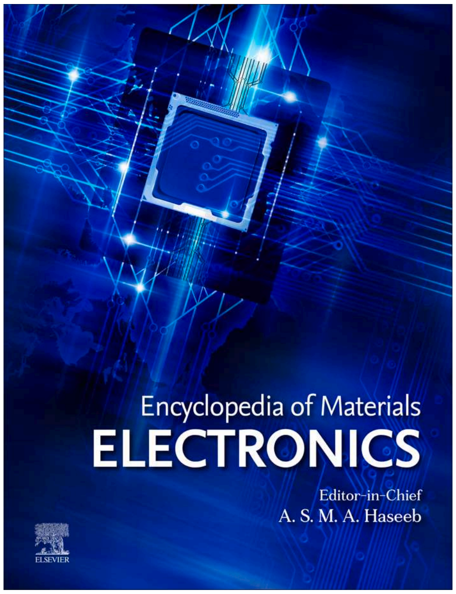

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Antennas as Sensors

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Abstract

The chapter describes the rationale, the basic concepts and the reference configurations for the "antenna-based sensors". The review includes real examples and case studies given by the state-of-the-art scientific literature.

Key Points

- Antennas can serve both communications and sensing purposes by sensing the nearby environment.
- Sensing can be performed by dedicated sensors or bare antennas. In the second case the sensing mechanism can be three: unmodulated sensing, modulated sensing, and sensing by auto-tuning antennas.
- Variations in the phenomenon to be sensed can be transduced in variations of the electromagnetic properties of antennas.

Introduction

The antenna is an interface device working as a transducer between a guided wave and a propagating one. From another perspective, the antenna can convert the energy carried by a time-varying current over its body into energy carried by waves traveling in a medium and vice-versa.

Antennas are mainly used to communicate, detect far emitters (radioastronomy), track moving targets (radar) and convey high-power energy into an object (heater and jammer). However, they can also be used as a key module of a sensing system wherein the change of a physical quantity to be measured is converted by the antenna in a change of an electromagnetic property revealed from the remote.

An antenna is the terminal part of any transmitter/receiver system. Its performance is characterized by electric parameters, namely the input impedance versus frequency when looking toward the circuit, and the radiation gain and the effective length versus angle and frequency, when looking toward the propagation medium. When an antenna is in touch with or placed close to an external object made by dielectric or metal, the local boundary conditions that the antenna sees are modified by the electromagnetic coupling with that object, and the current distribution on the antenna will be reshaped. Accordingly, the antenna parameters will change so that the measured radiation will carry information about said antenna/object interaction. Hence, the antenna act as a transducer from a chemical/physical process, involving a change of local boundary conditions close to the antenna itself to a measurable variation of an electromagnetic response.

The observable antenna's parameter(s) providing information about what is happening in the proximity is one (or more) of the following:

(i) the resonance frequency,
(ii) one or more between strength, phase, and angular distribution of the radiated or reflected field,
(iii) power delivered to a load in case of receiving antennas.

The kinds of sensing mechanisms described above can be exploited directly in an analog way, involving a continuous-wave regime, without any electronic component attached to the antenna. Instead, the sensing modality can be mediated by the use of a local modulator, thus enforcing a modulated regime by using a microchip transponder on board, even if no additional sensing device is used. Accordingly, three families of sensing mechanisms exploiting an antenna will be addressed next:

(i) unmodulated sensing,
(ii) modulated backscattering sensing,
(iii) sensing by auto-tuning antennas.

The third sensing family can be considered an evolution of the second one by using a new paradigm of integrated circuit (IC) transponders with a multi-state dynamic impedance. A further sensing family resorts to dedicated sensors, uses the antenna only for communications, and will not be addressed in the following.

For each transduction mechanism, the rationale and application examples are reported here together with the achievable resolution and accuracy.

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Background and Fundamentals

Antennas are inherently sensitive to the change of the background medium. For instance, in the case of a homogeneous space-filling material with magnetic and dielectric parameters ($\mu = \mu_0\mu_r, \varepsilon = \epsilon_0\varepsilon_r$), the input impedance Z_A of the antenna is a shifted and scaled replica with respect to that in the air according to the Deschamps equation:

$$Z_A(\omega, \varepsilon, \mu) = \sqrt{\frac{\mu_r}{\varepsilon_r} Z_A\left(\sqrt{\mu_r\varepsilon_r\omega}, \varepsilon_0, \mu_0\right)}$$

with $\omega = 2\pi f$

In general, antenna features, namely the radiation gain $G(\theta, \varphi)$, directivity $D(\theta, \varphi)$ and input impedance Z_A, depend on the current distribution along the conductor layout but also on their interaction with the surrounding environment. Currents spread along with the antenna shape according to its electrical length, the latter being proportional to the wavelength $\lambda = c/f$, with c speed of the electromagnetic wave into the surrounding medium. If the medium changes, e. g. the permittivity varies from air $\varepsilon = \varepsilon_0$ to $\varepsilon = \varepsilon_r\varepsilon_0$, the speed of the electromagnetic wave changes and the wavelength is accordingly scaled by $\lambda = c/\left(\sqrt{\varepsilon_r}f\right)$. Consequently, the electrical length of the antenna modifies with an impact on both impedance and directivity. The same principle also holds in the case of modification of antenna shape since the current distribution undergoes variations.

Furthermore, the gain $G(\theta, \varphi) = \eta D(\theta, \varphi)$ depends on the radiation efficiency η defined as the ratio between the radiated power P_R and the total power entering the antenna $P_{in} = P_R + P_j$, where P_j is the power loss. When the material surrounding the antenna changes, e.g. with modification in the imaginary part of its complex permittivity, the interaction with the antenna current produces a variation of the lost power P_J, and, consequently, of the gain.

Let us denote with $\Psi(t)$ a time-varying physical, chemical, or geometrical parameter of the environment surrounding the antenna and let us consider the Friis' formula describing the radio link between two antennas placed at a given distance d in polarization alignment. Antenna A is affected by the parameter $\Psi(t)$ in evolution, while antenna B is in rest condition. Then, the power delivered to antenna B, assumed as perfectly matched to its load, by antenna A is:

$$P_{A\to B}[\Psi] = \left(\frac{\lambda}{4\pi d}\right)^2 P_{in}G_A[\Psi](\theta, \varphi)\tau_A[\Psi]G_B(\theta, \varphi)$$

In particular, the power radiated by antenna A depends on the radiation gain and the power accepted by the antenna itself, quantified by the power transfer coefficient

$$\tau_A[\Psi] = \frac{4R_G R_A[\Psi]}{Z_G + Z_A[\Psi]^2},$$

where $Z_G = Z_G + jX_G$ is the impedance of the transmitter.

Accordingly, any modification in gain or the input impedance of antenna A is turned into a variation of the transmitted power and can be hence retrieved by antenna B through a proper analysis of the received signal in amplitude and phase.

Unmodulated Sensing

In the case of un-modulated sensing, the bare electromagnetic response of the antenna (namely its resonance frequency and the angular distribution of the radiated field) is used to earn information about changes happening in the close vicinity of the antenna itself.

Such changes can be due to different phenomena. In particular, changes in the position of nearby objects and in their status (i.e., damage/composition) can be monitored. Examples of each of these classes will be given next.

Unmodulated sensors have the benefit of extremely low cost due to the absence of any electronic component. On the other hand, they exhibit a very limited specificity to the process to be monitored. Though a proper design will manage to achieve good sensitivities to specific phenomena, it cannot fully remove the uncertainty produced by further (disturbing) phenomena in the sensor environment.

Sensing of Displacements and Deformations

The change of the mutual position between antenna and object to be monitored will impact the antenna response by modifying the antenna's near-field environment. Similarly, if the antenna is placed onto the object to be monitored and this moves away from other objects in the environment, such a movement can be detected from remote.

For instance, multiple antennas placed on the sides of a crack on a wall can act as crack sensors: a displacement of the first antenna, attached on one side of the crack, with respect to a second antenna on the other side, will result in an indirect measurement of the crack evolution (Rizzoli *et al.*, 2009). The operating principle used in this case is based on the dependence of the array radiation on the inter-element distance. As a matter of fact, two antennas acting as a broadside phased array (hence excited with the same phase and amplitude) having an inter-element distance in the range of]0.5;1.5[wavelength, will have first-

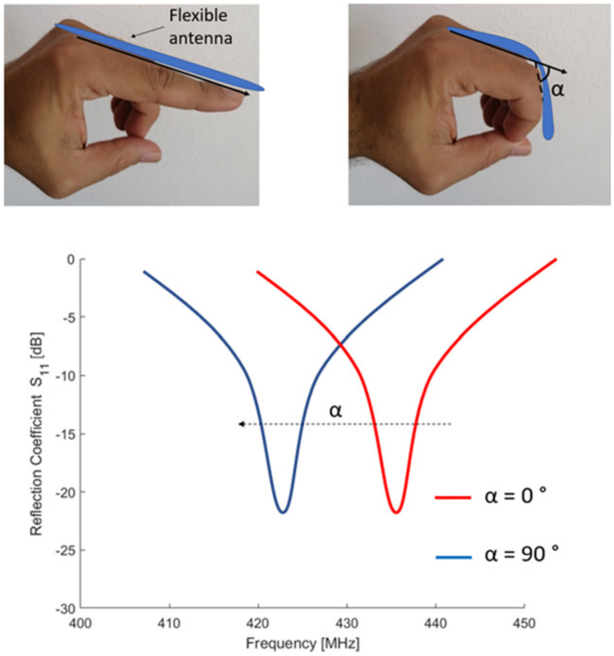

Fig. 1 Concept of an antenna as sensor for finger posture (top). Changes in the finger bending will cause variations in the frequency response of the antenna's reflection coefficient (bottom). Adapted from Su C.H., Wu H.W., 2019 An antenna sensor to identify finger postures. In: Proceedings of the IEEE Eurasia Conference on IoT, Communication and Engineering (ECICE), 571–574.

order nulls away from the broadside direction. The angular position of these nulls is dependent on the actual distance between the antennas. By measuring the shift in the null position, the mutual distance of the elements can be estimated.

If a flexible sensor is wrapped onto the object to be monitored and the shape of said object varies, this will be detectable thanks to the fact that also the shape of the antenna/sensor itself will have changed. For example, finger posture sensing can be obtained based on this mechanism (Su and Wu, 2019) by measuring the reflection coefficient of an antenna being bent (**Fig. 1**). The antenna is, in this case, printed on flexible material and attached to a finger. The finger movement will change the mutual position of two portions of the antenna, thus affecting the frequency profile of the reflection coefficient.

Sensing of Changes in the Health Status of the Object

The object to be monitored might be prone to changes in its status, such as damages, cracks, holes, as typical of metallic structures for aerospace applications or concrete structures for construction applications. The development of this damage, for instance, in terms of crack propagation, can be seen as a change of the status of the object and, accordingly, of an antenna placed over it. For instance, a metallic plate can be monitored (Mohammad and Huang, 2011) by printing a patch antenna on a substrate and using such metallic plate as the ground layer. Suppose the crack propagates in the metallic plate; the antenna's current distribution will be modified, resulting in a frequency shift in the reflection coefficient of the antenna, measurable by connecting a Vector Network Analyzer (VNA) to the antenna itself or wirelessly through the measurement of the radar cross-section (RCS) of the antenna.

Sensing of Changes in the Composition of the Object

Let us suppose that the chemical/physical composition of the object (or medium) in the proximity of the antenna changes, for instance, due to humidity absorption, freezing or other phenomena impacting the dielectric properties of the object/medium. In that case, the antenna will experience a different effective electromagnetic permittivity around it, ultimately causing a variation in the antenna response, as suggested by the Deschamps equation. This mechanism can be exploited (Vena *et al.*, 2016) to turn a chipless tag into a humidity sensor (**Fig. 2**).

Chipless tags are a specific class of unmodulated sensors, as they are composed of metallic parts only, without embedding any silicon chip. The radar signature they produce (due to their specific design) is used to extract a unique identifier. By integrating a sensing material onto the chipless tag, sensing capability can be achieved. For instance, silicon nanowires are known to have a good sensitivity to humidity.

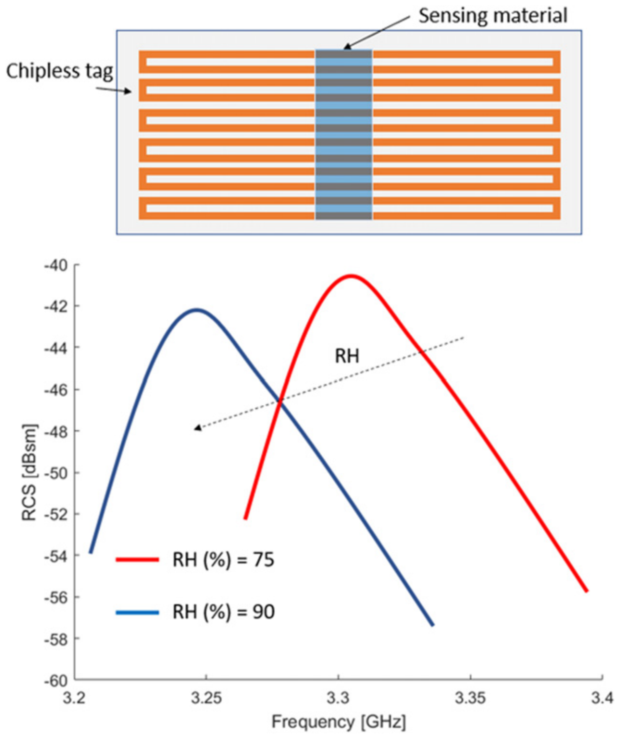

Fig. 2 Concept of chipless tags with humidity sensing material in the middle (top). Changes in the environmental humidity will cause variations in the frequency response of the antenna's radar cross-section (bottom). Adapted from Vena, A., Perret, E., Kaddour, D., Baron, T., 2016. Toward a reliable chipless RFID humidity sensor tag based on silicon nanowires. IEEE Transactions on Microwave Theory and Techniques 64 (9), 2977–2985.

Then, measuring the radar cross-section of the tag via an external antenna, the change in the relative humidity of the environment can be estimated through the analysis of the frequency shifts of the RCS peaks.

Sensing Through Modulated Backscattering

Modulated backscattering is a communication architecture in which a backscatter node, i.e. the *tag*, comprising an antenna and an integrated circuit, broadcasts information to an illuminator, i.e., the *reader*, by modulating and reflecting back the incident electromagnetic wave coming from the reader itself. The modulation, and consequently the reflection, is due to an intentional mismatch between the antenna and the IC impedance that generally varies among two high/low values, corresponding to the symbols of the coded information. At the reader side, the sequence of the transmitted bits can be retrieved by properly demodulating the reflected wave. The communication link is hence asymmetric: the forward reader-to-tag link is mainly aimed at exciting the tag and is characterized by high carried power. The backward tag-to-reader link is instead in charge of data transmission with power levels extremely low, being only a fraction of the impinging signal.

Modulated backscattering is currently implemented by Radiofrequency Identification (RFID) platforms. Well assessed in logistics for labeling, tracking and tracing goods and procedures, RFID is being increasingly adopted also for sensing purposes. Indeed, data transmitted back to the reader during the interrogation protocol are digitally encoded, but the strength of the backscattered power is impressed in an analog manner by the antenna configuration, the interaction with nearby objects, by the propagation modality, and even by the mutual position and orientation among the reader and the tags. Compared with unmodulated sensing, such an approach is more robust and effective since the reflected wave bringing the sensing information can be easily recognized and processed by the reader so that multiple sensors can be interrogated simultaneously.

RFID platforms can be deployed in both short-range (namely HF/NFC systems working at 13.56 MHz) and long-range (working in the UHF 860–960 MHz frequency band) systems. In the former case, the interaction with the reader is mostly one-to-one (inductive coupling), whereas in the latter case, information can be contemporarily broadcasted among a single reader and hundreds of tags, being the radiating elements of conventional antennas operating in far-field conditions. Antenna-as-sensor paradigms mainly apply to UHF RFID.

During a typical RFID communication, in addition to the Electronic Product Code (EPC) that univocally identifies the tag, reader and tag share different types of data:

(i) *Received Signal Strength Indicator* (RSSI), that is related to the reverse communication link, i.e. to the power backscattered by the tag toward the reader $P_{R\leftarrow T}(\Psi)$ and hence to the differential radar cross-section, Δrcs,

(ii) *phase*, $\varphi(\Psi)$ of the signal backscattered by the tag and related to the differential radar cross-section among the two modulating states,
(iii) *turn-on power*, $P_{in}^{to}(\Psi)$ that is the minimum power the reader must emit to wake up the tag, and that is an indicator of the direct link.

RSSI and turn-on power can be further combined to drop out the influences of the distance and the reader's and tag's gains and orientations. A propagation-independent indicator denoted as the *Analog Identifier* (AID) can be hence defined (Marrocco, 2011).

The previous parameters are strictly related to the tag antenna operating features and can be used as data inversion curves between the measured data and the evolution $\Psi(t)$ of the process:

$$\left\{P_{R\longleftarrow T}, P_{in}^{to}, \varphi, AID\right\} \longleftrightarrow \Psi(t)$$

Any variation of the surrounding environment Ψ able to affect the antenna gain and input impedance is transduced in a variation of the signals transmitted and received by the reader and can be hence related to a sensing activity performed by the tag itself. To remove possible baselines, the above indicators are generally normalized by their value in a particular reference state, say $\Psi(0)$, for instance, collected at the time of the tag's placement into the environment to be monitored. In this way, differences in the signals are evaluated rather than their absolute values. The sensing parameters can be collected at a fixed frequency or within the whole RFID band to provide integral metrics suitable for capturing macroscopic variations of the sensor-antenna response over frequency, such as the detuning and the attenuation or magnification of the response.

Two approaches can be defined to implement the sensing activity: (i) *bare antenna*, the sensing capability of which is only related to the natural sensitivity of an antenna to time-variant boundary conditions, and the (ii) *loaded antenna*, in which the sensing features depend on specific chemical and mechanical sensors integrated into the antenna structure as variable loads.

Bare Antenna

A bare antenna, with nothing else on board, can be exploited as a natural permittivity sensor for the remote discrimination of kind, amount and distribution of liquids (**Fig. 3**), powders, and biological processes (Occhiuzzi, *et al.*, 2013). The sensing activity (**Fig. 3**) requires analyzing the variation of the reverse communication link, e.g., the backscattered power of one or more tags attached to the container that have been matched in case of specific compounds (Marrocco and Amato, 2009; Capdevila, *et al.*, 2011). For the monitoring of bottle filling, the placement of multiple tags at different levels increases the overall sensitivity to the process by adding an ID modulation. For this purpose, if a tag is tuned for operation in the air, it will not respond when placed in touch with a high-permittivity liquid. Accordingly, by analyzing the set of IDs returned by a vertical array of tags, a discrete estimation of the filling level of the container is achieved.

The same principle holds when the process under observation induces a deformation of the antenna's shape, as in the case of moving surfaces or evolving cracks. The strain can be monitored by a meander-line antenna (**Fig. 4**). By applying an elongation, its shape will turn from a tightly twisted meander to a zigzag dipole, thus altering the pattern of the currents and hence the antenna's properties, such as the ratio of the actual backscattered power to the backscattered power measured during the steady-state.

A crack can be identified and monitored by using two passive RFID tag antennas placed on top of the crack (**Fig. 5**) so that its evolution will produce a change of the inter-antenna coupling and, in turn, of the phase of the backscattered field.

Loaded Antenna

A complementary approach to the bare-antenna is the loaded-antenna one, which requires providing the antenna with an external sensing element. This element could be either lumped into a device, connected in some part of the tag's antenna as well as distributed all over the antenna's surface as in the case of chemical-receptor coating. Overall, the sensor is considered as a lumped or distributed impedance loading, $Z_S(\Psi)$, on the tag's antenna. The perturbation of $Z_S(\Psi)$ caused by the change of the environment will accordingly produce a variation of the tag's gain and impedance, wirelessly detectable by measurement of the previously described indicators.

Volatile chemical compounds can be detected by resorting to carbon nanostructures (CNT) paint that is spread over a loop-driven flat dipole (**Fig. 6**). The device is able to sense the presence of ammonia in the environment, thanks to the absorbing property of the CNT. Changes in the properties of the carbon nanostructures will cause antenna-microchip mismatch and gain variations, readable through turn-on and backscattered power measurements.

Basic information on the motion of the tagged object can be achieved by including a mechanical device onboard the antenna. For instance, a two-chips tag can be connected to one-bit accelerometers (Philipose *et al.*, 2005), made of two mercury switches, each in series with one chip. By mounting the switches in an anti-parallel configuration, a "binary-code-shift keying" is achieved. The identificator ID1 is returned when the acceleration is parallel to the first switch, while the ID2 when acceleration is parallel to switch 2. Such a code-shift keying can also be achieved by resorting to inertial switches, which connect one of the two ICs to the antenna depending on the direction of the movement (**Fig. 7**) (Occhiuzzi and Marrocco, 2010).

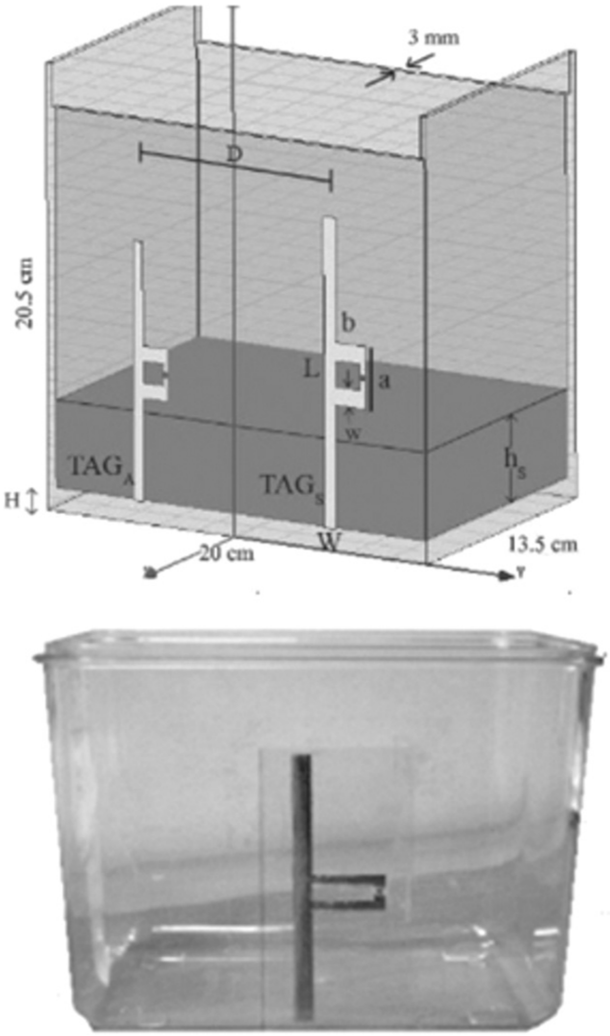

Fig. 3 Bare sensor-antennas for the sensing of filling level. Modified from Marrocco, G., Amato, F., 2009. Self-sensing passive RFID: From theory to tag design and experimentation. European Microwave Conference 1-4.

Design and Usability

Sensing capabilities are generally achieved at the expense of the degradation of the read distance since the changes of physical/chemical features of the environment are sensed by the passive tag through a deviation from its static gain and/or impedance matching. The true effectiveness of the antenna-as-sensor, therefore, is constrained to the tradeoff between sensing and communication.

The optimal configuration of the antenna has to be determined case by case by a synthesis of the sensor-as-antenna response, $\{P_{R\longleftarrow T}, P_{in}^{to}, \varphi, AID\} \longleftrightarrow \Psi(t)$, by proper shaping of the geometrical sizes, $A = \{a_1, ..., a_K\}$, of the antenna or of the eventual loading elements. Such a problem can be formalized as the minimization with respect to A of a multi-objective function, conveniently using a stochastic optimizer, such as the Genetic Algorithm or the Particle Swarm.

The effective capability and the achievable performances in term of precision and accuracy are defined at the system level by considering together tag, reader and communication link. The bare-antenna sensing mechanism is non-specific since the sensed data may be only indirectly related to a physical phenomenon under observation. By loading the antenna with a sensitive element, a more specific ad robust response can be instead achieved. Measurement uncertainties, unintentional environmental interactions, misalignments and resolution of readers play a major role in the data accuracy (**Fig. 8**) (Occhiuzzi and Marrocco, 2016). The environment-independent indicator, such as the analog identifier, revealed to be a more stable and robust metric, even if its dynamic range, and accordingly the corresponding sensing resolution, is generally lower than that of power metrics.

Additionally, data processing can benefit from automatic classification algorithms that can contemporarily manage multiple signals and limit the uncertainties by implementing learned recognition schemes. For example, **Fig. 9** shows RSSI measurements regarding ten tags simultaneously read for a given time; such measurements can be exploited for motion sensing through pattern recognition algorithms.

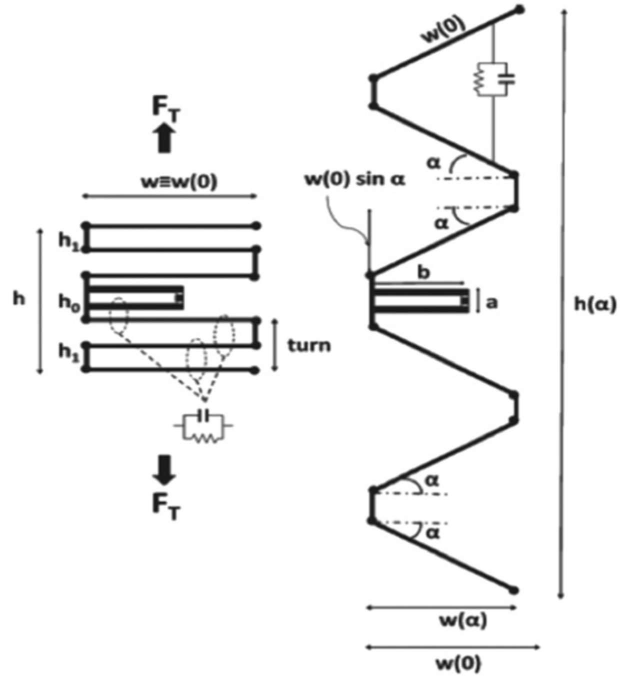

Fig. 4 Meander-line antenna for strain monitoring. From Occhiuzzi, C., Paggi, C., Marrocco, G., 2011a. Passive RFID strain-sensor based on meander-line antennas. IEEE Transactions on Antennas and Propagation 59 (12), 4836–4840.

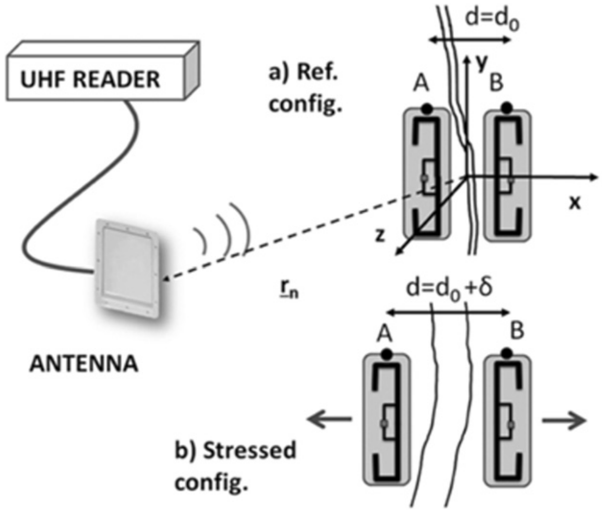

Fig. 5 Crack-sensor composed of two RFID tag antennas. From Caizzone, S., Di Giampaolo, E., Marrocco, G., 2014. Wireless crack monitoring by stationary phase. IEEE Transactions on Antennas and Propagation 62 (12), 6412–6419.

Sensing Through Auto-Tuning Antennas

The uncertainty affecting the antenna-as-sensor measurements due to the propagation channel can be strongly mitigated by exploiting auto-tuning (also known as self-tuning) ICs. An auto-tuning microchip can dynamically change its internal radiofrequency (RF) impedance to match that of the hosting antenna and maximize the power transmission coefficient. Accordingly, it can compensate for changes in the operating environment and preserve the antenna's radiation performance. The IC can also return a digital metric, generally named *sensor code* (SC), which is proportional to the retuning effort and can be employed to sense variations in the boundary conditions. Therefore, auto-tuning-based sensors use the SC for sensing while achieving stable communications thanks to automatic impedance matching.

ICs provided with the auto-tuning feature can be modeled as a resistor connected in parallel with a switchable network of capacitors (**Fig. 10**(a)) (Caccami and Marrocco, 2018). Accordingly, the equivalent input admittance of the microchip is given by a

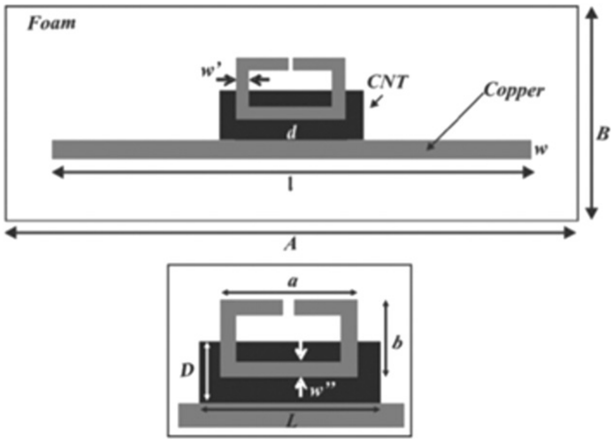

Fig. 6 Chemical-sensing loaded antenna of an RFID tag. The antenna is a loop-driven flat dipole doped with CNT. From Occhiuzzi, C., Rida, A., Marrocco, G., Tentzeris, M., 2011b. RFID passive gas sensor integrating carbon nanotubes. IEEE Transactions on Microwave Theory and Techniques 59 (10) (pp. 2674–2584).

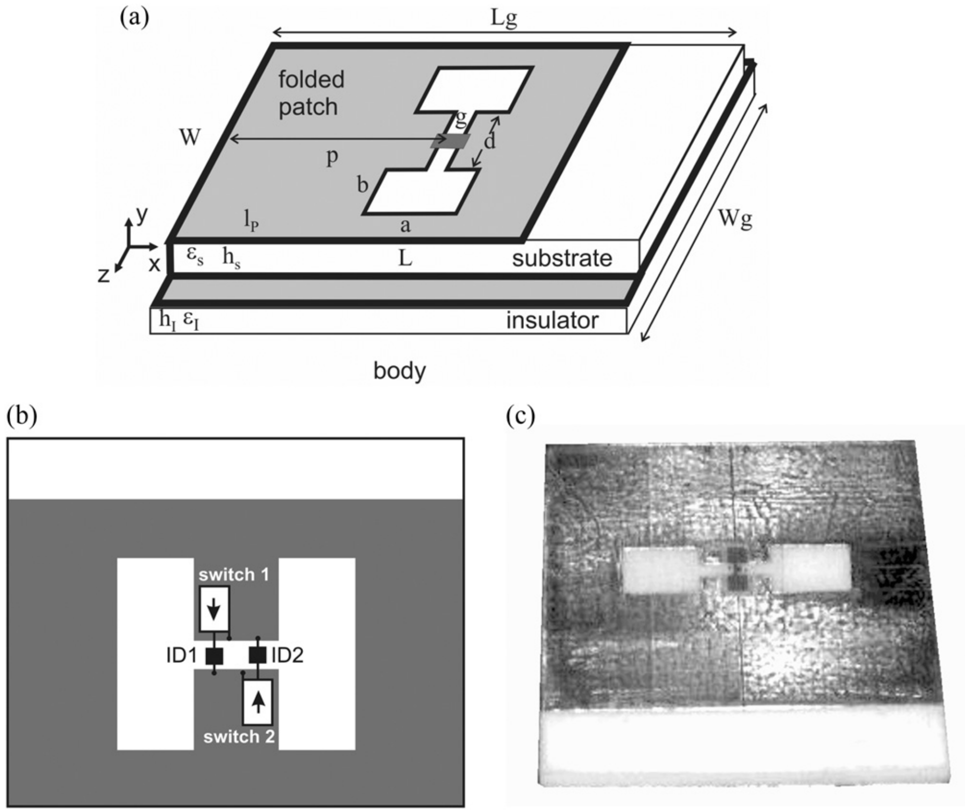

Fig. 7 Antenna integrated with two inertial switches connected with one IC each. One of the two IC is connected based on the movement direction, and the corresponding ID is transmitted. (a) Scheme of the folded patch on the human body, (b) the two inertial switches and the respective direction of actuation, and (c) a sensor-antenna prototype. Modified from Occhiuzzi, C., Marrocco, G., 2010. The RFID technology for neurosciences: Feasibility of Limbs' monitoring in sleep diseases. IEEE Transactions on Information Technology in Biomedicine 14 (1), 37–43.

fixed conductance and a variable susceptance:

$$Y_{IC} = g_{IC} + j\omega C_{IC}$$

where Y_{IC}, g_{IC} and C_{IC} are the admittance, the conductance and the capacitance of the chip, respectively. The variable capacitance $C_{IC}(n) = C_{\min} + nC_0$ can span from a minimum value $C_{\min}$ to a maximum value through an incremental step C_0. The number of equivalent connected capacitors n varies to compensate the antenna's admittance seen by the IC (Y_A) according to the following self-tuning equation:

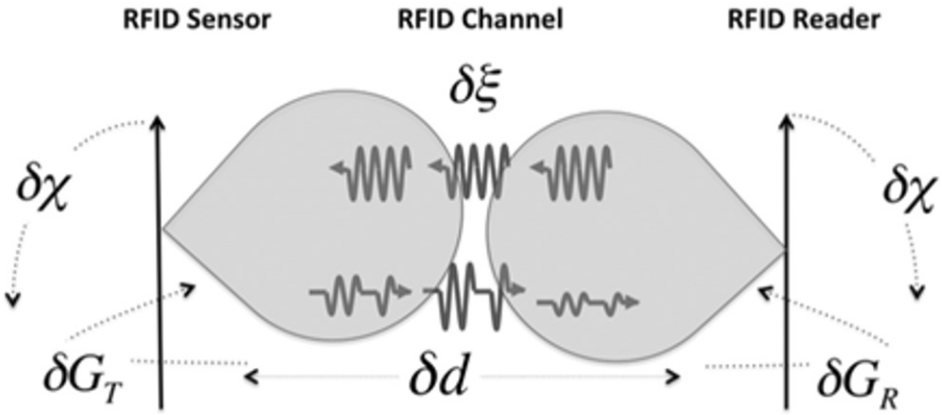

Fig. 8 Components of an RFID platform for sensing purposes (reader, propagation channel and sensor tags). The uncertainty sources $\{\delta G_R, \delta G_T, \delta\chi_P, \delta d, \delta\xi\}$ are the variations on the reader antenna gain, tag antenna gain, polarization, distance, and environment other than the measurand, respectively. From Occhiuzzi, C., Marrocco, G., 2016. Precision and accuracy in UHF-RFID power measurements for passive sensing. IEEE Transactions on Antennas and Propagation 16 (9), 3091–3098.

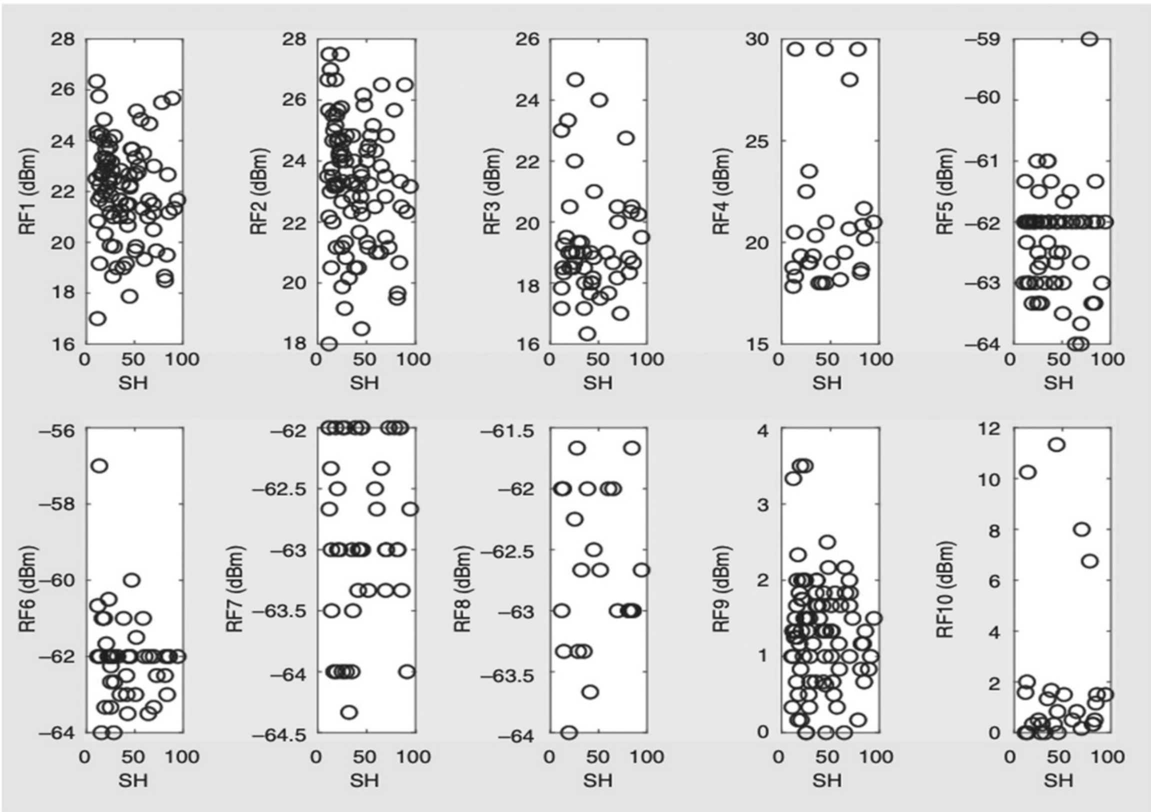

Fig. 9 RSSI measurements from 10 tag antenna simultaneously queried by a single reader for a given period. From Occhiuzzi, C., D'Uva, N., Nappi, S., *et al.*, 2020. Radio-frequency-identification-based intelligent packaging: Electromagnetic classification of tropical fruit ripening. IEEE Antennas and Propagation Magazine 62 (5), 64–75.

$$|B_A + B_C| = 0$$

where $B_A = \mathrm{Im}(Y_A)$ and $B_C = \mathrm{Im}(Y_C)$ are the susceptance of the antenna and the IC, respectively. The self-tuning equation achieves the perfect susceptance matching and optimizes the power transmission coefficient.

The auto-tuning antennas can be used for sensing purposes by exploiting the relationship between the antenna admittance and the physical parameter Ψ to monitor. If the auto-tuning IC works in the linear range, the SC value can be evaluated from the antenna susceptance as

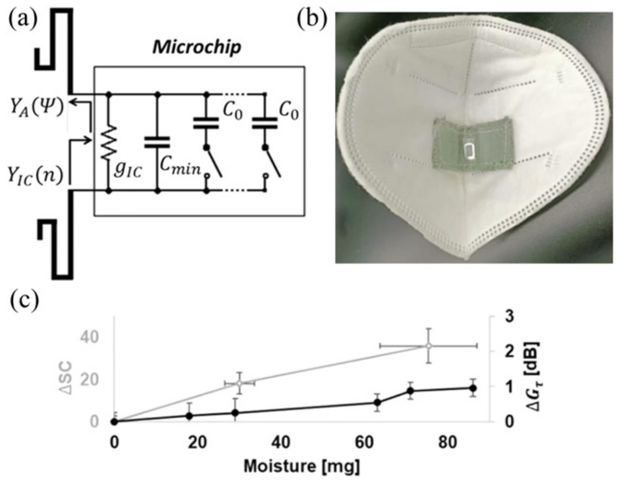

Fig. 10 Modeling of auto-tuning integrated circuits. (a) Equivalent model. From Caccami, M.C., Marrocco, G., 2018. Electromagnetic modeling of self-tuning RFID sensor antennas in linear and nonlinear regimes. IEEE Transactions on Antennas and Propagation 66 (6), 2779–2787. (b) Filtering facepiece respirator (FFR) tagged with an auto-tuning antenna-sensor. From Bianco, G.M., Marrocco, G., 2021. Sensorized facemask with moisture-sensitive RFID antenna. IEEE Sensors Letters 5 (3), 1–4. (c) Relationship between the Differential SC and the realized gain variations when the moisture inside the FFR increases. Based on (Bianco and Marrocco).

$$SC(\Psi, \omega) = N_{\min} + nint\left\{-\frac{1}{C_0}\left[C_{\min} + \frac{B_A(\Psi)}{\omega}\right]\right\}$$

where *nint* is the nearest integer number. The antenna susceptance B_A is unknown; thus, the relationship $SC(\Psi)$ must be experimentally determined through a calibration curve.

Application-specific baselines can be removed by calibrating the sensor code w.r.t. a reference condition Ψo introducing the Differential Sensor Code $\Delta SC(\Psi)$:

$$\Delta SC(\Psi) = SC(\Psi) - SC_0.$$

Auto-tuning antennas are highly susceptible to permittivity changes of the tagged object. For instance, this feature can be employed for estimating the moisture inside a filtering facepiece respirator (FFR) through an appropriate textile substrate. In this way, the antenna acts as a moisture sensor and can sense an excessively wet FFR which may not work anymore (**Fig. 10**(b,c)) (Bianco and Marrocco, 2021).

Sensing through auto-tuning antennas is possible only if the IC works in given conditions. If the retuning effort is huge or the power delivered to the antenna is excessive, the relationship between the SC and the measurand will be distorted by nonlinear effects that can hinder the sensor effectiveness. Constrained design techniques accounting for the nonlinearities are employed to simultaneously maximize the tag sensitivity and the read range (Bianco, *et al.*, 2020).

Auto-tuning antennas can also be exploited to simultaneously sense two physical parameters, provided that they independently affect the antenna's conductance and susceptance. While the auto-tuning perfectly compensates the susceptance variation, the conductance mismatch causes a reduction of the realized gain $\tilde{G}$. Accordingly, the sensor code and the RSSI will be used to sense a parameter each.

The antenna exploitation as a transducer can be further engineered by resorting to additional transduction mechanisms onboard the antenna, e.g., a humidity-dependent capacitance and a thermal-dependent resistance.

Conclusion

Antennas can be used as low-cost sensors by exploiting their natural electromagnetic coupling with nearby objects. Optimal results are achieved when the antennas are empowered with a battery-less microchip transponder according to the paradigm of Radio-frequency Identification. They can be used where accuracy is not the main issue as they mostly provide qualitative information. However, these devices can be embedded into objects and products and, therefore, they can be exploited over a large scale, thus becoming the building brick of the Internet of Things.

References

Bianco, G.M., Marrocco, G., 2021. Sensorized facemask with moisture-sensitive RFID antenna. IEEE Sensors Letters 5 (3), 1–4.
Bianco, G.M., Amendola, S., Marrocco, G., 2020. Near-field constrained design for self-tuning UHF-RFID antennas. IEEE Transactions on Antennas and Propagation 68 (10), 6906–6911.
Caccami, M.C., Marrocco, G., 2018. Electromagnetic modeling of self-tuning RFID sensor antennas in linear and nonlinear regimes. IEEE Transactions on Antennas and Propagation 66 (6), 2779–2787.

Caizzone, S., Di Giampaolo, E., Marrocco, G., 2014. Wireless crack monitoring by stationary phase. IEEE Transactions on Antennas and Propagation 62 (12), 6412–6419.
Capdevila, S., Jofre, L., Romeu, J., Bolomey, J. 2011. Passive RFID Based Sensing. In: Proceedings of the IEEE International Conference on RFID Technologies and Applications. pp. 507–512.
Marrocco, G., 2011. RFID grids: Part I—Electromagnetic theory. IEEE Transactions on Antennas and Propagation 59 (3), 1019–1026.
Marrocco, G., Amato, F., 2009. Self-sensing passive RFID: From theory to tag design and experimentation. European Microwave Conference. 1–4.
Mohammad, I., Huang, H., 2011. An antenna sensor for crack detection and monitoring. Advances in Structural Engineering 14 (1), 47–53.
Occhiuzzi, C., Marrocco, G., 2010. The RFID technology for neurosciences: Feasibility of Limbs' monitoring in sleep diseases. IEEE Transactions on Information Technology in Biomedicine 14 (1), 37–43.
Occhiuzzi, C., Marrocco, G., 2016. Precision and accuracy in UHF-RFID power measurements for passive sensing. IEEE Transactions on Antennas and Propagation 16 (9), 3091–3098.
Occhiuzzi, C., Caizzone, S., Marrocco, G., 2013. Passive UHF RFID antennas for sensing applications: Principles, methods, and classification. IEEE Antennas and Propagation Magazine 55 (6), 14–34.
Philipose, M., Smith, J., Jiang, B., *et al.*, 2005. Battery-free wireless identification and sensing. IEEE Pervasive Computing 4 (1), 37–45.
Rizzoli, V., Costanzo, A., Montanari, E., Benedetti, A., 2009. A new wireless displacement sensor based on reverse design of microwave and millimeter-wave antenna array. IEEE Sensors Journal 9 (11), 1557–1566.
Su, C.H., Wu, H.W. 2019. An antenna sensor to identify finger postures. In: Proceedings of the IEEE Eurasia Conference on IoT, Communication and Engineering (ECICE), 571–574.
Vena, A., Perret, E., Kaddour, D., Baron, T., 2016. Toward a reliable chipless RFID humidity sensor tag based on silicon nanowires. IEEE Transactions on Microwave Theory and Techniques 64 (9), 2977–2985.