Inkjet-printed Van-Atta ref ectarray sensors: A new paradigm for long-range chipless low cost ubiquitous Smart Skin sensors of the Internet of Things

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***Abstract*—In this effort, the authors improve upon most of the limitations of state-of-the-art chipless sensing technologies, by introducing a novel, and demonstrably robust, platform and reading scheme for long-range, wireless sensing. This platform was built upon a fully-inkjet printed and f exible $30\,\mathrm{GHz}$ square patch antenna Van-Atta ref ect-array, which provides high RCS over a broad range of interrogation angles, with only a $10\,\mathrm{dB}$ decrease in RCS at ± 70 degrees from boresight. Furthermore, the signal ref ected by the structure is cross-polarized with respect to that of the impinging wave, providing high polarimetric detectability. For this f rst application, the device was fully inkjet-printed on a polyimide (Kapton) substrate, whose humidity-dependent permittivity was taken advantage of, associated with an appropriate high performance signal processing scheme, in order to provide the f rst long-range capable, fully-printed chipless f exible sensor to date.**

***Index Terms*—Remote sensing, Chipless RFID tags, Inkjet printing, Flexible electronics, Microstrip antenna arrays, Internet of Things, Smart Skin**

I. Introduction

The 20th century has witnessed a quantum leap in communication and data collection and processing, enabled by the technologies of the digital revolution. Concepts such as the Internet of Things (IoT) and “Smart Skins” (SS) now promise to connect all objects, to form a global information and sensing-enabled devices network. In order to implement such concepts, disruptive technologies, which would allow for a low cost and environmentally friendly integration of such capabilities into any object, are still desperately needed. From this perspective, fully-printable (and therefore chipless) f exible sensing-enabled devices offer a tremendous appeal. Indeed, printing techniques offer the possibility of low cost manufacturing of f exible sensing-enabled devices, using a wide range of high performance materials, while radically limiting the environmental impact of the process, thanks to their fully additive nature [1]. Current implementations of such printable wireless sensing devices for strain [2], gas [3], [4], [5], displacement [6], temperature [7], touch [8] or humidity [9], [10] sensing usually rely either on variations of passive UHF RFID chip turn-on power [2], [5], [8], [9], [10], chipless frequency (resonance) based sensors [4], [6] or on time-encoded UWB chipless structures [3], [7]. However, both technologies are usually operated at frequencies of less than $5\,\mathrm{GHz}$, and are therefore hindered (as far as range is concerned) by the use of low gain, large beamwidth antennas. In this effort, the authors propose a novel device and interrogation method for extended range wireless sensing. The device is also entirely frequency scalable, low cost, f exible, fully inkjet-printed, and provides a cross-polarized response for polarimetric detection. This was achieved by using a highly coherent and cross-polarizing mm-wave frequency Van-Atta array conf guration, adequate signal processing, and by taking advantage of the humidity dependent permittivity of the polyimide substrate. First, the theoretical advantages of such a conf guration for long-range chipless detection are discussed in Sec. II. Then, the design, fabrication, and characterization of the array are presented in Sec. III before the testing conf guration, data processing scheme and wireless humidity sensing results of the system are shown in Sec. IV

II. Advantages of mm-wave frequency Van-Atta configurations for extended range chipless wireless sensing

Using $A = \frac{G\lambda^2}{4\pi e_a}$, and the Friis equation, the power received from a monostatic RCS-based reader system can be expressed as follows:

$$P_r = P_e e_{a,r}^2 e_{a,t}^2 A_r^2 A_t^2 F_t^2(\Theta) \frac{1}{(\lambda R)^4} \quad (1)$$

where λ, R, P_e, P_r, $e_{a,r}$, $e_{a,t}$, A_r, A_t and $F_t(\theta)$ are, respectively, the wavelength, the reading range, the emitted power, the received power, the aperture eff ciencies of the reader antennas (assuming identical antennas), the aperture eff ciency of the tag/target/sensor antenna, the physical aperture of the reader antennas, the aperture of the tag, and the radiation pattern of the tag. For constant aperture values (and, by approximation, constant reader and tag sizes) the received power changes as $\frac{1}{\lambda^4}$, which is a direct consequence of the higher gain of higher frequency antennas, for given apertures. Therefore, higher frequency operation can offer a very signif - cant increase in the detection performance and miniaturization of a reader/tag system. Unfortunately, this cannot usually be taken advantage of, as for electrically large tag antennas, $F_t(\Theta)$ drops very quickly, as the angle of interrogation moves away from boresight, yielding structures with extremely small interrogation angular coverage. However, the unique coherent ref ection properties of the Van-Atta array conf guration enable it with a large (and virtually scalable) aperture, and a largely angle independent monostatic response. Thus, no compromise has to be made between antenna aperture size (and therefore maximum RCS), and interrogation angle coverage. Furthermore, highly directive antennas (including beamformer arrays) can then be focused on the sensor, limiting environmental clutter detection, and its structure can readily be modif ed to produce cross polarized ref ected signals [11], offering an additional level of isolation over clutter-induced interference.

III. Inkjet-printed Van-Atta reflectarray design, fabrication, and characterization

For proof-of-concept purposes, the basic structure chosen was a series-fed linear patch-antenna array. In order to enable it with cross polarizing capabilities, the array is made out of square patches and has two independent feeding ports (as seen on Fig. 1), each of which independently excites two degenerate cross-polarized modes. The design frequency of $30\,\mathrm{GHz}$ was chosen, and Kapton HN ($\epsilon_r = 3.1$ and $\tan(\delta) = .003$), a low cost, f exible and humidity sensitive substrate was utilized for the design. At resonance, each patch antenna can be modeled as a parallel resistor, $R_{res} = 178\,\Omega$. Lines of length $\frac{\lambda}{2}$ were used to transfer this very impedance value to the main feeding line. The N antennas were then placed every λ in order to obtain an input impedance of $R_{in} = \frac{R_{res}}{N}$ at the input of the linear antenna array. In order to maximize the number of antennas (and therefore the gain), while keeping a reasonable width for the microstrip feed line, the number of antennas was set to f ve, and the characteristic impedance of the feed line was therefore $\frac{R_{res}}{5} = 39\,\Omega$.

Fig. 1. Inkjet-printed f exible linear antenna array

In order to effectively realize the Van-Atta ref ectarray structure (Fig. 2), f ve of these series-fed linear antenna arrays were set side by side, with two of the antennas rotated by $180°$ in order to optimize design compactness, and connected in such a way for the re-emitted waves to be in-phase in the direction of the impinging interrogation signal, and cross polarized with respect to the impinging wave. This was done by connecting the ports of each antenna to the opposite polarization port of the symmetrical antenna (with respect to the center of the structure), using microstrip transmission lines of identical electrical length.

Fig. 2. Inkjet-printed f exible Van-Atta ref ectarray prototype, next to a standard "credit-card" size RFID tag package

The antenna and the array were inkjet-printed on Kapton HN with a Dimatix DMP-2831 inkjet printer, using 3 printed layers of Silver Nanoparticle (SNP) ink from Suntronic. Copper tape was used to form the ground plane of the structure, yielding an extremely low cost and roll-to-roll fabrication compatible design. Two in-launch connectors were attached to the linear two-port antenna array before its S-parameter response was measured with an Anritsu 37369A VNA. The results (shown on Fig. 3) show good agreement with simulations and demonstrate the capability of the printed linear array for Van-Atta integration, with a minimum return loss, common to both ports, of less than $-17\,\mathrm{dB}$. The slight distortion of the measured return loss of the vertical polarization port, compared to simulations, is attributed to slight fabrication imperfections in the 45 degree bends of the microstrip feed line.

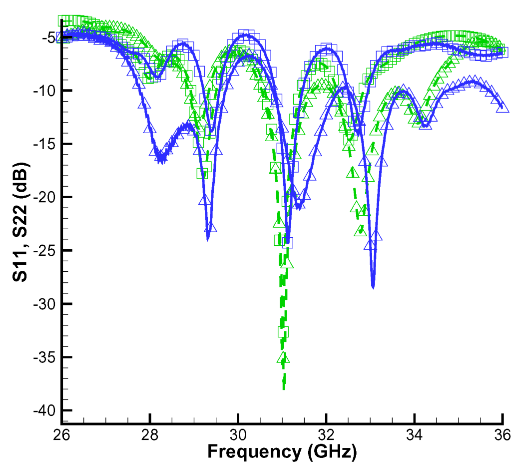

Fig. 3. Measured (blue solid) and simulated (green dashed) return loss for horizontal (triangle) and vertical (rectangle) polarization feeding ports of the series-fed patch antenna array

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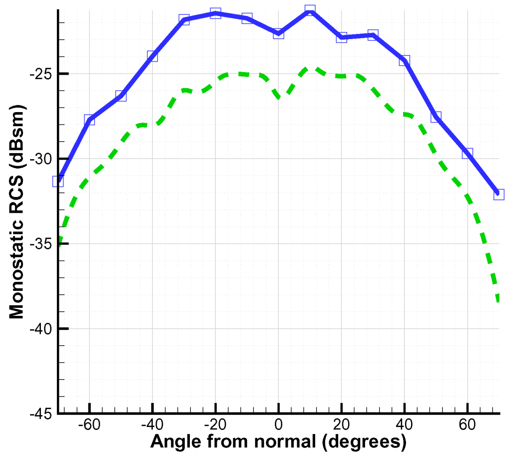

Fig. 4. Measured (blue solid) and simulated (green dashed) monostatic RCS of the Van-Atta ref ectarray

The monostatic RCS of the array was measured in an anechoic chamber, using two cross-polarized conical horn antennas (19 dB gain, 40 dB cross-polarization isolation and 17° of 3 dB beamwidth) connected to the ports of the VNA. The S_{21} values were recorded at varying angles and normalized to that of a 12 inch diameter metal sphere of known RCS, measured in the same conf guration. Measurements and simulations (Fig. 4) show excellent agreement in their trend, with measurements better than simulations by 3 to 4 dB, which can be attributed to an underestimation of the conductivity of the printed SNP traces during simulations. As a conf rmation of the Van-Atta operation, the RCS of the structure only varies by 10 dB over an angular interrogation range of 140°. This property enables this design with a unique combination of high RCS (and, equivalently, high gain) and broad interrogation angle coverage.

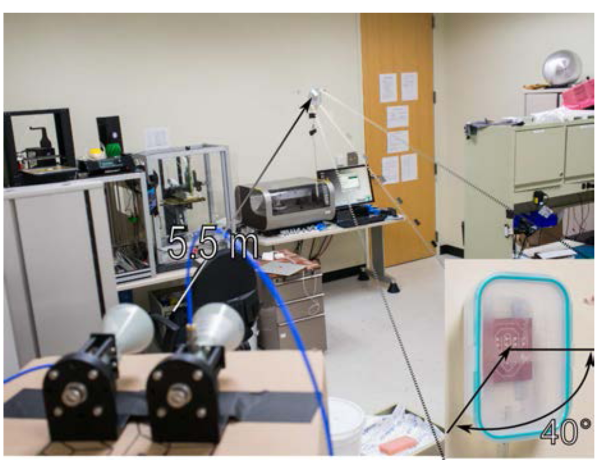

Fig. 5. Humidity sensing measurement environment

IV. Application as a low-cost extended-range fully inkjet-printed humidity sensor

In its previously described form, the array can be used as a rangef nder or a chipless RFID, where the ID can be stored in the resonance frequency of the array. However, it can also be implemented as an extended range fully inkjet-printed chipless f exible moisture sensor, by taking advantage of the humidity-dependent permittivity of the Kapton HN substrate. In order to test the sensor, the interrogation system previously used for the RCS characterization, to which was added a 21 dB amplif er in the emission channel (bringing the emitted power up to 14 dBm for better noise isolation) was utilized. The sensor ref ectarray was measured in the realistic, and extremely challenging, environment of a highly cluttered laboratory (Fig. 5), at long range (5.5 m), inside a humidity controlled enclosure, only separated from the room wall by a 3 mm plastic box wall, and interrogated at an angle of about 40° from normal incidence.

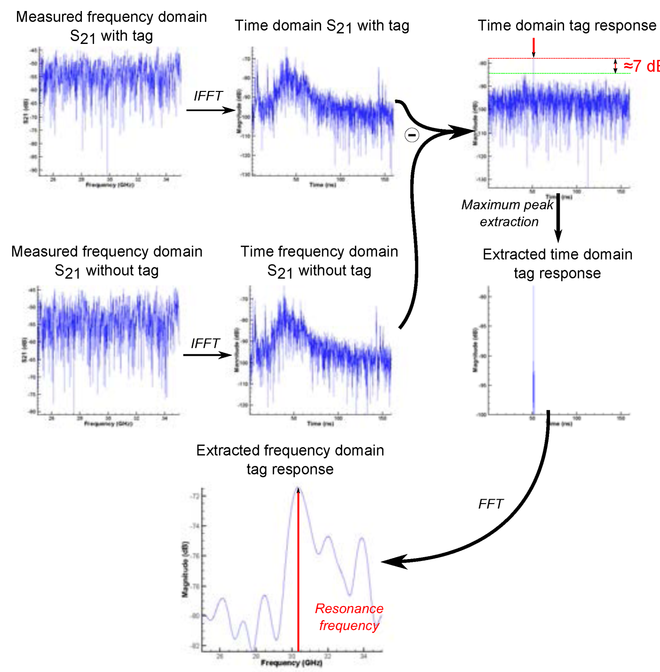

Fig. 6. Processing of measured frequency response for resonance frequency extraction

A computationally light data processing scheme was used to extract the resonance frequency of the array (Fig. 6). Two frequency domain measurements (25 GHz to 35 GHz), one with and another without the array, were taken. An inverse fast Fourier transform (IFFT) was then applied before removing the time domain measurement without the tag from that with it. A very clear tag peak then appeared and was extracted from the background. Finally, a fast Fourier transform (FFT) was applied to this time-domain data, in order to extract the resonance frequency of the tag. On the particular measurement shown on Fig. 6, the difference in magnitude between the peak associated with the sensors and the highest magnitude of the time domain response from the environment is about $7\,\mathrm{dB}$.

The results of such wireless sensing, f t with a linear regression function, are shown in Fig. 7. Because of the grounded nature of the structure, its resonance frequency is highly correlated with the permittivity of the Kapton substrate. As a consequence, its relative sensitivity ($\frac{1}{f_0}\frac{\Delta f}{\Delta RH}$) of 1.41×10^{-1} is extremely high (almost 1 order of magnitude better) compared to state-of-the-art non-grounded designs (2.24×10^{-2} [10]). To a greater extent, the high frequency operation also gives it an extra 30-fold absolute sensitivity improvement over UHF-operating tags. The high determination coeff cient (0.9993) of the linear regression also suggests an extremely high theoretical accuracy of 2.6% relative humidity (RH).

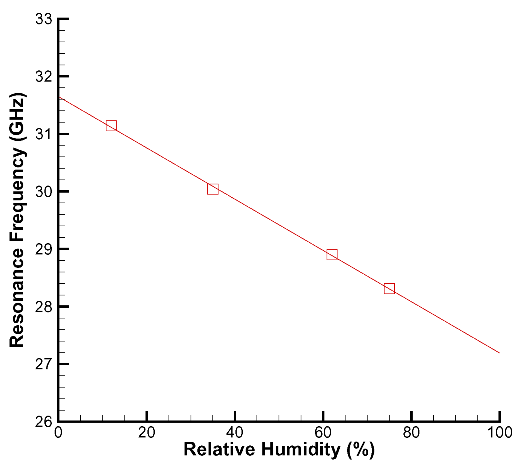

Fig. 7. Plot of measured resonance frequency of the inkjet-printed Van-Atta array as a function of ambient humidity level

V. Conclusion

In this work, the authors have presented a novel device and method for long-range chipless wireless sensing, combining inkjet printing and Van-Atta principles. As an application example, an inkjet-printed prototype was implemented and successfully tested as a moisture sensor. Furthermore, an unprecedented robustness to the presence of clutter and to variations in the angle of interrogation was demonstrated for enhanced interrogation ranges. In addition to this demonstrated performance, the design was entirely inkjet-printed in order to provide a roll-to-roll fabrication compatible, f exible and extremely low cost wireless sensor. Judging by these results, the use of different sensing materials , as well as further improvements of the reader conf guration, by the use of pulse radars, as well as higher gain beamforming arrays, could set the foundation for the emergence of the f rst generation of truly long-range, fully-printable, chipless, f exible, low cost, wireless sensors for ubiquitous applications in Smart Skins and the Internet of Things (IoT) topologies.

VI. Acknowledgment

The authors would like to acknowledge the support of DTRA for this work.

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