

I. INTRODUCTION

Different passive Radio Frequency Identification (RFID) systems have been adopted in automatic identification of various objects. One novel use of RFID is tag based sensing in which an RFID tag is used for sensing instead of identification. The use of passive RFID tags is especially interesting, because passive tags need no on-tag energy source for operation. Additionally, they can be embedded into object that is monitored since they are maintenance free, wireless and thin. There are two types of passive RFID sensor tags: an RFID tag with the traditional sensor attached as a part of the tag and a tag in which the sensing ability is integrated into the tag structure. In the former type the RFID tag is typically used in power supply and data transfer, and in the latter the tag performs the sensor function itself [1]. Especially the self-sensing tags are interesting, because they are relatively inexpensive and easy to manufacture. The cost of an individual self-sensing tag depends on the manufacturing volumes and materials, but the cost is no more than the price of a traditional passive tag. The challenge considering the self-sensing tags is the designing of the “sensor component” in the tag geometry.

In [1] the idea of using passive Ultra-High-Frequency (UHF) RFID tag in strain sensing was investigated. The strain sensitivity of the printed tags was based on the changes in the printed film and the dimensional changes of the tag during straining [1, 2]. However, no attempt was done to evaluate the performance of such strain-sensing tag on human body. In this paper the same sensing mechanism is used but the main focus is on the behavior of dipole-type strain-sensing tags on human body. The motivation of such investigation is the significant number of applications related to human body monitoring that this kind of strain sensor would offer.

RFID based strain sensing is a promising method considering human body movement monitoring. Since passive UHF RFID tags does not require any batteries or wires they are easily integrated into clothing. The human body movement (relatively large strains) could be monitored by attaching the strain sensitive tag in such places on the human body that experience strain (elbows, knees etc.). Such sensor could be used in many ways. It could count the movements during an exercise, for example. It could also be used to monitor a certain body limb or joint and for example its recovery and trajectory after surgery. The sensors could also be used to monitor that not too large of movement is done with a healing body limb. Also small strains could be

where P_{tag} is the power received by the tag antenna; G_t is reader's transmitting antenna gain; G_{tag} is tag antenna gain, and λ is the wavelength. Parameter Γ_{chip} is the power reflection coefficient. Obviously, P_{chip} in equation (1) is maximized by minimizing Γ_{chip} . In practice, this is achieved by designing the tag antenna impedance to be the complex conjugate of the microchip impedance. When the tag antenna is stretched, the power reflection coefficient is affected because the tag antenna impedance changes. In addition, the radiation efficiency and the directivity of the tag antenna changes due to the changed effective conductivity of the ink [2] and the changes in antenna dimensions. Since G_{tag} is the product of the directivity and radiation efficiency of the tag ($G = \eta_{rad} D$), G_{tag} in (1) changes during stretching. Since the above mentioned parameters affect the amount of power received by the chip, the minimum power required to activate the tag (threshold power) is changed and the deformation (strain) can therefore be observed wirelessly by measurement of the threshold power. [1]

If the polarization of the tag and the reader antenna(s) is not matched, additional power loss is caused by this. Polarization loss factor is excluded from equation (1) (and also from equation (2)) since the polarizations were matched in the measurements performed to the samples. The polarization loss is also presumed not to be a function of strain.

Another parameter which can be used to measure the strain in self-sensing stretchable tags is the backscattered signal power. The backscattered signal power is the time-average power detected from tag response at the receiver. Using the Friis' propagation model, the power of the tag signal at the receiver $P_{received,signal}$ is [14]:

$$P_{received,signal} = P_{transmitted} G_{tag}^2 G_t^2 \left(\frac{\lambda}{4\pi d} \right)^2 |\alpha (\rho_{matched} - \rho_{mismatched})|^2, \quad (2)$$

where $P_{transmitted}$ is the transmitted power from the reader, G_{tag} is the gain of the tag antenna, G_t is the gain of the reader (transmit/receive) antenna (G_t^2 is the product of transmitting and receiving reader antenna gain in the case of a bi-static reader), λ is wavelength, d is distance from the tag, $\rho_{matched}$ and $\rho_{mismatched}$ are the power wave reflection coefficients [15] of the tag in matched and mismatched chip impedance states and α is a coefficient which depends on the specific modulation details. Equation (2) shows that the received backscattered signal power depends on the power wave

The PVC substrate is meant for heat-pressing into textiles and thus it is easily integrated as a part of clothing allowing wearable sensor tags.

IV. MEASUREMENTS

Voyantic Tagformance RFID measurement system was used in the measurements [16]. The device is a complete measurement solution for evaluating the functionality and performance of EPC Class 1 Gen 2 tags. It is essentially a vector network analyzer with RFID capabilities. All measurements were performed in an anechoic chamber. Monostatic reader with a linearly polarized antenna of gain of 9.5 dBi was used. The measurement distance was 68 cm.

Power on tag (dBm) was used to study the threshold power of the tag. Power on tag is defined as the power that would be acquired at the location of the tag with a power matched 0 dBi antenna. Power on tag is equal to equation (1) when the realized gain of the tag $((1 - \Gamma_{tag})G_{tag})$ is $1 = 0$ dBi. It can thus be interpreted as the power which would be absorbed by the RFID chip if it was connected to a perfectly matched 0 dBi tag antenna [14]. The lower the measured power on tag, the higher the realized gain of the tag antenna.

The measured transmitted threshold power can be used to derive the power on tag. Power on tag is the transmitted threshold power normalized by the power loss factor (path loss) from the output port of the generator to the antenna port of a 0 dBi antenna. This means that power on tag is the threshold power multiplied by the power loss factor. It is the minimum power necessary to activate the chip, assuming 0 dBi tag antenna gain and perfect matching. The normalization of the transmitted threshold power makes it possible to compare the tag antennas consistently.

In addition to the power on tag, **the backscattered signal power** (dBm) is the time-average power detected from tag response at the receiver. It was measured by using the threshold power as the reader transmitted power. Both, the power on tag and backscattered power measurements were first performed in air in unloaded conditions. After this, strain was applied on the tag and the measurements were repeated at different strain levels.

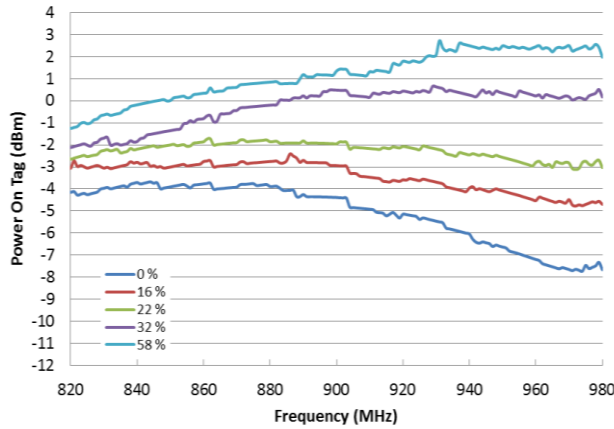


Figure 4. Power on tag of the tag on PVC at different strain levels on leg.

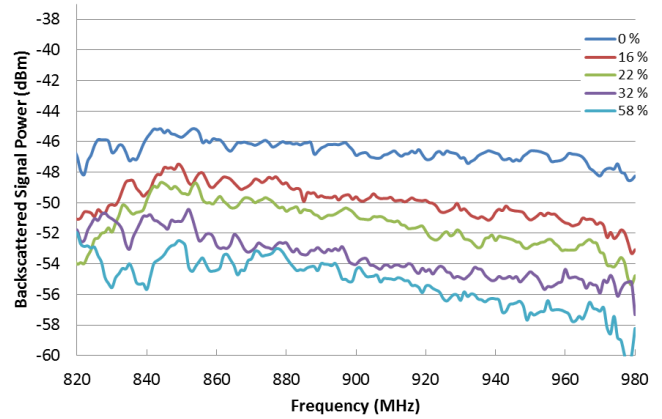


Figure 5. Backscattered signal power of the tag on PVC at different strain levels on leg.

To give a clear vision on the behavior of the difference of the behavior of the tag in air and on a leg, Figs. 6-9 illustrate the power on tag and the backscattered signal power as a function of strain at three frequencies that are 866 MHz, 915 MHz and 955 MHz which relate to the UHF RFID frequencies used in Europe, America and Asia.

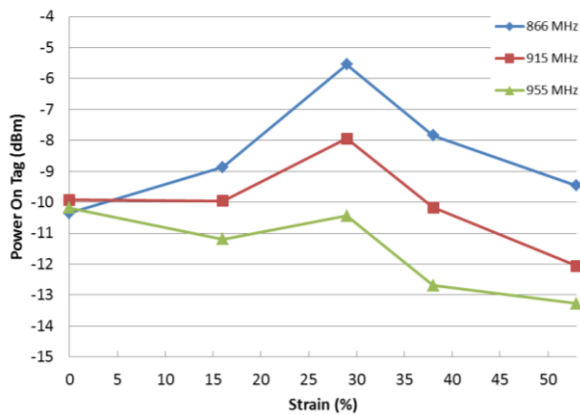


Figure 6. Power on tag of the tag on PVC as a function of strain in air.

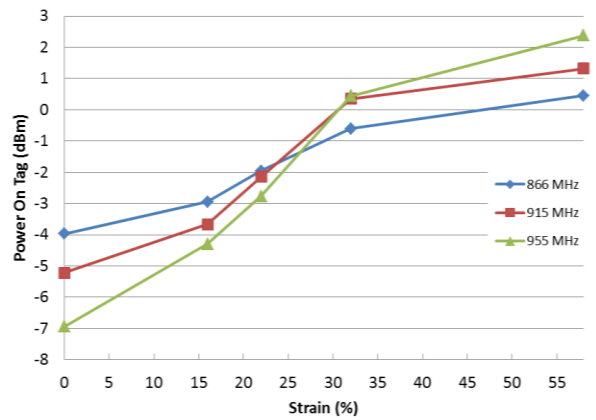


Figure 7. Power on tag of the tag on PVC as a function of strain on leg.

Fig. 6 show that the power on tag in air increases at 866 MHz up to 30% strain after which the curve start to decrease. At 915 MHz the power on tag at rest and at 15 % strain is the same and at 30% strain level, the power on tag has increased. In case of using measurement frequency of 955 MHz the power on tag first decreases slightly, but again at 30 % it has increased from the value

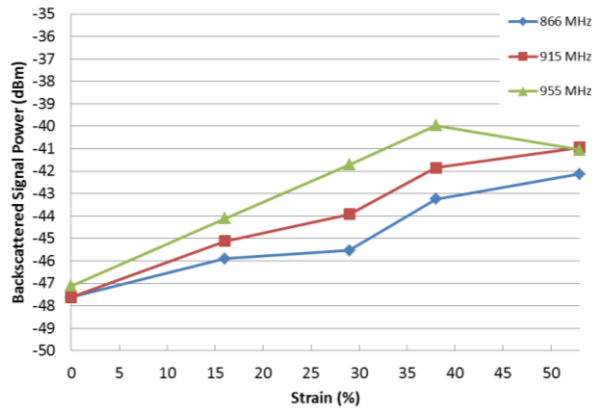


Figure 8. Backscattered signal power of the tag on PVC as a function of frequency in air.

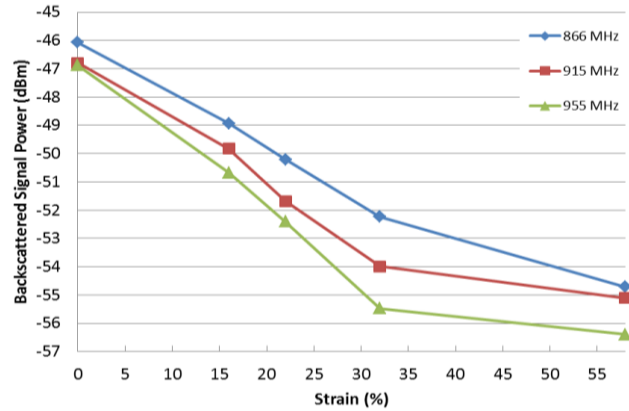


Figure 9. Backscattered signal power of the tag on PVC as a function of frequency on leg.

The backscattered signal power of the tag in air increases, partly due to increased antenna directivity. After further stretching the ohmic losses increase and the radiation efficiency decreases. This increase in ohmic losses finally start to dominate and the backscattered signal power start to decrease as a function of frequency. This is already seen from the results measured at 955 MHz. The change in the backscattered signal during straining in air is also caused by the term $|\rho - \gamma|^2$, because of the the power wave reflection coefficients are changed during straining. The coefficient α in equation 2 on the other hand is presumed independent on the strain. The increase of the backscattered signal power in air at relatively large strain levels is encouraging considering the tag-based strain sensing.

The backscattered signal power of the tag on leg also shows unambiguous behavior as a function of strain at 866, 915 and 955 MHz. The behavior is significantly different on leg but still useful considering strain sensing. Although the directivity of the tag on leg also increases due to increasing tag antenna length the losses also increase. The losses are greater if the tag is on leg as discussed already in the case of power on tag measurements. The ohmic losses also increase as a function of strain. The total losses are thus greater on leg and they might overcome the increase of the directivity. Also the power wave reflection coefficient in both chip impedance states (matched and mismatched) is affected by the presence of leg. Thus the term $|\rho - \gamma|^2$ may change differently as a function of strain than in case of tag in air.

polymer thick film silver ink. The effect of the strain in the wirelessly measurable parameters, threshold power and backscattered power was investigated. We found that the response from the tag was significantly changed when the tag was placed on human body. However, both the threshold power and the backscattered power were measurable from reasonable distance and the response was monotonic as a function of strain. Additionally the tags were manufactured from materials which can be integrated as a part of other structures, especially clothing. Stretchable passive UHF RFID tags of this study can thus be used in wireless strain sensors for monitoring human body movements as well as many other applications.

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