Implanted RFID Tag for Passive Vascular Monitoring

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Abstract

Starting from the physical evidence that passive UHF-RFID tags may be used as self-sensing devices to detect the state of the tagged object, this contribution address the monitoring of human vascular system by means of augmented Stents. It is shown through simulations and experimentations how transforming a mechanic implant, used to recover a stenosis, into a sensor and communication device embedding RFID chips for the remote detection of the quality of the vein itself and to prevent restenosis pathology.

1 Introduction

Beside the common applications to Logistics, the Radio Frequency Identification (RFID) technology has been recently recognized as potentially able to detect additional information about the tagged object, such as its physical state and its time-evolution, without any specific embedded sensor or local power supply [1]. The physical rationale of this idea, for which the tag acts as a self-sensing device, lies in the clear dependence of the tag's radiation performance on the physical and geometrical features of the tagged object or, more in general, on the close surrounding environment. The possibility to remotely monitor processes in evolution discloses interesting opportunities in Telemedicine and Human Healthcare in general, especially concerning implantable devices. A possible application of the proposed sensing paradigm may be the monitoring of *in-stent restenosis*, a repeated narrowing of the vessel caused by an abnormal accumulation of tissue inside the lumen of the implanted stent and able to sensibly decrease its flow. Restenosis results from hyperproliferation of *neointimal* cells (similar to muscular tissue) or from the formation of new *atherosclerotic* plaques (similar to fatty tissue) [2]. By acquisition of the sensors' response at different times (days or even hours) a map of the geometrical or chemical changes of the vessel could be produced, thus evaluating possible complications (Fig. 1).

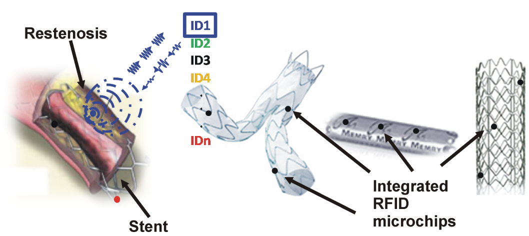

Figure 1: Idea of STENTags, e.g. conventional vascular tags augmented with RFID microchips to continuously detect the duct's health.

First attempts to use a vascular stent as powered radiating structure to support transcutaneous wireless telemetry have been recently described in [4] but without attention to sensing. In this work, instead, starting from the physical evidence that the stenotic plaque is characterized by dielectric and structural properties different from normal blood's, we investigate the feasibility of the stent-as-a-sensor, the *STENTag* device, which embodies medical, sensing and communication features. With particular attention to the carotid's in-stent restenosis, many numerical and experimental campaigns have been performed to demonstrate the technical feasibility of the idea and to understand the key parameters to master this multiphysics problem.

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2 RFID-Sensing Equations:

Starting from the standard RFID equations, it is possible to define three sensing indicators embedding the dependence of the tag's radiation performance on the variation of local parameters $\Psi(t)$, e.g. a shape factor of the biological process or, more in general, the local effective permittivity "sensed" by the tag's antenna. A first sensing indicator is the *backscattered power* $P_{R\leftarrow T}$ which is directly measurable by the reader:

$$P_{R\leftarrow T}[\Psi] = \frac{1}{4\pi}\left(\frac{\lambda_0}{4\pi d^2}\right)^2 P_{in} G_R^2(\theta,\phi)\eta_p^2\, rcs_T[\theta,\phi,\Psi(t)] \tag{1}$$

where d is the reader-tag distance, $G_R(\theta,\phi)$ is the gain of the reader antenna, η_p is the polarization mismatch between the reader and the tag, rcs_T is the tag's radar cross-section, related to the input impedance of the antenna $Z_A{=}R_A + jX_A$, to its gain $G_T[\theta,\phi,\Psi(t)]$ and to the modulation impedance of the microchip:

$$rcs_T[\Psi] = \frac{\lambda_0^2}{4\pi} G_T^2[\theta,\phi,\Psi(t)]\left(\frac{2R_A[\Psi]}{|Z_{chip}+Z_A[\Psi]|}\right)^2 \tag{2}$$

A second indicator is the *turn-on power* $P^{to}[\Psi]$, e.g. the minimum input power P_{in} through the reader's antenna forcing the tag to respond:

$$P^{to}[\Psi] = (\frac{\lambda_0}{4\pi d})^{-2}\frac{P_{chip}}{G_R(\theta,\phi)\eta_p G_T[\theta,\phi,\Psi(t)]\tau[\Psi(t))} \tag{3}$$

with $\tau[\Psi(t)]$ the power transmission coefficient of the tag and P_{chip} the microchip sensitivity.

A combination of the turn-on and backscattered powers finally gives the *Analog Identifier* (AID), a non-dimensional indicator independent on the distance and on the reader-to-tag orientation [3]:

$$F[\Psi] = \frac{P_{chip}}{2\sqrt{P_{R\leftarrow T}[\Psi]P^{to}[\Psi]}} = R_{chip}\,|Z_{chip}+Z_A(\Psi(t))|^{-1} \tag{4}$$

with $Z_{chip} = R_{chip} + jX_{chip}$ microchip's input impedance.

3 Mastering Sensing

The *sensor-less* sensing paradigm implies that there is no difference from the operative and structural point of view, between antenna and sensor, more precisely the *antenna is the sensor* and the *sensor is the antenna*. The sensitivity and selectivity of the system are thus strictly connected to the antenna's feature, in particular to its quality factor, and definitely to its bandwidth. However, due to the high conductivity of body tissues, implanted antennas are typically wideband structures and therefore new design methods need to be investigated to reduce and control the tag's sensitivity.

The overall design problem offers several degrees of freedom. In addiction to the tag layout, that must be compliant with the stent's characteristics and able to establish a robust communication link with the external reader, it is possible to consider additional variables typical of the RFID technology, such as the microchip properties and the matching conditions.

Shapes and the materials of typical vascular stent suggest the possibility to transform these medical devices into passive radio-sensors, by properly integrating, with minimal structural modification, one ore more RFID chips. A vascular stent is typically fabricated as a meshed tubular shape. According to the different mesh structures, in term of effective wavelength and currents' pattern, it is possible to associate the stent to an *electromagnetic equivalents* as helical coil, continuous/slotted cilinder, stacked loops or folded meander line.

Following [5], it is possible to classify the various commercially available microchips according to their *phase angle* $Q = X_{chip}/R_{chip}$, e.g. by the ratio between the chip input reactance and resistance. For a fixed value of power transmission coefficient, the higher is the Q the narrower is the tag's matching bandwidth. Tags matched to microchips with high phase angle therefore exhibit higher sensibility to the variation of impedance and thus they are more suitable to sensing activities.

Another interesting approach to manage the sensitivity of an implanted RFID sensor tag comes from the possibility to optimize the matching of the antenna in a specific realization Ψ_m of the process $\Psi(t)$. In particular, for a fixed microchip of impedance Z_{chip}, it is possible to impose:

$$Z_T(\Psi_m) = Z^*_{chip} \tag{5}$$

which gives $\tau(\Psi_m) = 1$, e.g. the maximum transfer of power to the chip. The sensing parameters in Sec.II are closely related to the matching condition and hence the shape of such curves may be engineered by a proper choice of the parameter Ψ_m, for instance to emphasize the variation of the early or the late dynamics of the process, as required.

4 Numerical Analysis

Before the design of a true STENTag, the achievable electromagnetic responses of a general implanted sensing tag are preliminary explored numerically by the help of Finite Difference Time Domain (FDTD) models. The neck and the internal carotid have been rendered as electromagnetic equivalent homogeneous solids, whose sizes and properties reproduce with good approximation the real human structures (Fig.2). The test antenna is a for now a simple 3.5cm coated dipole placed in the centre of the vessel. The restenosis evolution is accounted by gradually varying the dielectric properties of the tissue inside the vessel, moving from a healthy condition in which there is only blood ($\Psi = 0\%$ duct obtrusion) to severe pathological forms, in which muscular or fatty tissue totally occlude the lumen ($\Psi = 100\%$ duct obtrusion).

The simulated results for the backscattered power and the Analog Identifier are visible in Fig.2, having considered a best impedance matching condition as in (5) in case of intermediate restenosis condition $\Psi_m = 50\%$. Both proliferative events are clearly detectable all along the evolutions with the possibility to emphasize the system resolution in the first part of the process and detect also small tissues variations.

5 Prototypes and experimentations

A first realistic demonstrator of a STENTtag is obtained starting from a 4.5cm-long commercial stent augmented with a 1cm nitinol wire connected to an NXP microchip of impedance $Z_{chip} = 15 - j135\Omega$ and power sensitivity $P_{chip} = -15dBm$. The STENTag is hence experimented by means of a liquid phantom with chemical composition such to emulate the human neck's tissues. In particular, a $0.8cm$-diameter pipe, concentric to the container, emulates the carotid with the restenosis in evolution and it is filled, at different

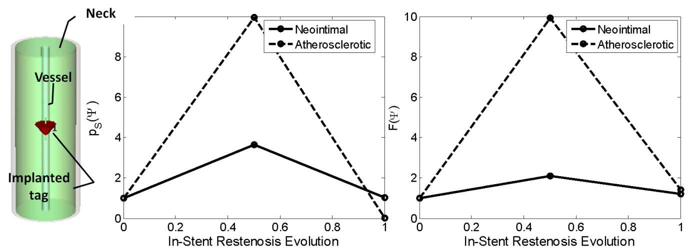

Figure 2: FDTD neck model and simulated backscattered power and Analog Identifier for a simple 3.5cm dipole sensing the two in-stent restenosis processes

times, by liquids of increasing permittivity. All the measurements have been performed by means of a UHF Thing-Magic reader, connected to a 6-dB gain circular polarized patch antenna.

The collected variation of the backscattered power indicator vs. the change of pipe's liquid is visible in Fig.3. It is well evident how the STENTag is really sensitive to the evolution of the physical process since the measured sensing indicator shows a nearly monotonic variation of about 50% even in the early departure of the liquid from healthy conditions (right-part of the curve), so corroborating the theoretical expectations.

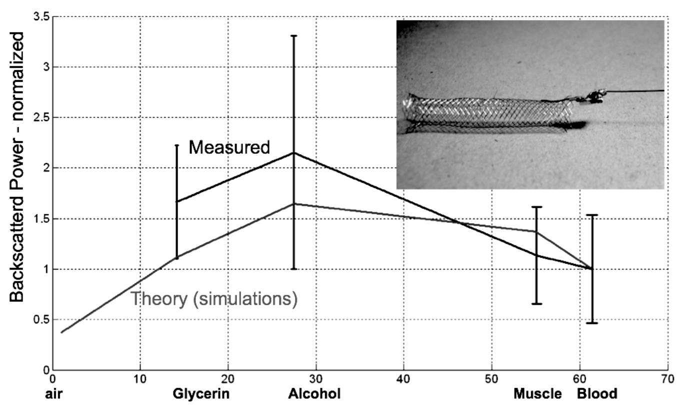

Figure 3: STENTag prototype. Measured Backscattered Power when varying the liquid composition into the pipe of a cylindrical phantom emulating the neck+carotid district.

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