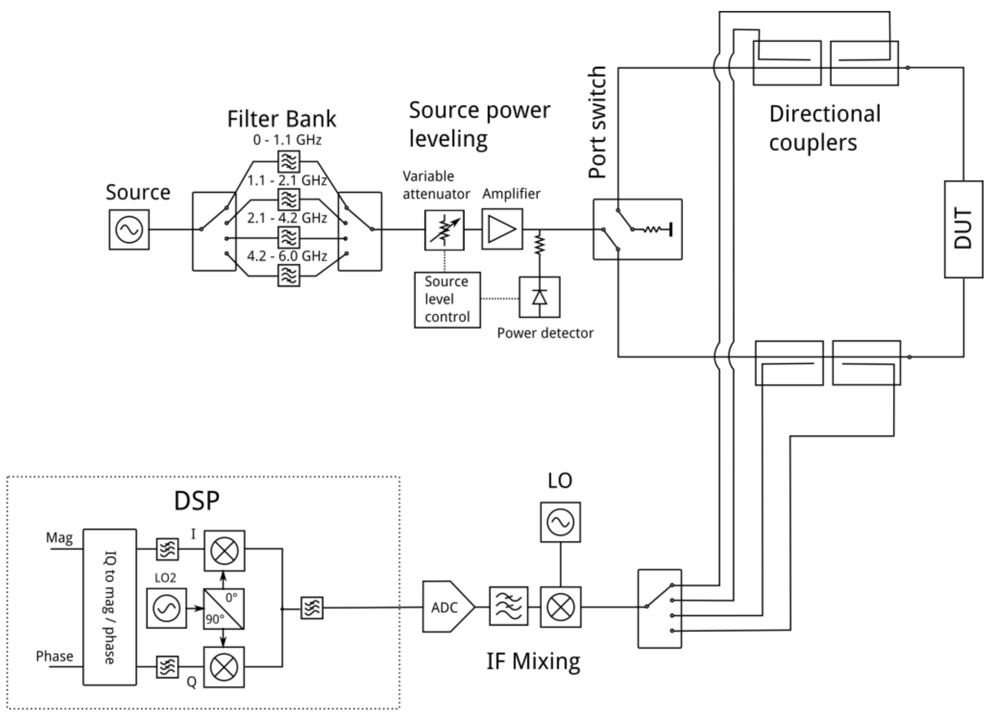

Figure 20: Two-port, single-receiver VNA schematic [4].

The schematic in Fig. 20 [4] is useful to understand the basic operation of a VNA. To begin with, a signal generator, based in a Phase-Locked Loop (PLL), creates signals in the desired range of frequencies. Those frequencies are transmitted to the Device Under Test (DUT) to excite it, and the waves are measured in amplitude and phase as a reference. Then, some part of the signal is reflected back to the source due to the impedance mismatch, and the waves are measured again. Finally, both the transmitted and the received signals are compared and the S-parameters are calculated.

A PLL is a negative feedback loop that consists of a Voltage Control Oscillator (VCO) and a Phase Detector (PD), whose function is to synthesize high-frequency signals with a precisely set frequency. The system is based in the fact that two signals of different frequencies always exhibit a time-varying phase difference, and thus achieving two signals whose phases are locked together results in two signals with the same frequency. Signal generators are usually based in this structure.

To perform correctly, a special component, known as directional coupler, is needed in VNAs to measure the signals that are sent and received. A directional coupler is a passive device that couples a defined amount of EM power in a transmission line to a measurement port, but that coupling is only active in one direction. This property enables differentiation between the transmitted and received power in a VNA, thus allowing calculation of the different S-parameters as a reflected-to-transmitted power ratio.

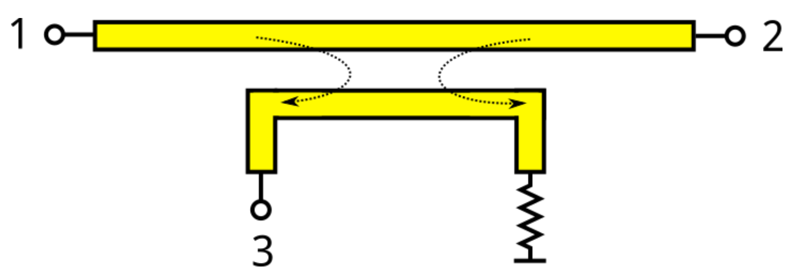

Figure 21: Directional Coupler [4].

In Fig. 21, a coupled-line directional coupler is presented. When a signal is transmitted from port 1 to port 2, some power will be coupled to port 3. However, in the opposite direction, when a wave goes from port 2 to port 1, the power will couple but nothing will be detected in port 3 because it will be absorbed by the grounded end. Using an array of directional couplers, two reversed for each port, transmitted and reflected power can be measured, and S-parameters calculated.

This method is used in many RF applications to detect changes in the resonant sensors' impedance. In [22], the authors use a VNA to monitor the passive sensor's response to different solvents, detecting the changes in resonant frequency and reflected power amplitude. In [25], a passive pressure sensor is also fabricated using the shift in resonant frequency as the main output in a reflection analysis.

Although the VNA method to measure the scattering parameters over a range of frequencies is proven to be accurate and convenient for different applications, it is important to determine if a portable and wearable VNA can be developed with the current technologies. The size of the device itself is one of the key factors, because it will determine the possible implementations of the device.

As shown in Fig. 20, a VNA consists of a signal generator, an array of directional couplers, and a signal processing tool. The signal generator can fit in a small-size integrated circuit, such as the AD9833, a programmable waveform generator in the range of 0 MHz to 12.5 MHz output frequency range [8]. Other commercial ICs can be found to fit the range of the Food-Intake Monitoring project, more likely to be around 200 and 600 MHz, or a custom CMOS IC can be built using RF circuit design tools such as Cadence Virtuoso. The signal processing tool, that detects phase and frequency of the desired signals, is normally built in a Digital Signal Processor (DSP). These DSPs are available with different resolutions and features, and they are commercially available as embedded ICs (e.g., TDA7590 DSP from STMicroelectronics). Finally, the last component that needs to be studied is the directional coupler.

Directional couplers act as passive devices that couple the power of two lines. The size of the lines is related to the wavelength (λ/4 in many applications); at MHz frequencies this length is on the order of cm. In [7], a reconfigurable low-power CMOS directional coupler is designed to fit applications in the range of 2-6 GHz. This CMOS IC is much more complex than the conventional couplers, such as the coupled-line coupler presented before, but the size is only 350 μm x 340 μm and consumes only 40 mW. Implementing a 200-600 MHz small-sized directional coupler will be a novel research topic, and will enable the development of a fully-portable VNA for the mouth sensor project. Moreover, the higher the frequency of operation, the easier to reduce the size of the directional couplers; thus, another option is to increase the sensor's resonant frequencies to the GHz range, facilitating miniaturization.

One interesting step to begin with is to reverse engineer the commercial miniVNA Tiny, a small-sized portable VNA that allows wireless reflection measurements but needs to be always connected to a smartphone or computer. It has a range from 1 MHz to 3 GHz, and a size of 5 cm x 5 cm x 2 cm. However, the accuracy of the device is not comparable to laboratory-oriented VNAs, but can give important information if the project needs to build a custom VNA.

Figure 22: MiniVNA tiny.

4.2 Near-field and far-field technologies

RF technology covers electromagnetic wave frequencies from 20 kHz to 300 GHz. This range can be divided more specifically into Low Frequency (LF), Medium Frequency (MF), High Frequency (HF), Very High Frequency (VHF) and Ultra High Frequency (UHF).

	f
LF	30-300 kHz
MF	300 kHz-3 MHz
HF	3-30 MHz
VHF	30-300 MHz
UHF	300 MHz-3 GHz

Table 1: The RF spectrum.

The electromagnetic field created by these waves has two different regions: near-field and far-field. Close to the antenna, the non-radiative or near-field behaviours dominate, and at greater distances the electromagnetic radiation or far-field dominates. The near-field systems utilize magnetic or inductive coupling, while the far-field systems employ the electromagnetic coupling [31].

The boundary between these regions is not clearly defined, and normally near-field refers to distances less than one main frequency wavelength, while far-field refers to distances greater than two wavelengths. Between those regions, there is a transition region where phenomena of both fields coexist.

One of the differences between the two regions is the field strength relation with distance. In the far-field, electric and magnetic field strengths vary inversely with distance from the source, so the radiated power intensity of EM radiation varies inversely with the square of the distance. In the near-field, the electric field varies inversely with the square of the distance, while the magnetic field varies inversely with the cube of the distance. This property results in near-field effects vanishing rapidly a few wavelengths away from the antenna.

Near field is generally used in systems operating in the LF-HF band, with reading distances within the radian sphere, whose radius is defined as $\lambda/2\pi$ (< 125 kHz: 2,400 m; 13.56 MHz: 22.1 m). The near-field antenna is simply an inductor, where the physical size is not dependent on the frequency of operation. Radiative far-field coupling is used in UHF and microwave RF applications, and the simpler antenna is a dipole, with a physical size of half a wavelength long. The higher the frequency of operation, the smaller the far-field antenna. For instance, at near-field operation frequencies, far-field antennas would be at least 11 m long, an incompatible size for RFID or other portable devices. RFID technology is available at different frequencies, such as 125 kHz, 13.56 MHz (e.g., Near Field Communication), 433 MHz, 915 MHz and 2450 MHz.

The authors in [9] have reviewed the different RFID technologies in human body implants. To begin with, LF RFID are very simple devices, with low data communication rates (5.2 kb/s) and without cryptography. Meanwhile, UHF (900 MHz) devices work with higher data rates; they are more complex and can be encrypted to improve security. Nevertheless, at these higher frequencies the attenuation due to water existing in the human tissue is important, making it inconvenient for implants. Finally, at HF the attenuation is not substantial, and it offers better data rates than LF devices. These features make HF RFID, such as 13.56 MHz NFC devices, suitable for human body implants.

With regard to the distance between the RFID tag and the interrogator in human body passive implants, it is generally short range [23]. Inductive coupling tags' operating distance is shorter than 10 cm at 13.56 MHz, and shorter than 1 mm at 2.45 GHz. Moreover, electromagnetic coupling technologies' range is between 1 m to 15.7 m at 900 MHz, and 7.5 cm at 5.8 GHz. Active tags have better results, because the amount of transmitted power can be increased. The distance is related to the type of technology (near or far-field), but also to the frequency, the part of the body where it is implanted and the type of sensor or tag (active or passive). Experiments are needed to determine the attenuation and maximum distance between the RF sensor and the interrogator, with different frequencies, technologies, and mouth models.

In conclusion, to determine which of the technologies is chosen in the Food-Intake Monitoring project, the frequency of operation needs to be first decided. To simplify the design of the antennas, the near-field technology, based only in the magnetic field coupling, seems to be the better solution. However, if the frequency of operation approaches the GHz range, the far-field technology will be more suitable for the application.

4.3 Coupled Inductors method

Near-field RF technology exploits the non-radiative magnetic field coupling to transmit power and data between a tag and an interrogator in RFID devices. To measure the output of the RF tri-layer sensor in the Food Monitoring project, this technology can be useful to maintain the transducer as a passive device and receive power and data from a portable reader.

The sensor can be modelled by an LC tank, consisting of a parallel resonator circuit with a variable capacitance. A resistor is added to simulate the losses of the sensor. To test the response of the sensor in different situations, different simulations have been done using Cadence Virtuoso Software. The values used in the simulation are not related to the real sensor, but they are calculated to have a resonant frequency of around 400 MHz as the original RF sensor (R= 60 kΩ, L= 158 nH, C= 1 pF).

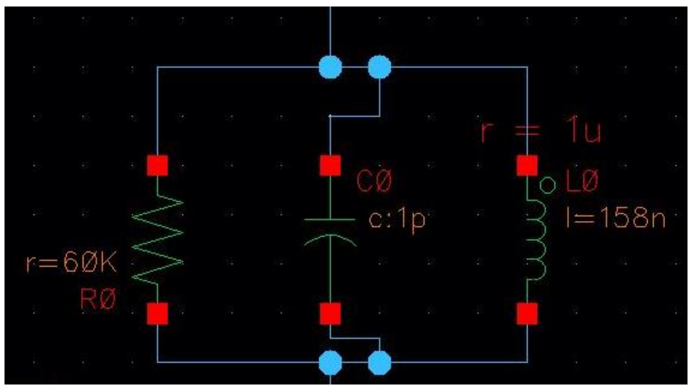

Figure 23: RLC tank schematic in Cadence Virtuoso.

The resonant frequency is calculated using:

$$f_R = \frac{1}{2\pi\sqrt{LC}} = 400.39 \text{ MHz} \quad (14)$$

An important parameter, related to the Scattering parameter and the reflection, is the impedance of the parallel circuit. The transfer function of the parallel impedance is:

$$Z(s) = \frac{\frac{s}{C}}{s^2 + s\frac{1}{CR} + \frac{1}{LC}} \qquad (15)$$

The frequency response of the resonator can be simulated using a Bode analysis:

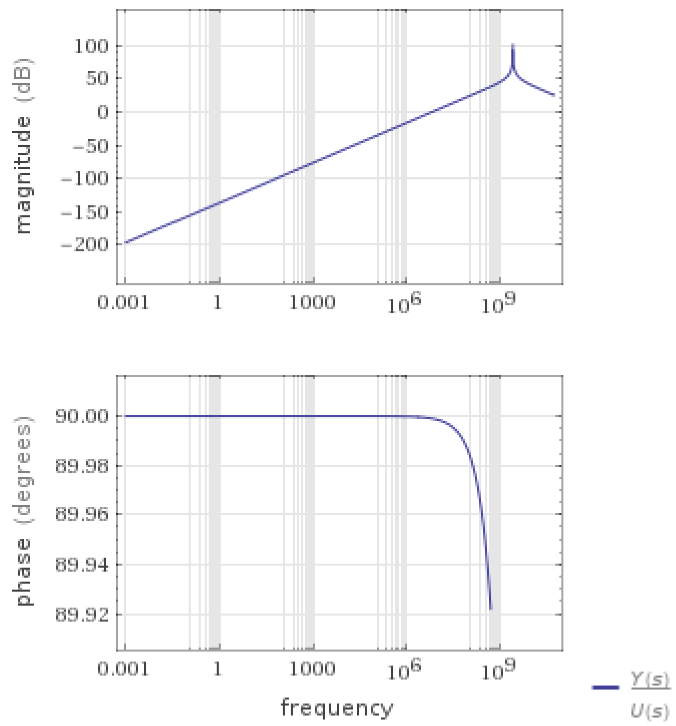

Figure 24: Bode analysis of the impedance using Wolfram alpha.

A peak in magnitude is observed at the resonant frequency of 400.39 MHz, as expected.

When two inductors are coupled with a magnetic field, they are characterized by the mutual inductance coefficient M, defined as:

$$M = k\sqrt{L_1 L_2} \qquad (16)$$

where k is the coupling coefficient, $0 \leq k \leq 1$, which represents the quality of the coupling; k=0 means the inductors are not coupled and k=1 is perfect coupling, only possible in theory.

$$\begin{pmatrix} \emptyset_1 \\ \emptyset_2 \end{pmatrix} = \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix} \qquad (17)$$

The flux and the current of both inductors are related with each inductance and the mutual inductance coefficient.

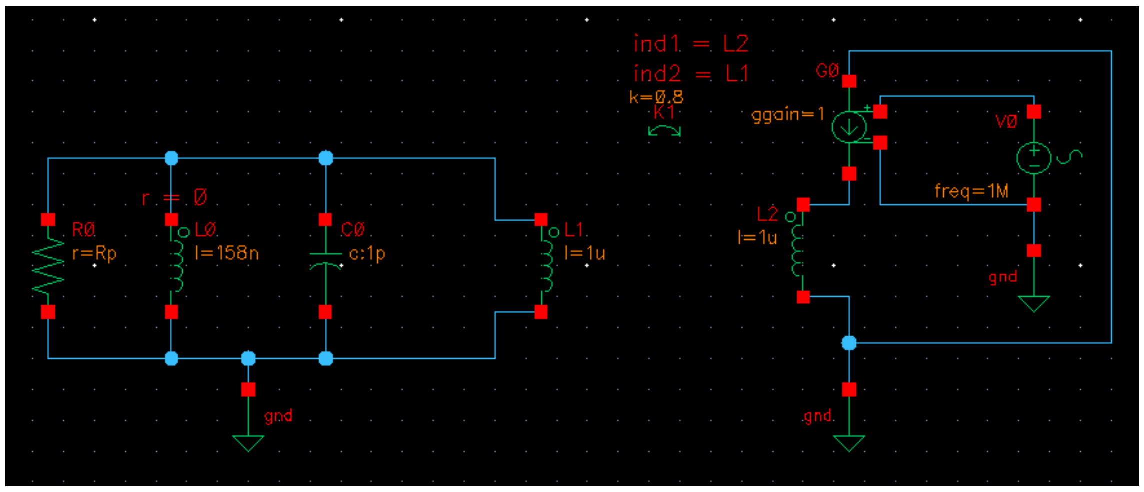

Figure 25: Schematic of the resonator system with coupled inductors.

As shown in Fig. 25, adding a 1 μH inductor to the RLC tank and to the interrogator system, with a current generator formed by a transconductance with unity gain, the coupled inductors method is simulated.

Simulation 1: Transient response, R=60 kΩ, current source: 1 MHz and k=0.8

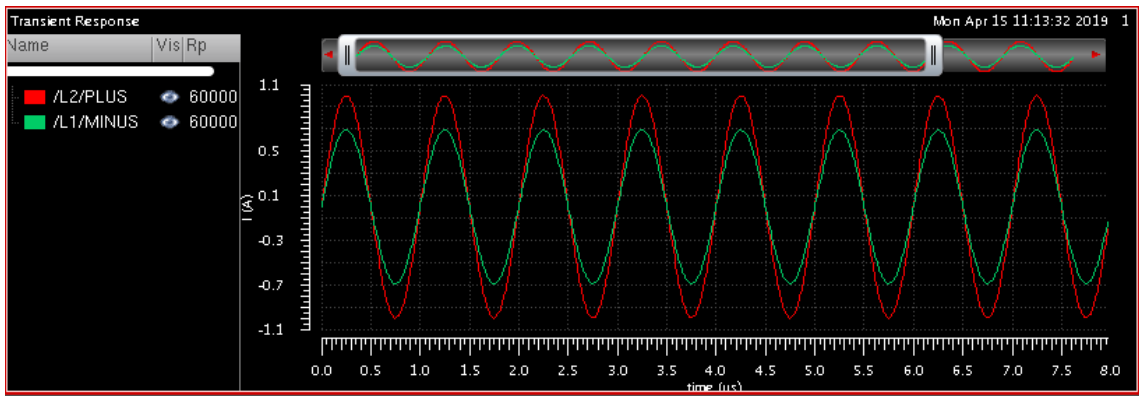

Figure 26: Current of the coupled inductors

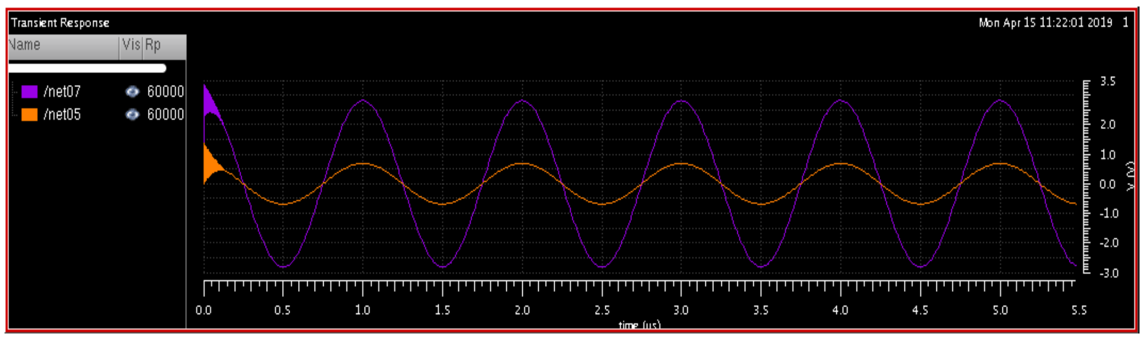

Figure 27: Voltage at the inductors

The current and voltage at the inductors are in phase, and current in L_1 (RLC tank) diminishes compared to the interrogator L_2 because the coupling is not ideal (k is set to 0.8, typical value in air).

Simulation 2: Ac Analyses (100 MHz – 1 GHz):

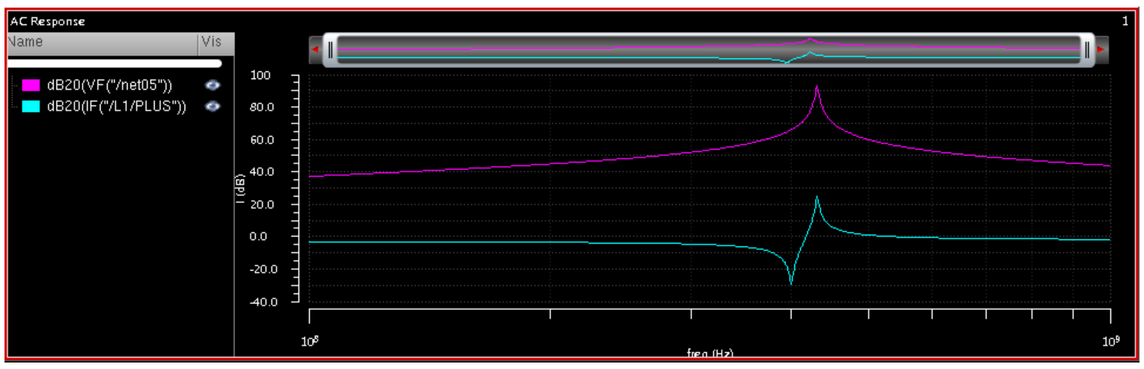

Figure 28: Voltage (up) and Current (down) at the resonator circuit.

Figure 29: Current in both inductors.

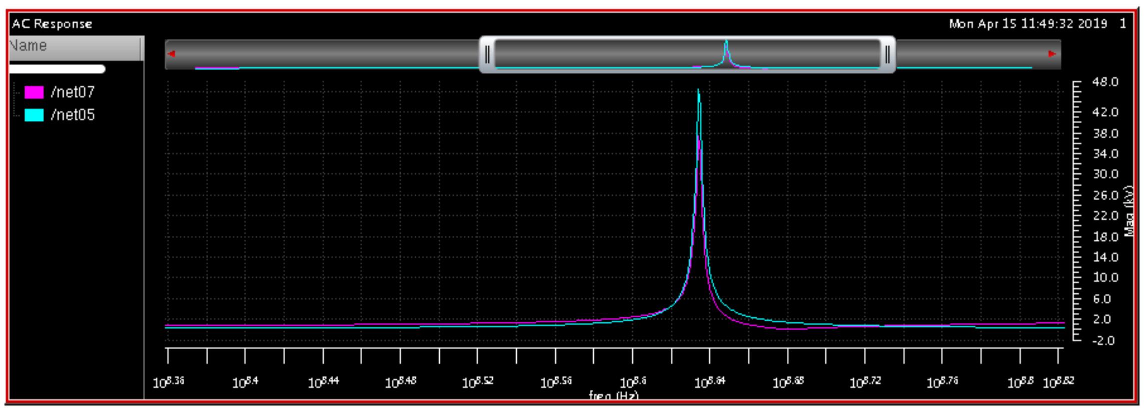

Figure 30: Voltage in the inductors.

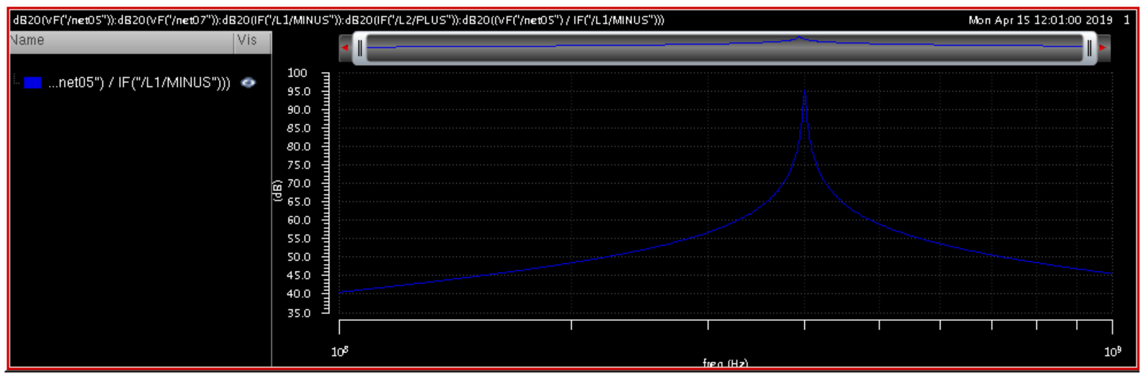

Figure 31: Impedance at the resonator, peak in 400.39 MHz.

Observing the graphs, the voltage and current in the inductors is affected by the antenna, provoking a shift in resonant frequency from 400.39 MHz to 430.87 MHz. A minimum value of current in the resonator can be observed in 400.39 MHz, the actual resonant frequency of the RLC tank. The impedance, calculated as the voltage divided by the current, has its peak in the correct frequency of 400.39 MHz, thus the result of the system is correct to measure the impedance's resonant frequency.

Simulation 3:

The RF mouth sensor has a resonant frequency between 300 MHz and 500 MHz. To model it, a variable capacitor is put in place, and a parametric analysis is performed. Using the equation for the resonant frequency, the values for C are calculated to be between 0.64 pF (500.49 MHz) and 1.78 pF (300.11 MHz).

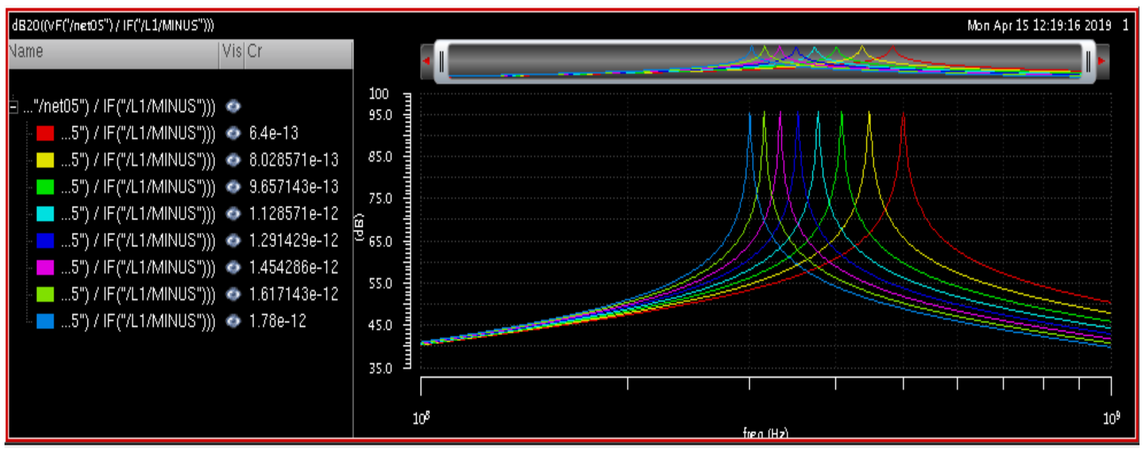

Figure 32: Impedance for different C values.

The plot in Fig. 32 shows the shift of the peaks in frequency depending on the C value. The magnitude of the impedance remains constant, so the electrical model of the RF sensor, that changes the impedance both in resonant frequency and amplitude, will need other variable components to characterize completely the transducer's behavior.

4.4 Power options

RFID tags can be passive or active, depending on whether the electronics are powered by the reader signal wirelessly or by a power source, respectively. In the case of the RF mouth sensor, based in a resonator metamaterial that shifts the resonant frequency according to the solvent or fluid where it is immersed, both options can be developed. This decision is very important in the evolution of the project, because the features and the design of the system depend greatly in this aspect.

To begin with, passive sensors with wireless power transfer (WPT) have a big advantage in human implants, because avoiding the need for a power source inside the body is very convenient. Wireless power transfer can also perform in near-field and far-field technologies, and is based on the same electromagnetic concepts as wireless data transmission [24]. Risks such as battery degradation can be avoided, and not having to replace and charge batteries make the maintenance easier. Moreover, the size of a battery can be double the size of the device itself, becoming a larger implant to introduce inside the mouth. The cost of passive systems is lower, because they need fewer components and are simpler than active devices.

However, active tags have also advantages in the food monitoring application. First, having continuous power enables more processing in the device. For instance, part of the calibration of the system and the food detection can be computed before the wireless transmission is done. Moreover, avoiding the power transfer with the external interrogator improves the distance of transmission, because the tag's power doesn't depend on the alignment of the antennas and thus the transmitted power remains constant. In addition, a full transceiver can be installed in the chip when the power is supplied by a battery [31]. Finally, concerning the security of a health application, encryption is easier in this case, because more complex digital circuits can be added to the device. One possibility to have an embedded battery and sensor is developing a tooth implant that replaces a real tooth, allowing all the necessary components to be in one only package, but the market options of this device will be substantially reduced.

Feature	Active	Passive
Size		
Biocompatibility		
Distance		
Complexity		
Security		
Cost		

Figure 33: Summary of power options' features.

One interesting scenario is to develop both an active and a passive device and, after having a full prototype of both types, benchmark the properties of both power options to decide whether or not including a battery. Although the additional features offered by active devices are very interesting, the simplicity and convenience of passive tags are important factors to consider on this decision.

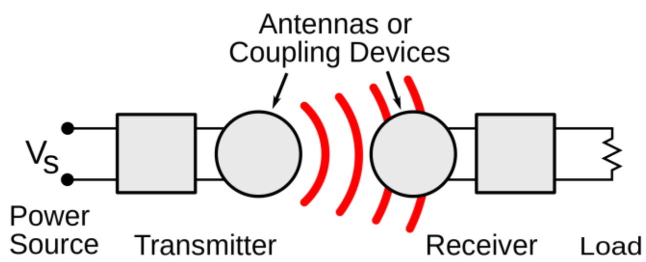

Figure 34: Wireless Power Transfer schematic.

4.5 FMCW radar

The size of directional couplers in vector network analyzers is a crucial obstacle to reduce the device's form factor. Other options such as increasing the frequency of operation can facilitate the miniaturization of this component, reducing the wavelength of the signals. However, other implementations to measure the reflection are also available.

In [26], a passive pressure sensor is developed. To measure the sensor's response, a different approach from the classic VNA is used: The Frequency Modulated Continuous Wave (FMCW) radar. This technique is also based in electromagnetic signals interrogation, to measure the resonant frequency of the pressure sensor.

A radar system is composed of a transmitter antenna, a receiving antenna and a processor. Radio waves are sent from the transmitting antenna, and the reflection of the signals in the object is measured in the receiving antenna to determine its properties. In this case, the scattering from a pressure sensor is measured, and the desired output is the resonant frequency. This system can be adapted to the Food Monitoring project, avoiding the use of directional couplers. However, the use of two antennas compared to the one-antenna design in VNAs also limits the form-factor reduction of the device.

To interrogate the RF sensor, the radar sends signals of an increasing frequency (chirp) to the passive sensor, and a signal is reflected back. The reference and the received signals are mixed and analyzed in the processing unit, to finally store the information before the next frequency step is sent. When the impedance of the sensor changes, the resonant frequency and the amplitude of the S-parameters will change accordingly. For this reason, the data captured by the radar is related to the sensor's measurement.

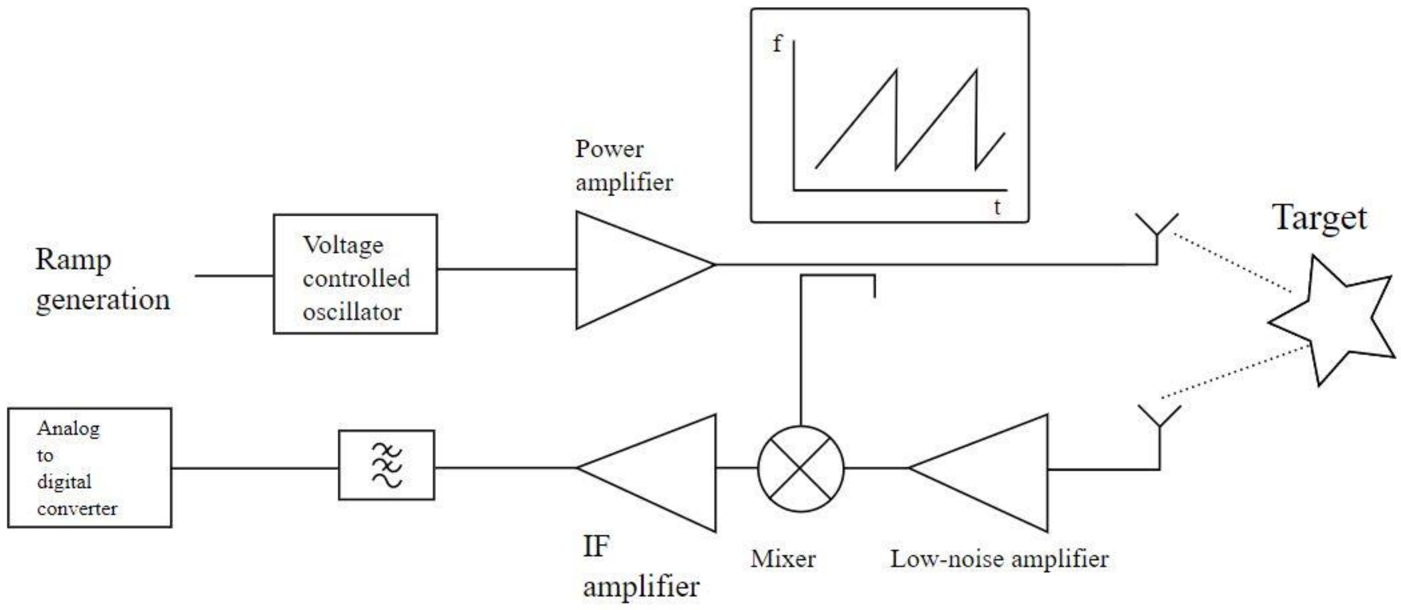

Figure 35: FMCW radar schematic [2].

The main advantage of this method is that the directional coupler array is avoided. Thus, the possibility of making a fully portable RFID reader for the Food Monitoring project exists using the current technology, without having to move the range of the sensor's frequencies above the GHz domain or to develop a new miniaturized directional coupler. The signal generator is also based in a PLL and a VCO, but instead of using only one antenna to send and receive the signals, two antennas with different objectives are used: one for sending and one for receiving signals. Having both antennas' data enables the processing unit to determine the S_{11} parameter, and thus characterizing the sensor's impedance.

In conclusion, the FMCW radar method is another viable option to develop a portable RF reader for the Food Monitoring project. This way, the sensor can remain passive, and only a near-field coil is needed inside the mouth apart from the BC-SRR structure. Moreover, the frequency of operation can still be around 400 MHz, avoiding the need to change the dimensions of the sensor in order to increase the frequency and to reduce the wavelength.

4.6 Safety regulations

Wearable devices, especially those that need implanted sensors in human bodies, have to comply with safety rules concerning the maximum power and frequency of operation. The communication system of these devices is one of the higher frequency parts, and power is also important when wireless power and data transmission are needed to communicate with implanted chips.

In 2006, the Institute of Electrical and Electronics Engineers (IEEE) approved the new "Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz". These rules, concerning mostly mobile telecommunications and wireless devices, follow some of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines, but it is not identical and covers a wider bandwidth [1].

The exposure limits for electromagnetic fields are harmonized in this standard. The maximum specific absorption rate (SAR) over an entire human body is specified to be 0.08 W/kg, to limit the heating of the human body. For the arms, legs and external part of the ears this limit increases to 4 W/kg, and the SAR in most of the parts of the body for localized exposure is 2 W/kg.

The IEEE also limits the maximum power of exposure, which is dependent on the frequency. In the range of 100 kHz to 100 GHz, the maximum incident power density is 1000 W/m^2 and 10 W/m^2, respectively. The lowest value is between 30 and 400 MHz, where the incident power is limited to 2 W/m^2.

In the RF sensor project, the frequency range is from 200 to 600 MHz. The most limiting incident power in the range is 2 W/m^2. However, this is a low-power application where the electromagnetic power is going to be in the mW range. Thus, the safety standards are not going to pose an obstacle to the communication system design.

5 Conclusions

An important function of wearable devices is still missing in the market: an accurate diet monitoring device. The Food-Intake Monitoring project aims to fill that void, by creating a portable food detection system. A novel RF tri-layer sensor has already been discovered in [22], and the University of California, Irvine is laying the foundation for developing an IoT system based in this transducer. This device consists in three different sensors and a machine learning algorithm, and will enable to detect the food and the quantity ingested by the users.

To begin the project, a portable tool to wirelessly obtain the output of the mouth sensor is needed. Different approaches have been studied, such as the VNA and the FCMW radar. VNAs are the standard to measure the S-parameters of passive devices, but the form factor of a particular component, the directional coupler array, makes it very difficult to make it portable. On the other hand, the FCMW radar seems a very novel way of getting the implant's data, and could be a solution for the size problem, even if a second antenna is needed.

Secondly, two different options exist to couple the external interrogator and the transducer in the RFID domain: The near-field and far-field technologies. The NF refers to the magnetic coupling of two inductors, whereas the FF coupling is based in electromagnetic waves. Antennas in NF are simpler, consisting only of two coupled inductors, a case that is also studied in the thesis, while in FF the size of a dipole is half the wavelength. The choice between them is based more on the frequency of operation than on any other factor, which is why the NF is imposed for this application, but could change if the frequency range of the sensor increases to the GHz range.

Another aspect studied in the thesis is the power options for the implant. Although maintaining a passive device is a very convenient alternative, reducing the cost, the complexity and the biocompatibility issues, as well as adding an embedded battery, can boost the processing and communications option of the sensor. Prototyping both devices and deciding which one is a better approach can be an adequate choice in this early stage.

Finally, the safety regulations for the RF electromagnetic exposure of the human body have been reviewed using the IEEE standard. Although the frequency range of the mouth sensor is placed in the most restrictive SAR limits, the application won't cause any limitations during the design of the communication system, but it is always something to take into consideration.

5.1 Future work

Once the communication system study has been completed, the project can move forward to the next stage. Prototyping a portable measurement device is a crucial investigation, and will trigger new obstacles and problems to be solved.

Moreover, depending on the robustness of the coupling between sensor and interrogator, the alignment of the antennas can be very important for the system to be accurate. The RF sensor used in this project is going to be placed inside the mouth, so a skin layer will be separating the transducer from the external interrogator. While eating, the jaw movements can provoke misalignments of the antennas that affect the transmission of data and eventually of power. It is important to design the communication system of the Food Monitoring project taking into account the alignment and the distance of the antennas.

Cybersecurity is a relevant feature in wearable devices, and the communications will need protection systems such as encryption. Moreover, other transmission options could be studied, like the skin conductance technology to transmit data wirelessly using the moisture of the skin layers. Finally, additional research can be pursued concerning the main mouth sensor: characterizing it electrically, using an impedance analyzer to get the response to different solvents, etc.

The Food-Intake Monitoring project has just started, and exhibits very good potential. A lot of work is still needed to make this new Wearable Device a real market option, but a group of researchers is currently working on it to satisfy the requirements of the users concerning diet.

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