RFID Technology for Wearable, Epidermal and Implantable Biomedical Devices

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Abstract

RFID (Radio Frequency IDentification) is a particularly promising technology that saw its origin during the Second World War and is, nowadays, gaining more and more interest in countless domains, ranging from communication to healthcare, from anti-counterfeiting to animal identification.
In particular, the use of this technology in the healthcare sector is showing a great potential both for on-body and in-body applications. Overall, it can be really helpful for people who suffer from impairments or disparate diseases, such as diabetes or epilepsy. Many aspects need to be taken into account in order to exploit this potential, one in particular is the proximity with the human body, which requires different designs, materials and testing.
The first aim of this report is to present the general characteristics of RFID systems and their classification, defining the main parameters to consider when designing such devices. The second section presents a short review of the newest discoveries and studies in the field of biomedical applications of RFID, with a particular focus on wearable, epidermal and implantable devices. Different fabrication methods for body-area RFID systems are reviewed and many critical challenges are presented, such as the need for robust, flexible, light-weight, safe and low-cost devices, along with the solutions that have been reported up to date. Sample studies are reported in order to show the results achieved with different designs and the problems that still need to be solved.

1 RFID Technology

1.1 General Characteristics

RFID systems are mainly constituted by three parts [1]:

1. A transponder, attached to the object to be identified;
2. A wave propagation medium;
3. A reader, linked to a computer where the application for data extraction is running.

The reader sends a request to the transponder, which replies. In some cases, the reader provides energy to the transponder, while in other cases the transponder has its own power supply. Both the reader and the transponder (or tag) are equipped with an antenna, which is the coupling element. The basic design is shown in Figure 1.

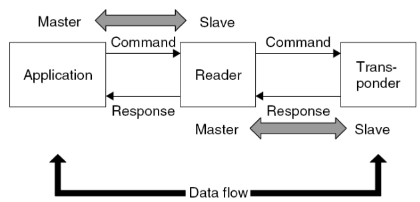

Figure 1: *Master–slave principle between application software, reader and transponder [2]*

RFID tags can also be used as sensors: a sensor node is a node that is capable of performing some processing, gathering sensing information and communicating with the other nodes. So, a sensor integrated RFID is composed by one or more sensing units, a Micro Controller Unit, a transceiver and, in many cases, a battery. RFID sensors can be of two types [3]:

- Chipless RFID sensors: these sensors do not contain any IC chip, so the tag has higher sensitivity and lower cost. More recently, chipless RFID-enabled sensor tags having different structures have been studied by Rasheed et al. [4].
- Chip RFID sensors: in this case, a RFID tag with an integrated battery is preferable with respect to a passive one, despite energy harvesting from the environment is being widely investigated. An example of this is reported in [4].

1.2 Classification on the basis of transponder power supply

- Active transponders: the power supply is provided by an on-board battery; it is made by a transceiver, whose sensitivity limits the distance from the reader, and a microprocessor in case you need computing power;
- Semi-passive transponders: only logic and memory management circuits are powered by batteries. The transmission is based on backscattered modulation of the field radiated from the reader, which means that the transponder receives energy from the reader's transmission and uses that same energy to send back a reply. The received energy travels through the tag's antenna and activates the chip. The remaining energy is modulated with the chip's data and flows back via the tag's antenna to the reader's antenna [5];
- Passive transponders: the energy required for the operation is completely extracted from the reader's field. These are used for simple, low power circuits. Passive tags are mainly composed by a substrate on which they are printed (paper, plastic film, etc.), a chip and a tag antenna. The chip contains the tag identification code, converts energy into tag feeding and modulates the reflected power to communicate this code.

1.3 Classification on the basis of frequency

The transmission frequencies are classified into different ranges: LF (30–300 kHz), HF (3–30 MHz) and microwaves, including UHF (300 MHz–3 GHz), SHF (3-30 GHz) and EHF or millimeter waves (30-300 GHz) [2]. In Figure 2 we can see the frequency ranges available for RFID systems. In the frequency range above 135 kHz the ISM (Industrial Scientific Medical) bands, which are internationally reserved for applications using high-frequency devices, are preferred.

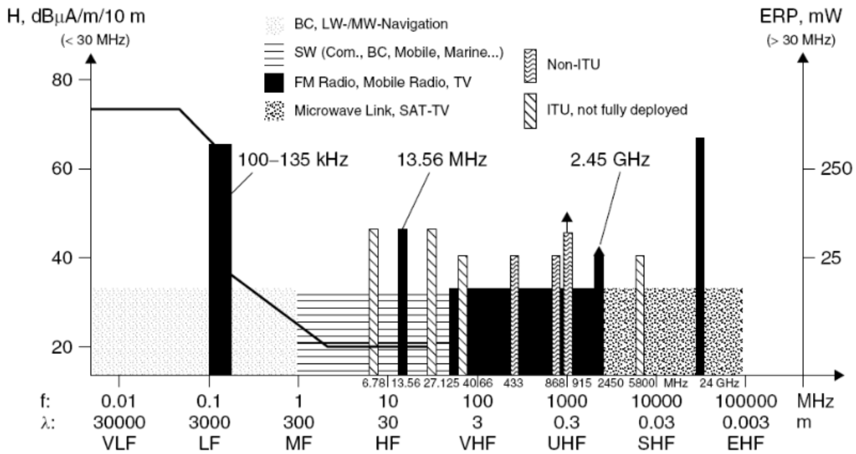

Figure 2: *Frequency Regulation for RFID Devices [2]*

1.4 Classification on the basis of read range

A subdivision of RFID systems according to range allows us to differentiate between close-coupling (0 – 1 cm), remote-coupling (few cm – 1 m), and long-range (> 1 m) systems. In the first two cases, when the frequency is in general lower than 30 MHz, we have coupling through the Magnetic field (inductive). In the case of long-range systems, usually when the frequency ranges from 868 MHz to 5.8 GHz, we have Electromagnetic wave propagation. We can also find long-range systems using surface acoustic wave transponders in the microwave range [2].

It is also useful to define the near field region and the far field region of an antenna. As we can see in Figure 3, the near field region is located close to the antenna and is subdivided into a reactive near field region, when $R < 0.62\sqrt{\frac{D^2}{\lambda}}$, and a radiating near field region, up to $R = \frac{2D^2}{\lambda}$ [6].

There are some aspects that have to be considered when evaluating the operating range, for example the accuracy of the transponder positioning or the minimum distance between transponders. It is not always necessary to maximize this range. It can be useful when seeking for a fast transmission, but it could also lead to worst accuracy and security issues [1].

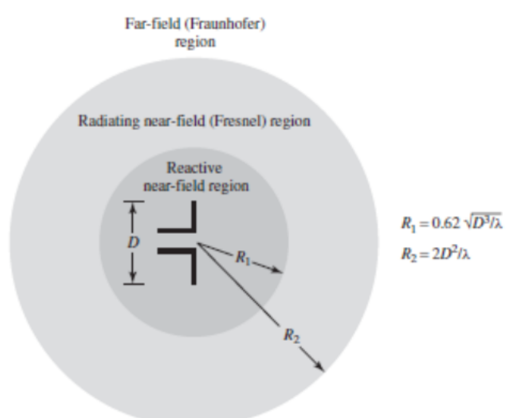

Figure 3: *Field Regions of an Antenna - Courtesy of Professor Andrea Michel [7]*

1.5 Antenna Parameters

The main parameters to be considered for antenna design are radiation efficiency, directivity and gain, polarization and axial ratio, side lobe level, back radiation, half power beamdwidth and first null beamwidth [7], but some of these will not be discussed in detail in this report. We need to define some fundamental quantities to be able to talk about antenna design and RFID applications:

- P_T Power transmitted by the reader, P_E Power received by the tag, P_S Power reflected by tag antenna
- G_T Gain of the reader antenna, G_R Gain of the tag antenna
- R Distance between antennas
- S Pointing vector at the tag antenna (W/m^2) S=$\frac{G_T P_T}{4\pi R^2}$
- A_E Effective area of tag antenna $A_E = G_R \frac{\lambda^2}{4\pi}$
- P_E Power received by the tag P_E=SA_E
- αf Free space attenuation $\alpha f = \frac{P_T}{P_E}$
- δ Penetration depth $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$ where f is the frequency, μ is the Magnetic permeability and σ is the Electric conductivity
- EIRP Effective Isotropic Radiated Power $EIRP = G_T P_T$: power that an isotropic antenna must irradiate to provide the same maximum radiation density.
- RSSI Received Signal Strenght Indication, measurement of the power present in a received radio signal [8].
- SAR Specific Absorption Rate, rate at which energy is absorbed per unit mass by a human body exposed to a RF field [9].

Knowing the value of P_E, we can compute the maximum distance between the antennas as

$$R = \sqrt{\frac{c^2 P_T G_T G_R}{4\pi P_{Emin} f^2}} \tag{1}$$

Then we can compute the power of the backscattered radiation by means of the Radar Equation, where σ is the Radar Cross Section which depends on the object's shape, size and electromagnetic properties.

$$P_{BS} = \frac{\sigma \lambda^2 G_T^2 P_T}{(4\pi)^3 R^4} \tag{2}$$

We can also compute the power received by the tag by means of Friis Equation, where α is the Impedance Matching between tag antenna and RFID chip and X is the polarization efficiency.

$$P_R = P_T G_T(\theta_T, \phi_T) G_R(\theta_R, \phi_R) (\frac{\lambda}{4\pi r})^2 \alpha X \tag{3}$$

To have maximum power transfer, considering that both the chip and the antenna have a characteristic impedance Z, we need that $Z_a = Z^*_{chip}$. We can the define the Power Transfer Coefficient $\tau = \frac{4R_C R_A}{|Z_C Z_A|^2}$. RFID chips are highly capacitive, which implies that the RFID antenna must be designed to exhibit highly inductive input impedance [10].
For passive tags, antennas have to be designed to collect as much energy as possible to feed the chip and to reflect part of it. Shape and size of the antenna depend on the operating frequency, but it is usually a $\frac{\lambda}{2}$ dipole. Figure 4 shows HF Loop Antennas for inductive coupling with a read range up to few centimeters left) and UHF Dipole Antennas for electromagnetic propagation with a read range beyond meters (right). For semi-passive tags, the antennas must be designed to maximize the power backscattering.

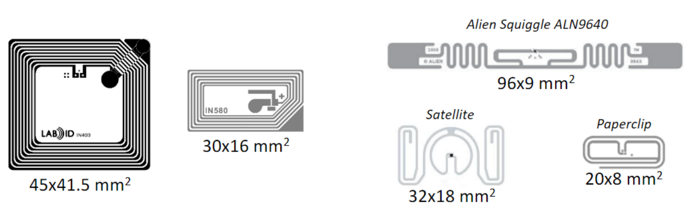

Figure 4: *HF Antennas (left) and UHF Antennas (right) - Courtesy of Professor Andrea Michel [7]*

2 Biomedical Applications

Electronic devices that can operate in proximity with or inside the human body are recently gaining interest in many domains, including biomedical applications. We can speak about ”on-body” electronics, which include wearable and epidermal devices, or “in-body” electronics, namely implantable, ingestible, and injectable devices. These devices can function as sensors to detect vital parameters or as stimulators of the nervous system. This report is focused on three type of healthcare applications: wearable, epidermal and implantable devices.

The proximity between the device and the human body gives rise to a number of issues, such as the choice of the operation frequency, the influence of the human body and the antenna design [10]. For what concerns the choice of the operating frequency, we can state that LF enables high penetration depths, exhibiting a limited read range of a few centimeters. HF works well in cases of deep penetration and typically achieves a read range of 1m. UHF offers long read ranges but it may have problems in penetrating biological tissues.

In the study conducted by A. Kiourti some examples of operating frequency and related applications are cited [10]: 400MHz for Brain-Machine Interfaces, 868 MHz for body temperature readings or limb prosthesis monitoring, 2.45GHz and 4.5GHz for respiratory monitoring.

It is very important to design RFID systems that are safe for the end users. Wearable and implantable RFID technologies need to conform to international and national safety guidelines for the specific absorption rate (SAR), which set the maximum allowable values for the SAR to preserve patient safety. The ICNIRP basic restrictions limit the SAR averaged over 10g of contiguous tissue to less than 2W/kg [11]. The IEEE C95.1-1999 standard restricts the SAR averaged over any 1g of tissue in the shape of a cube to less than 1.6W/kg [12]. The allowable FCC SAR limit is also 1.6W/kg, as averaged over 1g of tissue [13]. Figure 5 shows an example of SAR distribution induced in an anatomical head model by implanted RFID antennas.

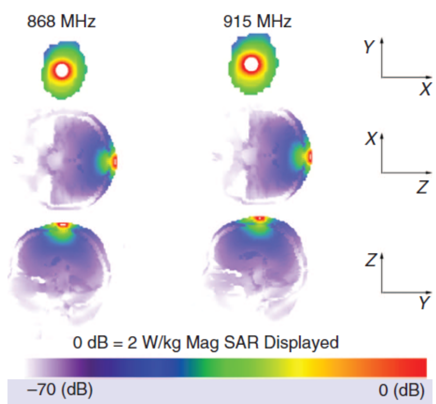

Figure 5: *Local SAR distribution induced in an anatomical head model by RFID antennas implanted under the scalp for intracranial pressure monitoring at 868 and 915 MHz [14]*

2.1 Antenna Design

Many information and references about antenna design have been extracted from a study by Nepa et al. [15].

Wearable Devices Concerning VHF/UHF wearable antennas, problems may arise from the fact that the wavelenght is comparable with the size of the human body sections the antenna can be attached to, leading to issues related freedom of moving and invisible integration into garments. There are many requirements, such as mechanical light weight, low profile, compactness, robustness, low cost, tolerance to stress and flexibility. Long read ranges are required when the RFID tags are used as low-cost wearable sensors for remote monitoring of vital signs and activities of a person.

At the UHF band, antenna layouts can include a ground plane to shield the antenna from the human body. A ground plane is a conducting surface, connected to the transmitter’s ground wire, which reflects radio waves and is large in comparison to the wavelength [16]. However, body effects become less pronounced as the operating frequency increases. Regarding the miniaturization of body-area RFID antennas, several techniques can be employed. Examples include meandering techniques, inverted-F configurations that fold the antenna parallel to its ground plane, integrating ferrite or using high-permittivity substrates. The high frequency allows the implementation of single-layer dipole-like antennas and multilayer antennas (patches, slotted and E-shaped PIFAs, meandered slots).

Of particular importance is also the issue of protecting wearable UHF RFID tags. This protection should be hydrophobic and maintain the softness and flexibility of the tag antenna [17]. A review of previous studies to characterize the possible ways to protect wearable RFID tags is conducted by Pei et al. [18]. Some listed examples are silk-screening techniques to fabricate antennas with different conductive pastes on polyimide film, cotton, or Gore-Tex substrate fabric, coverage of embroidered tags with a saline solution, use of textile glue to protect a silver plated stretchable fabric, epoxy coating. The aim of the study is also to compare different ways to protect the tags against washing. 10 identical tags are created for 23 configurations and they undergo 20 cycles of machine washing and 20 cycles of machine drying. During testing, the tags are placed 20 cm away from the reader, which is still within one wavelength at 915MHz, so it is in the near-field zone. Here we report the final considerations: fabric glue is the least effective protection method, since it causes a significant loss in RSSI and unstable antenna connections, also decreasing wearing comfort; medical bandage material is too soft to protect the IC; heat-bond hem tape appears to be the best IC protection method, because the fused tape fixes the IC onto the substrate fabric; silicone gel can protect the IC but it weakens the antenna connection; the thickness of the cover fabric does not matter much.

Epidermal Devices Also epidermal devices may face different problems: proximity to the skin is still an issue, but complications also arise from the continuous mechanical stress during body movements. The effect of skin deformation during natural gestures is well studied by Miozzi et al. [19]. In this study, anatomic segments are digitalized to extract deformation parameters, which are used to evaluate the performance of three layouts of antennas that are typically used in epidermal applications: the ring, the split ring and the meandered dipole. The ring looks the most insensitive layout to deformation regarding the gain, while the split-ring layout exhibits sensitivity to mechanical and electromagnetic indicators. The meandered dipole is the most mechanically resilient configuration, but its realized gain is 5 dB lower than the other layouts, because the meander sections where the antenna currents are in phase opposition induce power loss. Overall, the maximum electromagnetic degradation of the considered deformed antennas may exceed 3 dB, which means a reduction of the read distance of about 30%. From a design perspective, we need a margin of at least 3-4 dB in the antenna optimization in order to guarantee a reliable communication.

Implantable Devices Concerning implantable systems, short-range RFID backscattering technology is the best solution for realizing wireless powering and communication with the implant. Magnetic induction via loops is useful for wireless energy transfer through short distances and dissipative materials because loops provide effective magnetic coupling and low electric near fields. For example, the goal of the study by Rao et al. [17] was to design small implantable antennas capable of efficiently coupling with an antenna outside the human body. The aimed design is a loop antenna with the highest possible magnetic field for strong magnetic coupling. They also try to minimize the near electric field of the antenna to lower the generated SAR level in the tissues, which is demonstrated to be achievable with two approaches: segmenting the loop antenna and inserting capacitors or tilt the loop.

Ma et al. developed a miniature far-field antenna composed of a pair of inductively coupled split rings for deep brain implants [20]. The proposed antenna uses the inductive coupling between the two concentric rings and a lumped capacitor to achieve miniaturization and impedance matching between the antenna and the implantable medical microsystem. An IC ring and a LC circuit ring are placed concentrically on top and bottom sides of a polyamide substrate, as in Figure 6. The difference between the outer radius of the two rings and the capacitance of the lumped capacitor has a dominant influence on the antenna input impedance. The antenna is placed in the cerebrospinal fluid layer in the anatomical model with an implant depth of 16 mm and the change of the antenna placement leads to the rotation of the antenna main lobes as in Figure 7. An elliptic version of the antenna is also developed by assigning an aspect ratio of 0.5 to the two rings.

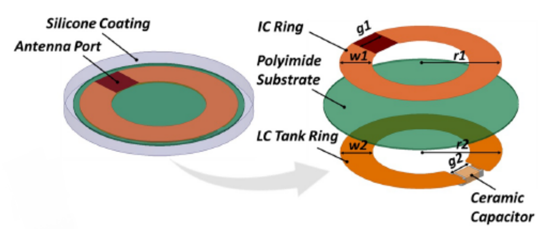

Figure 6: *Antenna Structure [20]*

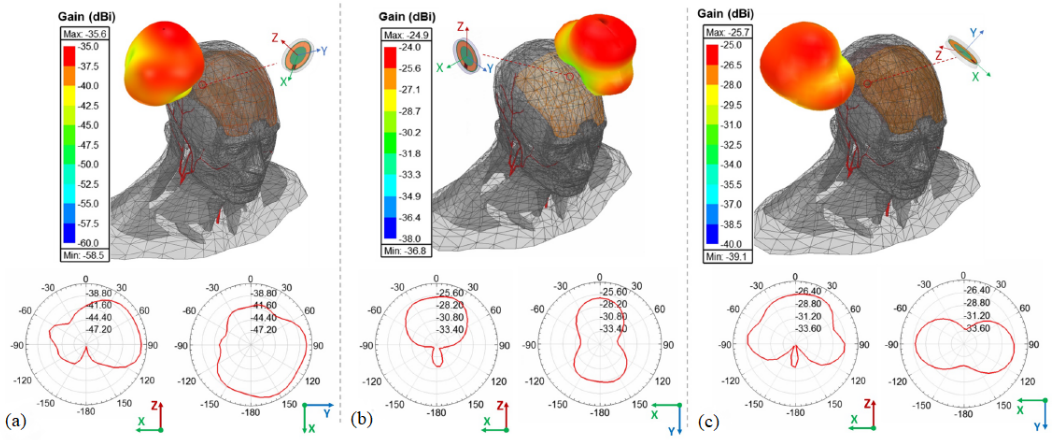

Figure 7: *Radiation patterns for (a) Horizontal placement of round antenna (b) Vertical placement of round antenna (c) Vertical placement of elliptic antenna [20]*

2.2 Device Fabrication

The fabrication of body-area RFID devices needs to take several considerations into account, including flexibility, low cost and robustness of the realized prototype. Materials have to be carefully selected, considering their conductive and non-conductive characteristics. Dielectric properties of the materials may not be known *a priori* and they can also be affected by the combination of different elements and by the fabrication processes. Wearable devices also need to be breathable in order to avoid moisture trapping inside the antenna. A number of fabrication techniques have been reported for wearable and implantable RFID devices:

- E-thread RFID devices rely on the automated or manual stitching of conductive threads upon a fabric substrate. E-threads are metal-coated polymer filaments twisted together to form a single thread, with a polymer core (Kevlar or Zylon) surrounded by silver to enable the realization of conductive antenna traces. The antenna performance is determined by the choice of materials, but also by the stiching density and direction. Embroidered antennas actually show some limitations with respect to traditional antennas, but a recently reported embroidery technique developed by Kiourti et al. was shown to achieve resolution as high as 0.1 mm, which is typical for traditional printed circuit boards [21]. This technique is also presented by Liu et al. [22], where four UHF RFID antennas are embroidered using Silverpan 250; one is a slotted patch antenna while the others are meandered antennas with different numbers of turns. The DC resistance is measured for the four antennas, observing that more turns in the antenna geometry imply higher resistance, leading to a reading range attenuation. The antenna performance is also degraded when attached directly on or close to human bodies.

- The screen printing technique implies printing conductive polymer thick films upon fabric substrates using stencils to form the desired pattern. The ink consists of metallic filler, binder material, solvents and additives and it is pressed through a screen onto the substrate with a blade. This technology is used by Kellomäki et al. to screen printing antennas on cotton fabric or 35% cotton/65% polyester knitted fabric [23].

- Inkjet technique uses inks made by metallic nanoparticle, conductive polymers, organometallic compounds and carbon nanotubes, deposited on flexible and stretchable substrates. It usually requires high temperature treatments, but new conductive inks that dry at room temperature and form an instantly conductive layer are currently being studied. Inkjet printing is particularly cheap, since the inks can be deposited on the substrate using low-cost inkjet printers.
  For biomedical applications, it is fundamental to use biocompatible substrates and consider the presence of sweat and the possible bending of the skin. A study was carried out by Amendola et al. using a silver nanoink consisting of an aqueous solution containing silver nanoparticles dispersed in a solvent of polymer latex and halide emulsion [24]. The aim is to test this ink over sheets and membranes suitable to host epidermal devices, such as inkjet tattoo-paper and many other types of skin-like membranes. However, due to the high impedance measured for these membranes, only the PVA-coated PET film is found to be adequate for ink adhesion. Additional research is therefore needed to find membranes that are really suitable for a comfortable application over the human skin. The technology is tested using a meandered rectangular loop (2.5 × 5 cm^2) connected to the IC through silver-based conductive glue. Figure 8 shows the prototype of the antenna printed over

PET substrate and the comparison between the simulated and measured gain of the antenna. The measured gain of a three-fold printed tag (realized with multiple overprinting) reveals to be comparable with that of bulk copper. This tag is also subjected to bending fatigue test, showing good resistance against repeated cycles of bending, and hence demonstrating the suitability to comply with the natural deformation of the human body.
A biocompatible coating layer is required to protect the antenna from oxidation. The study tests a silicon-based organic polymer and a polyurethane ultrathin dressing and both the polymers seem adequate to protect the ink.

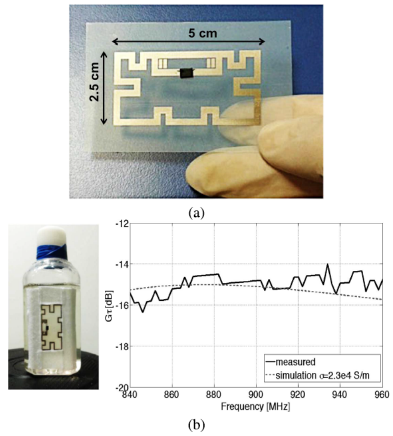

Figure 8: *(a) Inkjet-printed meandered-loop epidermal antenna over PET substrate. (b) Simulated and measured realized gains when the tag is attached onto a liquid phantom simulating the human body [24]*

- Rigid and small-diameter conductive wires, wrapped or folfed into the desired shape, have been reported for helix, dipole and loop antennas.
  A UHF RFID antenna designed by Lin et al. is implanted inside the body for vital information monitoring, and it is realized as a copper-based wire folded in the shape of a 20.3-mm × 0.8-mm × 0.8-mm dipole [25].
  This technique is used by Occhiuzzi et al. to integrate a sensor in a stent, which is a metal-mesh tubular device used to recover a stenosis and requires continuous monitoring in order to avoid an in-stent restenosis [26]. This device is called "STENTag" and is obtained integrating an RFID IC operating at 870 MHz in an existing stent by means of a 1 cm long Nitinol straight wire, protruding from the tubular grid (Figure 9). The STENTag is experimented in-vitro by means of equivalent liquid phantoms using a UHF reader, connected to a 5 dB gain linear polarized patch antenna placed at 20 cm from the phantom. The realized measurements are in agreement with simulations and the sensing capabilities of the proposed design seem enough to fully discriminate the early grade of restenosis.

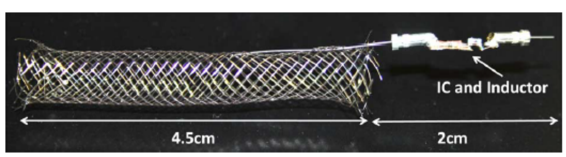

Figure 9: *STENTag prototype [26]*

- Traditional PCB RFID electronics are also popular for implantable applications. PCB fabrication entails the etching of a copper layer off its underlying rigid substrate, using milling, photolithography and other techniques.

2.3 Sample Studies

Wearable Devices

- Wearable RFID tags are proposed by Occhiuzzi et al. to detect the movement of human body segments [27] . The antenna is a rectangular plate folded around a dielectric slab with the longest face placed over the body through an optional dielectric

insulator slab (PVC film). The lenght of the patch is equal to $\frac{\lambda}{4}$. The RFID microchip is attached in the middle of the slot's central gap, as seen in Figure 10. The polarization is linear, parallel to the antenna main direction.
Two prototypes have been designed, fabricated and tested in real conditions; they have sizes 6x6 cm (TAG-1) and 6x9 cm (TAG-2). TAG-2 is expected to have a higher gain than TAG-1 ($G_{2,max} = 0dB$ v.s. $G_{1,max} = -3dB$ estimated), thanks to the larger size and to the wider ground plane. The realized gains are calculated by increasing the reader's power until the tag starts to respond, in order to know the collected power at turn-on, which equals the chip sensitivity, and invert (3) to get the gains. This evaluation is conducted with body rotation of 90°, 180° and 270°, finding that the gain is maximum in front of the antenna and minimum in the rear side.
Then, a fully integrated wearable sensor RFID tag, which uses a slightly modified version of TAG-2, is designed including a simple mechanical motion sensor. This system is compared with a 3-axis MEMS motion sensor placed behind the RFID tag. A significant correlation is visible between the two motion sensors. In particular, the RFID Motion Sensor is able to monitor every body event.

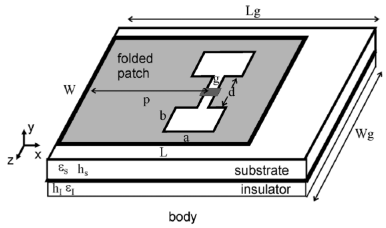

Figure 10: *Layout of the Proposed Tag [27]*

- The study by Casula et al. proposes the use of an eighth-mode substrate integrated waveguide circular cavity (EMSIW) in the UHF band, which minimizes the antenna size and optimizes the ground planein the UHF band [28]. This structure is suitable for wearable applications thanks to its good isolation, flexibility, potential miniaturization and good radiation. A closed-cell rubber foam is selected as a substrate and adhesive copper coated PET fabric is employed for the metallization. The antenna is designed starting from a SIW cylindrical resonant cavity, which is halved three times to get the EMSIW as in Figure 11. A prototype of the designed tag is manufactured using the commercial chip Impinji Monza 4 and a synthetic human tissue. The average measured read range is about 20% lower than the theoretical one (4.62 m vs. 5.82 m), probably due to the testing conditions. However, the read range remains stable when varying the antenna body-distance.

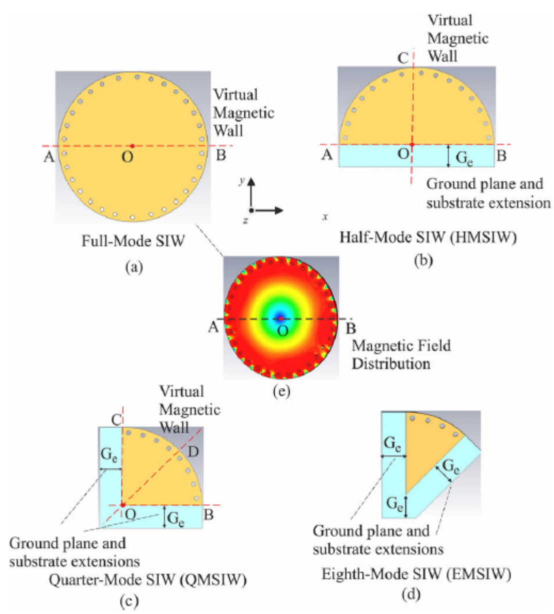

Figure 11: *Eight Mode SIW - Design Evolution [28]*

- The study by Manzari et al. is also aimed at discussing the feasibility of a body-centric system including passive RFID textile tags, with a quarter-wavelength patch [29]. The tags are placed in three parts on front torso, arm, and back, in horizontal and vertical orientation, and interrogated by means of a 6 dB circularly polarized patch antenna connected to the reader.
  The maximum measured reading distance is about 5m, arising with the tag over the arms with horizontal orientation, but in most of the configurations considered, the maximum distance is about 4.5m. Moreover, vertical polarization performs far better in the case of placement over the chest, while horizontal polarization appears more suitable for placement over shoulders and arms. However, the use of multiple tags seems to be promising to achieve a uniform coverage. The RSSI is then used to deduce the backscattered power in order to evaluate the effects of body posture and activity. In this case, the reader's antenna is a linearly polarized, quarter-wavelenght patch, with a maximum 3.3 dB gain, placed close to the waist. The tag on the chest remains oscillating around the same average value, while the tag on the leg is more susceptible to the change in position between the leg and the reader's antenna. The maximum SAR occurs underneath the antenna but it is one order of magnitude smaller than the absorption limit, meaning that the presence of the reader's antenna is safe for the body.

Epidermal Devices

- Epidermal RFID tags for human body temperature monitoring are discussed by Camera and Marrocco [30]. Body temperature is an important biometric indicator, which can provide information about the health condition of a person, in terms of fever detection but also to monitor peripheral perfusion, wound healing or hydration. In this study, the goal is to correct the samples to make temperature data nearly insensitive to the reading modality, by means of a correction model that relates the power collected by the chip to the induced disturb on the data. The tag design is the same used by Marrocco et al. [31], and it consists of a 30 x 30 mm^2 open loop coupled to a rectangular exciter loop inlay made by an aluminum trace over PET substrate and connected to an integrated chip. In this study, two conductive threads are considered: an insulated copper wire and a textile conductive yarn. The resulting epidermal tags are stretchable, soft and they fit the discontinuities of the body, as seen in Figure 12.
  The broadband realized gain is between -22 and -10dBi. Tests on some volunteers demonstrate that it is possible to guarantee a read distance of at least 75 cm in the 90% of the 420 data points combining frequencies, positions on the body and user characteristics. If placed onto the abdomen, the epidermal tag can even be read from up to 2 meters. For the purpose of temperature sensing, the system is first tested in a chamber with temperature varying between 36 °C and 38°C, applying the correction method [30], to find a maximum deviation with respect to a thermocouple of 0.2 °C. Then it is tested on human skin, with the reader connected to a circular polarized patch antenna with a reader-tag distance spanning between 5 and 30 cm, to find an error with respect to the thermocouple always less than 0.3 °C.

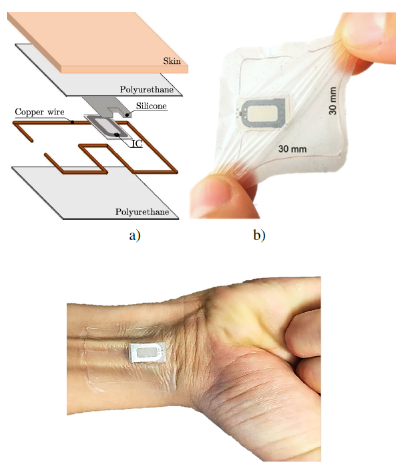

Figure 12: *Bio-integrated sensor tag for skin temperature measurement [30]*

- Hughes et al. fabricated a grid array antenna for on-body epidermal applications at the 5G sub 6-GHz band [32]. The proposed design is a grid array of four loop cells, to offer a radiation gain 6dB higher than a single loop, suitable to be applied in different body regions. Promising results have been obtained in terms of impedance matching and gain. 3.6 GHz antennas are demonstrated to be suitable to provide comparable read distance to on-skin UHF, whilst boasting smaller layout and higher data-rate.

- RFID technology is also viable for EMG signal acquisition. The study by Miozzi et al. presents numerical results for the design of an RFID-EMG device, including antenna and sensor interface, for the measurement of electromyography [33]. The same board hosts electronic components for analogic, power management and RF, and is decomposed into functional areas that group components absolving to similar functions to achieve a compact final layout. One group conveys and distributes the operating DC voltage, one allocates the analog components to amplify the EMG signal, and one comprises the RF part. The battery is placed on a separate detachable board. The antenna surrounds all the circuits and the electrodes are placed in the back. RFID communication is implemented in the UHF band and both passive and battery-assisted modes are available. The antenna and the EMG sensor circuit are designed on a 50µm thick Kapton flexible substrate. The system is tested using an emulation of the human body to characterize the realized gain and the reading distance by means of (1). The measured gain in the full configuration of the sensor is of -17.9dBi with a theoretical distance of 40cm that can be extended to 1m in battery-assisted mode. Finally, a single reader's antenna can interrogate multiple sensors at the same time: the user can switch easily from a single sensor to a multi-sensor configuration. The compact size and the flexible substrate also open the possibility of a subcutaneous implantation to get rid of some problems related to surface-mounted EMG sensors, such as sweating and sensor detachment.

Implantable Devices

- An important vital parameter to be constantly monitored is the glucose level in blood. For this purpose, Xiao et al. present an implantable sensor microsystem based on RFID, with an electrochemical glucose sensor and a ferrite antenna [34]. The sensor tag can detect the glucose level and wirelessly transmit the sensor data to an external reader. The sensor tag integrates glucose and temperature sensors, while the power transmission is based on two inductively coupled coils operating at 13.56 MHz. The signals from two sensors are processed by the same readout circuits to minimize the power and size. A continuous in vivo measurement in an animal has already been completed with rats, showing promising results.

- The wireless and fully passive reading of deep-brain neuropotentials using implanted RFID devices is demonstrated in two studies by Kiourti et al. [35, 36]. Deep brain neuropotential monitoring can improve the physical and mental well-being of humans, by, for example, detect and interrupt epilectic seizures. However, to exploit this kind of technology it is necessary to face some issues, such as the invasiveness of the implant, the possible damage of the brain tissue and the presence of batteries.
  The studies are aimed at creating a passive multi-channel implant made of 8 channels using an infrared transceiver/receiver, in order to detect as low as $20\mu V_{pp}$ per channel. The set-up consists of an implanted recorder placed under the scalp with the electrodes protruding through the bone into the brain and an interrogator placed outside the scalp. The interrogator sends a 2.4GHz signal to turn on the implanted recorder. The mixer in the implanted device uses this signal to generate a 4.8GHz$\pm f_{neuro}$ modulated signal that is transmitted back to the interrogator, where f_{neuro} is the frequency of the neuropotentials. This product is backscattered by the implant's antenna and received by the interrogator. For recording at multiple brain locations, several probes are connected to the wireless recorder and turned on/off with an infrared controlled switch. This setup is both used in in-vitro and in-vivo scenarios. It achieves the expected $20\mu V_{pp}$ sensitivity in all channels under in-vitro conditions. In the in-vivo scenario some issues are caused by the impedance of clinical electrodes and the DC offset voltage caused by the electrochemical reaction in the electrodes. Kiourti et al. integrated a Bipolar Junction Transistor into the implant, which serves as an impedance buffer between the electrode and the circuitry to eliminate the offset [36]. It is also found that at the smallest frequency where neuropotentials may be identified, namely 0.5 Hz, the electrode impedance is as high as 33 kΩ. Given that neural signals may be as low as 0.5 Hz in frequency, a capability to match to at least 33 kΩ of electrode impedance is therefore necessary for the neurosensing system. A patch antenna which exhibits dualband resonances at 2.4/4.8 GHz and with a 40 mm × 40 mm size is used to validate the performance of the system both in free space and via a tissue-emulating model (pig skin), capturing Signals as small as 100 µVpp and 200 µVpp, respectively. This is achieved in the worst-case scenario of 33 kΩ of electrode impedance. This implies that the system can monitor all neural spikes and most of the local field potentials in real-world settings. Kiourti et al. also studied the importance of matching the brain implant to its associated electrode, showing potentiostatic measurements of clinical microelectrodes with impedances in the tens of kΩ to MΩ range [37].

3 Future Prospectives

The employment of RFID technology for healthcare applications seems to be very promising for people who require constant monitoring of vital parameters or are suffering from severe impairments. The technology is still open to new studies and advancements in multiple fields, ranging from the design of antennas to the coating and protection of the systems. Examples that haven't been presented in this report, but are currently under investigation, are RFID technologies that monitor the status of prosthesis, orthopedic fixings, therapeutic RFID devices, and so on.

Many challenges are still to be faced. We have already presented some technical issues that may arise from the use of these applications, but some others may be listed. For example, privacy concerns may arise from the transmission of personal data through RFID devices, so that many disciplines, including signal processing and cryptography, are working towards solving these problems. The cost of the tags is tipically low, although the cost of the readers is still quite prohibitive for everyday applications. Reliability and reproducibility of the RFID readings is a key requirement, especially for people who need continuous monitoring of their vital parameters, such as the glucose levels in blood. Many technical concerns, including robustness of the transmission, communication distance and energy harvesting have still to be faced to find new solutions. Despite this issues, RFID for biomedical application may represent a life-changing technology, it is gaining interest in the scientific world and the related market is expected to face an exponential grow in the years to come.

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